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Energy, Disaster, Climate Change: Sustainability and Just Transitions in Bangladesh

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GOVERNMENT OF THE
PEOPLE'S REPUBLIC OF BANGLADESH
DHAKA

I am very delighted to learn that the Asian Institute of Technology (AIT), Thailand is going to publish a Bangabandhu Chair Special Issue of International Energy Journal titled **"Energy, Disaster, Climate Change: Sustainability and Just Transitions in Bangladesh"** dedicated exclusively to the Sustainable Energy Development discourse of Bangladesh. It is indeed a great honour for us that a prestigious academic institution such as AIT is publishing this Bangabandhu Chair special journal at a time when the people and government of Bangladesh are celebrating the birth centennial of Father of Nation Bangabandhu Sheikh Mujibur Rahman (Mujib Year- 17 March 2020-17 March 2021). I commend AIT on its noble initiative to disseminate pertinent information on sustainable energy to experts, students and practitioners for valuable reference purposes. On the part of AIT this is a fitting honour to the Father of the Nation Bangabandhu Sheikh Mujibur Rahman and his lasting legacy.

I express my sincere thanks to the AIT and particularly 'Bangabandhu Chair' Professor and Doctoral Research team for their arduous research work on sustainable and integrated smart energy modelling for Bangladesh under the priceless support and tutelage of AIT. Bangladesh is keen to develop its national institutions and share best practices for sustainable energy, climate change mitigation and adaption. I am confident that future research and policy advocacy initiatives of AIT would focus on disaster risk reduction and preparedness mechanisms. The Delta Plan 2100 that Bangladesh aspires to implement with the support of local and international experts and professionals could be a subject matter for detailed academic scrutiny at the AIT campus under future collaborative programmes. I hope that Bangabandhu Chair Professor at AIT will make new initiatives on energy and climate research for the benefit of the future generation of scholars and practitioners in both countries as well as in the global arena.

(Dr. A. K. Abdul Momen, MP)

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Energy, Disaster, Climate Change: Sustainability and Just Transitions in Bangladesh

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To Quote Bangabandhu Sheikh Mujibur Rahman:

"My greatest strength is the love for my people, my greatest weakness is that I love them too much."
{from : https://quotes.yourdictionary.com/author/sheikh-mujibur-rahman/}

"It is not possible to build golden Bengal without golden people"
(The last public address at Suhrawardy Uddan, 26 March 1975)

"I do not say anything to intellectuals. I respect them. I would only say this to them that, please use your intellects for the welfare of the people. I do not say anything more than this".
(The last public address at Suhrawardy Uddan, 26 March 1975)

"As a man, what concerns mankind concerns me".
(Unfinished Memoirs, 3 May 1973)

"We can suffer but we don't die. People's strength is the biggest force for the challenge of survival. Our aim is to achieve self-dependence"
(Addressing the United Nations, 23 September 1974)

"The world is divided into two halves, the oppressed and the oppressors. I am with the oppressed".
(At the conference of Non-Alliance Movement, Algiers, 6 September 1973)

(from: https://www.7thmarch.com/quotations/)

1. INTRODUCTION

Bangladesh, a country of 160 million people with declining population growth rate, to deliver human wellbeing equitably is justifiably poised for high economic growth rate. Framing 21st century economic growth agenda to achieve not only narrowly focused GDP (Gross Domestic Product) growth but focused towards human wellbeing is especially challenging for countries who are late comers in the economic development process compared to those who experienced fast growth phase during the past century. As of now, in the South Asian region, Bangladesh is the fastest growing economy. In 2015 the country leaving behind the status of a least developed country crossed the bar and entered into the Lower Middle-Income Country group as per World Bank's classification. The country has declared the aspiration of reaching the developed country status by 2041. Bangladesh is passing through rapid transitions in multiple dimensions and sectors to attain transformative change within the next two decades. Going by the historical antecedents from around the Asian region, the timeframe to attain the aspiration level appears to be achievable technologically and economically. How social justice and fairness issues will get addressed within the country especially in a carbon constrained world is central to the scientific debate today globally as well as regionally and nationally.

How far Asian historical antecedents can guide future socio-economic-environmental growth pattern of Bangladesh is open for debate at this juncture of time. Challenges of 21st century fast growing economies are unique as global common goal of sustainable economic growth is an accepted frame for work to all the countries since the millennium summit of 2000. In this connection, committed expenditure on energy infrastructure and likely growth in investment centered around the energy sector is growing in multiple directions. Energy will continue to be of central importance over at least next three decades to push and thereafter stabilize the economy on a higher economic growth trajectory for coping with major equitable human wellbeing needs of 21st Century Bangladesh. Climate change concerns and also an additional need to become resilient to increasing threats of disasters with already

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~1° C temperature rise for countries with poverty and lower level of development are added constraints towards growth (Roy *et al*. 2018). Understanding the current status and critical analysis of opportunities are important to find solutions. Humanity progressed through learning by doing but visioning of possible pathway for development is a prerequisite (Roy et. al., 2019). However, it is undeniable that fundamental need is to make the energy sector sustainable, secure and disaster resilient as it holds the lifeline of economic and social growth within planetary boundaries. Recurrent and cascades of natural disasters and climate change induced challenges that threat Bangladesh make the developmental challenges complex.

2. SOME RELEVANT IMPORTANT CONCEPTS IN RECENT DEVELOPMENT DISCOURSE

Human wellbeing is the ultimate goal of humanity's progress towards well living (Hayward and Roy 2019). One intrinsic challenge of energy for development in the context of Bangladesh is how to meet the increasing demand for energy services and under what fuel mix. Procedural justice demands faster provision of modern energy sources to all. Question is how to meet this imperative without worsening climate system and enhancing disaster risks. As Bangladesh aims for catching up with developed country status by income growth indicator such as Gross Domestic Product (GDP) it can manage this transition path from middle income status of today to set an example where social inequity and environmental damages are kept to the minimum. No single indicator or action can measure multidimensional progress of a nation. This is now well established and acknowledged in the literature (Dasgupta et al., 2015). Unless a broader human wellbeing perspective is taken as goal of the fast-growing economy multidimensional challenges cannot be addressed adequately and peacefully. Interestingly many industrialized countries are making it a political agenda to adopt human wellbeing rather than income growth as a national developmental goal (OECD 2019).

There is clear shift now from traditional development models to Sustainable Development models to work with for enhancing human wellbeing within planetary boundaries. Sustainable development defines those developmental efforts as sustainable which not only benefits the current generation but also ensures without undermining welfare of the future generation by at least maintaining and investing in the productive base of the economy. While Daly's operational principle (Hanley. N, J. Shogren and B. White 1999) talks about investing the income earned from exhaustible resources to develop service flow from renewable resources, reducing cumulative pollutants to zero, respect for natural growth and assimilative capacity of the environmental and natural resources are equally emphasized. Those who believe that technology does play a role in advancing human activities accept the substitution possibilities among various capital forms: natural, human and manmade. There can be debate about the magnitude and extent of this substitution possibilities but the take home message from this discourse is every nation and all economic actors need to focus on managing the capital portfolio with at least three assets in it: physical man made, natural and human- through genuine investment (Roy 2013). So, developmental discourse is going beyond single dimensional indicator defined by income alone/ GDP as an indicator of development and getting into the realm of multiple indicators with links to natural capital and resource endowments and management of them. From this interlinkage (Figure 1), operational principles for sustainable development is becoming a global action agenda through political endorsement in international cooperation of the Millennium Summit, Millennium Development Goals (MDGs) and various 2015 cooperative agreements. Since 2015, the landmark UN agreements (*e.g.*, the Sendai Framework for Disaster Risk Reduction [SFDRR], Paris Agreement, and Sustainable Development Goals have set the goals, targets, priorities for practical actions to reset and pre-set the developmental actions on Sustainable Development Path by 2030 (Pal 2020).

Climate Change is an unprecedented challenge to developmental process of this century (Roy 2009). Never before geographically fragmented world had to think of managing a global common asset like climate system. Fragmented goals, fragmented decisions were the development way. To avoid further worse impacts of climate change, it is important to keep global temperature rise well below 1.5°C and for that the global economy must achieve net-zero emissions by middle of this century (IPCC 2018) (Jackson *et al.* 2017). It is very clear that energy supply and demand sectors need to transform emissions from current fossil fuel use pattern to contribute the maximum to this mid-century net zero target. Land use and ocean sector also have very significant roles to play but energy sector is going to be the leader for transformation. This provides both challenges and opportunities for the energy sector for all countries. Crisis from climate induced changes will be larger, deeper and far reaching than that of the financial meltdown of 2008 and the global pandemic of 2020. With this comes unlimited opportunities to work on projects with long-lasting positive impacts. It needs to be in the mainstream discussion that Greenhouse Gas emission 'reduction' itself is an economic activity and an opportunity to find new investments, social practices and values and lifestyles (Roy and Pal 2009). New economic activities are going to be around investments on low carbon and no carbon activities. The prosperous economies are going to be those which recognize that the solution lies in additional investments on natural and environmental resource development. Sustainable development, environmental services are becoming key drivers of businesses. Late comers in development process have the advantage of becoming early movers in the new economy which adopts holistic approach toward human existence (Roy 2009).

Natural hazards can pose serious threat to a country's economy as well as people. Assessment and monitoring of any natural hazards like cyclone, flood, earthquake, landslide, etc. in a region are of vital importance for the enterprises responsible for disaster risk reduction (DRR) and disaster risk management (DRM) (Sekac et al, 2016). With changing climate compounded risk due to interaction of multiple hazards or events that combine to produce extreme disasters are capable of generating widespread losses (IPCC, n d.) through cascading effects. The idea behind **cascading effects** is that primary event can trigger a chain of effects that can, in turn, cause secondary consequences amplifying the magnitude of primary event. As the matter of fact, cascading effects are non-linear, complex, and multidimensional and evolve constantly over time. In case of disasters, the impact of physical events or the development of a principal technological or human failure generate an escalation of secondary effects in other human or non-human systems that result in physical, social, or economic disruption. This escalation is more problematic than primary calamities because of their impacts on critical infrastructures, which represent vital elements to the preservation of social functions (Alexander 2013, Pescaroli, 2016). Resilience to energy infrastructures to achieve the priorities laid down in UN Sendai Framework for Disaster Risk Reduction 2015-2030 is paramount for the sustainable societies and achieving overall development agendas especially for Bangladesh, which is recently graduated from Least Developed country (LDC) to Low-Middle income country.

Disaster and Bangladesh

According to *Asia Pacific Disaster Report 2015 (UN-ESCAP*), Bangladesh is one of the most vulnerable among 15 countries with high exposure (10^{th} in exposure) and risk (5^{th} in risk) respectively. Every year the country faces many natural disasters like floods, cyclone, tidal surges, tornado, thunderstorm, river and costal erosion, landslides, salinity intrusion, hailstorm, extreme weather events etc. It is therefore likely that both acute hazards (such as flooding or cyclonic events) and chronic hazards (drought, sea level rise and saline intrusion, for example) will be more damaging to human lives and properties in the contexts of flourishing economic conditions where more investments will create more economic activities, *e.g.* infrastructure and human engagements in areas susceptible to different hazards.

Traditionally the country's disaster coping capacity evolved in reactive mode based on the lessons learned from success and failures of disaster management actions and processes. The Bengal Famine of 1943, severe consecutive floods in the years 1953, 1954, 1955, severe cyclone in 1970, famine in 1974 due to Brahmaputra flooding and crop failure, widespread and prolonged floods in 1987, 1988, cyclone strike in 1991, then cyclone Sidr in 2007 and Aila in 2009 are all big disaster events in Bangladesh in the past half century. The *floods* of 1988, 1998, and 2004 were catastrophic resulting in large scale destruction of physical assets and properties, loss of lives. A total of 129 cyclones of different categories hit Bangladesh coasts from 1978 to 2013 with annual mean occurrence of 3.6. It is important to note that cyclones appeared to be the deadly disasters in Bangladesh. Cyclones caused about 90 percent (567587 numbers) of total deaths due to natural disaster during 1950 – 2016 (EM-DAT, 2016). *Earthquake* poses threat to the lives of people, damage of property and economy in Bangladesh because of its location in the tectonically active Himalayan orogenic belt. In recent memories, 1997, 1999 and 2003 earthquakes in greater Chittagong regions caused local level damages. Study suggests that around 250,000 buildings in the three major cities- Dhaka, Chittagong and Sylhet are extremely vulnerable to earthquakes (MoDMR 2015).

Climate change is accelerating the intensity and frequency of disasters. Disasters have been the main contexts for centuries for Bangladesh communities within which they have been adapting to the challenges for everyday living and gradually strengthened capacities to thrive. Bangladesh could attain economic growth >6% through the last decade, boost budget revenue and strengthen financial discipline; poverty declined from 40% in 2005 to 24.7% in 2014) despite being exposed to natural hazards and unprecedented human migration in the region. It was estimated in the past that 14% of Bangladesh's GDP is exposed to disasters on an annual basis (Planning Commission, 2012). However, now with changing climate context disaster and sustainable development have become more complex as the speed of traditional adaptation is considered to be much slower than the speed of changes expected under changing climate. So special attention is needed in the intersection of energy, climate change and disasters with human wellbeing at the centre and sustainable development as the model of growth (Figure 1).

National reports on climate change in Bangladesh (*e.g.* National Communication Reports to UNFCCC 2002 and 2012, BCCSAP 2009, INDC 2015) give accounts on climate change trends and describe impact. The reports mention that the contributions of Bangladesh to global greenhouse gas (GHG) is less than 0.35% but the country is likely to experience the highest level of impacts. It is also suggested in the national documents that no action or limited actions would cause the country to lose 2% of the GDP by 2030 and 9.4% by 2050 (INDC 2015) and these will lead to more poverty ridden conditions, impact human wellbeing dimensions, result in displacement of millions of people. The most important issue to mention here is that local understanding on climate change is still poor. The local understanding based on critical assessment of climate variabilities (*e.g.* temperature, rainfall, humidity, wind direction, sunshine hour, wind pressure etc.) are inadequate. Less efforts in commissioning scientific research projects which is cardinal to data driven rational policy/decision making is one of the primary reasons why tackling climate change problems still remain in difficulty in Bangladesh (Islam and Neelim 2010), Brammer (2014), Shamsuddin *et al.* (2015), Alam (2011). The government of Bangladesh carried out research investigations such as CPEIR (Climate Public Expenditure and Institutional Review 2012), CFF (Climate Fiscal Framework 2014, 2018) aiming towards mainstreaming and align necessary instruments

(Development Project Proposal, DPP by Ministry of Planning; and national account tracking system through Budget and Accounting Classification System, BACS by Ministry of Finance etc.). In this contexts, science driven policy recommendations are of primary importance which can shape an action agenda for sustainable development path for Bangladesh in coming 8th Five Year Plan.

In addition to BCCSAP and CFF, Climate change challenges are given priorities in the 7th Five Year Plan (2016-2021) including the Perspective Plan of Bangladesh. It is important to note that the government of Bangladesh plans to undertake 15 research projects as outlined in BESF (Bangladesh Environmental Statistics Framework 2016-2030 through Bangladesh Bureau of Statistics; proposed cost is about 0.5 billion USD) which are strongly aligned with UNFDES, DRSF (Disaster Related Statistics Framework), PEI (Poverty Environment Initiative - integration between poverty and environment).

This is the **first volume of the Bangabandhu Chair Special issue of *International Journal of Energy***. In this special volume our aim is to present how the intellectuals and experts from within the country, region and from outside the region situate sustainable energy transition of Bangladesh in the context of national economic growth aspiration, responses to climate risk, disaster risk and dynamics of regional cooperation and global common good goal.

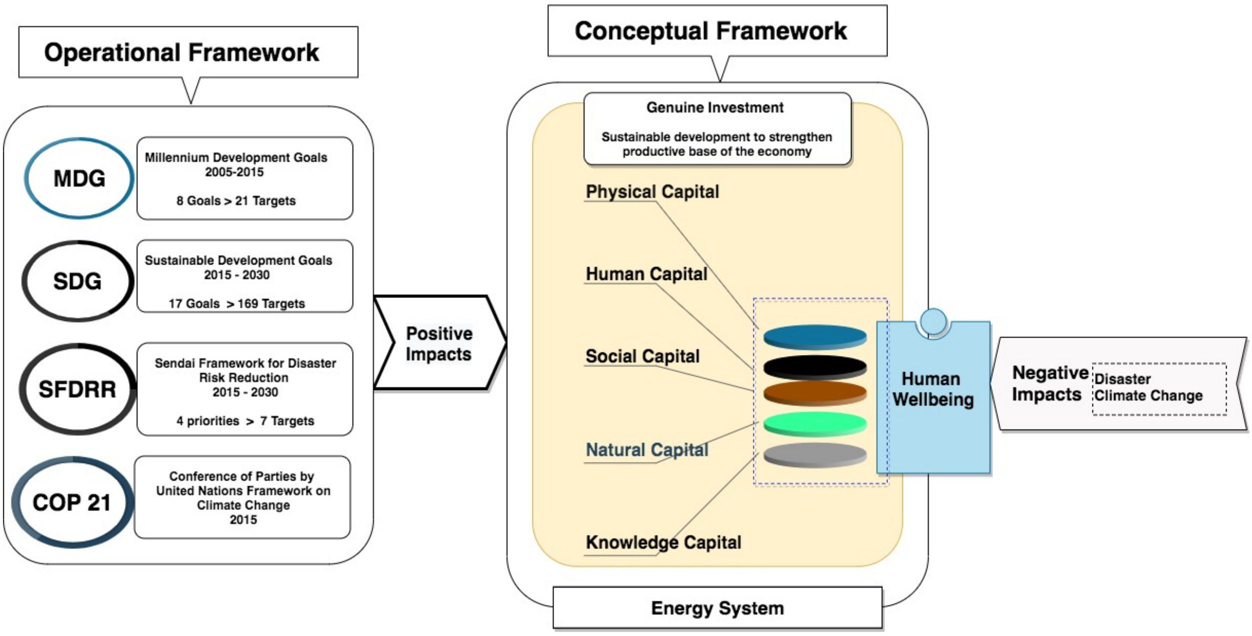

Fig. 1. Interlinkage among Human wellbeing, Disaster, Climate Change for Sustainable Development in the context of Bangladesh.

3. OUTLINE OF THE SPECIAL ISSUE

This volume examines the hypothesis that current complex developmental challenge faced by fast growing developing countries like Bangladesh provide opportunity for these countries to break away from historical single dimensional economic growth reflected through GDP centric path which created a path dependency towards increasing inequity and injustice in resource sharing and environmentally unsustainable world (Roy and Pal 2009). Countries like Bangladesh can leapfrog and adopt the new innovation paths to their own contexts for creating new path dependency towards fairness and justice by creating multidimensional sustainable development pathway (Roy et. al. 2018). So, our framework in which core is sustainable development for human wellbeing with justice allows us to take a deeper look at the (1) existing energy systems both from supply side and demand side to understand the embedded structure and scope of incremental as well as transformative change (2) find ways to minimize destructions and damages to short duration natural disasters (3) manage transition without compromising justice through proactive preparedness for reducing impacts of slow onset long term and cumulative highly likely events like climate change. The articles compiled in this journal volume through double blind peer review process address following broad research questions:

- How can Bangladesh economy grow at more than 7% through next three decades and make attempts towards setting new normal for energy supply sector moving beyond fossil fuel dependence at the same time creating decent jobs?
- What is the scope of new major innovations that can be embedded in energy demand sectors

like buildings, transport etc. through domestic and international collaboration?

- For a natural disaster exposed nation like Bangladesh how people, community and institutions interact to build resilience organically and which needs to be strengthened by scientific approaches?
- How is the nation reacting and influencing the climate change debate globally with national preparedness?

As the original inspiration for this volume comes from the thematic area "Energy Sector Development in Bangladesh" of Bangabandhu Chair endowment at AIT, Thailand by the Government of Bangladesh, Ministry of Foreign Affairs and also given the Journal's core focus on Energy, all article have focus on Bangladesh and majority of the articles focus on energy. It is complemented by articles on climate change and disasters as they pose a valid threat to sustainable energy sector development directly or indirectly. Content diversity has been managed in such a way that policy makers in Bangladesh can get useful tools and information to decide on a course of action with sustainability goal. Researchers on Bangladesh economy can get a status review of a branch of knowledge and identify the research gaps that can add value through future knowledge gap filling studies.

Fossil fuel sector which is providing energy supply of Bangladesh today cannot be continued for long time both due to resource depletion and secondly due to rising demand. The first nine articles focus on the energy supply side innovations which are technically, economically, environmentally feasible and acceptable from social justice point of view.

H. Mahmud and J. Roy set the scene by presenting the challenges for fast growing economy like Bangladesh by comparing the current challenges *vis-à-vis* Asian countries who were growing fast in the second half of the past century. The shift in global perspective of development towards sustainable development makes it an imperative for energy sector to become sustainable. This means a new innovation path and new exploration of alternative solutions for demand and supply of energy even for a country like Bangladesh.

The article by *Roy et al.,* discusses one likely energy transition roadmap for Bangladesh beyond the natural gas-based energy solution. The study proposes the new use options for the existing gas infrastructures to plan in energy system around geothermal sources. The country needs to preplan leapfrog to sustainable energy solution now. This represents the scope of energy transitions considering the current and future challenges and opportunities based on available infrastructures, human capacities and institutions.

Article by *Samanta et al.,* discusses how design optimization in Biodiesel production from palm oil can provide a sustainable alternative fuel solution for Bangladesh. The authors performed a laboratory investigation about how palm oil can effectively be converted into diesel and be used in a range of sectors where diesel is commonly used.

Article by *Katekar et al.,* makes an assessment and Way Forward for Bangladesh on SDG-7:Affordable and Clean Energy. The authors provided a comprehensive assessment of energy sector of Bangladesh by focusing on (i) decision making landscape of the sector, (ii) energy demand, production and consumption aspects, (iii) current energy-mix and heavy dependence on non-renewable gas reserve which is forecasted to be extinguished by the year 2026. The paper also made a comparative assessment of energy sectors of the South Asian countries. The authors commended the progress made by Bangladesh since independence in 1971, quoting the impressive growth rate in GDP, per capita income and at the same time called for necessary actions towards attaining SDG targets.

Article by *Manimekalai et al.,* elaborated a comprehensive guideline on what is the current status of energy storage technologies/devices and what is the current status within Bangladesh and what are the alternatives one can explore going forward. One gets an idea that globally it is the Pumped hydro storage technology which dominates the storage practices in power sector. While battery storage and the variety of options exist with chemical, thermal processes as well. The top currently winning storage device in use within Bangladesh is not the state of the art so which provides scope of new technology choice, development of enough technical and human capacity, supply chain, policy incentive, market competition for going forward.

Article by *Islam and Singh* is a futuristic case study for Bangladesh with a high growth rate of Plug-in Electric Vehicles (PEVs) (20-25%) and rooftop solar PV (8%) for decarbonization. How such changes can be handled by utilities need attention from now. The installations of solar photovoltaics (PVs) in the distribution system including rooftop photovoltaic (PVr) change the shape of the daily demand profile in a way that makes the load curve to look like a duck due to high penetration of solar energy for a specific period of daytime. So, this study provides a detailed analysis which can provide guidance for new technology and policy planning.

Arefin et al., highlight the current state of research taking place in Bangladesh regarding the development of photovoltaic solar cells and the potential for thin-film solar cells to effectively harness solar energy. The use of different kinds of plasmonic metal nanoparticles (NPs) such as core-shell NPs, NP dimers made of metallic alloys and hybrid bow-tie shaped NPs with thin-film solar cells are discussed. These nanoparticles are found to significantly improve the efficiency of thin-film solar cells. It is expected that fabrication of such plasmonic solar cells will not pose a major technological challenge due to the advanced stage of fabrication technology of Si due to its widespread use in the electronics industry. Hence, Bangladesh can also have bright prospects to be a part of a multi-billion-dollar solar cell industry and become a market leader like it is in the ready-made garments (RMG) industry. Thus such "plasmonic solar cells" with a higher current conversion efficiency can lead to fewer solar cells needed to produce a specified amount of electricity, and thus potentially significantly reducing the price and increasing the accessibility of the "green energy" in developing nations like Bangladesh.

Gorantla et al., shows in a rapidly urbanizing country energy saving is one of the opportunities which needs to be used for reducing burden on supply side. How proper selection of window glasses reduces the energy consumption in the built environment is explained. The objective of this work is to ascertain the best glazing and its orientation to save the high air-conditioning costs in buildings of the Dhaka in Bangladesh. This article presents the experimental results of solar optical characteristics of four different glasses such as clear, tinted bronze, tinted green, and bronze reflective glasses. Burnt brick buildings were modeled with four different glasses and analyzed for air-conditioning cost-saving prospects.

Article by *Ruba Al-Foraih et al.,* emphasize the importance of developing the transportation infrastructure to reduce dependence on private vehicles and to encourage the use of public transportation facilities. The method paper evaluates the economic impact of implementing energy efficiency strategies in the transportation sector using a system dynamic model and associated scenario analysis that can be applied to Bangladesh.

The article by *Hossain et al*., provide an insight on high seismic risk on energy infrastructures in Bangladesh due to the seismogenic gaps in the active faults. Author mapped the exposure and seismic vulnerability of energy infrastructures in Bangladesh and, *e.g.*, gas fields, gas production facilities, processing plants, gas transmission network, oil refinery, power grid. The study also suggests, guidelines based on a comprehensive seismic zonation map and site-specific probabilistic seismic hazard map for all major engineering constructions, specifically large-scale energy infrastructures.

The discussion by *Khan et al*., introduces new form of discussions for possible integration of the issues like energy security, disaster risk management and climate change. The authors show the importance of energy in disaster management vis-à-vis emergency response and recovery processes. In doing that synergies among the sectors and related challenges are identified and a number of suggestions towards integration are provided.

Sanyal et al. conducts a comparative assessment of coastal hazards and their resultant impacts on communities and physical systems/resources in the countries located in the Asian coastal regions and maritime areas. The authors also discuss the types of natural hazards in Asian coastal countries and categories based on exposures to hazards. The paper primarily focused on climate induced hazards and vulnerability that are narrated in the National Communication Reports (NCR) submitted to UNFCCC by 22 coastal countries of Asia. The paper explains that complex and interconnected human-nature interface in the coastal areas evolved based on the long-term knowledge, understanding, and familiarity of the coastal communities with the systems and resources they are settled in.

The authors *Esraz-Ul-Zannat et al.* assess the impacts of climate change induced disasters in southwestern coastal city Khulna, Bangladesh. The city faces a number of hydro-meteorological hazards such as urban flooding, waterlogging which creates different kinds of secondary forms of impacts like waterlogging, overflow of sewers, scarcity of safe water in the city. The authors indicated that the locational attributes of the city such as flat and low-lying topography and its proximity to the Bay of Bengal made this coastal city susceptible to hazards which will be exacerbated under the influence of climate change, especially sea level rise and extreme weather conditions. The authors examine the likely impacts of sea level rise by performing different kinds of city-scale spatial analysis.

The article by *Islam et al*., reviewed the chronological progression on climate change knowledge and actions in Bangladesh to understand the climate resilient development. The study also indicates decisions, actions, and interventions in regard to climate change turbulence in the conceptualization of the crisis, impact reduction project formulation, finance management, and implementation processes. The study characterizes the climate-resilient development through mainstreaming climate change investments / expenditures of the government of Bangladesh. The chronology of significant works on climate change in Bangladesh undertaken by different agencies since 1989 is useful documentation.

Finally, an interesting aspect of this volume, from a sustainable development perspective, is that all of its lead authors, as well as a large majority of its other contributing authors, are from the region and from the country. While this author mix outcome has been mostly incidental, as it is outcome of an open call for papers widely circulated, it does demonstrate that there is a pool of highly qualified researchers and thinkers all around the world ready to commit time and effort to influence academic and policy discourses at the highest levels in the field of sustainable energy transformations, climate change and disaster risks in the context of Bangladesh. Unfortunately, despite the efforts of the editors it was not possible to keep all the submissions as 30% had to be rejected after double blind peer review process either due to divergence of the objectives from the thematic goal of this special issue or because they did not satisfy the scientific rigour and standard of the Journal.

Guest Editors synthesizes the recommendations that emerge from the research studies and presents at the end in the form of a white paper which will be useful for decision makers in Bangladesh. Guest editors acknowledge with thanks cooperation from a large number of experts from various continents and institutions for their full cooperation, sometimes very tight timeline for review, taking the burden of reviewing more than one article, and sometime to review twice/thrice after resubmission in response to review comments. We acknowledge with thanks the voluntary time commitment of reviewers. Our sincere thanks to all the experts Professors/Dr/Ms/Mr. Abdul Salam, Amir Safari, Alak Pal, Anamika Barua, Anjal Prakash, Anupa

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Sustainable Energy Sector for Fast Growing Economy like Bangladesh: How Relevant are the Past Asian Precedents?

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Hasan Mahmud*, [1] and Joyashree Roy*, #, +

Abstract – *This article presents a comparative analysis of the historical fast growth phase of the selected Asian countries-South Korea, Malaysia, Singapore and China and Bangladesh focusing on the energy sector. The countries fueled their fast growth phase in the past century by heavy dependence on high carbon fossil fuel. In the changed framing of development through climate change induced sustainability criteria, latecomers in the development process like Bangladesh of this century are better positioned to critically think in building a sustainable energy sector as majority of energy systems will be built now. Unlike Asian predecessors who might need to prematurely shut down carbon intensive energy facilities or decarbonize the existing ones at a high cost, Bangladesh has multiple opportunities to build new low carbon energy infrastructure avoiding high lock-in effect. For Bangladesh current power generation capacity is envisaged to grow by almost a factor of three over next two decades. Setting the goal of steering the energy sector on sustainable pathway through source diversification, cheap renewable and cleaner fuel penetration, energy efficiency, reliable access can not only drive the economic growth faster but positively impact human wellbeing and reduce inequity simultaneously for the fast growing Bangladesh through next two decades.*

Keywords – *Asia, Sustainable energy sector, Bangladesh, Fast growing economy, Fossil fuel.*

1. INTRODUCTION

Bangladesh with ~160 million people has attained lower middle-income country status in 2015 with ~6.5% yearly GDP growth rate over the last decade and attained over 8% growth in the 2019 [1]. This fast rate of economic development will need to be at least maintained given the committed national goal of catching up with the developed country status by 2041. Moreover, post COVID19 recovery phase necessitates this growth rate for lifting the economy from extreme job and production losses. To revive, stabilize and sustain the economic growth energy sector will play crucial role as a major driver of social, economic and environmental development. One class of traditional development economics literature [2] argues in favor of looking for precedence in catching up by the late comers in development process through replication of development process of predecessors. While leapfrog is also shown as a possible way forward option where there is no need to follow the same historical path of development stages. In this paper, we present lessons learnt from an analysis of the historical fast growth phase of the selected Asian countries -South Korea, Malaysia, and Singapore focusing on the energy sector. Evidence clearly show these countries during last five decades fueled their growth by heavy dependence on fossil fuel. Development context today in the world has moved to the goal of sustainable development especially after adopting the agenda titled "Transforming our world: the 2030 Agenda for Sustainable Development" in 2015 UN General Assembly. Around the same time Paris agreement has been signed by the countries including Bangladesh.

In this backdrop the objectives of the article are: to define first what do we mean by fast growing economy in Section 2 below and in Section 3 to compare energy supply sector of Bangladesh with Asian predecessors. Section 4 develops the narrative to show how the fast growth phase can adopt overarching sustainability goal and take advantage of changing energy market condition to create a new window of opportunity for Bangladesh towards targeting a sustainable energy sector development in next two decades. Section 5 presents the discussions and conclusions.

2. FAST GROWING ECONOMY: DEFINITION AND CONCEPT AS ADOPTED IN THIS STUDY

Economic growth is the increase of goods and services of an economy. Typically, the production of goods and services are measured by the metric Gross Domestic Product (GDP) and economic growth rate is shown by GDP growth rate [3]. Status of economic progress has been varied at any point of time across the nations and regions. While some countries experience high GDP growth (China 8.26% annual average between 2009-2017), some face moderate growth (Costa Rica 3.47% annual average between 2009-2019), some are stagnant (Finland 0.11% annual average between 2009-2019) and

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some face even negative (Greece -2.81% annual average between 2009-2017) [4]. Thus, the countries can be classified based on their historical growth rate and these can be fast growing, moderately growing, stagnant and negatively growing country based on their growth rate.

Countries are commonly classified as developing and developed from 1960 for policy discussion and resource transfer from richer to poor [5]. Although there is no formal way for defining countries as developing, 159 countries are categorized as developing by United Nations. American and European countries with Australia, Japan and New Zealand are categorized as developed, and the remaining countries are considered as developing [6]. International organizations classify the countries based on their different aspects of development as shown in Table 1. First group of LDCs was listed by the UN in its resolution 2768 (XXVI) of 18 November 1971.

Table 1. Classification of the countries by IMF, UNDP and World Bank.

Typology	IMF	UNDP	World Bank
Developed countries	Advanced countries	Developed countries	High income countries
Developing countries	Emerging and developing countries	Developing countries	Low and middle income countries
Developed countries share in 1990	13 %	25 %	16 %
Developed countries share in 2010	17 %	25 %	26 %

Source: [7]

Table 2. World Bank country classification.

Threshold	Per capita GNI (current USD), using Atlas method of WB
Low-Income	less than 995
Lower Middle Income	Between 996 and 3895
Upper Middle Income	Between 3896 and 12055
High Income	More than12055

Source: [10]

Classification criteria of IMF are i) level of income per capita ii) diversification of export iii) integration to global financial system. However, the criteria are not limited to these factors alone. Other factors are also considered for classifying the countries [8]. UNDP classify the countries depending on the value of Human Development Index (HDI) that considers various dimension of development. HDI is calculated from the three main indicators: achievement in life expectancy, income and education of a county. Besides, it also incorporates some other features of development such as political freedom, personal security and adjustment of inequality [9]. World Bank classification considers per capita Gross National Income (GNI). The most recent World Bank classification criteria are shown in Table 2 and the status of selected Asian countries are shown in Table 3.

3. ASIAN PREDECESSORS AND BANGLADESH

3.1 Comparative Analysis of Economic Growth Patterns of Selected Asian Countries

Several Asian countries experienced remarkable economic progress in the past century but over varying time periods. South Korea and Singapore achieved more that 8% annual GDP growth rate during the period 1966 to 1990. Although, in late 1990s, financial crisis hit these countries, this high GDP growth rate continued for more than 25 years. It has become an interesting example to countries, who started the development processes late, to follow the similar economic growth path in their own countries [12], [13]. Young, 1995, found that instead of total factor of productivity (TFP) improvement in these East Asian countries remarkable economic growth was driven by high growth of capital and labor input.

Table 3. Asian countries and status.

Country	Status
Bangladesh[2]	Lower middle income from 2014
China	Become lower middle income in 2001 and upper middle income since 2010
Malaysia	Upper middle income since 1992
Singapore	High Income before 1987
South Korea	High Income since 2001

Source: [10]

[2] 2018 meet UN Graduation from LDC for the first time [11]

There were population growth and rise in labor participation rate in all these countries. Amplified flow rate of national savings led to rapid growth in capital stock. Gross domestic saving (% of GDP) increased from 13% in 1966 to 46% in 1990 for Singapore and 11% in 1966 to 39% in 1990 for South Korea. But maintaining long term high growth is difficult by only increasing inputs as that can lead to the decline of marginal productivity of capital. Thus, the resumed rapid growth indicates that later these countries found ways to stimulate growth in TFP [4], [14].Singapore followed import substitution driven development strategy before 1965. But, it changed to export based economy after its independence in the year 1965. Labor intensive industry was transformed to high capital based heavy industry mostly between 1970 and 1980. Singapore also emphasized the expansion of tourism and other services by prolonging working hour and creating brighter city during the night [15].

South Korea's GDP growth had been on an annual average rate of 9.6% from 1963 to 1996 [4]. The economy was dependent on agriculture in 1960s and faced all types of obstacles like any other developing country [16]. In 1961, military led government focused on economic development using low wage educated labor force for producing goods for export. Development shifted from labor based industry to high capital industry with the rise of wage. Manufacturing sector that focused on textile and footwear initially, shifted to steel and heavy industries in 1970s and to automobiles and electronics in 1980. The rapid industrialization and economic growth helped South Korea in 1996 to join in OECD group [17].

China achieved remarkable economic progress with 9.8% growth rate of GDP annually between 1978 and 2009 [18] .The driving factors for this huge growth were export, consumption and investment growth. The economy of China is in transition phase and moving from primary industry to secondary and tertiary industry. The focus moved on export based light industry and tertiary industry. The increasing number of secondary industry increased urbanization rate and the income of the people. Thus the number of middle income people also rose significantly [19].

During the period of 1961 to 1997, Malaysia experienced rapid economic growth with a rate of 7.37% annually. Later it experienced two financial crises in 1998 and 2009 [4]. Before 1957, Malaysia was an agriculture dependent low-income country and mainly based on tin and rubber production. State led effort towards diversification of the economy is one of the key drivers of outstanding economic growth. Initially, the country focused on agricultural diversification by replacing the production of rubber to palm oil and others. The second part of diversification was primary to secondary industries. Malaysian economy observed fast structural change during 1955-1970. Agriculture dominated primary industry share dropped in GDP from 46.5% in 1955 to 36.1% in 1966. On the other hand, secondary and tertiary industry sector rose from 11.2% to 15.4% and 42.3% to 48.6% respectively during the same time span. During 1970, manufacturing and construction sector experienced significant growth and by the year of 1990, the economy became further industrialized. Initial industrial growth was inspired by import replacement policy. Later, the wave went to export based manufacturing industries in 1970. Besides, State aided tax concession policy also helped to intensify these industrial growth [20].

Bangladesh has embarked on a significant economic growth path over the last decades. The structure of Bangladesh economy has moved from agro-based to non-agricultural manufacturing industry oriented economy although there is significant improvement through agricultural modernization. Contribution of the industry sector in GDP increasing with time from 6.06% in 1972 to 27.27% in 2017. On the other hand, agricultural sector contribution in GDP is reduced from 59.60% to 13.41% during the same period. This structural change is dominated by the export of labor intensive ready-made garments industry that provide 81.23% of total national export with an annual increase rate of 8.6% in 2016-17 [4], [21], [22]. Heavy industry such as metallurgy, machinery and equipment, energy, chemicals, building materials *etc.* are also growing.

Move towards heavy/export oriented industries in all countries mentioned above was made possible by significant increase in energy supply to meet the growing demand. But with increasing wage, the structure of the economy shifted from labor intensive industry to capital intensive heavy industry that further geared up energy demand. Bangladesh is now based on labor intensive export oriented industries. Following the path of predecessors would mean extensive energy intensive industrialization to sustain its economic growth and wage can be expected to rise with time following the traditional growth theory [2]. Thus, it is expected that Bangladesh will move towards capital intensive heavy industry or new digitalization and new pattern of industrial growth to sustain its fast economic growth. However, COVID19 crisis and immediate impacts and possible changing global trade and labor rules will make it even more imperative for Bangladesh to revisit its structure of industrialization and domestic market expansion and shorter supply chain to make the economy resilient [23], [24]. Energy sector centric manufacturing and activity expansion on sustainable path can be a major growth driver in post pandemic recovery pathway for Bangladesh.

3.2 Energy Demand Growth and Fuel Mix: Comaprative Analysis of Fast Growth Phase of the Asian Countries

The progress of energy sector has been a major determining factor for economic growth and development [25]. After independence in 1965, Singapore focused on the investment in oil refineries.

But diversification of manufacturing sectors led to gradual reduction in share of oil related products share in industrial GDP from 50.0% in 1974 to 18.3% in 2002 [26], [27]. During seventies and early eighties, the industrial structure of Singapore was transformed from labor intensive industry to high capital heavy industry. These capital intensive industries are heavy machinery industries, electronic industries, oil refineries and petrochemical industries that require more energy than the labor intensive light industry. Besides, to expand the service and tourism sector, Singapore prolongs working hour and makes the city brighter at night. In addition, people use more house space or more people use large space home. Household energy consumption increased for additional use of lighting, TV sets and other electrical appliances Thus, the energy demand of Singapore is increasing extensively with significant increase of economic growth [15]. Energy demand and GDP growth of Singapore are shown in Figure 1.

From the Figure 1, it is clear that the main source of primary energy in Singapore continues to be imported oil. However, natural gas is penetrating slowly. Coal use since 2015 and renewables since 1990 are still almost negligible in terms of share in total energy.

In China to support the outstanding annual economic growth of 9.8% between 1978 and 2009, energy consumption increased from 571.4 to 2329.53 Mtoe with a rate of 5.87% annually [4], [28]. For economic expansion of China, it experienced relatively lower growth rate of energy requirement [29].There are two reasons behind this. First one is the rate of industrialization and urbanization. And the second one in the export driven economic growth and producing high energy consuming products. Population growth indirectly impacted energy consumption and use patterns. Economic transformation of China goes through a transition phase between primary and secondary/tertiary industries. The focus goes for the structural upgradation and optimization of the industries in China on export based light industry and tertiary industry. However, increased number of secondary industry including metal, automobile, chemical, textile processing *etc.* rose energy intensity in China [19], [30].

There is a dramatic increase in Chinese energy demand between the years 2001 to 2011. During this time, energy consumption rises at a rate of 9.05% with the GDP growth rate of 10.56%. There are two factors behind this enormous demand growth of energy: economic industrialization and rise of middle-income class. Almost half of the Chinese GDP comes from industrial sector and it consumes about 70% of total energy. Again, this industrialization leads to expansion of old cities and create new cities. Moreover, the industry dominated economic growth leads to increase average working wages that ultimately enlarge the size of middle-income class. While the middle income class was 10% of the total population in 2000, it became 40% in 2010. This income rise led to change in their consumption pattern. Thus, more people are moving towards urban life and have better access to energy that ultimately increases the energy consumption [31]. Energy consumption and GDP growth rates in China from 1965 to 2017 are shown in Figure 2.

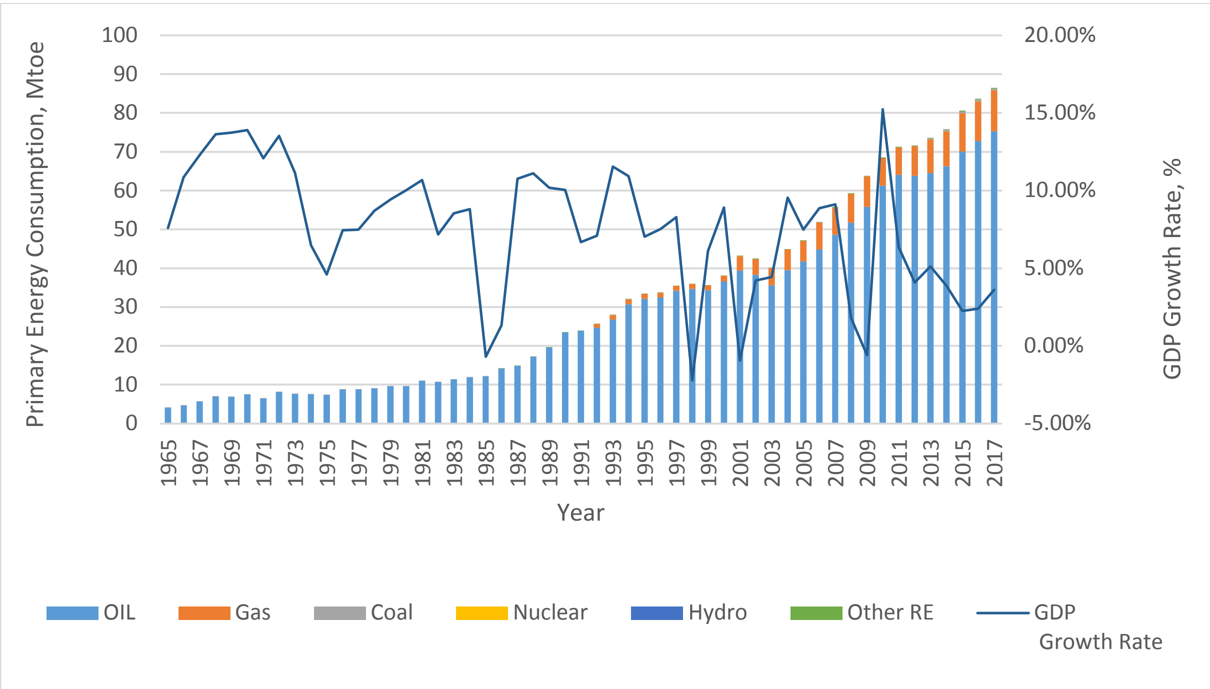

Fig. 1. Primary energy consumption by source and GDP growth of Singapore.
(Source: [4], [28])

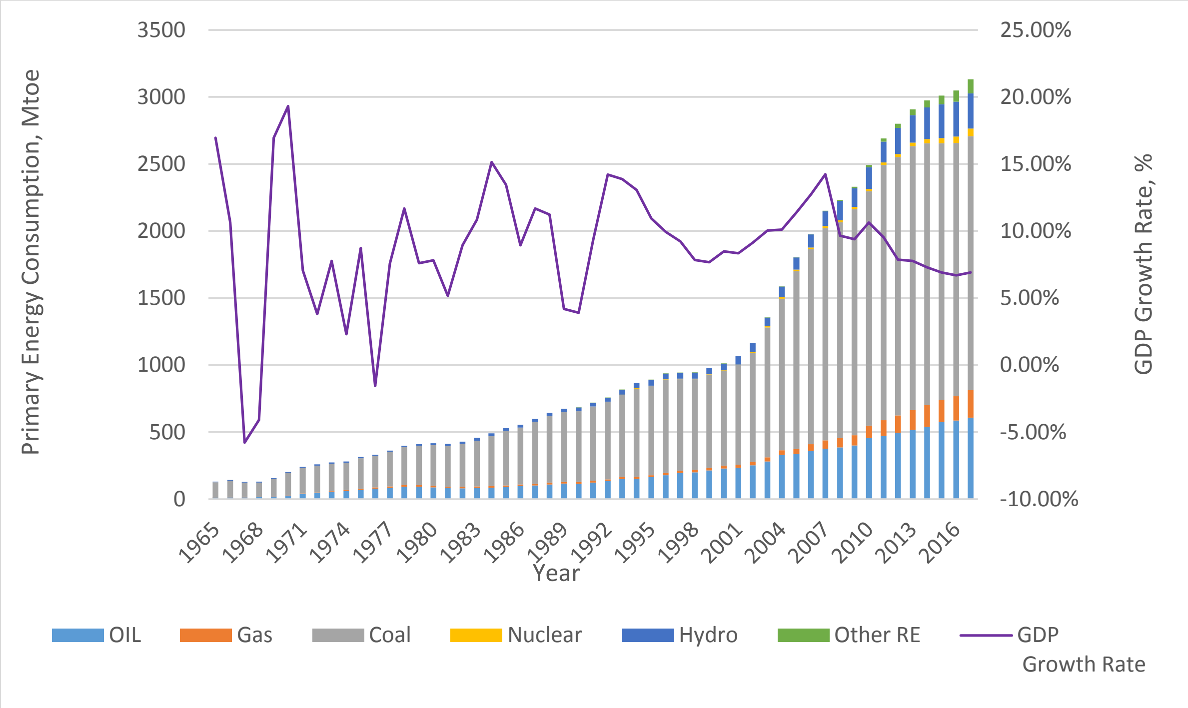

Fig. 2. Energy consumption and GDP growth rate in China between 1965 and 2017.
(Source: [4], [28])

Coal is still dominating as the source of primary energy in China and thus historically provides highest share of energy to support remarkable economic growth. During 1965 to 2017, coal share in total primary energy reduced from 87% to 50.6%, but supply of coal increases from 114 to 1893 Mtoe in the same period. Specially after the millennium, rapid economic growth, increased urbanization rate and energy shortage resulted in dramatic rise in the consumption of coal from 679 Mtoe in 2000 to 1914 Mtoe in 2015 with 7.2% annual growth rate. Oil is another important source of primary energy in China that has significant effect for accelerating its economic growth. After the reform program of economy in 1978, China experienced significant economic growth with improved living standard. As a result, the consumption of oil grew rapidly from 91 to 560 Mtoe between 1978 and 2015 with annual rate of 5%. But China did not have much reserve of oil and became crude oil net importer after 1993. Besides, continuous increase of economic growth with improved living standards resulted in significant development in automobiles and aviation sectors since 1990 that ultimately led to rise in oil consumption in China sharply. Thus, from 1965 to 2015, oil share in total consumed energy has risen from 8.3 to 18.6% [28], [32]–[34].

China has enormous reserve of natural gas resources, but the development of local natural gas industry is much slower. The government plan is to substitute coal by developing natural gas. Besides, energy production from nuclear source has risen significantly from 4.0 Mtoe energy production in 2001 to 56.2 Mtoe in 2017 at a rate of 28%. But still it accounts for only 1.79% of total national consumption.

China began to develop renewable energy since the world energy crisis in 1970s to accelerate the production of electricity from renewable source. This resulted into 5.5% share of consumed energy from renewable sources in 2004. During 2005-2009, significant support from the government made outstanding advancement of technology for renewable sources and increased the renewable energy consumption from 90.9 to 146.2 Mtoe with a rate of 10% annual growth. 11.41% of total energy is from renewable sources in 2017 with an amount of 368. 25 Mote [28], [33], [35], [36].

Energy consumption of Malaysia also followed the same pattern with the economic growth. With rapid economic growth of 7.46% between 1965 and 1997, energy consumption growth was 9.45% and with moderate economic growth of 4.53% between 1998 and 2017, energy consumption growth was 4.72% annually [28]. The highest energy consuming sector is the transportation sector that accounts for 37% of total energy, followed by industry sector 28%, agriculture sector 17%, and residential sector 13% and non-energy use 20%.

Several energy policies have been implemented by the government to sustain rapid economic growth. National petroleum policy was implemented in 1975 for effective utilization of oil resource as oil was the main contributor of primary energy at that time. Aiming the long life of oil and gas reserves, national depletion policy was implemented in 1980. After that focus was on fuel divergence and policies were adopted in 1981

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and 2002 respectively to overcome the dependency on oil and balancing the consumption of oil, natural gas, hydro, coal and renewables as primary source[37], [38].

In 1978, total primary energy supply was 8.352 Mtoe where 72.63% was provided by oil, followed by 24.2% from gas, 2.89% from hydro and 0.3% from coal. Primary energy supply and GDP growth of Malaysia from 1978 to 2017 are shown in Figure 3. The fuel diversification policy resulted in declining the share of oil supply in total primary energy. In 2017, natural gas and oil provides almost equally 36.96% and 36.99% of total energy respectively, followed by 20.08% from coal and the remaining from hydro and other renewables. (BP, 2018).

The country modified fuel diversification policy for many times to cope with the two international oil crisis in 1973 and 1979. Overtime, the dependency on oil became lesser but at the same time to support its economic growth, the consumption of coal and natural gas increased significantly. The consumption of coal rises to 20.0 Mtoe in 2017 from 3.6 Mtoe in 2002 with an annual rate of 22.12% [28].

South Korea experienced remarkable GDP growth with annual average rate of 9.62% from 1965 to 1996 [4]. This growth was attained by transforming agriculture based economy to fully industrialized high tech economy. Initial focus was towards export based labor intensive industry to utilize low cost educated labor. But as the wage went up, labor intensive textile and footwear industry moved to steel and heavy industry in 1970s and to automobiles and electronics in 1980.

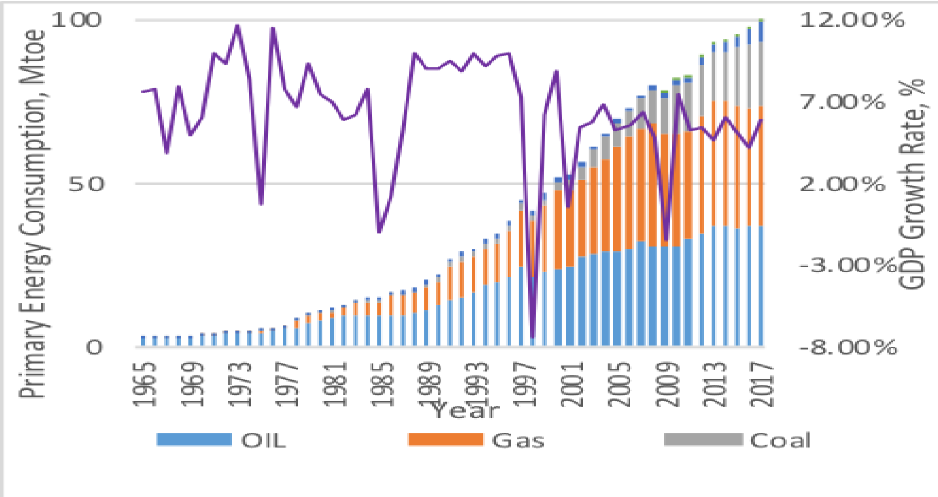

Fig. 3. Consumption of energy and growth rate of GDP in Malaysia between 1965 and 2017.
(Source: [4], [28])

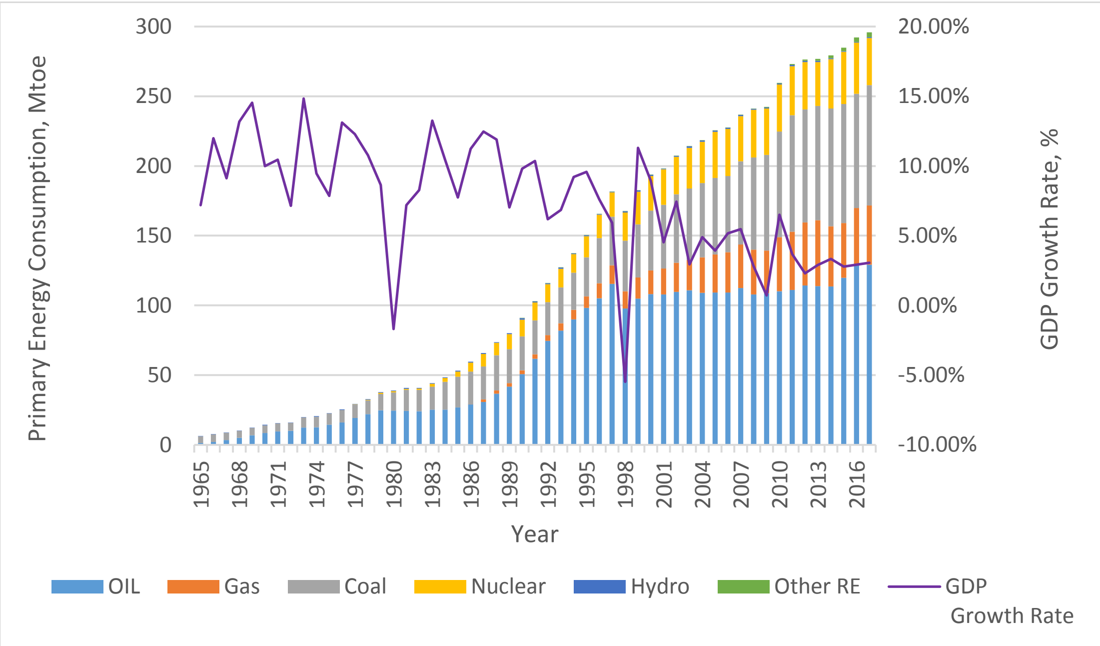

Fig. 4. Energy consumption and GDP growth in South Korea between 1965 and 2017.
(Source: [4], [28])

Even with the limited resource, the rapid industrialization and economic growth over the last decades transformed it into a developed nation and in 1996 it joined OECD [17] .The primary energy supply and growth in consumption in South Korea from 1965 to 2017 are shown in Figure 4. Initially coal was the main source of energy. But with time, it went for oil, nuclear, gas and a small share of renewables to support its economic growth [28].

South Korea imports more than 95% of its energy. After the independence, it supported the industries that could replace import (1962-1967). Later, heavy chemical industries were supported in its five-year plan for the period of 1967 to 1971. During that time, imported oil was the major primary energy source and it was 58% of total primary energy consumption in 1970 with 40% coal and small share (2%) of hydro. After the Oil crisis in 1970, energy ministry targeted oil free policy to reduce oil share in total primary energy consumption and it went for nuclear power production in 1981 that has been increasing with time to support its economic growth. With higher economic growth, the country focused on energy efficiency improvement including distribution sector development and energy price adjustment for proper energy management that led to the reduction of energy intensity (energy required/GDP) with a figure of 4% from 1983 to 1987 and 10.2% from 2000 to 2010. Furthermore, the country went for power market deregulation in 1990 and supported green energy in 2000 [39]–[41].

Bangladesh has experienced significant economic growth over last one decade. The structure of Bangladesh economy is moving towards non-agriculture based from agro-based economy although there is significant improvement in agricultural modernization. Energy demand of Bangladesh is also growing. During the year 2005 to 2017, while annual average GDP growth is 6.37%, the energy demand growth rate has been higher at 6.74%. Primary energy consumption increased from 16.1 to 33.0 Mtoe in the same period [1], [28] .Primary energy supply of Bangladesh are shown in the following Figure 5.

Bangladesh has increased the share of locally produced Natural Gas as primary energy source but the gas reserve is depleting fast [42]. Thus, to continue its high economic growth, nature of development of energy sector is going to be a vital driver. Now the question for Bangladesh is what should it prioritize: heavy industry (iron and steel, basic metal *etc.*) growth like China, Singapore, Malaysia, South Korea or grow with focus on new trend of future digitalized economy? Both needs energy in some form or the other.

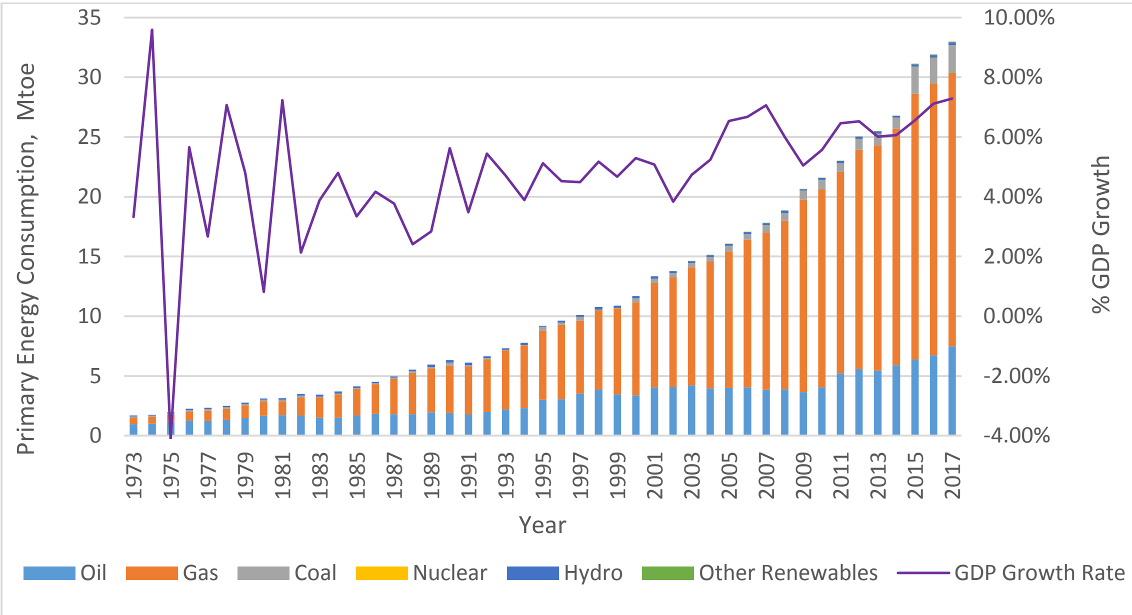

Fig. 5. Energy consumption and GDP growth in Bangladesh between 1965 and 2017.
(Source: [4], [28])

4. SUSTAINABLE ENERGY SECTOR DEVELOPMENT IN BANGLADESH: WINDOW OF OPPORTUNITY

In the past century energy sector development was mainly consistent with fast GDP growth. With changing paradigm of development in favour of sustainable development in this century energy sector also needs to be synergistic with multidimensional targets of human wellbeing. United Nations Department of Economic and Social Affairs (DESA), International Energy Agency (IEA), Eurostat and European Environment Agency (EEA) produced a long list of indicators [43] for energy sector to be consistent with sustainable development. To ensure sustainable development, in 2015 all members of United Nations called for Sustainable Development

Goals(SDGs) that consist of 17 goals to ensure prosperity and peace for all people by 2030. These 17 SDGs are integrated action that balance social, economic and environmental sustainability. SDG 7 is to ensure access to affordable, reliable, sustainable and modern energy. As the development is directly related to energy, SDG 7 is linked to all other SDGs and this interlinkage should be identified by the policy maker to make an SDG responsive energy plan and ensure sustainable energy development [44].

Table 4. Comparative analysis of energy, GDP growth rates and emissions in fast economic growth phase.

Country	Fast economic growth phase	Annual average growth rate (%)		Total CO2 emission, MT	Annual avg. CO2 emission per capita, MT	Energy sector
		GDP	Energy consumption			
Singapore	1965-1997	9.09	6.70	1,008,135	11.01	Imported and refined oil still dominate the energy sector. After 1991, imported natural gas has penetrated in the energy mix.
China	1978-2009	9.8	5.87	107,239,299	2.77	Heavy reliance on coal, gas, oil. Local coal provided the highest share of energy at 71% in 1978, 72% in 2009 and 60% in 2017. Oil share in energy mix was 23% in 1978, 17% in 2009 and 18% in 2018. With the development of local natural gas resource, its share in the energy mix increased significantly from 24.7 Mtoe in 2001 to 177.6 Mtoe in 2015 with a rate of 15.1%.
Malaysia	1965-1997	7.46	9.45	1,372,118	2.50	Before 1978, locally produced oil was fulfilling more than 90% of its energy demand. Natural gas become a significant source of energy since 1978. The total primary energy supply was 6.108 Mtoe in 1977 where 91.68% was provided by oil, followed by 4.47% from gas, 3.67% from hydro and 0.2% from coal.
South Korea	1965-1996	10.70	11.05	4,998,751	3.84	Coal was the main source of energy during its initial industrialization. In 1970, 59% of energy was supplied from oil, 39% from coal and the remaining 2% from hydroelectricity.
Bangladesh	2005-2017	6.37	6.74%	817,586	0.46	Bangladesh is a new fast growing economy. Locally Produced natural gas is the main energy source. The country started to import natural gas from 2018 to meet its growing demand. Imported and refined oil also provide significant amount of energy. Coal share is increasing since 2005. The energy mix was changed from 71% Gas, 25% oil, 3% coal, 1% hydro to 69.3% Gas, 22.69% oil, 7.09 % coal, 0.71% hydro and 0.3% renewables.

Source: Summary by authors from various sources mentioned in the text.

While Bangladesh adds new capacities in power sector and other energy service demands over next two decades it can align to satisfy multiple objectives under three broad categories: social, economic and environmental. In sustainable energy sector development, primary target of rapid energy supply growth is seen at the same level with significant energy efficiency improvement and energy security [45]–[47]. Unless enhanced supply is simultaneously synergistic with social goals of equity in access, affordability and environmental target of clean air, water *etc.* 21st century energy sector development will not be consistent with sustainability goal. These are also linked to high decent job creation target. Bangladesh economy now is trying to catch up with the similar pattern and rate of economic growth as other fast growing economic countries in the region during their rapid growth era of past century. Therefore, significant growth in energy sector is inevitable and needs to be assured.

As the country's domestic resource endowment of natural gas is depleting due to historical dependence and limited reserve, the country is currently struggling with the persistent problem of the gas based energy system and how to make transition more sustainable in future [48]. The major transition in energy sector to gas based energy sector happened in 1975 in Bangladesh with nationalization of the gas fields [49]. Extraction, transportation infrastructure, manpower development and institutions, regulatory mechanisms, price-subsidy all were centered around increasing penetration of gas in total energy mix as is already evident from Figure 5 above. A new transition now poses several challenges but expands opportunities also as major share of future energy supply will be built now and in coming decades. From multilevel perspective landscape level changes through adoption of global collective actions towards sustainability where Bangladesh is also a party [50], the pressure is building up for change. However, this is also, coinciding with national level need for diversification of almost monolithic natural gas dominated sector. So, the cheap fossil fuel driven faster economic growth of Asian tigers in the past century is an old narrative and is changing very fast (Figure 7). This change needs to be articulated to decision makers and political level to overcome the persistent problem of fossil fuel dependency. Once backstop technology wind and solar are competitive now in global market place in terms of levelised cost of energy (Figure 6).

In case of Bangladesh energy sector, as the electricity supply needs to increase in next two decades by a factor of 3, strategic action is necessary to diversify the sector in terms of primary energy sources. Current gas dependent regime can be diversified by increased penetration of new renewable energy sources and technologies for meeting additional demand. This can provide opportunity for sustainable energy transition. The processes of change are represented conceptually in Figure 6.

However, national plan to diversify energy sector by introducing 50% of its power generation from coal and 10% of electricity generation from renewables by 2041 [52] is in contradiction with landscape level changes. Global assessment reports are assuming contribution of coal use without Carbon Capture and Storage or Use (CCS/U) to become zero as soon as possible to manage stabilization of global warming well below 2ºC [53]. So new investment in coal power capacity needs to be revisited in the line of sustainable energy sector transition with new proven clean technologies. These are not only for power generation but includes both distribution sector and demand side planning. Modernization of fossil fuel era, digital advancement to enhance renewable energy penetration by massive revolutionary reforms in generation, distribution, consumption and smart production of energy through technologies like big data, IoT, cloud computing, block chain technology, smart grid, efficient energy storing are the emerging trends. Theoretically connecting all energy sectors like production, distribution, consumption and storage through intelligent network technologies bring the opportunity to overcome the imbalance of production and consumption easily [54]. However, feasibility and readiness of Bangladesh in terms of human capacity to integrate all these revolutionary changes need serious consideration or strategic action plan. Since, such digitalization for energy sector management needs reliable energy supply and manpower building, given the global sustainable goals and SDG 17 international cooperation, path needs to be chosen through appropriate institution building by the decision makers in Bangladesh. Bangladesh is a much advantageous position than other fast growing countries from past century as not the entire 100% of the country's energy sector is locked in fossil fuel path. If electricity sector needs to expand 3 times, then only 1/4th of energy sector *i.e.,* 25% of the future energy sector is currently locked-in on fossil fuel path. Increase in energy efficiency in end use sector and a variety of clean/renewable energy penetration for achieving SDG 7 target by 2030 provides enormous scope for Bangladesh to create employment in energy sector, opens up prospect of new business opportunities and manpower planning and education. This cannot be achieved without strategic sustainable transition planning for the energy sector through participatory process of engaging all actors likely to be involved in the process as shown in Figure 7.

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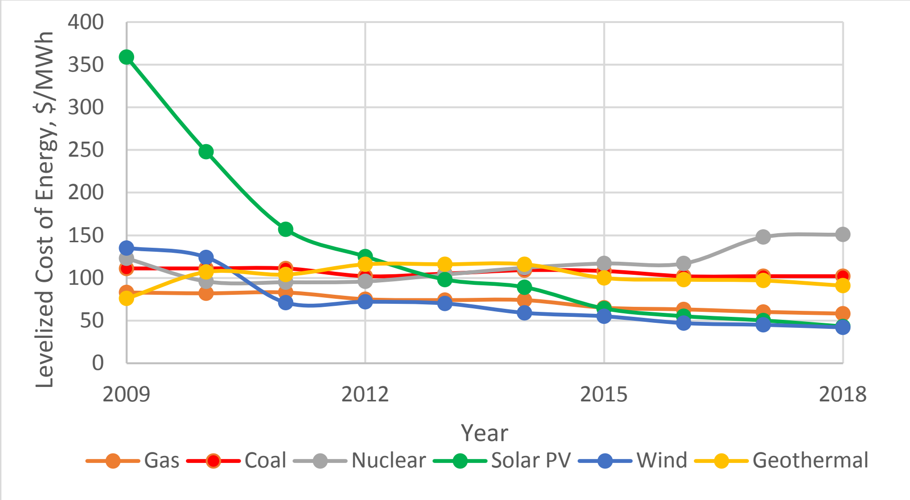

Fig. 6. Levelized cost of energy.
(Source: [51])

So which way forward for Bangladesh will depend on a successful strategic energy-power coupled sector growth planning. Also, with rising income and household appliance demand, residential electricity use is also predicted to increase. So, the question is what alternative options for Bangladesh to develop a sustainable energy sector that can lead to needed fast economic growth and provide adequate access to energy for all.

Bangladesh while taking off in next couple of decades can take advantage of global market developments in energy sector. The story line of cheap fossil fuels driven economic growth in the previous century is no longer valid (Figure 6). Renewable energy is getting cheaper very fast. With the possible future carbon price burden or the other constraints looming over fossil fuel sector, the relative cost is going to be even more favorable to renewables. Figure 6 shows how renewable energy is becoming economically competitive with alternative fuels. So, it is becoming clear that countries which will build path-dependency along cleaner fuel path will be the winner in this century.

5. CONCLUDING REMARKS

Economic structure is country specific, but the structural transformation of the fast growing Asian countries of past century followed almost homogeneous pattern of heavy industry growth led economic activity pattern fueled by fossil fuel. Initial growth phase was supported by agricultural modernization and import substitute industries. But with time, the contribution of agriculture sector was reduced and high growth came from export based labor intensive industry later transformed into capital intensive heavy industries. Next phase focused on service sector or light modern high-tech industry. The energy sources in this fast growth phase came from mostly local energy resources but was dominated by fossil sources which is still continuing to be the case.

Singapore's GDP grew 9.08% annually from 1965 to 1997 with the increase of 6.7% annual energy consumption. Oil dominated the energy mix. Chinese economy grew at 9.8% annually during 1978-2009. Energy consumption dominated by coal, oil and gas increased at a rate of 5.87% annually. Rapid economic growth of Malaysia at yearly rate of 7.46% from 1965 to 1997 resulted in significant rise of annual energy consumption at 9.45% during this period. South Korea achieved remarkable economic growth 9.62% annually from 1963 to 1996 that raised its annual energy consumption 11.05% during this period. Imported oil and coal were the main source of energy during its initial industrialization. Besides, the country also have focused on energy efficiency improvement including distribution sector and energy price adjustment for proper energy management since 1983. Each country had much higher per capita emissions levels during their fast growth phase compared to more recent fast growth phase of Bangladesh.

Bangladesh, with 6.37% GDP growth rate and 6.74% energy demand growth rate annually, is a new emerging country in this decade still with very low per capita emissions [4], [28]. The economy has moved to labor intensive export oriented industry sector during initial fast growth phase. Whether Bangladesh adopts heavy industry path or digitized economy path will have to very much depend on its sustainable energy sector plan given the changed global context and new opportunities. Bangladesh, in coming decades going to increase its power generation capacity three times from its current capacity, has the advantage to take the benefit of changing market condition and global cooperation in implementation of new renewable and cleaner fuel sources to sustain both the energy sector and the economy and low per capita emissions. This study gives rise to multiple research questions around setting up of priorities in achieving sustainability in energy sector faster, barriers to be overcome and deriving a road map with national future scenarios in vision.

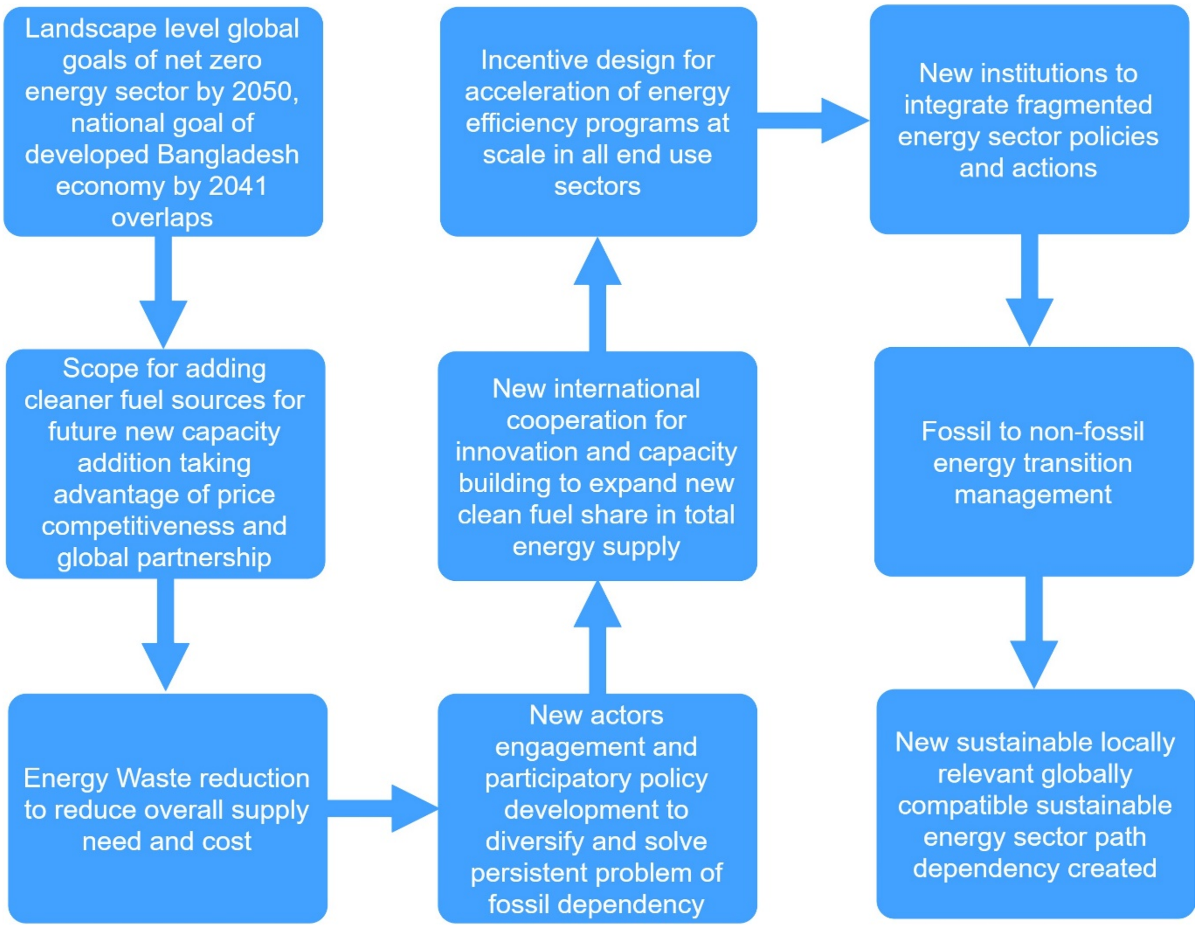

Fig. 7. Window of opportunity for Bangladesh in bending the process of change towards sustainable energy sector compatible with national and global goals.

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Moving beyond Gas: Can Bangladesh Leapfrog and Make the Energy Transition Just by Exploring the Role of Geothermal Energy and Gas Infrastructure?*

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Abstract – *How a natural gas rich developing economy like Bangladesh growing at ~7% annually in the pre-pandemic period can envision a roadmap for Sustainable and Just energy transition using the investments in gas infrastructure is discussed in the article. Bangladesh is caught up in a complex combination of likely risks of rising stranded assets, redundancy of jobs in the fossil fuel sector, need for cleaner available innovation and technology through global partnership to meet the inevitable increase in energy service demand. We make a case for the new use option of Bangladesh drilling wells and the infrastructure dedicated so far to extract and use domestic natural gas reserves. Utilization of gas exploration wells and depleted wells for the generation of geothermal heat and power can help in leapfrog with a drastic reduction in the cost of installation of geothermal plants and without job loss. This article provides learnings based on other country experiences related to the use of depleted wells for geothermal production. Available data from one of the gas reservoirs for three wells in Kailashtila gas field has been used to assess the potential. The simulation result shows that using existing wells as a geothermal heat source with heat pumps is not the best option for cooling only applications. Absorption chiller would be a better choice for heat-based cooling. However, a combination of seasonal cooling and heating with heat storage in geothermal wells during hot periods and heat utilization for space heating during cold periods presents a very attractive energy solution option. But more detailed systematic studies including detailed calculation of geothermal energy generation potential for Bangladesh with feasibility assessment can be conclusively done with site specific data access and are necessary to fully explore the technical and economic potential.*

Keywords – *Bangladesh, geothermal energy, just energy transition, leapfrog, natural gas.*

1. INTRODUCTION

In 2015 the world has achieved consensus in the declaration of a few global agenda. Interestingly a wide variety of scientific efforts at various contexts, levels and scale started to give shape to these agenda in reality. This article sits at the intersection of two such agendas. First, is the adoption of the Paris Agreement at the COP21 and the other is the adoption of the Sustainable Development Goals (SDG) framework. Three years later in 2018 IPCC special report [1] on Global Warming of 1.5°C presents the assessment based on available scientific literature that accelerated deep decarbonization is at the core of mitigation strategy consistent with 1.5°C warming compared to the pre-industrial level. The same report also presents the high agreement and robust evidence of consequences evaluated by the scientific community in faster and deeper mitigation strategies through possible threats to multiple social and economic dimensions of sustainable development for countries currently having a high dependency on fossil fuels for income generation, contribution to national income, economic development and generation of employment. The same concerns are coming from those which are representing voices around possible job loss, loss of investment flow despite new resource identification, high risks of stranded assets, lower revenue earning with fluctuating oil and gas prices, dwindling reserves [2]. The literature on solutions and policy instruments talk of need for diversification of economy and energy sector to ease these adverse consequences of transition and need for creating enabling conditions [3]. The diversification discourse is mostly dominated by focus on new investment opportunities limited to wind and solar energy sectors. Also, the countries at risk discussion get dominated by GCC (Gulf Countries Council) countries. All these discourses ignore multiple challenges and realities in many small but fast emerging developing countries' perspectives. Bangladesh which is growing at more than 7% and is aiming for developed country status before middle of the century needs special attention.

The objective of this study is to answer the research question, how can Bangladesh take advantage of the

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accelerated need for global transition while addressing the 'trilemma in energy transition'? The trilemma is: how an oil and gas dependent country can potentially leapfrog to new sustainable energy form without job loss, asset loss and by using international cooperation under Sustainable developmental goal (SDG 17). So, this study presents the basic hypothesis within an analytical frame of 'energy transition trilemma' in section 2. Section 3 describes the current and future challenges for sustainability of Bangladesh energy sector to set the scene. Section 4 represents how geothermal energy technology can use gas/oil infrastructure and how is it happening in other countries to inform technical feasibility issues for Bangladesh, section 5 illustrates geothermal exploration status and potential in Bangladesh. Section 6 uses simulation methods to assess geothermal potential of gas wells in Bangladesh using actual well level data and represents preliminary results from the modeling and simulation for geothermal energy utilization. Last section 7 adds concluding remarks with emphasis on scope for practical way forward with possible international partners for cooperation.

2. ANALYTICAL FRAMEWORK

We consider that national circumstances will continue to influence energy transitions paths within overarching global commitments and narratives of sustainable development. Primary energy resources are all transformed to deliver final energy service demands such as cooling/heating, illumination, mobility, electricity *etc.* [4]. We argue that a country like Bangladesh which has made a historically huge investment in gas infrastructure, human capacity building and institutions [5] have created some kind of technological and institutional lock-in effect in fossil fuel based energy sector creating barriers for shifts to other energy sources. To make the transition to happen Bangladesh can explore ways and means to minimize direct economic and social costs of transition by exploring geothermal sources that can continue to use the same available gas infrastructure and human capacity with some reskilling and supplementary innovation through international cooperation (SDG 17). IPCC special report on 1.5°C [1] talks about the benefits of a portfolio approach in mitigation technology and strategy selection. Multiple technologies, policies and subsystem transitions need to be searched for instead of one size fits all kind of solution. We name this as 'trilemma of energy transitions' with reference to oil and gas based fossil fuel energy systems, which are caught up in a complex combination of problems due to likely uncertainty and redundancy of human resource currently engaged in the sector, sunk costs and stranded asset due to prospective early retirement of infrastructure and projected reduction in investment and need for finding a cleaner substitute for fossil-based energy carrier [6].

Our basic premise is energy system transition needs to be guided and requires innovation, large scale investment and long period of time with long term developmental goal. So, any transition plan needs urgent energy transition strategy management plan and institution to start early on conceptualizing a new innovation plan, piloting the same to understand feasibility and challenges to overcome them gradually in a demonstration project. The commercialization stage takes much more challenges as enablers need to be in place to guarantee commercial success, such as: policy, finance, human resource with new skill and public acceptance. History of energy system transition has seen many failures, slow down, trapped in valley of death in innovation chain in the absence of systems approach and enablers [7].

We represent the current transition challenge for countries like Bangladesh by Figure 1 currently endowed with gas reserves and infrastructure to use it and with matching high domestic human skill. We hypothesize that one of the sustainable energy transition path can be to make use of geothermal energy resources to diversify the energy supply portfolio to meet demand for cooling purpose and/or if feasible for power generation. Geothermal energy resource based system in Bangladesh can use the gas drilling infrastructure, wells, human skill and help in leapfrog in renewable energy path with strategically chosen international partners. The same infrastructure with additional innovation can play an important role in Hydrogen based economy also but that is kept outside the purview of this article.

The Government of Bangladesh adopted the Renewable Energy Policy in 2008 and the subsequent power sector master plan in 2010 and 2016 have objectives of developing renewable energy resources to harness the existing potential and adoption of renewable energy technologies wherever possible. The policy also aims at scaling up renewable energy share in electricity generation as the country is fast depleting domestic natural gas reserves. However, current national discourse makes no reference to geothermal in renewable energy potential portfolios as a part of the solution.

3. BANGLADESH ENERGY SECTOR: CURRENT AND FUTURE CHALLENGES

Bangladesh economy is growing currently with 7.86% annual growth in GDP with per capita income moving up to USD 1751 in 2017-18 from USD 843 in year 2009-10 [8]. The success story of Bangladesh is unique. Studies show that, the larger part of this economic transformation has been supported by the growth of the power sector, social changes, especially women empowerment, girls' education, children's health improvements (life expectancy is now 72 years), population growth reduction, NGO participation in development sector and microcredit program stimulating social interactions and involvement of rural women in

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economic activity [9], [10]. Now maintaining and advancing this decade long remarkable success in a sustainable and equitable manner is an opportunity as well as challenge and the focus should be given to the removal of the bottlenecks in infrastructure and challenges in energy sector, and response to climate change.

In Bangladesh, current installed capacity in power sector is around 20 GW, but actual generation is less than 12 GW, which falls short of current demand [11]. The government projects demand to reach at least 60 GW by 2041[12]. Lack of reliability and intermittency of grid supply is another major obstacle for development in Bangladesh. World Bank survey indicates power outages are major obstacle, with businesses experiencing several hours of outages per day. Bangladesh is overwhelmingly reliant on heavily-subsidized domestic sources of natural gas (61% of total generation). Domestic gas reserves are slowly being depleted, which is leading to import of much more expensive LNG, requiring either significant new subsidies or price increases. The majority of new power supplies coming online include coal, imported LNG, nuclear, and regional trading. Due to seasonal water flows and limited land area, conventional renewables are not seen as a primary contributor. Gas production is still government-controlled. Bangladesh intends to import power from India, Bhutan, Nepal, and Thailand (via Myanmar). Progress on this front is already underway: Bangladesh is doubling the capacity of its interconnection with India to 1 GW, and the government has begun exploring with neighbors' potential co-investments in hydroelectric power plants [13], [14]. But these are not going to be sufficient for securing energy supply going forward. So, search for new energy sources which can provide long term self-reliance and sustainable non-intermittent source and security of supply is important for Bangladesh energy sector.

Fig. 1. Energy transition trilemma: Possible solution for leapfrog.

4. GEOTHERMAL AND OIL AND GAS DRILLING WELLS: OPPORTUNITIES AND CHALLENGES

This section deals with how technologically geothermal energy can use existing gas/oil infrastructure and how is it happening in other countries to justify technical feasibility. What is the resource potential global /for some countries? Where is the technology in terms of commercialization/ demonstration scale? The share of intermittent renewable energy from solar and wind in the grid has increased globally rapidly during the last decades. Technology development, cost reduction and supportive policy decisions have made this transition possible. However, the issue of intermittency of the renewable power already cause difficulties for grid stability and grid control.

Different from solar and wind, the geothermal energy is dispatchable and therefore, it could be a strong contributor to full transition to decarbonized energy system by supporting the grid. Geothermal energy has been steadily utilized for heat and power generation for many years, although not with a major share in total global energy generation. The main reason for the limited utilization of geothermal energy has been the high cost of infrastructure installation of such plants, where the drilling and well construction stands for the major part of the total investment cost. Therefore, reducing the drilling and well construction costs for geothermal installations have been discussed for years, without a major breakthrough. Utilization of oil and gas exploration wells and depleted wells for generation of geothermal heat and power has gained attention recently, since this would result in long desired drastic reduction in cost of installation of geothermal plants for clean energy supply. There are some obvious advantages with reusing the existing wells, such as reduced cost, but there are also challenges related to use of depleted wells for geothermal production, which need to be understood and handled accordingly to enhance growth of this dispatchable renewable energy source.

There have been several studies reported by researchers over the globe where the potential of geothermal energy generation from depleted wells have been investigated experimentally and theoretically (please see references [15] to [26]). These studies have demonstrated the readiness level of the technologies as well. To better understand the possibilities and challenges of reusing the existing depleted wells, the readers need to have a general understanding of the physical well construction and the legislative framework concerning ownership, use and finally plug and abandonment (P&A) of the wells. So, there are both technological and institutional, legal, economic and management issues that can impact the energy generation potential from depleted wells. Some of the opportunities and the challenges are discussed below:

- From an energy generation point of view, the main parameters impacting the energy generation capacity of the wells are the available temperature and the flow rate of the working fluid at the well head (at the surface level). Higher flowrate means higher energy generation capacity, which requires wells with large diameters. However, keeping the diameter large to the target depth would result in very high cost of drilling and well construction. It could be mentioned here that the wells drilled for oil and gas production are usually ending with a diameters between four and seven inches at the final section of the well, which is not exactly the optimum size from the geothermal energy generation point of view.
- From the remaining lifetime and well integrity aspect, one needs to understand the construction of the petroleum wells, which at each section and depth is presented by the following layers from outside in; the formation, the cement layer and the casing (steel piping inside the well). Utilizing existing wells for geothermal energy production requires sufficient remaining lifetime of the well, which motivates additional investments in geothermal energy. The well casing might have been exposed to erosion and corrosion at different sections of the well, which will limit the useful remaining life of the well. The quality of cementing job and the condition of the cement in place are also important factors for the remaining lifetime of the well. An important step in utilization of the existing wells for geothermal production is assessment and qualification of the wells for geothermal production. Programs for systematic analysis and evaluation of the existing wells, as well as identification of measures that provides safe and secure operation of the geothermal plants will be necessary to start now for an affordable and large scale utilization of existing wells for geothermal energy production.
- From a legislation point of view, one should consider the responsibility for plugging and abandonment of the wells (P&A), since P&A stands for considerable capital costs followed by the long-term responsibility associated with well monitoring. When the allowances for exploration and production of petroleum is given to a company, the P&A responsibility for the wells is also given to the petroleum producing company. Thereby, the petroleum company is responsible for closing and monitoring of the wells so that no unexpected events take place even after the P&A. So, transaction cost economics would favor petroleum companies to become geothermal energy generation companies. However, if another company/organization would take over the depleted wells for geothermal energy generation the issue related to P&A will assume a new dimension. It might become a problem if the petroleum company is not ready to accept the responsibility for P&A after the years of geothermal production. Therefore, one of the major showstoppers for using existing wells for geothermal energy production in some countries are around the P&A and the legal responsibility issues related to it. However, flagging this issue at this initial stage of discourse is useful as they need deeper and newer attention as opportunities and challenges are new.
- There are plenty of depleted and exploration wells

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over the globe, but the legal and economic issues for the abandoned wells need to be revised in new paradigm of sustainable development and climate action to enable geothermal production from these wells. The rules and regulations concerning wells to be operated by more than one company/organization in not clear today. Therefore, there is a need for clarification of technical, economic, legal responsibilities for the involved companies when using existing wells for geothermal energy generation and social and political issues for the country under consideration

4.1 Other Country Experiences

The use of existing infrastructure for transport of equipment and distribution of the energy from the wells is a major advantage of the existing wells, which further reduces the total cost of the geothermal energy from abandoned wells. Several pilot studies have been carried out in various countries to evaluate the energy generation potential of the depleted wells. The results show that between 3 and 5 MW electricity can be produced from one depleted and sealed well with electrical efficiencies of about 10-15%, when using double pipe heat exchanger (coaxial tubing in the well with injection between existing well and outer pipe and production from the inner pipe with sufficient isolation between the inner and outer pipes). However, the amount of energy generated and the cost of it will be different depending on location, depth and other circumstances. Beside heat and power, which have been in focus for energy service generation, there are also examples where the geothermal heat has been utilized for poly-generation with several useful products/services as outcome (*e.g.* desalinated water, *etc.*) [17], [18]. The economic viability of the geothermal energy is under researched and needs to be investigated for different markets and locations to help find the optimal solution selected contextually.

Assuming electrical efficiency between 10% and 20%, a temperature difference of 30°C to 55°C between inlet and outlet, and a mass flowrate of 10 to 60 kg/s, one can estimate the power output [kW], using water as working fluid (see Figures 2 and 3). For more detailed mathematical calculations, the readers are referred to the publications in the reference list [15] to [24].

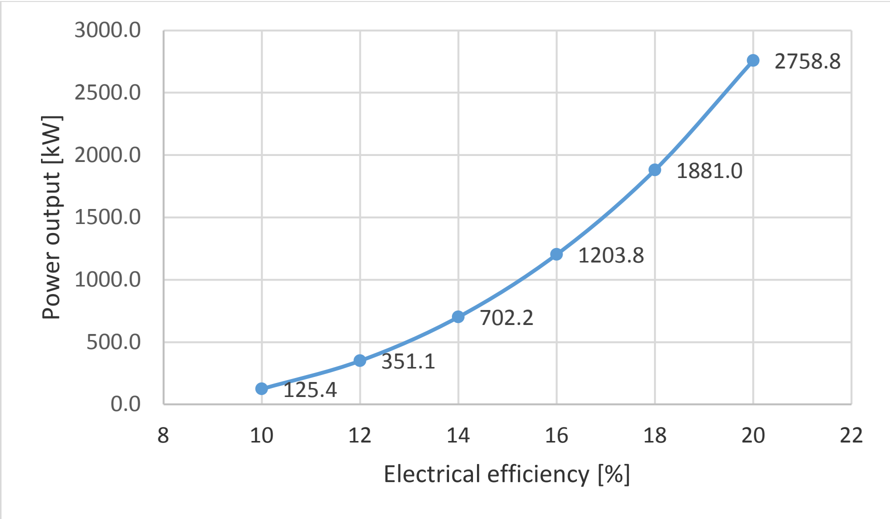


Fig. 2. Power output as function of electrical efficiency.

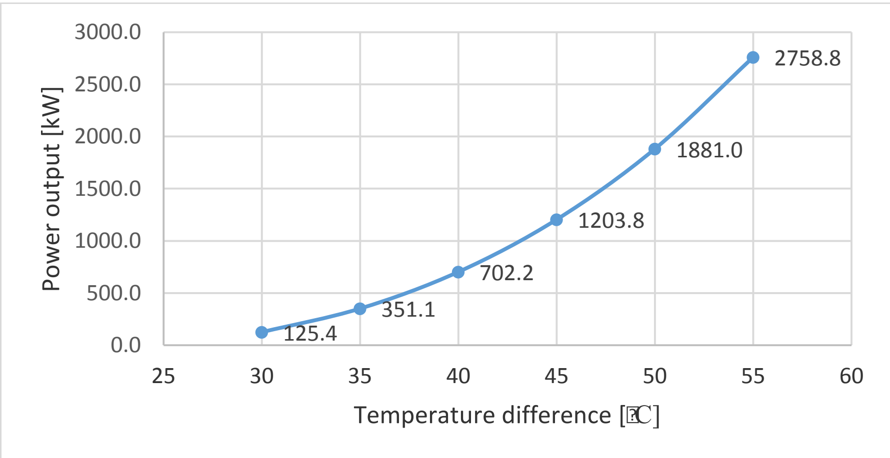


Fig. 3. Power output as function of temperature difference.

5. GEOTHERMAL EXPLORATION STATUS IN BANGLADESH

Several studies [27]–[37] identify the prospects of geothermal energy and concluded that there are several potential site for the geothermal energy extraction in Bangladesh but more detailed systematic studies including detailed calculation of geothermal energy generation potential with feasibility assessment are necessary to fully explore the geothermal potential. Geological survey of Bangladesh drilled an exploratory well for geothermal resource at Thakurgaon districts in 2011 and the recorded temperature gradient was 44.75°C at a depth of 560 m [33]. In 2011, a private company, Anglo MGH Energy, was declared to build the first geothermal plant in Thakurgaon district with a capacity of 200 MW [38], but the project did not commence finally for reasons unknown to the researchers.

5.1 Potential Geothermal Area in Bangladesh

Based on the geo-tectonic setup, the potential area for geothermal energy is divided into two different sections: (1) Northwest shield area (2) southeast deep sedimentary basin [37]. The northwest area has an average temperature gradient of 30°C /km, whereas the southeast deep sedimentary area is 20°C /km [36]. Tectonically, northwest shield area is subdivided as (a) Sub-Himalayan Foredeep (b) Rangpur Saddle (c) Bogra shelf and the southeast deep sedimentary basin is subdivided as (a) Deep Sedimentary Basin (b) folted belt [30].

The southern part of Bangladesh lies on Sub-Himalayan foredeep area. The average thermal gradient is only 22.5°C. One well (Salbanhat-1) was drilled in Tetulia where 79°C at a depth of 2500 m was recorded [30]and 110°C at a depth of 4000 m [33] was projected.

Concerning the Rangpur Saddle area, currently hard rock has been collected from Madhyapara and coal from Barapukuria. High temperature was detected at these coal bearing zone and hard rock structure. Below the coal seams of Barapukuria mine, there is a sandstone called Gondwana sandstone where 50°C was observed at a depth of 400 m. The coal seams work as an insulator for increasing the temperature of the basement. Besides, in this area, warm water with a temperature of 36°C was observed in irrigation wells at a depth of 80 m at Thakurgaon. In coal mine, observed temperature was 50°C at 400 m, 40.5°C at 380m and 52°C at 440m. The author concluded that if a well is drilled in this area, there is chance of getting enough temperature for electricity production. As hard rock and coal mine are in the same geological structure then there might be a need for fracturing to penetrate into the low permeability region [30].

Bogra shelf is the transition zone of Rangpur saddle and Bengle foredeep. Magnetic and seismic survey of these zones were done by Stanvac Oil Company in the mid nineteen fifties. Four deep wells were drilled in this area (Singra, Kuchma and Bogra) and the temperature gradient of 35°C /km were obtained in these wells. The most promising one, Singra-1, recorded a temperature higher than 150°C at the bottom of the well. Thus, the deep wells at Singra, Kuchma and bogra have high potential for geothermal energy generation [30], [33].

Deep sedimentary basin consists of the area between hinge line tending SSW-NNE from Sylhet-Mymensing-Pabna and Arakan Yoma Folded System called Bengal Foredeep region. The area has several troughs and highs namely Faridpur Trough, Hatiya Trough, Sylhet Trough, Modhupur high [28]. In the Hatiya trough, shahbajpur 1 well has a significant temperature gradient of 29.5°C /km that might be a potential location for geothermal energy extraction [27]. But cool sediments are continuously loaded in this deep sedimentary basin and very low thermal gradient (average 20K/km) was observed. Thus, although there are some deep abandoned wells, the area has limited potential for electricity production [30], [37].

The most prominent tectonic element, parallel to Arakan Yoma Fold, is the folded belt. The western part of the folded belt is the most prospective oil and gas area of Bangladesh with 12 gas fields. Several hot springs were observed in Sitakund anticline structure at Barapkundo and gobindachara with a temperature gradient of 35 k/km. Besides, wells at Bakhrabad and Saldanadi have the thermal gradient of 30°C /km and 27.2°C /km respectively [30], [33]. As there are many high deep, dry and abandoned wells available in this area with significant thermal gradient, these could be a prospective geothermal energy source.

5.2 Thermal Gradient of Deep Exploratory Wells

To explore and develop oil and gas reserves, a number of wells were drilled over the years in the eastern part of Bangladesh. The measured subsurface temperature of these wells are available [29], [37], [39]. The drilling depth of these wells ranges from 2100m to 4977m. Using the temperature data, a thermal gradient map of Bangladesh was developed as shown in Figure 5. The most prominent zone for geothermal energy was obtained at Singra 1 well location in northwest shield area with more than 150°C bottom hole temperature. Whereas, in the Southeast deep sedimentary basin area, potential thermal gradient was obtained at Shahbajpur 1 well at a rate of 29.5°C /km located in Hatiya trough followed by Saldanadi 1 well at a rate of 27.2°C/km.

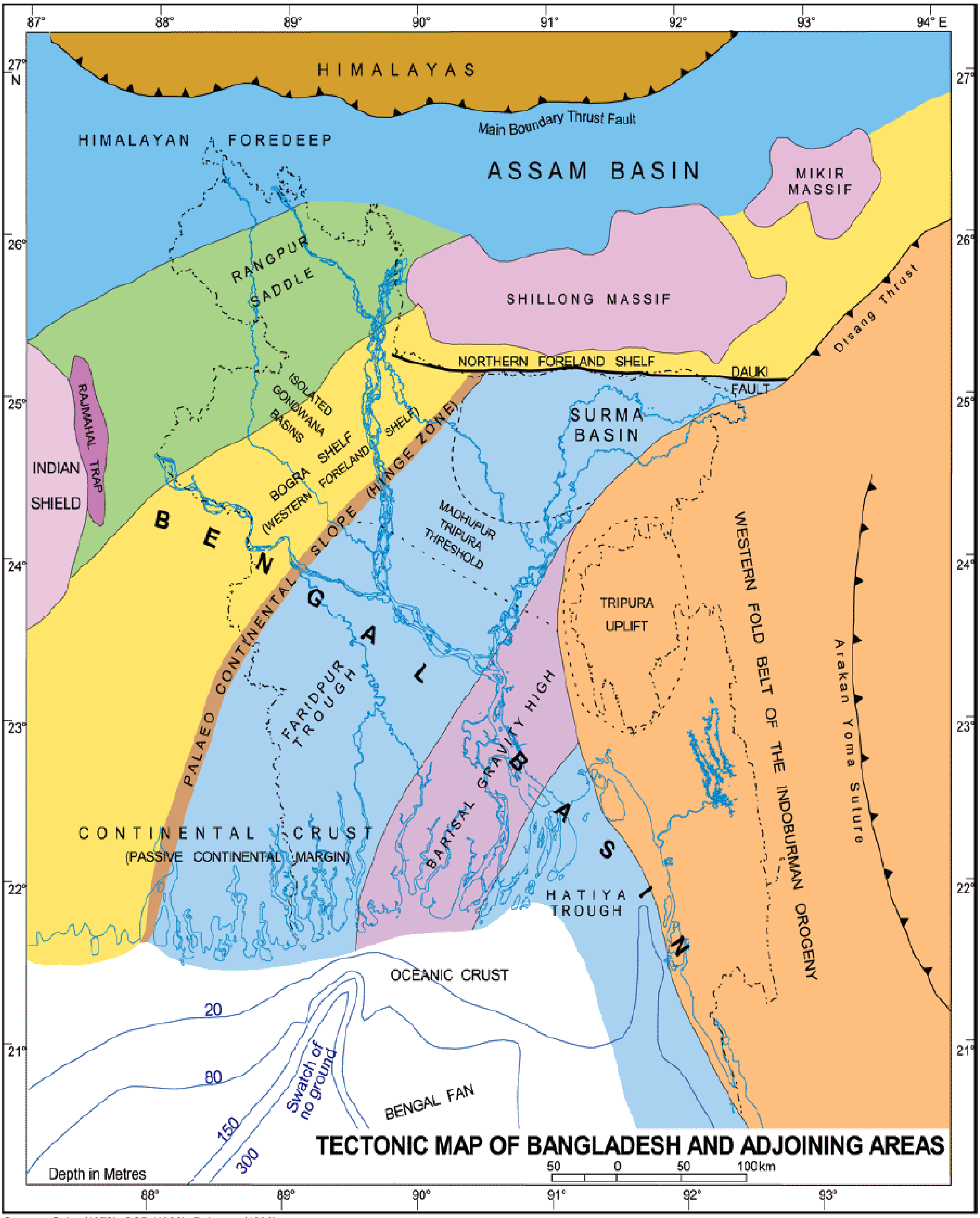


Fig. 4. Tectonic map of Bangladesh.
(Source: [28])

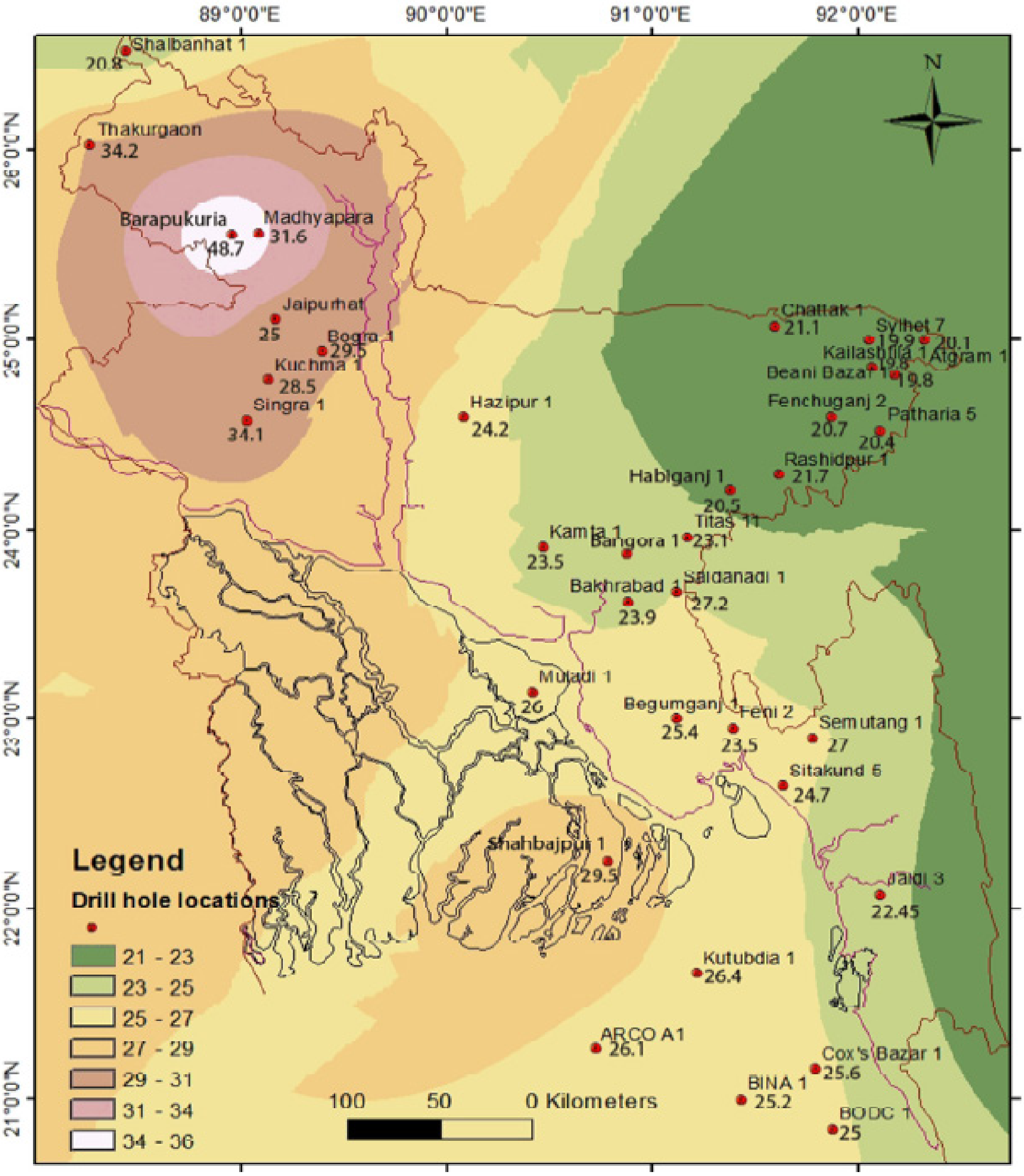


Fig. 5. Well wise temperature gradient of Bangladesh.
(Source: [37])

6. THE CASE STUDY: KAILASHTILA GAS FIELD'S WELLS FROM BENGAL FOREDEEP REGION IN NORTHWEST REGION OF BANGLADESH

6.1 Design and Simulation in IPSEpro

To understand potential of geothermal energy, a case study of one possible site to utilize wells in Bangladesh has been used to derive implications. The choice has been driven by data access. Three deep gas wells from Kailashtila Gas Field (Table 1) with reservoir temperature of about 63°C and surface-wellhead temperature of 42°C were used for the modeling and simulation work. Cooling application using heat pump was studied and the results of the parameters studies carried out are presented here. One of the wells was considered as production well and the other two as injection wells. Design and Simulation in done by IPSEpro Software system.

IPSEpro, a commercial simulation tool, was used for modelling and analysis. The parameter values used for simulation are shown in Table 2. The environmental temperature range of 25°C to 40°C was used for system performance analysis. The system setup as IPSEpro model is represented in Figure 6 with the state properties at specific points. The properties represent specific enthalpy, temperature, pressure and mass flow rate.

The cooling system consists of 4 main elements, condenser, expansion valve, evaporator and compressor. As working fluid used R134a refrigerant in cycle. It is worth mentioning that selection of the working fluid plays a significant role for the system performance. Saleh *et al.* [44] showed that 31 pure component working fluids are suitable for use in Organic Rankine Cycles (ORCs). In these studies the critical temperature, normal boiling temperature, and critical pressure for the working fluids were arranged in specific order to give an indication of their suitability as working fluids for ORCs. Lee *et al.* [45] carried out parametric analysis on an energy recovery system. They concluded that the ORC system efficiency depends on the normal boiling point, the critical pressure and the molecular mass of the working fluid.

Since the properties of the chosen working fluid have a significant impact on the performance of the ORC cycle, appropriate thermodynamic properties of working fluid can result in higher cycle performance and low costs. According to [46], the ideal organic working fluid should have high molecular weight, small heat content (low enthalpy), high critical pressure and temperature, low operating pressure to avoid danger of explosion or rupture, small specific volume high condensing pressure to prevent air inflow into the system, low cost, low heat latency and being nonflammable, corrosive or toxic.

Table 1. Well data of Kailashtila gas field upper gas sand.

Particulars	KTL2	KTL3	KTL6
Well diameter	354.33 mm	354.33mm	508mm
Well depth: MD (TVD)	3260(2259)m	3522(2273.4) m	(2302) m
Product flow rate- kgs-1	0.628 kgs-1	0.628 kgs-1	0.628 kgs-1
Reservoir pressure	3221 bar, at	3232.1 bar, at	3241 bar, at
Reservoir fluid temperature	63.16 °C	62.78 °C	62.78 °C
Reservoir fluid heat capacity kJ/kg.K	21.009 W/m2/K	15.9 W/m2/K	-
Reservoir fluid density kg/m3	0.628 kg/m3	0.62 kg/m3	0.63 kg/m3
Ambient temperature	25-32 °C	25-32 °C	25-32 °C
Surface temperature, ºC	42.22 °C	42.22 °C	-
Surface wellhead pressure, bar	176 bar	171.7 bar	182.36 bar

Data source: [40]-[43]

Table 2. Main fixed parameters of organic Rankine cycle.

Parameters	Value
Wellhead/surface temperature of geothermal fluid, °C	42
Requested cooled environment temperature, °C	22
Evaporator inlet temperature from environment, °C	25-32
Evaporator heat transfer area, kW/K	0.80
Condenser heat transfer area, kW/K	46.33
Pressure ratio	20
Compressor efficiency, %	80

Table 3. R134a refrigerant properties used in this study.

No	Properties	R-134a
1	boiling point	-26.1°C
2:	auto-ignition temperature	770°C
3	ozone depletion level	0
4	solubility in water	0.11% by weight at 25°C
5	critical temperature	122°C
6	cylinder color code	light blue
7	global warming potential (GWP)	1200

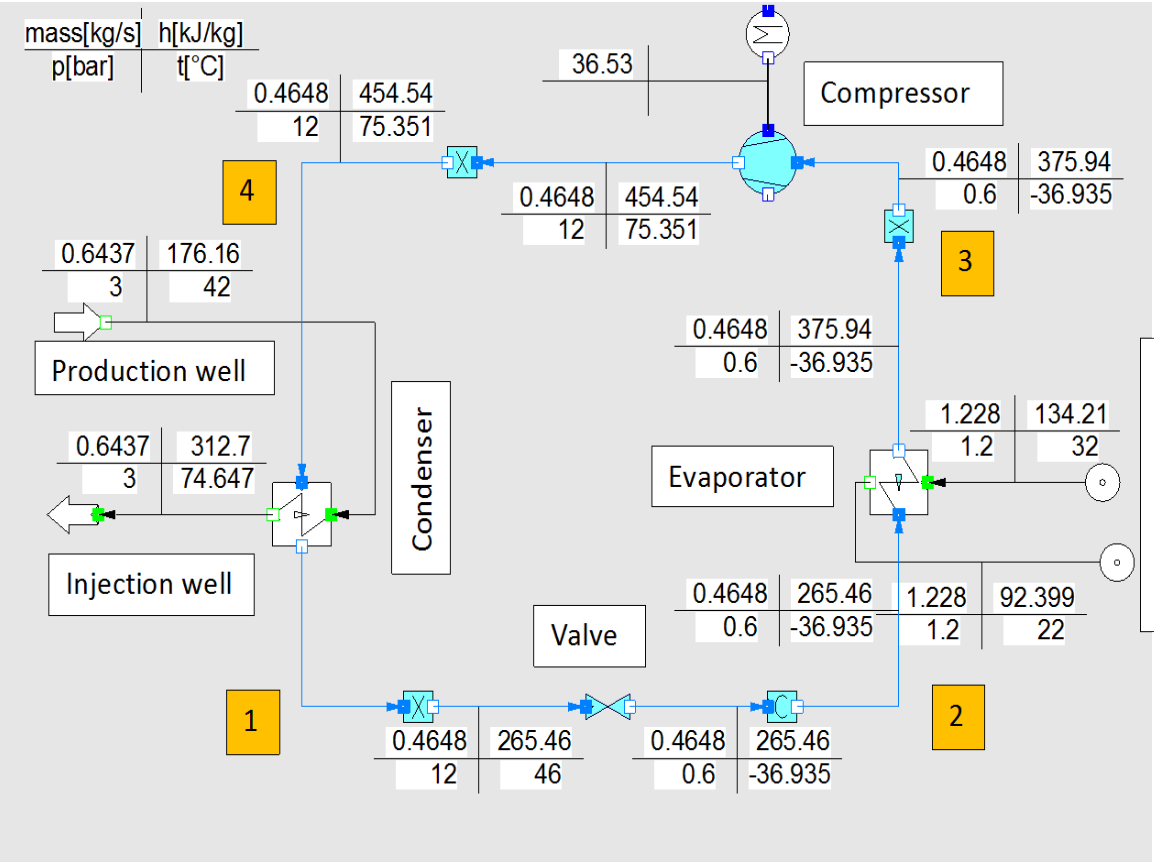


Fig. 6. IPSEpro simulation model.

6.2 Results and Discussion

The objective of the simulations conducted was to study the potential of using existing wells as geothermal source for cooling purposes (being a temperate country Bangladesh has high space cooling demand). The settings for simulations carried out were indoor temperature of 22°C, outdoor temperature between 28 and 40°C, and a wellhead temperature of 42°C. The product heat transfer area and the heat transfer coefficient for the evaporator and the condenser were kept constant through all simulations. The overall cycle performance depends mainly on the isentropic efficiency of the compressor. Table 4 shows the example for simulation results for outdoor temperature of 32°C.

For thermodynamic calculations and performance analysis a suitable working fluid is required, mainly considering the heat source temperature. For this purpose, the refrigerant R134a was selected as working fluid for IPSEpro simulations. Figure 7 shows the Pressure-Enthalpy diagram of R134a, containing necessary thermodynamic properties of the working fluid.

Simulation results for parameter studies within a temperature range between 28-40°C outdoor temperatures are shown in Table 5. Research target for 22°C indoor temperature at existing environment temperatures has reached. According to the results in Figure 8, environment temperature has not significant impact to design cycle data.

The properties of the working fluid at different states are marked on the P-h diagram in Figure 7.

Table 4. Simulation result for 32°C outdoor temperature.

Phase	State	P, bar	T, °C	h, kJ/ kg	s, kJ /kgK
Saturated liquid	1	12	46	265	1.21
Liquid +vapor	2	0.6	-36.94	265	1.29
Saturated vapor	3	0.6	-36.94	375	1.76
Supercritical gas	4	12	75.35	454	1.80

Table 5. Parameter study results for outdoor temperature of 28 to 40°C.

$N_{simulation}$	T_{env}, °C	Tgf, °C	W_{comp}, kw	$Q^{co}l$, kw	m_{gf}, kg/s	m_{col}, kg/s	m_{ref}, kg/s	COP
1	28	74.706	35,39	49,749	0.6224	1,983	0,4503	1,41
2	30	74.677	35,96	50,552	0,6330	1,511	0,4576	1,41
3	32	74.647	36,53	51,355	0,6437	1,228	0,4648	1,41
4	34	74.622	37,00	52,010	0,6524	1,037	0,4708	1,41
5	36	74.593	37,53	52,762	0,6624	0,902	0,4776	1,41
6	38	74.563	38,07	53,508	0,6724	0,800	0,4843	1,41
7	40	74.534	38,59	54,248	0,6823	0,721	0,4910	1,41

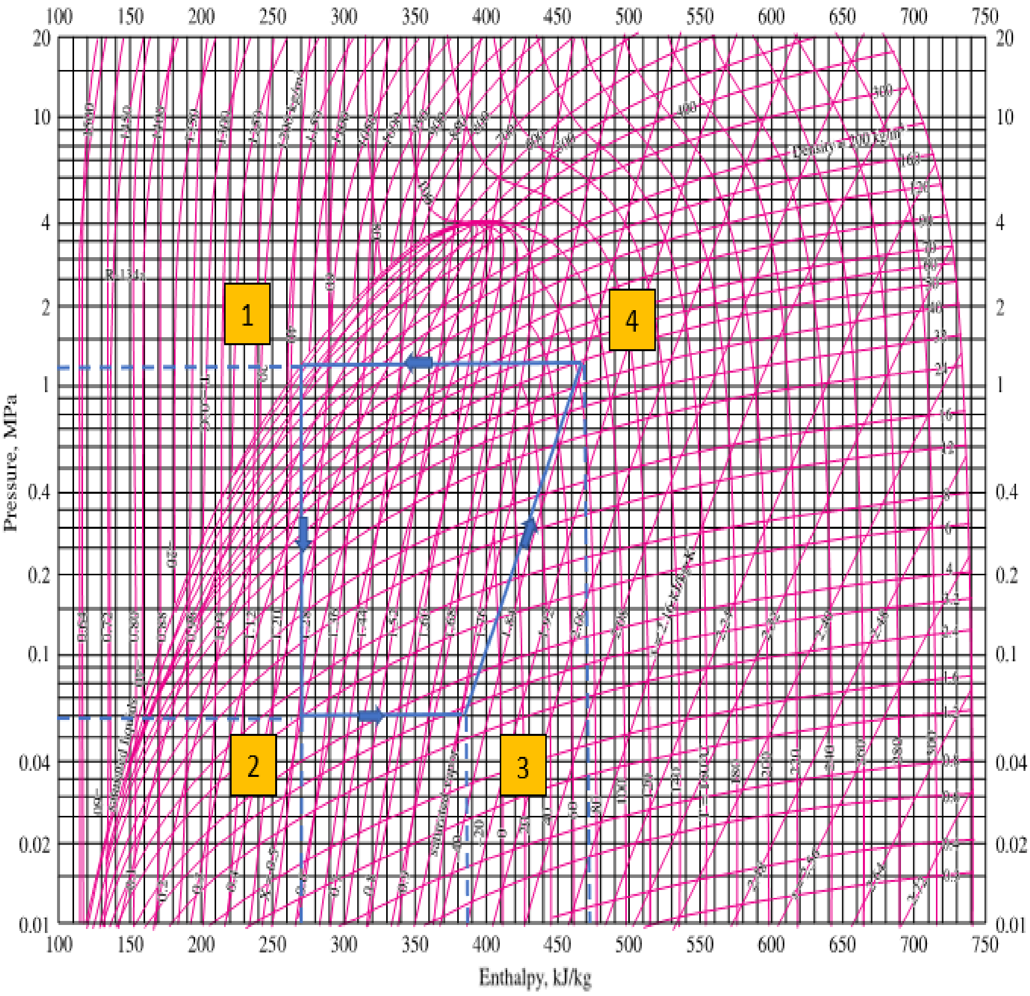


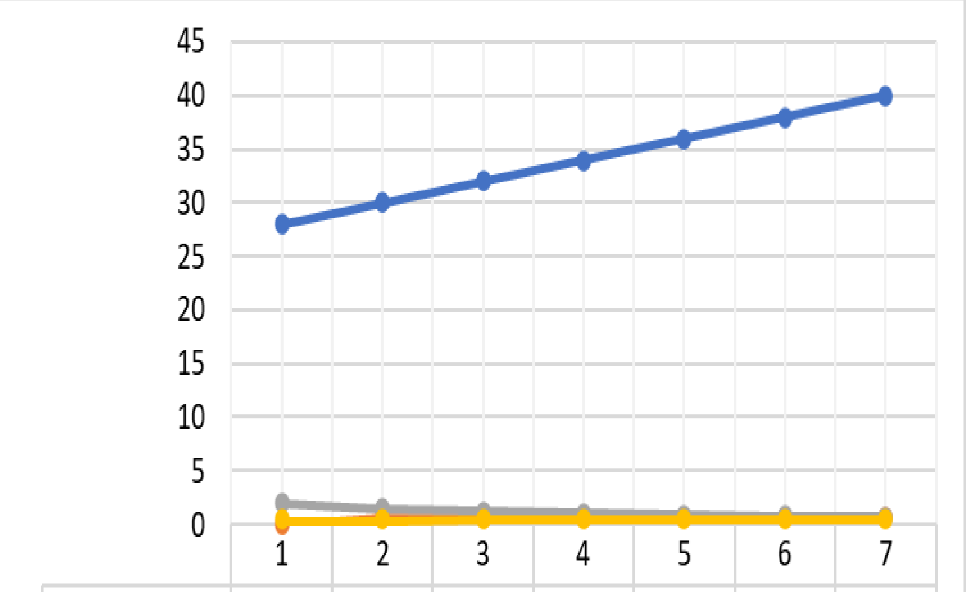
Fig. 7. Presure versus enthalpy diagram for refrigerant R134a.

Figure 8 shows that the mass flow rates of the well (mgf), coolant (mcol) and refrigerant (mref) do not change significantly with change in the outside temperature (Tenv) varying between 28 and 40°C.

Figure 9 shows the variations in geothermal fluid temperature (Tgf), Compressor power consumption (Wcomp) and rate of heat transfer to the refrigerant passing through the Evaporator (Qcol)Relation between environment temperature (Tenv) when the outdoor temperature is changing between 28-40°C The net power consumption increases from 35.39 kW to 38.59 kW (8.6%).

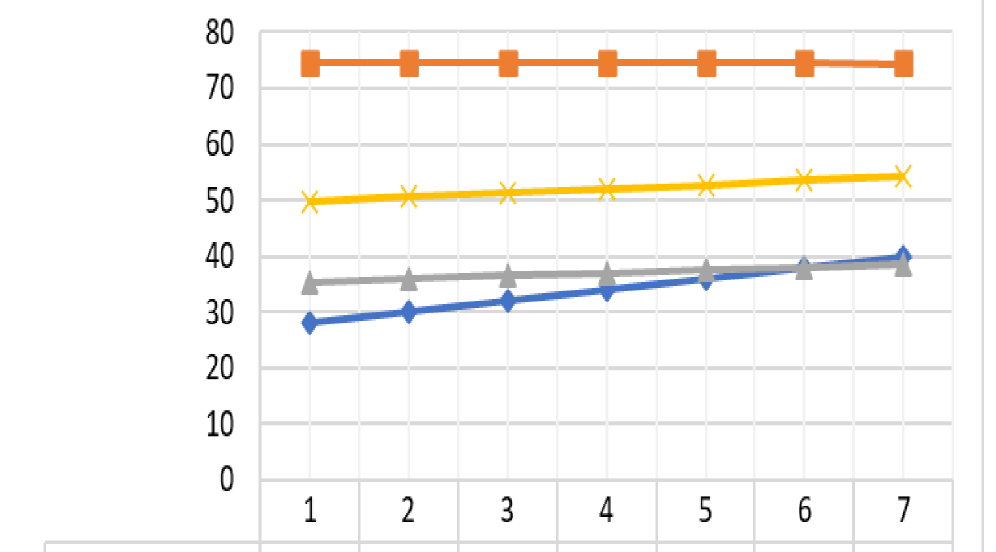
Figure 10 shows that the changing outdoor temperature has marginal impact on various parameters listed on the figure.

The study carried out shows that using existing wells as geothermal heat source with heat pumps is not the best option for cooling only applications. Absorption chiller would be a better choice for heat based cooling. However, combination of seasonal cooling and heating over a year, with heat storage in geothermal wells during hot periods and heat utilization for space heating during cold periods presents very attractive energy solution option.



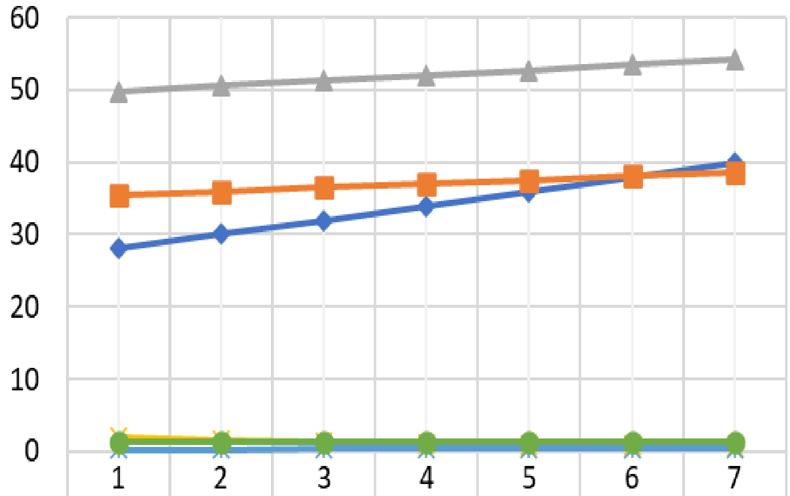
	1	2	3	4	5	6	7
Tenv, °C	28	30	32	34	36	38	40
mgf, kg/s	0	0.63	0.64	0.65	0.66	0.67	0.68
mcol, kg/s	1.98	1.51	1.23	1.04	0.9	0.8	0.72
mref, kg/s	0.45	0.45	0.46	0.47	0.47	0.48	0.49

Fig. 8. Relation between T_{env}, m_{gf}, m_{col} and m_{ref}.



	1	2	3	4	5	6	7
Tenv, °C	28	30	32	34	36	38	40
Tgf,°C	74.71	74.68	74.65	74.62	74.59	74.56	74.53
Wcomp, kW	35.39	35.96	36.53	37	37.53	38.07	38.59
Qcol, kW	49.75	50.55	51.36	52.01	52.76	53.51	54.25

Fig. 9. Relation between T_{env}, T_{gf}, W_{comp} and Q_{col}.



Tenv, °C	28	30	32	34	36	38	40
Wcomp, kW	35.39	35.96	36.53	37	37.53	38.07	38.59
Qcol, kW	49.75	50.55	51.36	52.01	52.76	53.51	54.25
mcol, kg/s	1.98	1.51	1.23	1.04	0.9	0.8	0.72
mref, kg/s	0.45	0.45	0.46	0.47	0.47	0.48	0.49
COP	1.41	1.41	1.41	1.41	1.41	1.41	1.41

Fig. 10. Relation between Tenv, Wcomp, Qcol, mcol, mref and COP.

7. CONCLUSION

This paper starts with three major challenges for Bangladesh with increasing depletion of domestic gas reserves, how to make a transition to a new energy sector scenario with adequate social justice and less or no fossil fuel share over time and what will happen to the large gas infrastructure. A way forward towards solution has been built on the argument of leapfrogging to geothermal energy as a potential alternative source. Hydrogen can also be seen as a solution for leapfrog but this article does not cover hydrogen. The prospective locations of geothermal energy resource based on information available from official data sources is presented in the maps after considering past efforts within the country. But we realize it needs to be updated through new exploratory studies. Other country experiences in similar lines serve as an encouragement to explore the case of Bangladesh. However, it becomes clear that technical feasibility and institutional feasibility need to be understood well given the prospect. To understand technical feasibility simulation is designed by IPSEpro to study the potential of using existing wells as a geothermal source for cooling purposes, and real-world data for renewable applications are used for performance analysis. The modeling results contribute to the enhancing of further utilization of the existing depleted wells. We are aware of the limited data access and use in this study. Therefore, to understand full potential future research need access to more data on existing wells in Bangladesh. It is expected that this article will generate interest to explore geothermal potential in Bangladesh and will attract companies and businesses to provide technological cooperation. As an example we cite the case of Norway which is oil-gas producing country and is expanding its geothermal energy share. Like Bangladesh, in the same decade of seventies Norway emerged as a major petroleum producing country but unlike Bangladesh, Norway used its oil and gas mainly for export to Europe and accumulated huge rent over the years and invested the same for R&D in energy sector. The mature petroleum fields on the Norwegian continental shelf are reaching the end of their economic lifetime in the North Sea and will soon be subject to P&A. Utilizing the depleted fields for energy generation and energy storage have been reviewed carefully in Norway lately and there are certain opportunities identified for reuse of the existing wells. However, the Norwegian petroleum fields are mostly at deep water area and thereby the costs related to reuse of the existing wells might be considerably higher than *e.g.* for the countries where all or a majority of the wells are drilled onshore [47]. In comparison, Bangladesh used domestically the drilling activity and gas withdrawal for early phase of economic development of the economy. This is still acting as a major source of energy for the country's economic development. But as the country grows towards targeted middle income by 2021 and by 2041 towards high income status as envisaged by political leaders of the country, new innovation needs to enter into the developmental action agenda very fast. Moreover, our observation is that Bangladesh with all on shore wells have advantage for exploring the possibility of geothermal technology rather easily compared to Norway. Norway has been very successful concerning development of petroleum exploration and production technologies. Therefore, the accumulated Norwegian knowledge, supported by the modern and state of the art technologies available can be seen as a scope for potential technological international partnership development to enhance further utilization of the existing depleted wells for energy generation in Bangladesh. If successful this transition to geothermal option will alleviate the uncertainty around social justice in energy sector transitions. This will also enable to reduce national risk of stranded asset in the form of abandoned gas infrastructure and trained manpower arising from depleting gas reserves. This at the same time will also help in leapfrogging through diversification of the current monolithic dependence on gas as primary energy sources of energy and to expand the renewable energy portfolio beyond solar and wind based technologies. Latter two cannot fulfil the expected growth of demand of reliable electricity in Bangladesh given the scarcity of unfertile land mass. In Bangladesh the regulation debars shift of agricultural fertile land for solar energy project. As most of its land is fertile and provide food security through agricultural activities, unused non-agricultural land is difficult to find in densely populated country for solar and wind projects [48].Therefore, a careful socio-technical and economic-environmental assessment would be required to evaluate the energy production and storage capability, by reusing existing wells. Since gas sector is still government controlled and with high international cooperation it may be easier for Bangladesh to overcome well ownership and closer deal for used up wells compared to many other countries. If we follow the various criteria for successful transition [49] then political, social, environmental feasibility indicators are compatible with geothermal energy pathway for Bangladesh. However, a demonstration stage pilot project for feasibility assessment in all the dimensions is necessary for learning local context better to manage transitions. This cannot happen in Bangladesh without global cooperation. Timing of urgency of national need to solve energy transition trilemma match with the timing of urgency of global climate change mitigation response need (SDG 13) and opportunities under SDG 17 for international cooperation in implementation. This study demonstrates the need and method of assessment to enhance focus on geothermal energy generation and use strategically in Bangladesh in fast economic growth phase (SDG 8) through smooth and peaceful transition in the longer run (SDG 16). This will not only build a sustainable energy future for Bangladesh (SDG7) with justice in transition assured but will also act as an energy sector development model for oil and gas rich many developing economies with necessary global partnership development (SDG 17) in innovation (SDG 9) and knowledge transfer.

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NOMENCLATURE

m_{gf}	- geothermal fluid mass flow, kg/s
m_{ref}	- refrigerant R134a mass flow, kg/s
m_{col}	- cooling fluid mass flow, kg/s
T_{env}	- cooling environment fluid temperature, ^{0}C
T_{gf}	- geothermal fluid temperature, ^{0}C
T_{ref}	- R134a fluid temperature, ^{0}C
W_{comp}	- compressor net power consumption, KW
Q_{col}	- evaporator heat transfer, KW
CoP	- coefficient of performance

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Producing Biodiesel and Optimized by Taguchi Design against Palm Oil as Sustainable Alternative Fuels in Bangladesh

Abhishek Samanta*[,1], Sourav Goswami[+] and Prokash C. Roy[+]

Abstract *– In food and cosmetics industries palm oil is considered as main element though it is treated unhealthy to human body. However, in case of energy industries palm oil has been realized as sustainable alternative feedstock recourses for biodiesel which can balance energy scarcity while conserving essential ecosystems with biodiversity. This present study illustrates formation of small batch (10-25 liters/batch) biodiesel in the laboratory against oil based palm. An orthogonal approach with L9 Taguchi was selected to find out the transesterification optimization parameters involve reaction time, methanol to oil ratio, reaction temperature and Catalyst concentration. The production process of biodiesel was performed by varying different conditions being methanol to palm oil molar ratio (M/O) and the wall warmth. The maximum yield was settled to be 86% by using M/O value 6 and wall warmth 55°C by experimental approach. Properties of biodiesel were tested, namely density, flash point, kinematic viscosity and calorific value. The density was found to be 898 kg/m³, flash point 179.33°C, kinematic viscosity 4.98 mm²/s and the calorific value was found to be 37.06 MJ/kg. These values are very relative to the standard values of biodiesel composed from oil based palm.*

Keywords – *biodiesel production, palm oil biodiesel, POME, sustainability, Taguchi method.*

1. INTRODUCTION

Diesel is used widely in the transportation sector, especially to run trucks, locomotives, aircraft engines, military vehicles and passenger cars. The economy of any country is directly dependent on the availability of diesel. In 2019 Energy and Mineral Resources Division, Ministry of Power, Energy and Mineral Resources, Bangladesh reported that around 6.6 million metric tons of petroleum products and crude oil are generally imported in Bangladesh each year and about 68.9% fossil fuel based energy consumption happens where the share of biomass based energy was only 29.1% in the year 2017-18. It was reported that petroleum based product demand has increased about 2-4% per annum and by 2030 the demand will be around 10 million tons in Bangladesh [1]. Addition to that, drastic rise in transport facilities will take place for the port facility service in Mongla and Chittagong ports. Scarcity of diesel may undermine the growth of a nation by jeopardizing functions of various kinds in different sectors. Diesel is however, a non-renewable resource and its usage should be strictly monitored. With the ever-growing population, the numbers of vehicles on the streets are increasing on a daily basis, producing a massive demand on diesel. This demand cannot be met with the required supply unless the fossil fuel reserves are extinguished. In Bangladesh, diesel is the predominant petroleum based fuel among other fuels, about 70% consumption (Figure 2) in form of diesel has been occurred in year 2017-18 [1]. However, this paper aims to attain three objectives such as (i) prepare biodiesel in the laboratory from palm oil in the presence of methanol and KOH catalyst, (ii) determine the properties of prepared biodiesel in order to compare the results with standard values. (iii) determine and compare the response magnitude of biodiesel for a number of parameters using ANOVA.

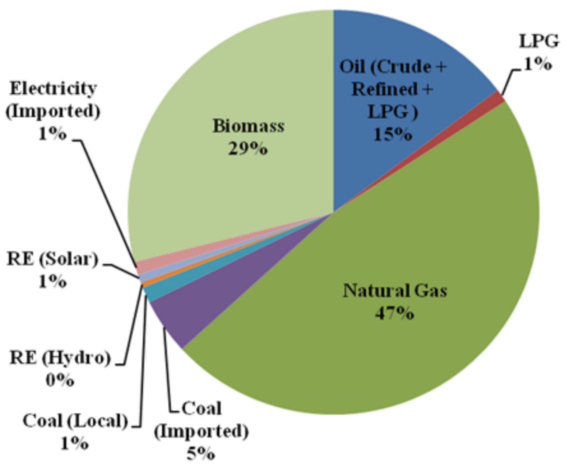

Fig. 1. Various types of energy resources consumed in Bangladesh year 2017-18 [1].

A wealth of literature is available on related issues and learning lessons from the literature may help to develop a board understanding about it. Narayana *et al.*

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[2] reported an optimal condition for maximum yield of biodiesel for mass production as 6:1 molar ratio of methanol to Pungam oil, 1.92 percentage weight of catalyst at 55℃. Biodiesel is a good example of an alternative fuel. Intrinsic approach describes durability and constancy of environmental, fiscal and social facet of humanity is termed as Sustainability. Reliability of biofuel (vegetable oil) in unmodified diesel engine was tested on the desire of French government for energy independence in its province (Africa) [3]. In 1900 at Paris Exhibition, peanut oil fueled small diesel engine by company Otto and then castor oil powered locomotives were showed prosperity by Rudolph Diesel [3]. In the time of Second World War vegetable oils were treated as crisis fuel, shipping of cottonseed oil had been restricted in Brazil. Since 1930, attempts have been taken to assimilate divergent renewable fuel, which are primarily achieved by research academy, universities and government management [3]. PRO-alcohol was developed in 1975 to establish the production of ethanol for transport sector. It was envisioned blends of 30% vegetable oil in diesel for fully substitute fossil fuel in future. At the same era, a specialized method the transesterification of vegetable oil was recommended. Regrettably the initiative was discarded cause of crude oil price fall in International retail and high production cost for biodiesel [3]. Methyl ester of oil based palm as alternative for diesel had been established since 1988 by Research Institute in Malaysia [4]. Kapilakarn and Peugtong [5] presented an economic design to determine the optimal operating conditions of biodiesel yield. It has been reported that at 6:1 methanol to oil ratio at 70℃ with 20 minutes reaction time provides the optimal condition to reduce the operating cost [5].

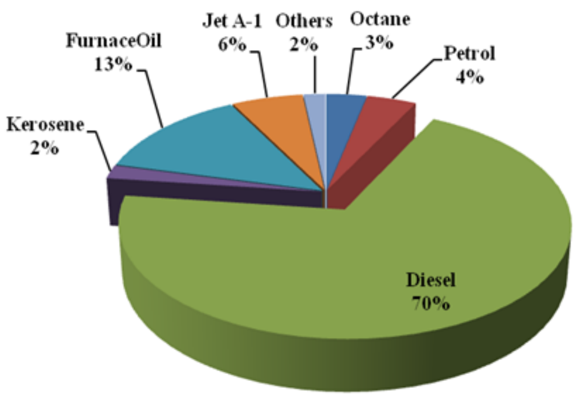

Fig. 2. Percentage of diesel consumption among other petroleum based fuel in Bangladesh year 2017-18 [1].

Oil based palm is gleaned from palm fruit sapling, native Western Guinea. The palm tree was later introduced to different states. In Malaysia palm tree was popularized since 1870 as exquisite plant. In 2014 the universal productions of oil have expanded about 155.8 million tons. Only in Malaysia there was 60% growth of palm agricultural land by 2005 [6]. The fruit of the palm tree is produced two or three years after being planted. Palm tree produce fruit for twenty five years. The amount of oil produced per hectare is more as compared to other oilseed crops. In the year of 2014, the government of Malaysia had mandated the adoption of 5% palm oil methyl ester biodiesel (B5 POME) with petroleum diesel in transport sector entire nationwide [7]. In 2018 researchers have claimed that industrial palm oil can yield sufficient biodiesel (POME) to effectively balance Malaysia's full diesel consumption. Diesel engine manufacturers provide engine warranties on consumption of biodiesel up to B7 in Malaysia and the fact that without any major modification diesel engine can handle biodiesel-diesel blends up to B100 (100% biodiesel) can promise better future environment [8]. Araby *et al.* [9] estimated the important fuel requirements of Palm oil and POME blend with diesel and results indicate that blended fuel values were very adjacent to petroleum diesel till 30% (B30). About 91.07% palm oil biodiesel yield was reported at 70°C with 2 to 3 hours reaction time at a 1:15 molar ratio of palm oil to methanol with catalyst concentration of 3 to 6 wt% KOH along with the support of heterogeneous catalysts, although consumption of potassium based species was observed in both spent catalysts [10].

Enthusiastic researchers from Bangladesh have taken initiatives to develop biofuels [11]. Introduction of 5% bioethanol blend with conventional fuel in transport sector has been planned by Bangladesh Government, [12] though; no such activity has been reported in Bangladesh. Feedstock resources for biodiesel in Bangladesh have been reviewed [13]. Though, the production of bioethanol from renewable feedstock has been overlooked. Among the various feedstock palms retain high relevance. In ancient world palm was used for sugar producing. Addition to that palm can flourish in grim habitats and their sap consists of about 10-20% sugar [14]. The sap can be collected without destroying the palm tree aged about 5-100 years. A male palm tree could produce 140.42 kg sugar based mass with 29.85% sugar concentration per annum; however a female tree can provide 195.56 kg sugar based mass [14]. Nabi *et al.* [15] from Bangladesh reported 96 vol% biodiesel yield at 60°C with 22 vol% methanol and 0.45 wt% catalyst concentration from a vegetable feedstock. Also the reduction in carbon monoxide emission along with engine noise and smoke with all biodiesel blends was reported [15].

Many states have taken already initiatives for carbon dioxide emission mitigation. With regard the universal carbon cycle; biodiesel is mediated to be carbon dioxide inactive. More special conveniences cover very less sulphur fuel which is crucial in next generation catalytic converter and diesel particulate filter, along with less emission, steep cetane number, and biodegradation in marine environment [16]. Manufacturing of biodiesel or fatty acid methyl ester requires vegetable oil and can be identified into heterogeneous, homogenous with catalytic or noncatalytic approach based on catalyst concentration. Normally homogenous approach is followed in economic manufacturing [17]. Biodiesel conversion from vegetable oil occurs chemically by transesterification of large, branched triglycerides with alcohol. As compared, biodiesel is also very user-friendly since it can be mixed with any proportional of diesel and can be suited to diesel engine without prior adjustment [18]. Mahanta *et al.* [19] reported at laboratory level transesterification maximum conversion to biodiesel was about 72% at 600C operating temperature with 20 wt% of methanol for Pongamia pinnata as feedstock and about 82% conversion to biodiesel with 25 wt% of methanol for Jatropha curcus as feedstock. Also, it was observed that both biodiesel meet the ASTM specifications [19]. The scarcity of fossil fuels is posing a serious threat in all sectors. The evolving states are in relentless monetary discrepancy cause of importing fuel price [20]. Agarwal and Dhar [21] have conducted experiments with 20% biodiesel blend in a generator engine. It was reported marginal increment in brake specific fuel consumption but noticeable improvement in thermal efficiency for biodiesel blend compared to diesel [21]. Alternate fuels are of utmost importance presently. Biodiesel is one such alternative fuel which can run in traditional diesel engines. The biodiesel manufactured from palm oil shows characteristic compatible to diesel and suitable without modifying the engine. In the present work, manufacturing and examination of palm biodiesel as a fuel had been done established on literature available.

2. PRODUCTION OF POME, MATERIALS AND METHODOLOGY

2.1 Materials

Commercial grade palm oil was acquired from regional market, Kolkata, West Bengal as the unprocessed ingredient for biodiesel production. The fatty acid (FFA) content was less than 0.6%. The oil was then filtered and dried for 2 hours at temperature 90-100°C in oven to extract contamination and moisture. Other analytical grade reagents methanol (assay 99%, Merck and Co.) and alkaline catalysts KOH (assay 97%, Merck and Co.) were acquired from venders for this experimental study.

2.2 Design of Experiments (DOE) using L9 Taguchi

OVAT or one variable at a time is not practical for organized optimization process as the other variables are also important for maximum yield of biodiesel. Accordingly, software governed approximation are preferred which cover RSM (response surface methodology) consisting of CCD (Central Composite Design), or one factor approaches consisting of Taguchi Orthogonal Arrays (OA). To develop the optimum parametric circumstance for a process an enormous quantity of experiments are usually required [26]. The Taguchi method emerged by Dr. Genichi Taguchi has the very distinctive specialty of not explore every workable parameters combination, basically shrinking the bulky optimization method to a few run. Taguchi OA applies orthogonal arrays to resolve the least of notable runs within associated variables at different levels of each variable that are acceptable in anticipating the optimum response within a remarkably reduced number of experimental runs. This results in a least number of required runs which are recommended for a proper prediction of the response [24]. The runs were systematically randomized to reduce analytical errors. Traditional optimization methods for any experimental investigation are complicated and difficult to practice. Manual optimization is a hard task because the increase in process parameters and levels the number of experiments increases largely. Taguchi method utilizes to sort out this problem with lesser number of experiments [22, 23]. Taguchi method applied on the mean and variance of performance parameters to analyze the influence of various restriction of a process that resolves the convenient operations. It is a convenient method for optimization of various parameters affects the operations and the extent to which they can be varied. This method is not specifically investigated all the possible parameters combinations but only few pairs of combinations [24]. The required number of experiments and their parameters can be finalized from the Orthogonal Arrays (OA).

In the midst of different parametric criterion regulating the yield of biodiesel such as Methanol to oil ratio, Catalyst concentration, Reaction time, Reaction temperature, alcohol type and quantity, catalyst type, stirring speed or agitation, moisture quantity in reactant and quality of the oil, only four largest affecting parameters with three levels (L = 3, P = 4) have been treated in this paper (Table 1). The effects of selected parameters at three various levels have been observed by attending only nine experiments as per L9 OA. To reduce the errors all experiment has been repeated three times. The minimum feasible total of experiments 'N' is determined against the total of levels 'L' and total no of design and selected control parameters 'P' adopting the correlation $N = (L-1)P+1$. [25].

Table 1. Parameters chosen at three levels for L9 design.

Parameters	Variables	Levels 1	Levels 2	Levels 3
Methanol to oil ratio	A	5:1	6:1	6.5:1
Catalyst concentration (%)	B	0.5	1	1.5
Reaction time (hour)	C	2	2.5	3
Reaction temperature (°C)	D	50	55	60

Transesterification hinges on specific essential variables such as reaction temperature, extent of excess alcohol, and catalyst concentration, reaction time and RPM of stirrer. RPM are kept constant for present experiments RPM=1500. Parameter level was set as:

Methanol to oil molar ratio: 5:1, 6:1, 6.5:1
Amount of KOH (wt% of oil): 0.5, 1, and 1.5
Reaction temperature (°C): 50, 55, 60
Reaction time (hour): 2, 2.5, 3

Four parameters, 3-levels experiments are considered by Taguchi method in the form of L9 OA to optimize the different parameters influencing the process. From the OA, the required number of experiments and their conditions can be confirmed. . Based on the information from L9 orthogonal there are a total nine (9) experiments (see Table 1) that have to be conducted and each experiment has to be conducted 3 times, to assure repeatability.

2.3 Signal to Noise Ratio (SNR)

Taguchi method evaluates SNR based on test data. The important factor SNR of Taguchi design differentiates it from conventional design methods which specify the attributes of the experimental responses. This ratio expresses a test level which furnishes the optimum performance in the test factors. There are distinct SNR like 'larger the better' (LTB), 'smaller the better' (STB) and 'Nominal the better' (NTB). STB for minimization problem, LTB for maximization problems and NTB for normalization problems can be selected. In this research 'larger is better' for biodiesel yield percentage is suitable as the objective is to define maximum biodiesel yield optimum conditions for different parameters. To determine the discrepancy amid the experimental and aim amount of performance parameters, use of loss function (LF) was suggested by Taguchi. The LF amount has moreover been reformed in a signal to noise ratio (SNR). SNR based empirical information assessment has been executed for the recognition of optimal parameter combinations. Considering the equitable is to obtain max yield of biodiesel, out of the possible distinct SNR quality characteristics, depended on the nature of variables, Larger-the-Better (LTB) has been embraced. Respectively, design criterion will be the level with the highest SNR. By using SNR reasoning, it is feasible to access optimum level of each parameter and optimum set of parameters producing the maximum biodiesel yield [24]. The distinct SNR like 'larger the better', 'smaller the better' and 'Nominal the better' can be obtained by the following equations. Where 'Y_i' is the result of each experiment measured from experiments, 'n' is the number of trials and 'j' is the number of design parameters.

Larger the better-

$$SNRi = -10\log\frac{1}{n}\left(\sum_{j=1}^{n}\frac{1}{y_j^2}\right) \tag{1}$$

Smaller the better-

$$SNRi = -10\log\left(\sum_{j=1}^{n}\frac{y_j^2}{n}\right) \tag{2}$$

Nominal the better-

$$SNRi = 10\log\left(\sum_{j=1}^{n}\frac{y_j^2}{s_j^2}\right) \tag{3}$$

Where,

$$y_i = \frac{1}{n}\left(\sum_{j=1}^{n} y_{ij}\right) \text{ (Response mean)}$$

$$s_i^2 = \frac{1}{n-1}\left(\sum_{j=1}^{n} y_{ij} - \overline{y_i}\right) \text{ (Variance)}$$

i = experiment number, and n = number of trials.

To identify the factor with large scattering, ANOVA analytical method can be applied [27]. In this paper, the results from experiments can be inspected by performing analysis of variance based on the orthogonal arrays to exhibit the degree of influence of each factor that remarkably influenced the response variables. The comparable mathematical relations entrenched with ANOVA are given in Equations (4), (5), (6) and (7) [27]. Equation (4) provides the mean value of SNR, where number of the trials is given by k. Variations of the overall mean (SS) sum of squares is expressed by (5). The influencing factors mean (SS_i) is calculated as (6). The individual factors contribution percentage of the selected response variables will be treated to conclude the optimized combination and calculated through Equation (7) as follows:

$$\overline{SNR} = \frac{1}{9}\sum_{k=1}^{9}(SNR)_k \tag{4}$$

$$SS = \sum_{i=1}^{9}(SNR_{ij} - \overline{SNR})^2 \tag{5}$$

$$SS_i = \sum_{j=1}^{3}(SNR_{ij} - \overline{SNR})^2 \tag{6}$$

$$Contribution\% = \frac{SS_i}{SS}\times 100\% \tag{7}$$

The SNR were inspected for all biodiesel yield percentage. In conferment with the output, the best sequences were decided, and ANOVA was practiced to draft the scale of individual contribution. ANOVA estimates the effect of one or more aspects by correlating the response variable means at the different aspect levels.

2.4 Experimental Setup and Production of POME

Vegetable oil obtained from various sources are very useful to prepare biodiesel cause it has almost similar fuel properties and compatible to diesel and suitable without modifying the engine. The primary solvent relevant for transesterification of triglycerides is methanol. Methanol is preferred for it is easily available in the market along with cheap price and advantages of chemical and physical properties also it can quickly react in transesterification process. Catalyst improves reaction by dropping its activation energy, potassium hydroxide (KOH) is used as catalyst.

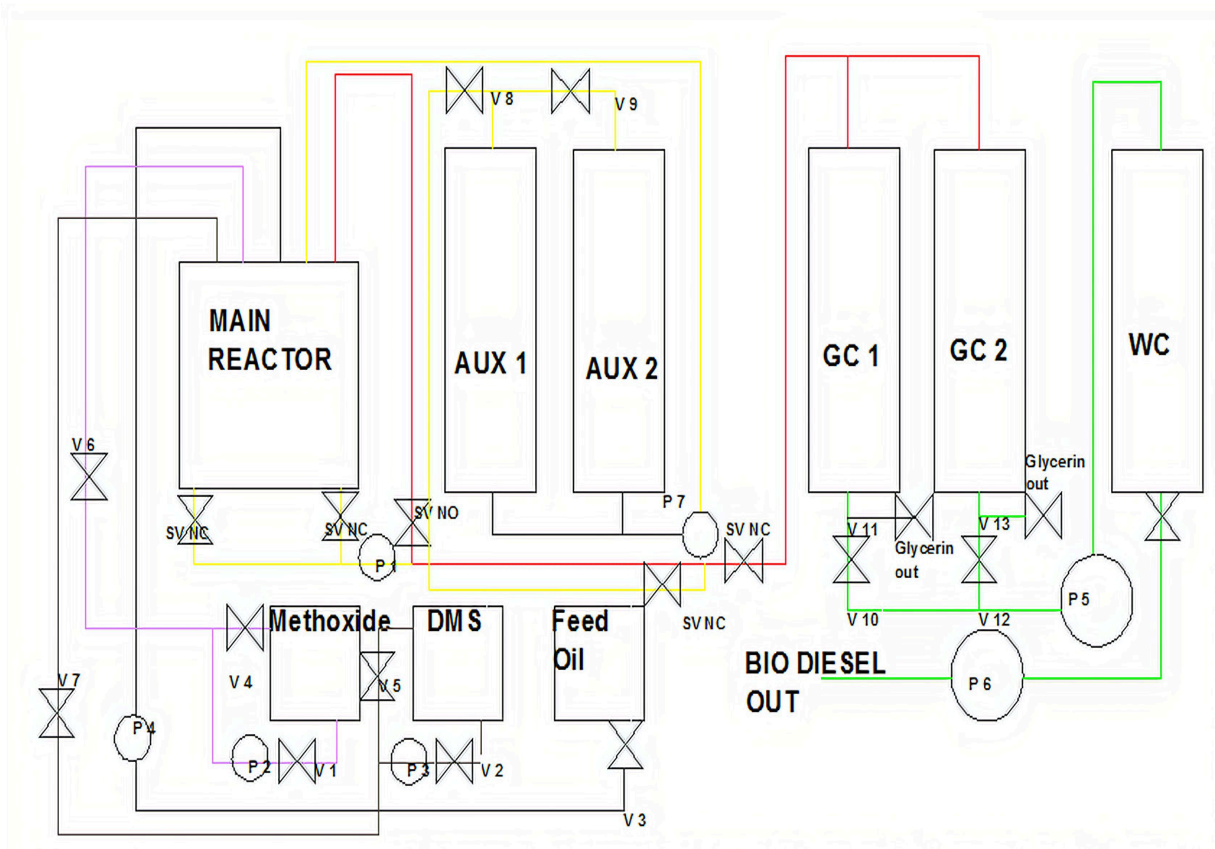

Fig. 3. Biodiesel production experimental set-up for small batch (10-25 liters/batch).

The experiment set up consists of nine cylinders. Out of them, five are useful for the preparation of palm oil biodiesel. In the schematic diagram as shown in Figure 3, in the lower part, out of three chambers the first chamber from the left is for catalyst, second one is for alcohol like methanol, ethanol and last one is for mixing. These chambers are connected by pump which helps in pumping alcohol and catalyst to the main reactor cylinder. Also three valves are there which controls the rate of flow. For the acceleration of rate of chemical reaction, in the main reactor chamber fan is there that helps in proper mixing of reactant. Temperature sensors and controllers maintain required temperature inside the cylinder. Temperature control is essential for higher yielding and of minimum time requirement. Main reactor chamber is linked by pump, valve to WC chamber, here mixture remains for some time and due to different molecular weight, upper portion is filled with diesel and lower part with glycerol. At the bottom most part of the WC chamber, a valve is there that opens and glycerol comes out. The remaining portion of the product that is biodiesel is taken later. Biodiesel at that time is not pure. Further purification is necessary. For that washing should be done repeatedly with water until pH value of water comes to 7.

The reaction of vegetable oil with alcohol is called transesterification or alcoholysis to form esters and glycerol. The reaction is shown in the following equation.

CH_2-OOC-R_1			Catalyst (KOH)	R_1-COO-R'		CH_2-OH
|						|
CH-OOC-R_2	+	3R'OH	↔	R_2-COO-R'	+	CH-OH
|						|
CH_2-OOC-R_3		Alcohol methanol		R_3-COO-R'		CH_2-OH
Glyceride				Esters		Glycerol

Transesterification is very rapid with alkali-catalyst compared to acid catalyst. Potassium hydroxide is used as catalyst to boost the reaction rate and biodiesel yield. Surplus methanol is applied to shift the reversible reaction to the product side.

After separation of phases purification of biodiesel is necessary and attends by washing to nullify the catalyst in biodiesel. This process should be continued until pH value of water comes to 7. Free fatty acids can be recovered from the ester phase by distillation at 30-50°C. Finally wash biodiesel should be kept at 50°C for eight hours in a heater oven and then biodiesel is ready for use. The biodiesel procured was measured based on literature [24] and used to evaluate the biodiesel yield using the following equation.

$$Yield(\%) = \frac{weight - of - Biodiesel}{weight - of - oil} \times 100 \quad (8)$$

The relevant fuel properties for produced POME were examined with standard methods and validated with literature (Table 2). Using the fuel volume and mass, density has been determined. A viscometer (Brookfield Model: DV-II) was used to resolve the kinematic viscosity. Flash point was resolved by a flash point tester (Silver Pensky-Martens, Model: VT4643) and heating value was measured by bomb calorimeter (Parr Instrument, Model: 6100).

Table 2. Measured value and standard value comparison of POME.

Properties	Method	POME	POME [9]	ASTM 6751	EN 14214
Density (kg/ m³)	-	898	877	870-900	860-900
Kinematic Viscosity (mm²/ s at 40°C)	ASTM D2983	4.98	4.56	1.9-6.0	3.5-5.0
Flash Point (°C)	ASTM D93	179.33	196	>130°C	>120°C
Calorific Value (MJ/ kg)	ASTM D4809	37.06	41.3	-	-

Table 3. Fuel properties of produced POME compared to petroleum diesel.

Properties	Method	POME	Diesel
Density (kg/ m³)	-	898	832.6
Kinematic Viscosity (mm²/ s at 40°C)	ASTM D2983	4.98	2.96
Flash Point (°C)	ASTM D93	179.33	68
Calorific Value (MJ/ kg)	ASTM D4809	37.06	45.9

Table 4. Uncertainty of the measured quantities and measurement accuracy.

Properties	Units	Uncertainty (%)	Measurement accuracy
Density	(kg/ m³)	± 0.01	± 0.1
Kinematic Viscosity (at 40°C)	mm²/ s	± 0.11	± 0.01
Flash Point	°C	± 2.42	± 0.1
Calorific Value	MJ/ kg	± 0.13	± 0.001

2.5 Uncertainty Analysis

The uncertainty while collecting data from experimental instruments had been caused by various operational and physical limitations. An uncertainty analysis was made to ensure accuracy in respect with preciseness and repeatability of the experiment results. The uncertainties of collected data along with the measuring equipment accuracy are very important to substantiate the correctness of the experimental data. Using root mean square method the analysis was organized, when the total uncertainty U of a quantity Q had been predicted, relying on independent variables X1, X2,.,Xn (Q as a function of X1, X2,.,Xn) carrying particular errors ΔX1, ΔX2,..,ΔXnas given by following equation [28].

$$\Delta U = \sqrt{(\frac{\partial U}{\partial X_1}\Delta X_1)^2 + (\frac{\partial U}{\partial X_2}\Delta X_2)^2 + ... + (\frac{\partial U}{\partial X_n}\Delta X_n)^2} \quad (9)$$

In Table 4 percentages of uncertainty and measurement accuracy of the measured experimental values.

3. RESULTS AND DISCUSSIONS

3.1 Determination of Optimal Condition of the Experiment by Taguchi Method

Yielding of biodiesel is biodiesel obtained from the amount of oil invested. The yield of biodiesel is dependent on many factors. The variable factors are applied at 3 levels to design the experiment at MINITAB 17. Here in the experiment 0.5%, 1% and 1.5% of the total reactant are used as catalyst. The effect of different M/O ratio was established along with time taken for transformation in biodiesel from oil based palm. As the methanol to palm oil ratio was increased, yield first increased and then decreased, it was found that the yielding reached a maximum at 6 M/O. When the time taken to reach equilibrium was highest, the yield was also highest at 86.2%. In Table 5 effect of reaction temperature was established along with time taken. The yield was found 86.2% and time was taken 3.167 hours. It was found that yielding reached a maximum at 55°C. When the time taken to reach equilibrium was highest, the yield was also highest at 86.2%. It has been obtained from these experiments that the optimum conditions for production of biodiesel are: catalyst should be 1% of the total volume, methanol to palm oil ratio should be 6, and wall temperature should be 55°C. The empirical outcomes (Table 5) indicate that the Experiment No 5 has the max value of SNRA and experiment No 4 has the lowest value of SNRA. In this present study, the escalation of POME yield is the objective, which is why LTB SNR model was applied.

The effect of process control parameters on average SNR for biodiesel yield are the key to find out optimum condition for this experiment. Thus, Figure 4 shows a plot of b/w process control parameter Vs average SNR. From this Figure 4, it is concluded that optimum condition of various parameters are methanol: palm oil = 6.5: 1, KOH = 1wt% of oil and reaction temperature = 55°C Reaction time = 3 hour. It means that experiments number 5 has the maximum yield and highest value of SNRA; this would be the optimum stabilized set of parameter. Where other parameters are RPM = 1500 is kept constant.

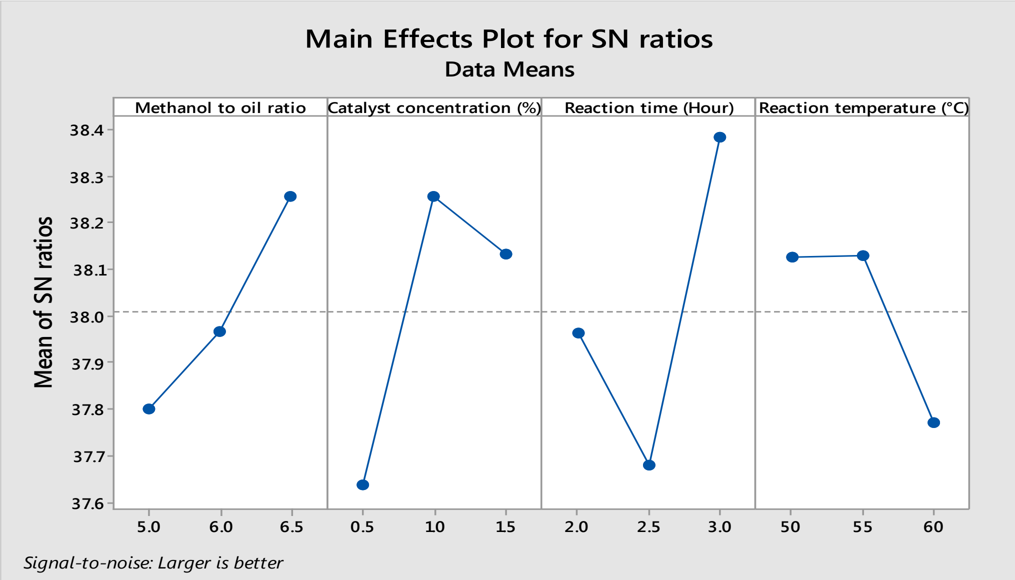

Fig. 4. SNR of each parameter at different level.

Table 5. Percentage of yield and SNR for 9 experiments.

Exp. No.	M/O	Cat cons (%)	Time (hour)	Temp (°C)	Mean Yield (%)	SNRA1
1	5:1	0.5	2	50	75	37.5012
2	5:1	1	2.5	55	78	37.8419
3	5:1	1.5	3	60	80	38.0618
4	6:1	0.5	2.5	60	71	37.0252
5	6:1	1	3	55	86.2	38.7101
6	6:1	1.5	2	50	81	38.1697
7	6.5:1	0.5	3	55	83	38.3816
8	6.5:1	1	2	60	81.5	38.2232
9	6.5:1	1.5	2.5	50	81	38.1697

Table 6. Response table for signal to noise ratios larger is better.

Level	Methanol to oil ratio	Catalyst concentration (%)	Reaction time (Hour)	Reaction temperature (°C)
1	37.80	37.64	37.96	38.13
2	37.97	38.26	37.68	38.13
3	38.26	38.13	38.38	37.77
Delta	0.46	0.62	0.71	0.36
Rank	3	2	1	4

3.2 *Analysis of Variance*

ANOVA is applied to gauge the response magnitude (in percentage) for each given parameter in the L9 orthogonal array. In this experimental study, ANOVA computes the relation with each parameter of biodiesel production. The utmost important parameter is determined and its contribution also identified by using ANOVA. Reaction time and percentage of catalyst concentration are the utmost important parameters and its contribution is 38.67% and 31.85% for POME production. Contribution percentage of biodiesel production for other two parameters like, M/O ratio and reaction temperature are 16.69%, and 12.79%, respectively shown in Table 7.

Table 7. Data obtained from ANOVA (Analysis of Variance).

Source	DF	Contribution	Adj SS	Adj MS
Methanol to oil ratio	2	16.69%	27.12	13.56
Catalyst concentration (%)	2	31.85%	51.73	25.86
Reaction time (hour)	2	38.67%	62.82	31.41
Reaction temperature (°C)	2	12.79%	20.77	10.39

3.3 *Fuel Properties of POME*

Testing of biodiesel POME is an important task prior to use in engine applications. Different properties like density, lower calorific value, viscosity, flash point is tested in different laboratory and it has been checked whether properties are compatible for engine application or not. Density of biodiesel is measured by measuring the volume of the biodiesel and mass. Mass is measured by an electronic device and volume by a measuring cylinder. Table 2 indicates that the properties of produced biodiesel (POME) are comparable with the biodiesel American standards ASTM D 6751 and European standards EN 14214.

Biodiesel should be advised clear and relieved of contamination. It is elementary but crucial test which is executed in a test tube indicates quality of biodiesel. The biodiesel viscosity is almost two times greater than petrol and diesel and viscosity has tremendous effect on temperature, in cold countries there is problem during the starting condition, at low temperature viscous is high so fuel is not better atomized. The kinematic viscosity or subjective defiance is an essential criterion for fuel injection and fuel injection pump. European standards EN 14214 serves an adequate scope from 3.5 to 5.0 mm^2/ s but American standards ASTM D 6751 provides an extensive scope 1.9 to 6.0 mm^2/ s. Flash point is crucial for handling of fuel, storage and transport. Flash point determination depends on instrument, and may be open or close accordingly to the apparatus used. Closed flash point of any oil is always lower than open because the enclosed vapour space facilitates the accumulation of vapour in sufficient quantity to ignite at a lower temperature than in the open apparatus. The Pensky-Martens closed tester apparatus is used to measure the flash point of the biodiesel sample. This apparatus is used for all liquid fuels having flash point above 120°F. Calorific value is an important parameter of a fuel, which is defined as the energy per unit mass of the substance at standard temperature and pressure. The higher the calorific value of the fuel the greater the energy content. The calorific value of biodiesel is generally higher than all other liquid fuel and coal but little lower than the diesel fuel and petrol. The bomb calorimeter consist of a water bath, a stirrer mounted on a disconnected bearing and driven by motor, calorimetric jacket, a thermometer, and a switch box leading the current into the motor and igniting the fuel in the bomb. It has been observed from Table 2, the density of POME, flash point and kinematic viscosity are obtained to be marginally fluctuated compared to literature.

4. CONCLUSIONS

Biodiesel was prepared in the laboratory from palm oil in presence of methanol and KOH catalyst. After changing the parameters, the yielding was calculated and the optimum conditions were found. The properties of the biodiesel sample, such as viscosity, calorific value, density and flash point were tested. The results obtained were very close to the standard values. The maximum POME yield obtained was 86.2% and conditions were M/O ratio 6:1, KOH 1.0wt% of oil, reaction temperature 55 °C and reaction time 3 hour. ANOVA computes Reaction time and percentage of Catalyst concentration are the utmost important parameters and its contribution is 38.67% and 31.85% for POME production. Contribution percentages of biodiesel production for M/O ratio and reaction temperature are 16.69%, and 12.79% respectively. By varying the M/O ratio and the wall temperature various yields and reaction completion times were obtained. The optimum conditions were methanol to palm oil ratio as 6 and the wall temperature as 55°C. The density, kinematic viscosity, flash point and calorific value of the biodiesel were found to be 898 kg/ m^3, 4.98 mm^2/ s, 179.33°C and 37.06 MJ/kg respectively. Ultimately, based on the empirical findings and literature reviewed, it was envisioned that palm has immense effectiveness for biodiesel and bioethanol generation without causing food deficit in Bangladesh. Agricultural production of palm would produce plenty of employment for the growing community, and would not cause the dilemma food versus fuel.

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Assessment and Way Forward for Bangladesh on SDG-7: Affordable and Clean Energy

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Abstract *– In 2019, Bangladesh was one of the world's fastest-growing economies with a GDP growth rate of 7.9%. However, the county is facing challenges such as energy scarcity, widespread poverty, and overpopulation. This article discusses the energy scenario in Bangladesh in terms of energy resources, supply mix, access to electricity and cooking fuels. It describes major issues and challenges, macro and micro initiatives taken by the Government of Bangladesh to attain SDG-7. The manuscript also compares the progress of Bangladesh with other South Asian countries. Finally, the paper recommends some policy interventions to attain SDG-7 as early as possible. This study concludes that Bangladesh is severely facing the problem of energy scarcity to maintain sustainable economic growth. It has been also observed that Bangladesh has a limited focus on renewable energy utilisation. With the huge availability of renewable energy potential, Bangladesh will not only solve the problem of energy scarcity but also save huge expenditure on imports of fossil fuel.*

Keywords *– energy accessibility, energy security, energy supply and demand, renewable energy, sustainable development, SDG.*

1. INTRODUCTION

The Sustainable Development Goals (SDGs) confirm the pathway to achieve a better and more sustainable future for people from every corner of the world. SDGs address global challenges such as poverty, inequality, climate change, environmental degradation, peace, and justice [1]. Table 1 describes 17-SDGs in a concise form, which the world needs to achieve by 2030.

Energy is a driving force to the socio-economic development of every country [2]. Now the world population enormously raised the energy demand; consequently, the world is facing an issue of an energy shortage [3]. SDG-7 ensures access to affordable, reliable, sustainable, and modern energy for all. It would be easily recognised that the attainment of SDG-7 is essential for the attainment of other SDGs, such as SDG-3, 4, 6, 8, 11, and 12 as shown in Figure 1.

Bangladesh is a country located in the north-eastern part of the Indian subcontinent. Figure 2 illustrates a geographic map of Bangladesh [4]. It is a rapidly emerging middle-income country from its independence in 1971. The country is recognized all over the world for dramatically reducing poverty [5].

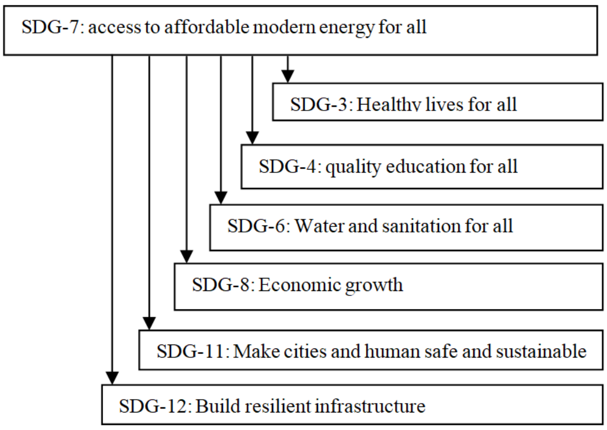

Fig. 1. Interlinking of SDG-7 with other SDGs.

Fig. 2. Country map.

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Table. 1. Sustainable development goals [1].

SDG- 1	End poverty in all its forms everywhere
SDG- 2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
SDG- 3	Ensure healthy lives and promote well-being for all at all ages
SDG- 4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG- 5	Achieve gender equality and empower all women and girls
SDG- 6	Ensure availability and sustainable management of water and sanitation for all
SDG- 7	Ensure access to affordable, reliable, sustainable and modern energy for all
SDG- 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
SDG- 9	Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation
SDG- 10	Reduce inequality within and among countries
SDG- 11	Make cities and human settlements inclusive, safe, resilient and sustainable
SDG- 12	Ensure sustainable consumption and production patterns
SDG- 13	Take urgent action to combat climate change and its impacts
SDG- 14	Conserve and use the oceans, seas and marine resources for sustainable development
SDG- 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
SDG- 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
SDG- 17	Strengthen the means of implementation and revitalise the global partnership for sustainable development

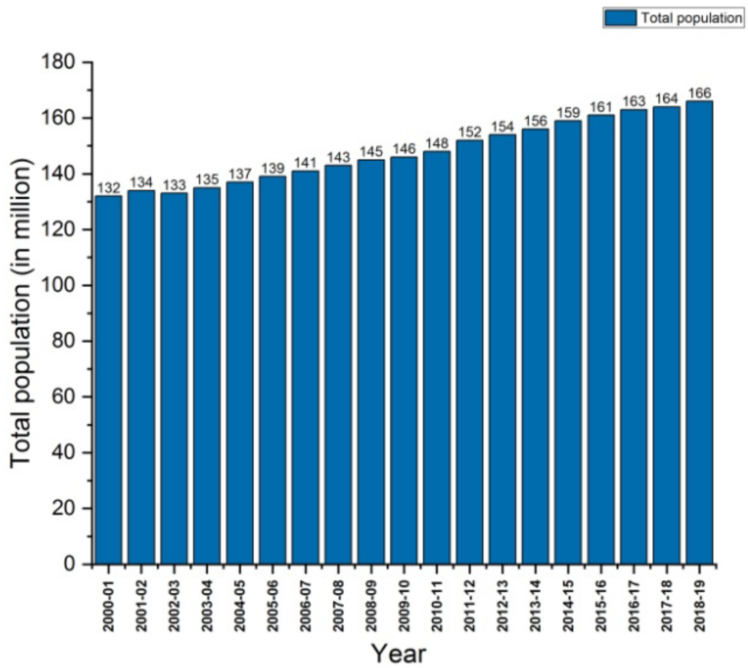

Fig. 3. Population growth [6].

Bangladesh is a densely-populated country, occupying of the geographical area of 147570 square kilometres. As illustrated in Figure 3, the population of the country is growing at a rate of 1.1% per annum [6]. Table 2 shows other statistical details of the country [7].

Bangladesh is a fast progressing country with a constant increase in GDP at an average rate of 6.5% in the last decade (see Figure 4). With rapid growth, the country is facing a scarcity of energy for households, transport, agriculture, and the industrial sector [9].

This study aims to understand the present status of national energy management, future issues, barriers, and efforts required to ensure energy security, sustainability to attain the SDG-7. This paper overviews the current energy scenario, energy accessibility to people, macro and micro-level initiatives taken by the Government of Bangladesh to achieve SDG-7. The manuscript also compares the progress of Bangladesh with other South Asian countries. Finally, the paper recommends some policy interventions to attain SDG-7 as early as possible.

Table 2. Country statistics [8].

Total population (2016)	162952000
Gross national income per capita (PPP international $, 2013)	2810
Life expectancy at birth m/f (years, 2016)	71/74
Total expenditure on health per capita (Intl $, 2014)	88
Total expenditure on health as % of GDP (2014)	2.8

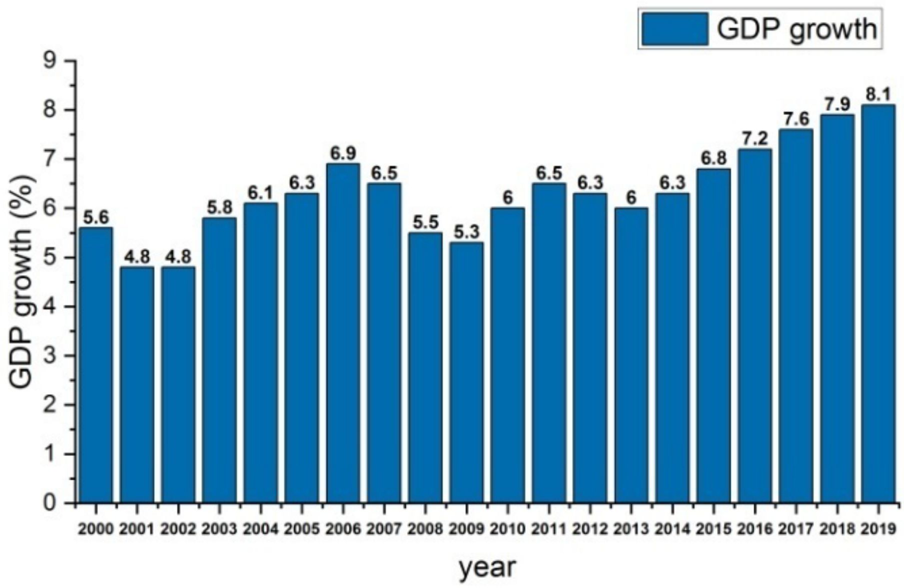

Fig. 4. GDP growth rate [9].

2. METHODOLOGY

Several peer-reviewed research papers of international repute and reports published by various distinguished organizations such as the UN, WHO, UNICEF, IEA, IRENA, IEEJ and Government of Bangladesh have been collected from several websites. They are categorised based on the type of energy sources used for electricity generation, cooking, and national initiatives for energy security, sustainable developments, and policies. All papers and reports are read multiple times, and significant findings have been noted down. Various facts and figures are compared to investigate the progress of Bangladesh on SDG-7, as well as present and future challenges to attain SDG-7. Figure 5 illustrates the numbers of publication/reports referred to accomplish this study.

3. PROGRESS OF BANGLADESH ON SDG

United Nations Sustainable Development Goals (SDGs) aims to end poverty and hunger from the world and to build up a sustainable world. In September 2015, the world accepted the 2030 agenda for SDGs [10]. There are a total of 17 sustainable development goals (SDGs) and 169 targets associated with them. The SDG-7 is associated with energy whose details are given in Table 3 [10].

Bangladesh has to provide clean and economical energy access to all households and businesses, improve the energy efficiency of equipment, reduce the carbon footprint on the environment and develop sustainable technology and infrastructure for energy production and distribution as to align its development with SDG-7 Targets (Table 3).

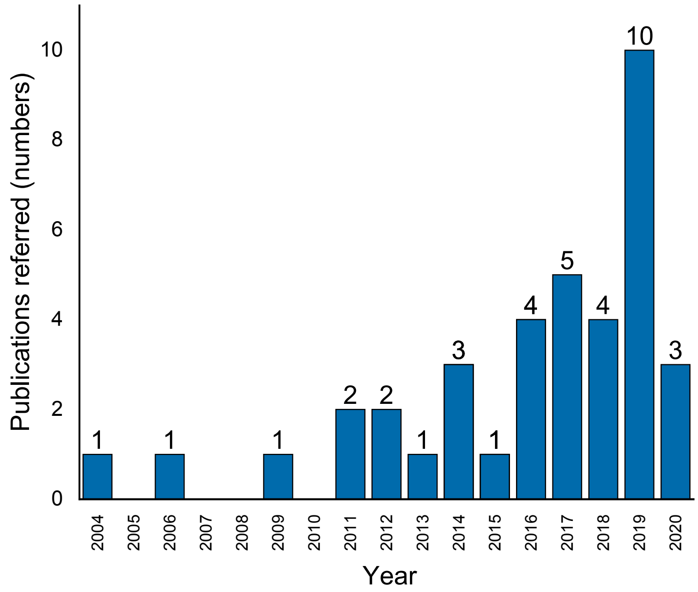

Fig. 5. Numbers of publication/reports referred.

Table 3. Details of Sustainable Development Goal-7 [10].

Goal 7: Affordable and clean energy	
Target 7.1	Make sure worldwide access to reasonably priced, reliable, and contemporary energy services by 2030.
Target 7.2	Significant increase in the share of renewable energy in the universal energy mix by 2030.
Target 7.3	Doubling the global rate of improvement in energy efficiency by 2030.
Target 7.4	Improve worldwide co-operation to make easy access to clean energy research and technology by 2030.
Target 7.5	Expand infrastructure and advancement in technology for supplying modern and sustainable energy services for all in developing countries by 2030.

3.1 Present Energy Sector Scenario

Electricity generation in Bangladesh is highly dependent on fossil fuels. Figure 6 shows that 57.33% of energy has generated by using natural gas, followed by furnace oil and coal. The share of renewable energy is less than 1%. In the year 2019, total net energy generation was 70533 GWh, which is 12.53% higher than the generation in 2018. Out of this 35107 GWh, the energy was generated by the public sector, and 28640 GWh energy was generated by the private sector. In addition to this, 6786 GWh energy was imported from India [11].

3.2 Energy consumption and demand

It is well known that poverty eradication, economic growth, development of sustainable infrastructure, and security depends on energy availability [12]. At the time of independence in 1971, only 3% of people in the country had access to electricity. Year by year, energy access to people is increasing at a rapid rate. Now, the Government of Bangladesh is committed to ensuring access to clean, affordable, and reliable electricity for all by 2021 [13].

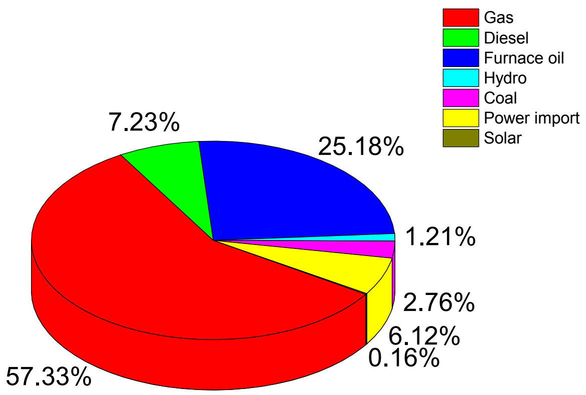

Fig. 6. Primary energy mix [11].

Primary energy mix (Figure 6) shows that most of the primary energy demand is fulfilled by burning natural gas. The current demand for natural gas is above 3200 Million standard cubic feet per day (MMSCFD), with average supply and shortfall of 2740 and 500 MMSCFD respectively. Table 4 illustrates the Bangladesh gas reserve capacity. A total of 26 gas fields are present in the country; out of that 20 fields are in production. Total estimated proven gas consumption is 20.77 trillion cubic feet (TCF), and the recoverable probable reserve is 6.35 TCF. It is reported that 13.52 TCF gas was produced up to 2015, so only 13.6 TCF of recoverable gas is available [9].

Table 4. Bangladesh gas reserves [9].

Reserve type	Trillion Cubic Feet (TCF)
Gas Initial in Place (GIIP)	39.80
Proven + Probable + Possible (3P)	30.82
Proven + Probable (2P)	27.81
Proven (1P)	20.77
Remaining Recoverable (2P)	11.92
Used (Consumed) as of 30 June 2018	15.90

Figure 7 shows yearly gas production and its future forecast. It is estimated that the natural gas reserve of the country may end in 2026. The government is trying to meet the growing demand of energy by importing liquefied natural gas (LNG). After gas, diesel and coal are mainly used as fuel for energy. Table 5 shows major coalfields and their capacity in the country. Daily coal production is 4000-5000 metric tonnes. Presently country imports 1090940 metric tonne coal, 1090940 metric tonnes crude oil, and 4752607 metric tonnes refined oil to satisfy present energy demand [9].

Table 5. Details of coal mines [9].

Field	Depth of Coal seam (m)	Reserve (Million Metric Tons)	Percentage of total Reserve (%)
Barapukuria	118-510	390	11.81
Phulbari	150-240	572	17.33
Khalislrpir	257-480	685	20.75
Dighipara	328-107	600	18.18
Jamalgong	640-1158	1053	31.90

Figure 8 compares energy consumption in 2014 and its future demand in 2041. During this time frame, it is forecasted that natural gas consumption will decrease from 57% to 38%; however, the demand for oil and coal will significantly increase. The coal demand will increase from 3% to 20% (by more than 560%), and oil demand will increase from 17% to 25%. Another noticeable forecast is that nuclear energy will also come in to picture with 9% of its share in energy production in 2041. Presently, the Government of Bangladesh is in the process of establishing the 2400 MW nuclear power plant. The use of bio-fuel and bio-mass will significantly be reduced from 23% to 3% in 2041 that will bring a significant reduction in domestic sector indoor pollution. But, the share of renewable energy will remain marginal (0.16%) in 2041 [14].

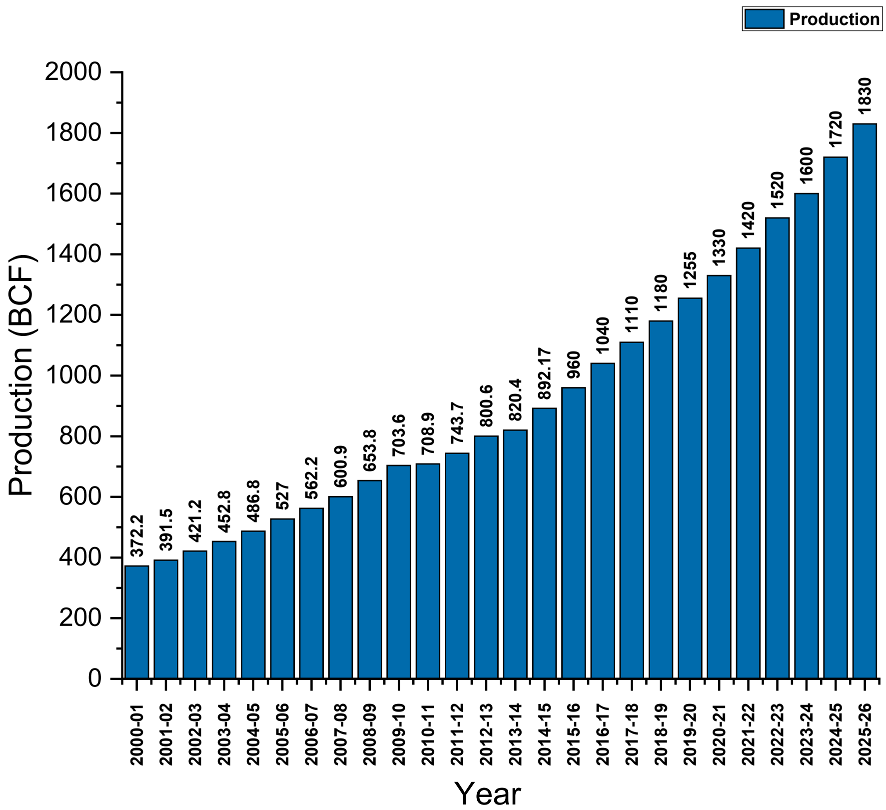

Fig. 7. Yearly gas production rate and its forecast [9].

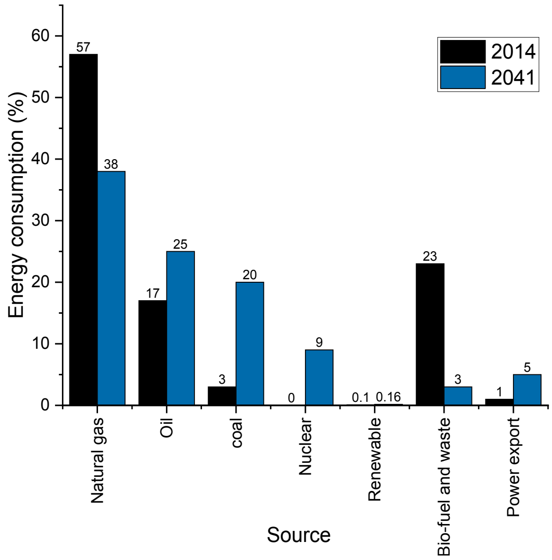

Fig. 8. Primary energy projections [14].

With the mission 'Electricity for all' in 2021, the Government of Bangladesh is meticulously moving towards energy production and distribution, which can be easily identified with a remarkable increase in per capita energy consumption (see Figure 9). In the last two decades, per capita, energy consumption is almost linearly increased from 100 kWh to 325 kWh.

Every year, the country is increasing its electricity generation capacity consistently. Figure 10 illustrates the percentage increase in the energy generation capacity of the country over the preceding years. In the year 2017-18 and 2018-19, energy generation capacity was increased by 15.6% and 17.66% respectively [9].

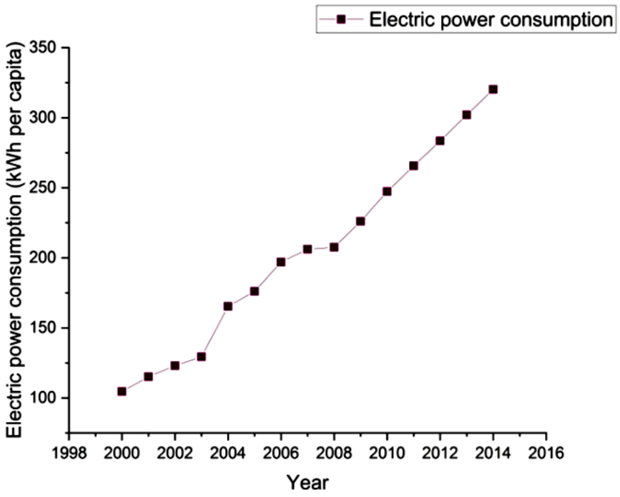

Fig. 9. Electricity consumption per capita [14].

The government of Bangladesh is succeeded to maintain a higher installation capacity than maximum demand. Figure 11 compares installed capacity and maximum demand as on the date. It shows that the installed capacity is greater than the maximum demand of the country, in addition to this, the gap between installed capacity and maximum demand has widened during the past decade [13].

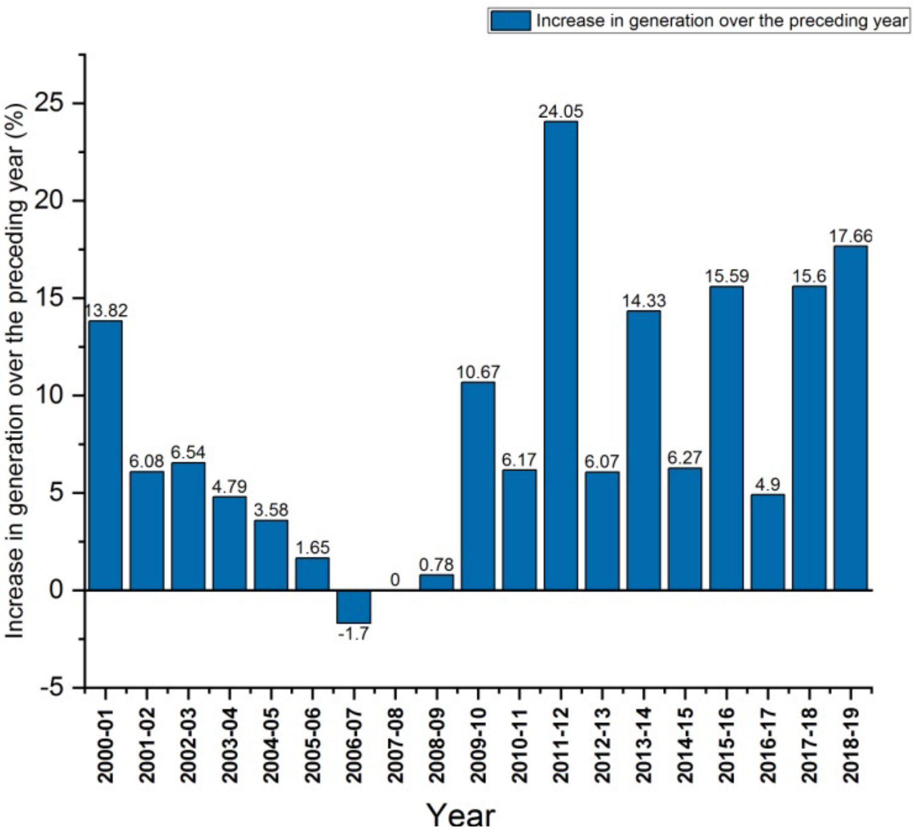

Fig. 10. Increase in a generation capacity [9].

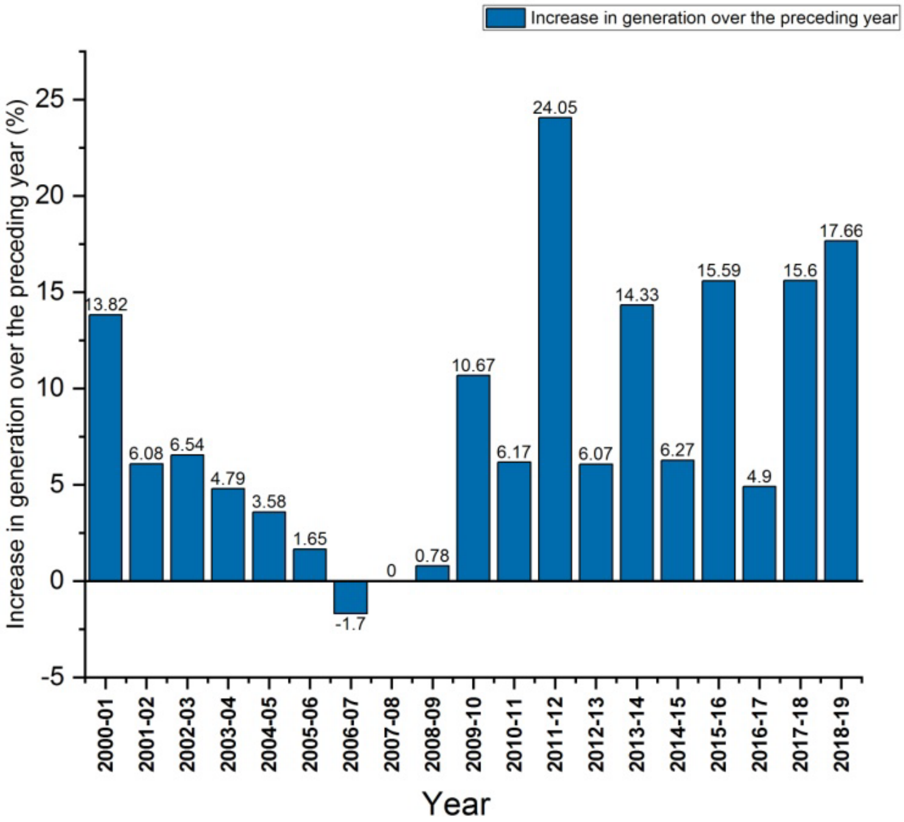

Fig. 11. Installed capacity and maximum demand [13].

Electricity consumption per capita measures the average kilowatt-hours (kWh) of electric power generated by the country per person per year [15]. Per capita, the energy consumption of Bangladesh is less (see Figure 12), and only 84.9% of the population has access to electricity in the country (see Figure 13). Maximum electrification has been done in cities and industrial area. 95% urban and 78.5% rural households are enlightened with electricity as shown in Figure 14. Work on rural electrification is in progress at a rapid rate [13].

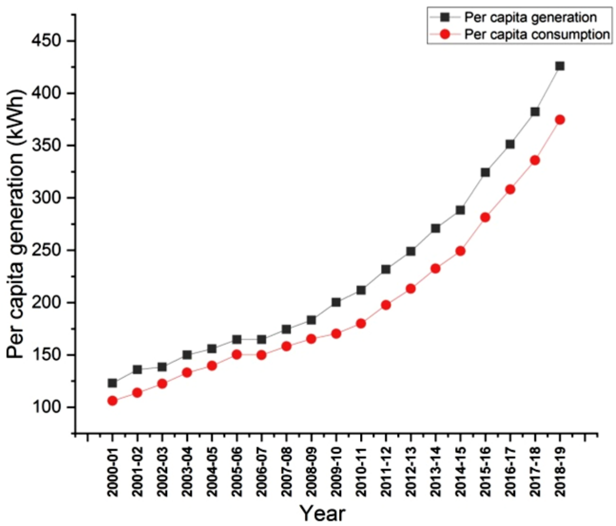

Fig. 12. Per capita energy generation of Bangladesh.

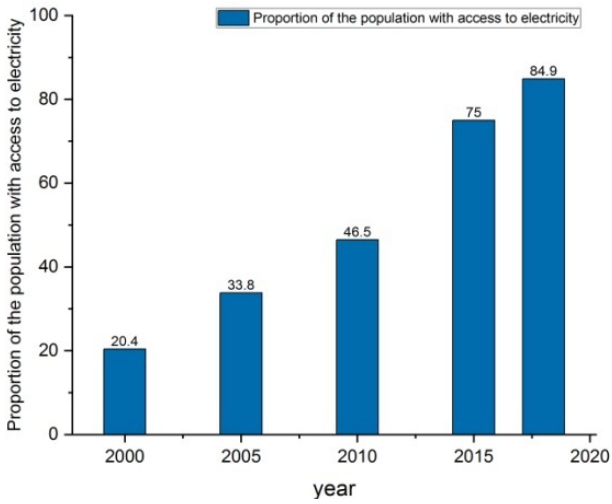

Fig. 13. Population with access to energy [13].

Although the country has installed capacity higher than its present maximum demand (Figure 11), the country is succeeded to provide electricity to only 84.9% of people (Figure 13). The major reasons behind this shortage are actual generation capacity of power plants is less than its rated capacity and distribution losses. Particularly in the rural and coastal areas, the country lacks in energy infrastructure. Figure 15 shows that at present, the country has a 9.12% distribution loss. But it is very remarkable that during the past two decades, there has been a significant reduction in distribution loss from 26.11% in the year 2000-01 to 9.12% in the year 2018-19 [16].

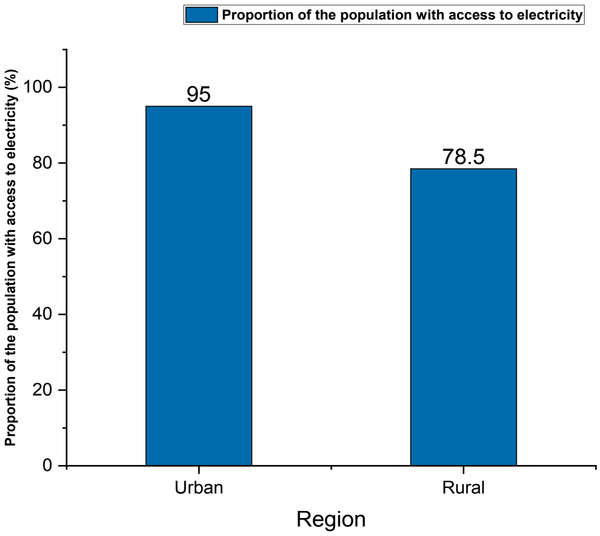

Fig. 14. Population with access to electricity [13].

A country is progressing consistently, the percentage of people with access to electricity is also increasing. Figure 16 shows electricity consumers in the domestic and agricultural sectors. Electricity consumers in the agriculture sector were less and also found to be decreasing from the year 2000-01 to 2004-05; however, later on, consumers in domestic as well as the agriculture sector are increasing consistently. There has been some decrement also noticed from 2015 through 16 to 2016-17, but afterwards, domestic and agriculture consumers are again increasing [16].

A similar trend is also observed for industrial consumers (Figure 17). Small industrial, small commercial and large industrial and commercial electricity consumers are consistently increasing from the year 2004-05. Figure 16 demonstrates that country is progressing in the agriculture and industrial sector; consequently, the GDP of the country is increasing consistently (see Figure 4) [16].

With the rapid and consistent increase in electricity consumption, the demand for fossil fuel is growing significantly [17]. The requirement of natural gas, furnace oil, diesel, and coal is constantly increasing from 2000-01, which is fulfilled by importing these fuels (Figure 18). The country is, therefore, paying heavy fossil fuel import bills, as shown in Figure 19. It shows how expenditure over the fossil fuel of public sector power plants is significantly increasing from the year 2010 [13].

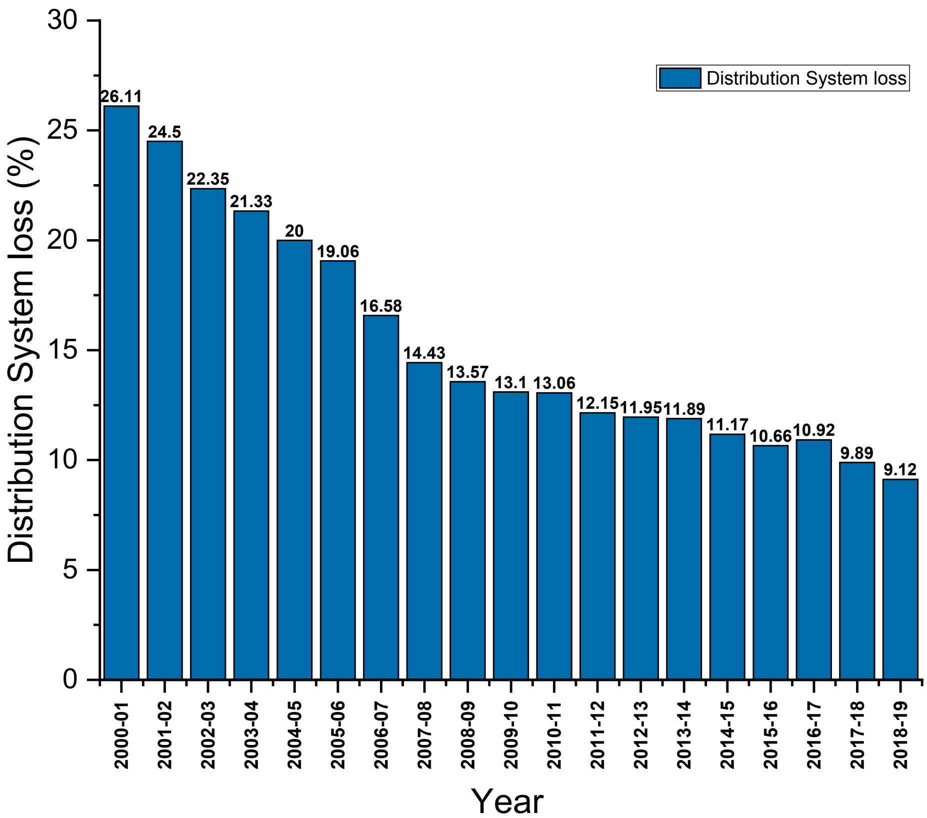

Fig. 15. Distribution system losses [16].

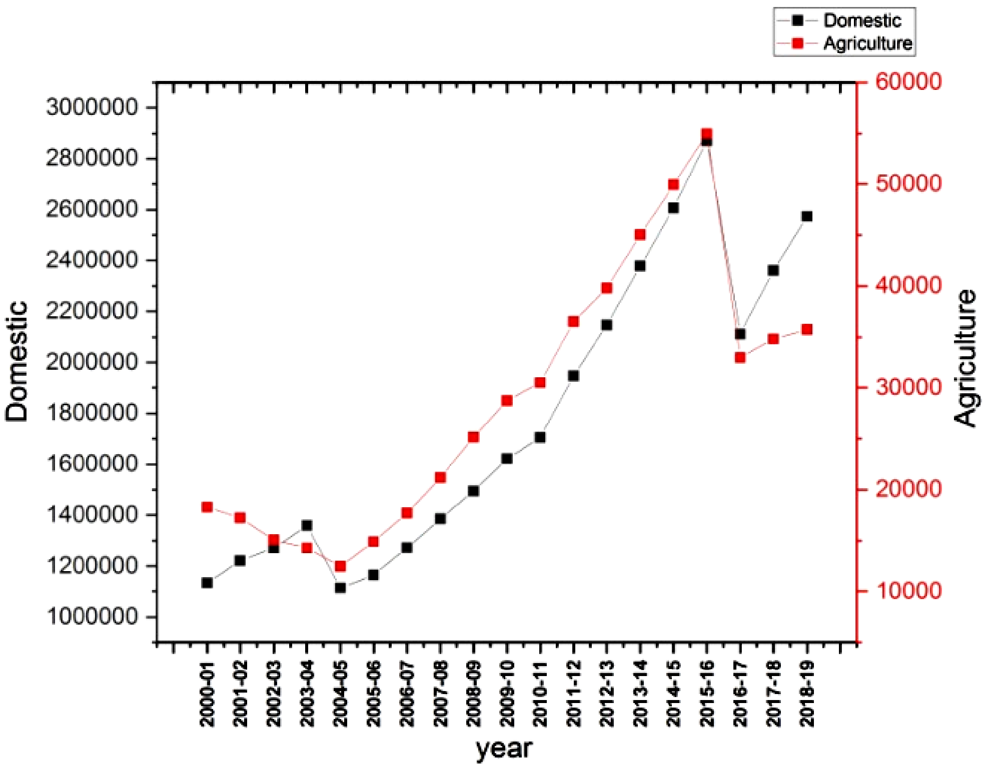

Fig. 16. Electricity consumers in the domestic and agriculture sector [16].

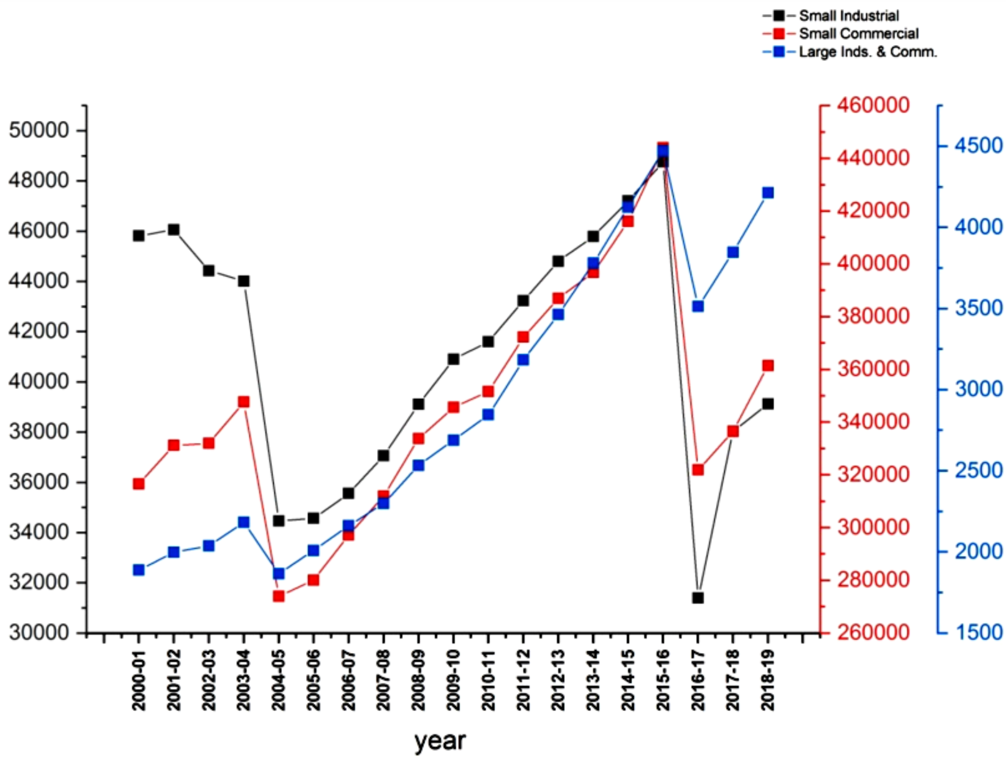

Fig. 17. Electricity consumers in the industrial sector.

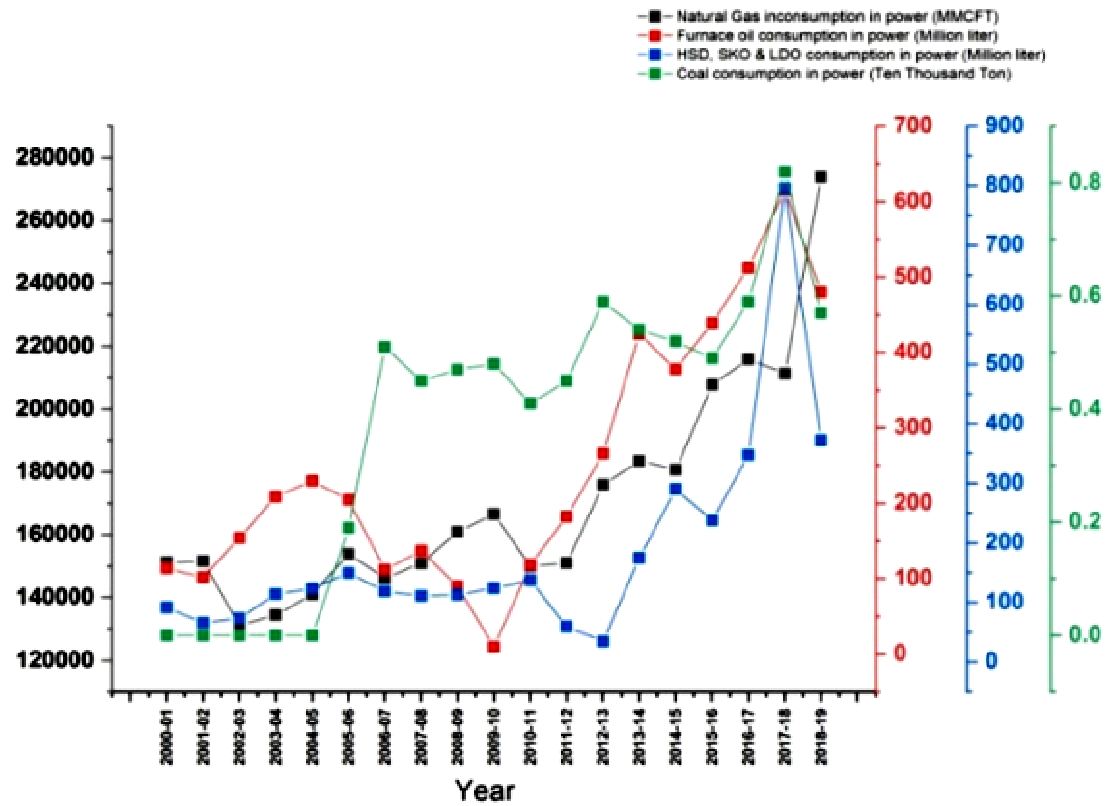

Fig. 18. Fuel consumption for energy generation [16].

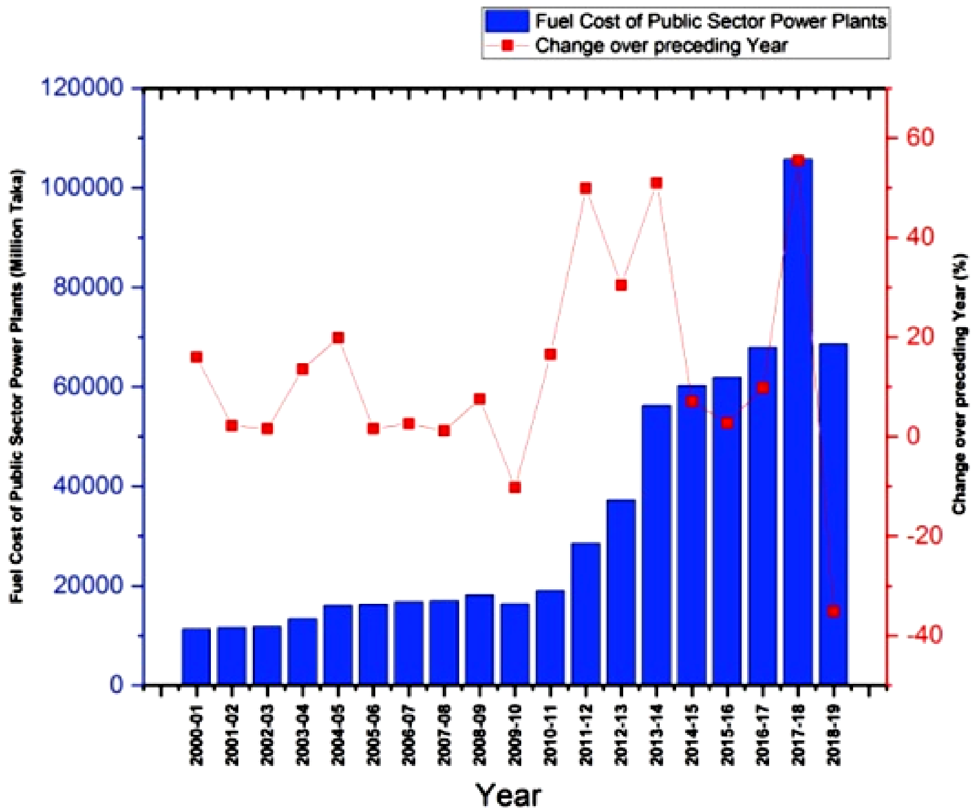

Fig. 19. Fuel cost of public sector power plants [16].

3.3 Progress in Renewable Energy Sectors

Solar and wind energy are the most useful renewable source of energy sources to generate electricity [18], [19]. From various reports of Bangladesh Government illustrate that country has the substantial potential of solar and wind energy. The country has almost 6250 square kilometres of available land where 156 GW of solar power can potentially be harvested through utility-scale solar farms (see Figure 20) [5].

Table 6 demonstrates solar energy potential in the country, which can be exploited to fulfil the energy demand to some extent.

Similarly, the country has at least 150 GW of wind power (on- and offshore) from sites that spread over 3200 square kilometres, mainly in the southern part of the country as shown in Table 7. This potential can be used to maximize local electricity generation [16].

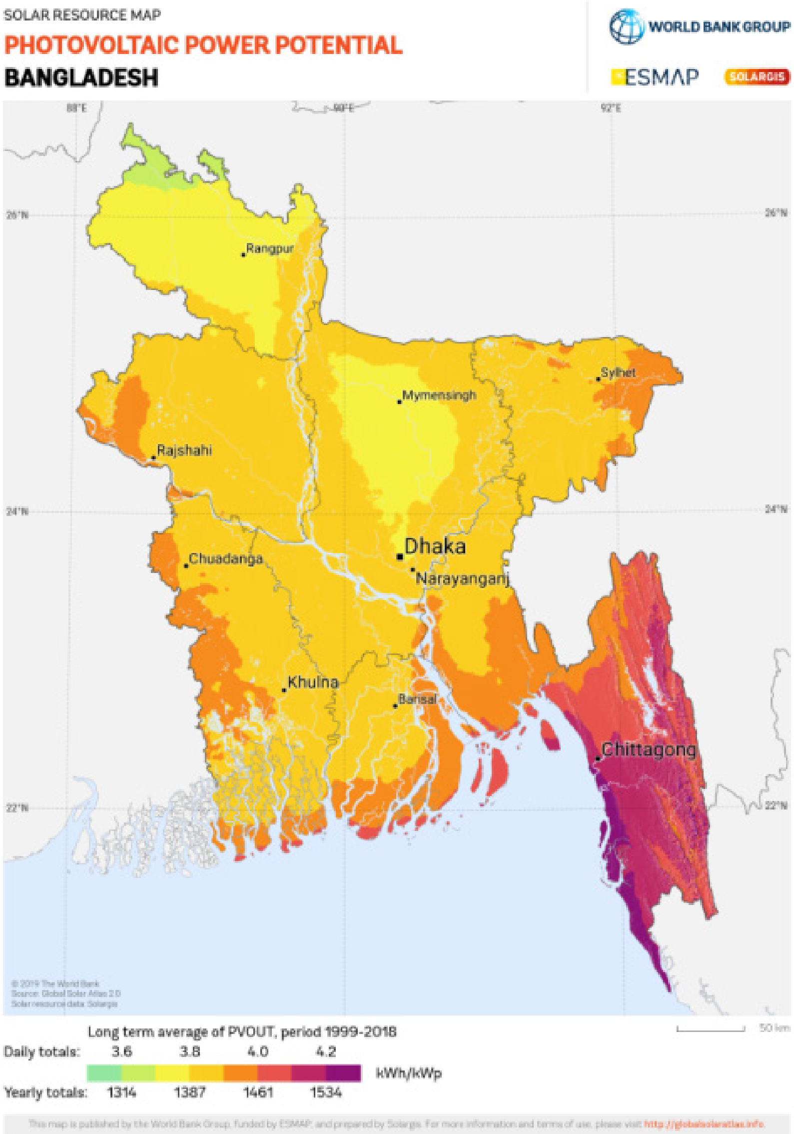

Fig. 20. The photovoltaic power potential of Bangladesh [5].

Table 6. Solar energy potential.

Resources	Maximum installable generation capacity (GW)	Maximum recoverable electricity (TWh/year)
Solar photovoltaic- rooftop	35	40
Solar photovoltaic- utility-scale	156	177
Solar photovoltaic- floating PV	31	35
Solar photovoltaic (total)	191	217

Source: ISF, January 2019, values are rounded.

Table 7. Wind energy potential.

Resources	Maximum installable generation capacity (GW)	Maximum recoverable electricity (TWh/year)
Wind- onshore	16	55
Wind- offshore	134	525
Wind total	150	580

Source: ISF, January 2019, values are rounded.

Currently, renewable energy share is less than 2% in the primary energy mix. Sustainable and Renewable Energy Development Authority (SREDA) stated that country has installed capacity of 633.36MW, in which solar, wind, hydro, biogas to electricity and bio-mass to electricity technologies are in use (see Figure 21). Solar energy contributes to the highest share of 63.08% with an installed capacity of 318.16 MW [20].

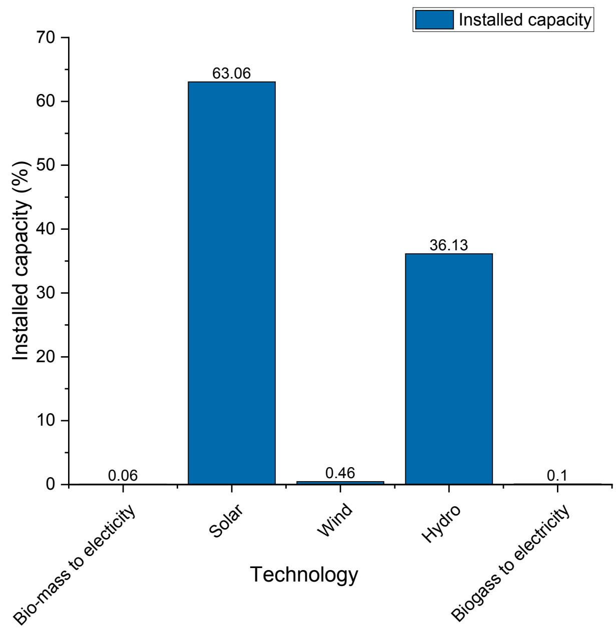

Fig. 21. Installed capacity of renewable technologies [20].

The country kept the goal of 10% energy generation using renewable energy by 2020. It has been forecasted that till 2025, solar photovoltaic and wind will overtake hydropower. The share of renewable power generation (PV, wind, and ocean) will increase from 12% to 23% by 2030 and 56% to 65% by 2050. Therefore, smart grids, demand-side management, energy storage capacities need to be expanded to increase the flexibility of the renewable power system for grid integration, load balancing, and a secure supply of electricity. Today, 51% of Bangladesh's energy demand for heating is coming from the use of traditional unsustainable biomass [14]. This load can be significantly reduced by promoting solar water heater, solar dryer [21]. Similarly, the technology of solar distillation systems [22], solar cooker[23], solar air heaters [24] must be promoted widespread, particularly in the remote and rural region. Solar distillation technology can be also useful even in small industrial applications [25].

4. PROGRESS OF BANGLADESH ON SDG-7 AS COMPARED WITH OTHER SOUTH ASIAN COUNTRIES

The principal boundaries of South Asia are the Indian Ocean, the Himalayas, and Afghanistan. This region is home to 2 billion populace living in eight different countries, namely Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka [26]. In this region, Bhutan and Sri Lanka are succeeded in providing 100% electricity access to all households; Bangladesh is also approaching to achieve this goal in recent years. Bangladesh produces power mostly from fossil fuel; hence contributes to GHG emission. Bangladesh stood on the third rank after India and Pakistan with GHG emission of 86.51 $MtCO_2$ as shown in Figure 22. Bangladesh can utilize its huge solar and wind energy potential to reduce its fossil fuel dependency, GHG emission, and can earn more carbon credits. In this way, the country can face the problem of climate change to some extent, i.e. attainment of SDG-13 [27].

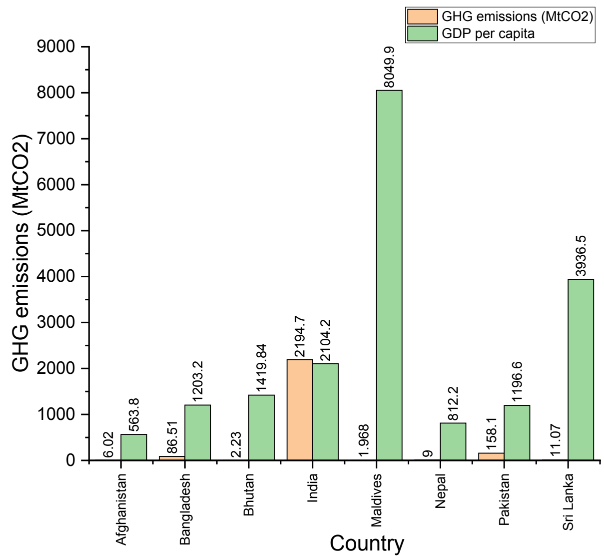

Fig. 22. GHG emissions (MtCO2).

From Figure 23, it can be recognized that among the South Asian countries, Bangladesh has lower per capita energy consumption (464 kWh per capita). It indicates that the people of Bangladesh have lower access to energy, particularly in the rural area; consequently, the economic growth of the country is comparatively slower as compared with other South Asian countries. This can be easily recognized by comparing the GDP of South Asian countries as shown in Figure 24.

Table 8 shows that the population of major Asian countries do not have access to the clean cooking energy source. Countries like India, Bangladesh, and Pakistan have more than 100 million people without access to clean cooking energy source [28].

Figure 25 shows the global economic rank and score of different South Asian countries. Bangladesh stood 11th out of 12. It means that people in Bangladesh are relatively underprivileged as compared with some other South Asian countries. The main reason behind this is the wide infrastructure gap as compared to other South Asian countries [29]. Multiple Indicator Cluster Survey (MICS) 2012-2013 conducted by UNICEF states that in Bangladesh, 88.2% of households use solid fuels, and 67.6% of household use of wood for cooking. Firewood is the most popular for cooking; almost 50.5% urban and 72% of rural households use firewood for cooking [20].

Bangladesh stands 8th out of 20 countries in the category of the number of people without access to electricity with 24 million people have no access to electricity, as shown in Figure 26.

Various reports published by the government of Bangladesh illustrate that there is a dependency on single fuel (natural gas) in the primary energy mix. Despite abundant renewable energy sources available across the country, the share of renewable energy in the primary energy mix is found very low as compared to other South Asian countries (see Figure 27) [30].

Table 8. Population without access to clean cooking energy [28].

Country	Number of people (Million)
India	853
Bangladesh	143
Pakistan	102
Afghanistan	26
Nepal	23
Sri Lanka	17

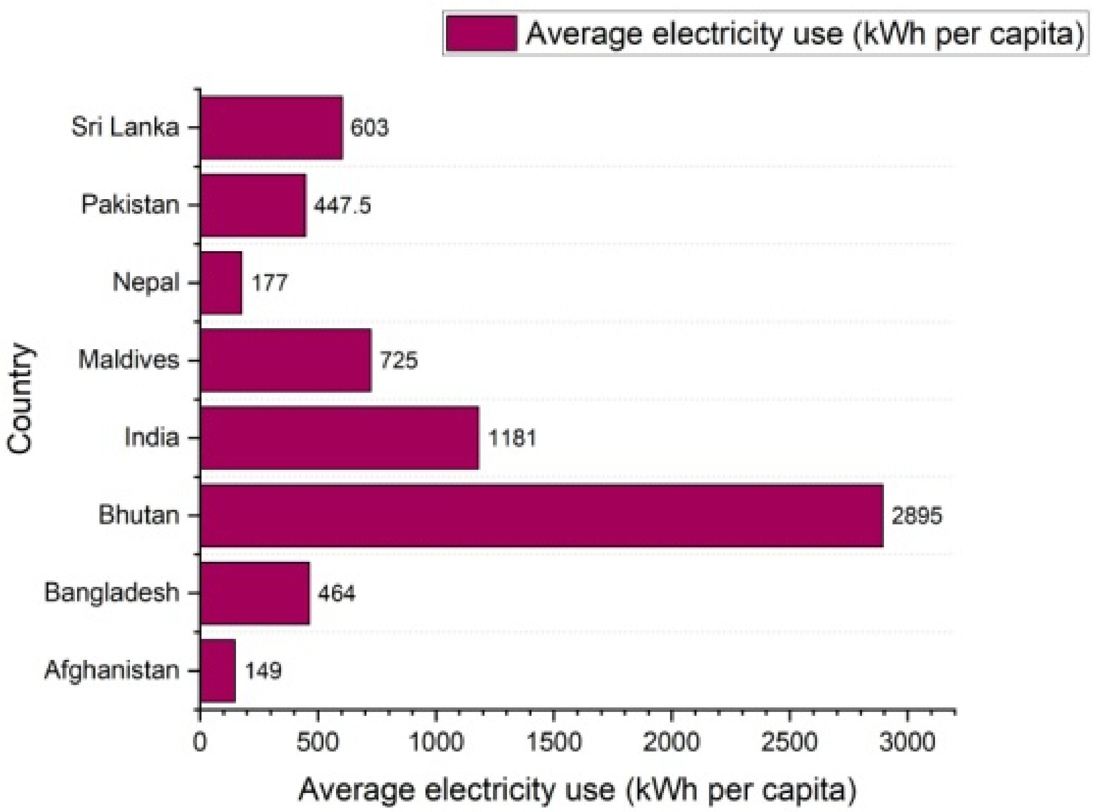

Fig. 23. Per capita energy consumptions of South Asian countries.

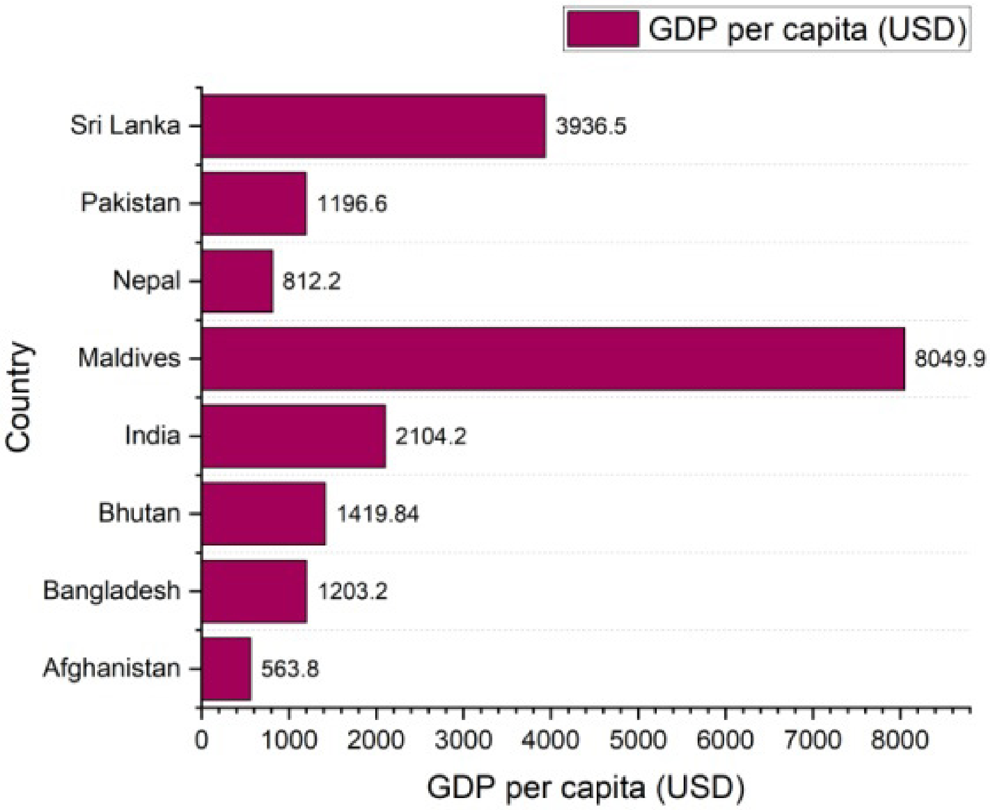

Fig. 24. GDP per capita of South Asian Countries.

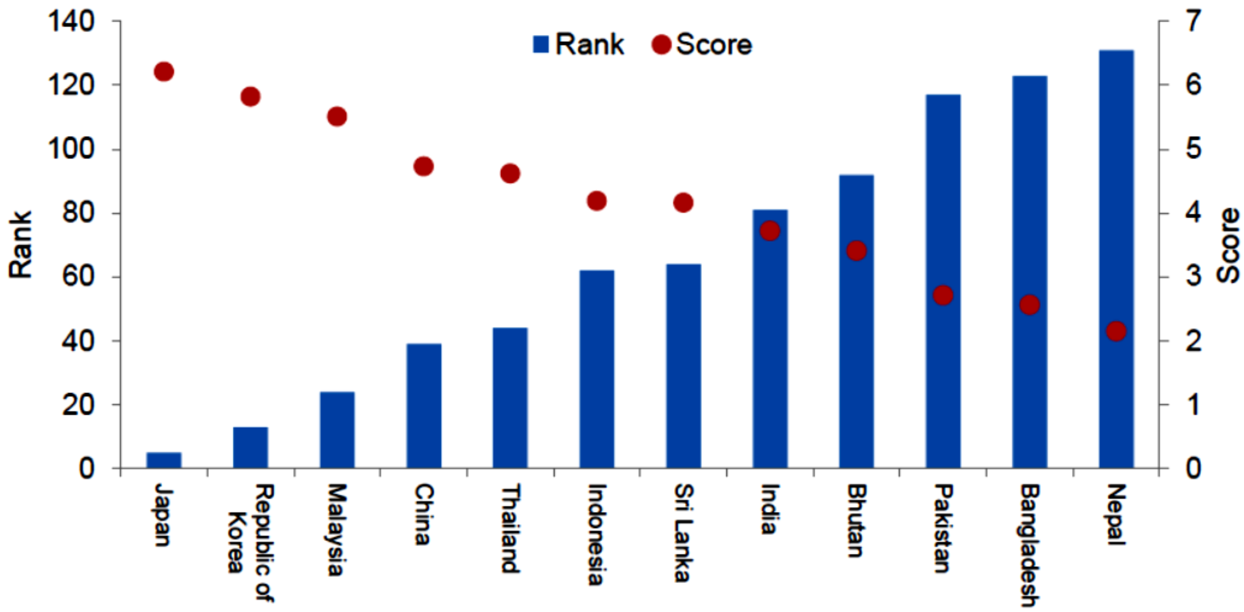

Fig. 25. Score and rankings of selected Asia-Pacific countries in the global [29].

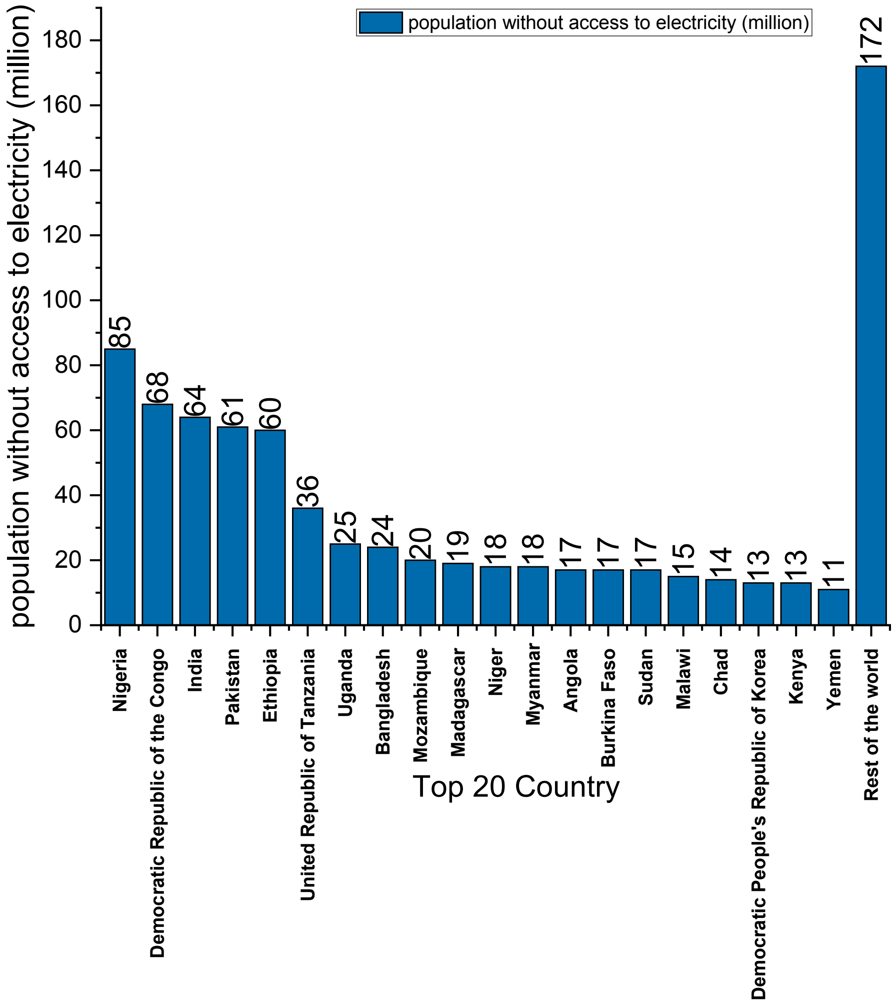

Fig. 26. Top 20 countries for people without access to electricity.

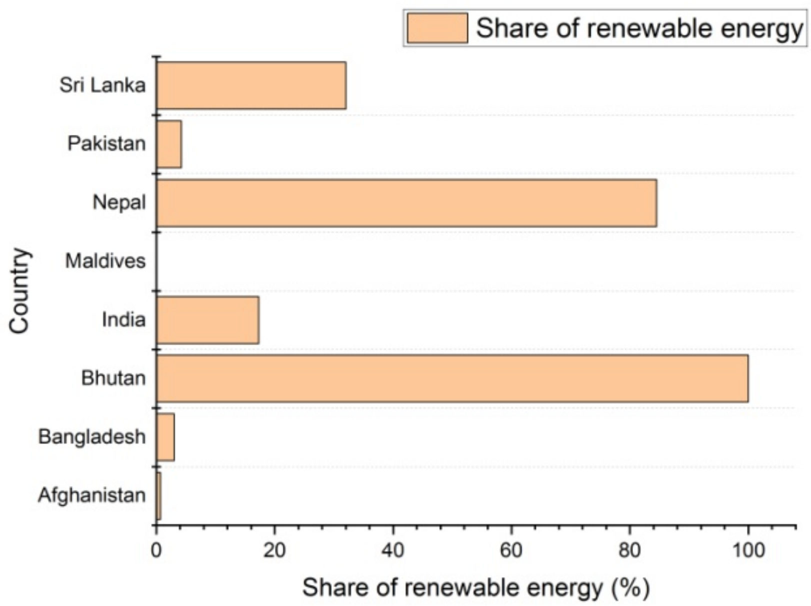

Fig. 27. Share of renewable sources in energy generation in percentage [16].

5. BARRIERS AND FUTURE CHALLENGES

There are many challenges in front of Bangladesh to attain SDG-7 such as [31,32]**:**

Policy level challenges

- Less priority is given to use renewable energy.
- Poor execution of renewable energy policies.
- Unnecessary fossil fuel financial subsidies.
- Lack of incentives for participation in renewable energy programs.

Technical challenges

- Insufficient local manufacturing units.
- Limited technical capability to design, install, operate, and maintain renewable energy services.
- Lack of standardized technology.

Economic challenges

- High installation and capital cost of renewable energy equipment.
- Long payback periods.
- Insufficient knowledge of market potential.
- Insufficient financial support from the government.

Information challenges

- Partial facility for renewable energy data collection, analysis, and project development
- Insufficient knowledge associated with renewable energy technologies, equipment suppliers, and financiers.
- Lack of information about renewable energy for policies.

5.1 Macro and Micro Initiatives to Attain SDG-7

The country is taking widespread efforts to attain SDG-7. Following are some outstanding initiatives:

5.1.1 Power balance constraints

World Bank Report-2018 states that 10700 people die annually due to indoor air pollution. To reduce indoor pollution, the Government of Bangladesh is promoting the use of efficient cookstoves. This program began in May 2013. Nearly 1.6 million clean stoves were installed in homes by January 2017. The government has launched the next phase of this program to install an additional 5 million stoves in the next five years and 30 million cookstoves by 2030 [33]. Due to the implementation of this program, GHG emission has been reduced by 2.890 MtCO2eq and firewood consumption has been reduced by 58%. Cookstoves have saved over 375.84 takas per stove per month with an annual saving of over 600 takas. This program reduces the time taken by each user to collect firewood by 102 hours per year. Government has kept the mission to reach 25 million people by 2030 [34]. In addition to this government can also develop waste oil cooking stove for small scale industries [35].

5.1.2 Electricity by Bio-mass Gastification

The country is moving forward to generate electricity by Bio-Mass Gasification and also planned to develop a coalfield of Phulbari, Dighipara, Khalashpir, and Jamalganj region for the future energy security [9]. The country has estimated total power generation from agriculture residue about 1178 MWe. From rice husk and bagasse estimated potential is 1010 MWe and 50 MWe respectively, and other resources can contribute 118 MWe. The share of forest and municipal waste could also be 250 MWe and 100 MWe respectively. National Database of Renewable Energy states that as on date one system is in operation named as SEAL biomass-based electricity project of 400 kW capacity at Thakurgaon [36].

5.1.3 Bio-gas

It is also noticed from various government reports of Bangladesh that, the country is not focusing on waste to energy conversion. Urban, semi-urban and rural, agriculture, and industrial waste can be used for energy generation indirectly in limited use to fulfil the demand of energy of particular community in rural and remote regions just like waste oil cooking stove for small hotels and restaurants [35]. Biogas plant for kitchen and rural waste to cater to the energy need of households is another attractive alternative [37]. First bio-gas plant in Bangladesh was set up in 1975. Now the government is operating scheme of the bio-gas plant through Slum Improvement Project (SIP). As of 2017, a total of 71396 biogas plants are in working, which saves around 8.52 tonnes of carbon dioxide emission annually.

5.1.4 Gramin-Shakti

Bangladesh government has started “Grameen Shakti” (GS) in 1996. It is a not for profit organisation working for the implementation of renewable energy programs in Bangladesh. It was started by the Grameen Bank’s (GB) managers to create a sustainable and profitable business. GS has developed a financial mechanism to promote solar home systems (SHS) in rural areas on a commercial basis. GS has a local Branch office which is very helpful to build rapport, creates awareness about SHS. GS also offers repair and maintenance services at free of cost to all its customers during the payment period. GS local office staff members are cross-trained to conduct sales, installations, after-sales service, and maintenance, as well as payment collections. The organizational structure of GS offers maximum operational flexibility to serve the people of the rural and remote regions. Till November 2017, GS installed 1 million solar-home systems [38].

5. CONCLUSION

This paper presents progress and challenges to attain SDG-7 by Bangladesh. From this study, the following conclusions are drawn:

- Bangladesh is facing the problem of energy scarcity to sustain economic growth.

- Most of the population of the country living in rural and remote regions do not have access to clean energy and electricity.
- Only 84.9% of the people of Bangladesh have access to electricity.
- Almost 143 million people in Bangladesh do not have the accessibility of clean cooking fuel sources.
- They use largely biomass for cooking and other domestic use.
- Bangladesh has taken many remarkable initiates at the macro and micro levels to attain SDG-7.
- Grameen Shakti is one of the best initiatives taken by Bangladesh.

Following are the few recommendations for effective implementation and attainment of SDG-7 for Bangladesh:

- Bangladesh must have diversification of fuel in primary energy consumption patterns. Presently, there is an enormous dominance of a single fuel (natural gas) in the energy.
- Bangladesh has a limited focus on renewable energy.
- Despite abundant renewable energy sources available across the region, they have not been efficiently tapped.
- With the huge availability of renewable energy potential, Bangladesh will not only solve the problem of energy scarcity but also save huge expenditure on imports of hydrocarbons.
- The governments of Bangladesh must promote the use of solar PV systems, solar cookers, solar distillation, and portable biogas plants for kitchen waste to cater to the energy need of households.

NOMENCLATURE

GB	Grameen Bank
GDP	Gross domestic product
GHG	Greenhouse gases
GS	Grameen Shakti
ISF	International Securities Finance survey
LNG	Liquefied natural gas
MICS	Multiple Indicator Cluster Survey
MMSCFD	Million standard cubic feet per day
PV	Photo-voltaic
SDGs	Sustainable development goals
SHS	Solar home system
SIP	Slum Improvement Project
SREDA	Sustainable and Renewable Energy Development Authority
TCF	Trillion Cubic Feet
UNICEF	United Nations International Children's Emergency Fund
WHO	World health organisation

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Review of Current Status of Fossil Fuel, Renewable Energy and Storage Devices: Context Bangladesh

Manimekalai P.*[,1], Ravi S. [+], Ravichandran M.*, and Raymon Antony Raj[+]

Abstract *– This article highlights the current status of various energy sources both non-renewable and renewable and various storage devices that are in market practice in Bangladesh. The country, the eight most populated one in Asia has an installed electricity generation capacity of 20,000 MW. On an average only 77.9% of the population has access to electricity. The upliftment of the socio economic status of people leads to the growing demand for power. The power demand will be more than 30,000 MW by 2030. The depletion of fossil fuel leads to rethink the use of renewable sources of energy. The increased demand of power is overcome by the proper utilization of solar energy in recent years from 2017 to 2018 by having the maximum generation of 200 MW. Unlike regular storage devices in the conventional system, the ever-increasing power demand has led to increase in the utilization of the storage devices especially the battery. Usage of electromagnetic and mechanical storage systems will reduce the amount of carbon and toxic metals like lead, sulphur, etc. released to the atmosphere. Bangladesh has an estimated target of meeting its 50% power demand in 2030 by only using renewable sources and non-polluting storage systems. Moreover, the article gives lot of research focus to the market researchers with various advanced storage techniques discussed in one place. The availability of energy sources, power demand, and storage options clearly indicate that the sustainable development depends on energy conservation rather than energy utilization.*

Keywords *– batteries, fossil fuels, global warming, renewable energy sources, storage devices.*

1. INTRODUCTION

The economic reform and growth of population urge the utilities to meet the increased demand for energy. But the fossil fuels depletion and environmental issues like greenhouse gas emissions, global warming sea level rise, flooding owing to glacier melt is leading the society to focus towards renewable energy sources [1]. According to business standard 18.9.2020, the global climatic risk index 2020 listed Bangladesh as the nation in seventh place among 10 countries greatly affected by climatic change impacts for a span of 20 years 1999-2018. The intermittent nature of renewable energy sources (wind, solar, *etc*.) creates necessity for storage of energy in off-peak hours and supply for matching peak demand. Energy storage systems (ESS) can carry out the above work and eliminate the investment for additional generation, transmission and distribution for meeting the supply-demand gap due to intermittency [2].

Table 1. Power generation by type of fuel [3].

Fuel type	Installed capacity in MW	Percentage
Hydro	230	1.00
Natural gas	9413	61.00
Furnace oil	3443	22.00
Diesel	1380	6.49
Coal	524	3.00
Renewable energy	3	0.00
Power import	660	4.00

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2. CURRENT POWER GENERATION STATUS OF BANGLADESH

The power grid of Bangladesh has installed capacity of 15,953 MW in 2017-18 and the fuel wise installed capacity is shown in Table 1 [3].

The installed capacity has been upgraded to 20,000MW up to September of 2019. The power generation by fuel type for the year 2017-18 is in Table 2. The total power generation is 62,677.91 GWh.

Table 2. Power generation in Bangladesh by type of fuels in 2017-18 in GWh [3].

Type of fuel	Power generation in GWh	Percentage
Hydro	1024.31	1.60%
Natural gas	39804.2	63.50%
Furnace oil	10849.71	17.30%
Diesel	4520.31	7.20%
Coal	1692.87	2.70%
Renewable energy	3.79	0.10%
Power import	4782.72	7.60%

From Tables 1 and 2 it can be seen that the major contributing source of power generation is natural gas. Natural gas contributes 63.5% of power generation of Bangladesh. Further natural gas utilization share is 17% in industrial sector, 12% for household purposes, 8% in manure preparation and 16% for transport sector was clearly mentioned in Figure 1. Because of the above contribution of natural gas the enslavement on natural gas is rising drastically. The natural gas production chart and the position of gas reserves up to 2041-42 were depicted in Figures 2 and 3. The production of natural gas for the year 2018-19 is 25.18 billion cubic meters (bcm) [3].

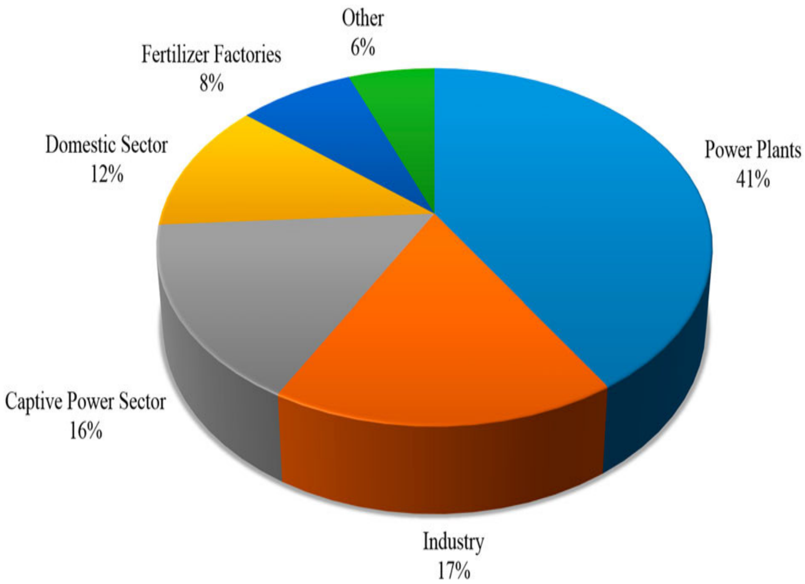

Fig. 1. Specification of natural gas utilization [5].

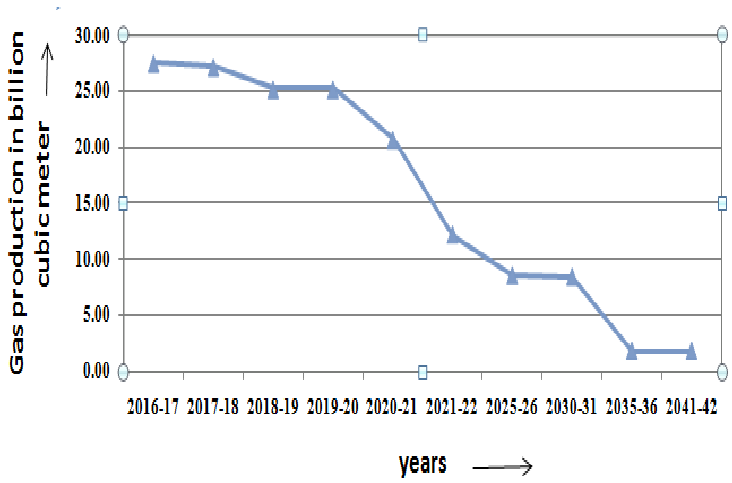

Fig. 2. Projection of gas production in Bangladesh [6].

Next to natural gas, oil occupies the second position in the power generation sector. For oil, Bangladesh mainly depends on refined and unrefined petroleum fuel.

Petroleum products such as diesel, petrol, furnace oil were used for power generation which fulfils 20% of the power needs of the country. Only 6% of the liquid fuel consumption is indigenous production by condensing gas the remaining part imported. About 1.2 million metric tons of crude oil and 5.5 million metric tons of refined petroleum products were under trade in process.

Bangladesh is enjoying a coal reserve of 31,000 million tons which can be an alternate source for natural gas and can serve the energy requirement for nearly 50 years. Fortunately, coal of Bangladesh possesses good heat generation capacity and low sulpur content [3]-[5].

Further, the point to be noted is that other than hydro all other power generating stations will pollute the atmosphere and contribute to the greenhouse gases which in turn leads to global warming. The global warming is responsible for the rise of temperature, health hazards, floods and storms, *etc.* in Bangladesh [6].

The greenhouse gas emission (GHGs) from agriculture, land use and waste are the emissions from non-energy sources and emissions from power, transport, buildings and industry are energy related emissions [7]. The sector wise greenhouse gas emission is pictured in Figure 4.

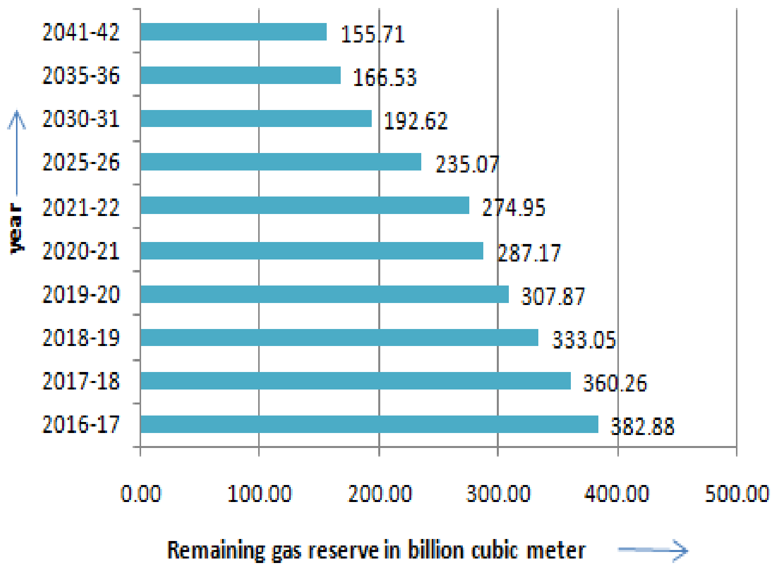

Fig. 3. Remaining gas reserve (km^3) in Bangladesh [6].

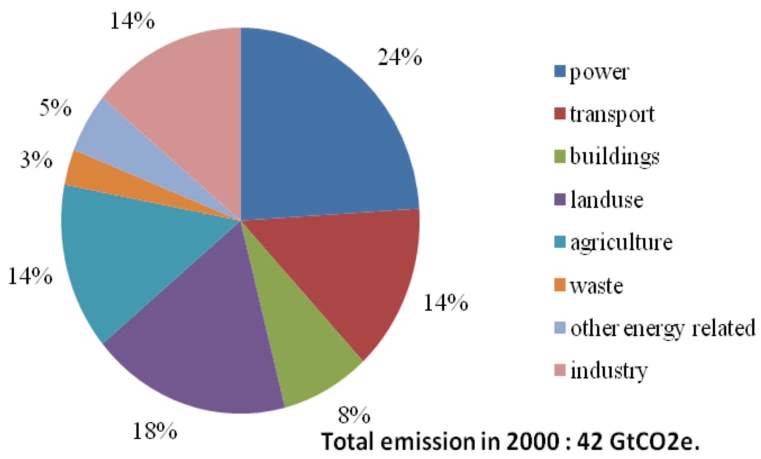

Fig. 4. Sector share of GHG emissions in 2000 [7].

It can be noticed that the major emission comes from the power sector. Power sector mainly depends on fossil fuels. The fast depletion of fossil fuels such as natural gas, coal, diesel, *etc*. and their continuously increasing cost and the environmental pollution due to the usage of fossil fuels are the motivations to think of some alternate sources which are non-polluting and non-exhaustible in nature.

According to International Energy Agency the fossil fuels will get depleted in about hundred years. At this juncture moving to renewable energy sources will help to reduce the emission of greenhouse gases and to come out from the dependency on fossil fuels.

3. RENEWABLE POWER GENERATION STATUS OF BANGLADESH

Among all renewable energy sources (Figure 5) the major renewable energy sources of the country are solar, biomass, bio-gas, hydro and wind [9].

3.1 Solar Energy

Bangladesh is in perfect location for solar energy harvesting, between 20˚34' and 26˚39' latitudes north and longitudes 80˚00' and 90˚41' east. The average solar radiation/day is 4-5 kWh/m^2 in Bangladesh which is sufficient for solar power generation. The solar home systems (SHS) mostly used photovoltaic (PV) power generation systems in Bangladesh which can be clearly understood from Figure 6.

The Bangladesh government has a goal of having "Electricity to everyone" within 2021, this SHS acts as a tool to achieve the goal. This SHS programme is considered as the best one ever in solar power progress by the global society. The SHS conserves the usage of 18,000 tons kerosene/year and creates 70,000 job opportunity. The SHS was started by Infrastructure Development Company Limited (IDCOL) [10]-[11].

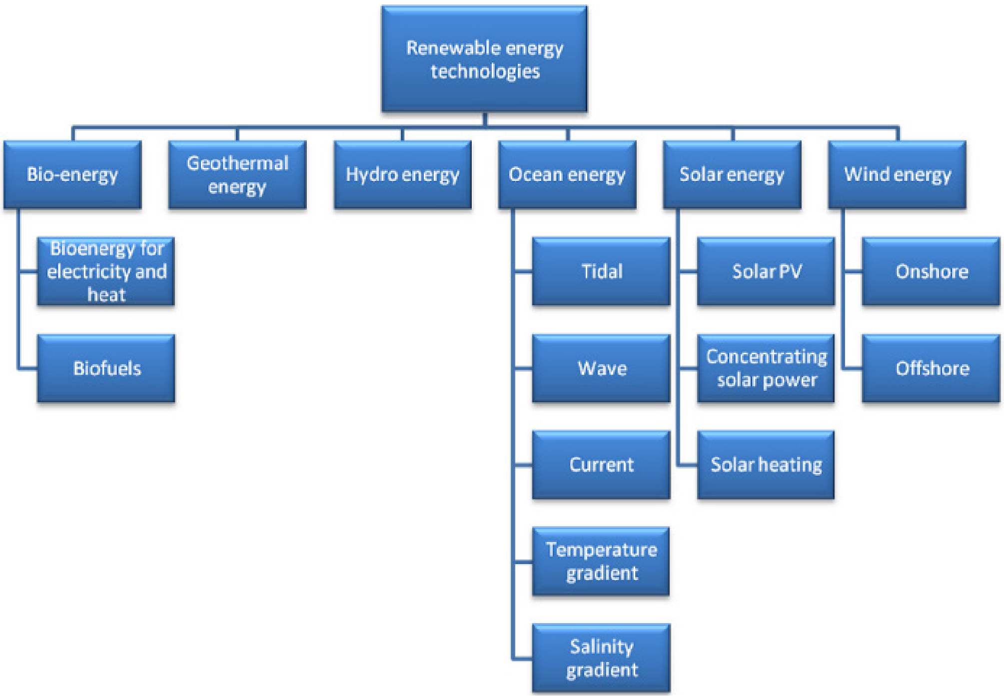

Fig. 5. Renewable energy sources– an overview [8].

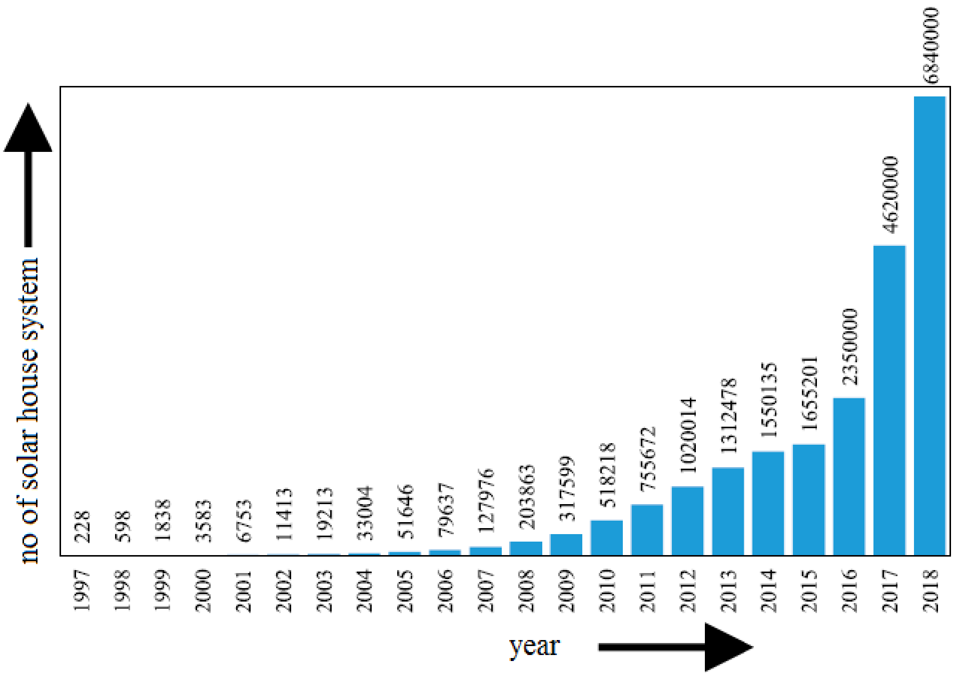

Fig. 6. SHS in Bangladesh up to 2018 [5].

3.2 *Wind Energy*

The kinetic energy of wind rotates wind turbines which produces electricity. The geographical location of Bangladesh restricts the use of small scale wind turbines for power generation. The wind power depends on the velocity of the wind. In the islands and southern maritime face of Bangladesh the average wind speed lies between 3-4.5 m/s from March to September and 1.7-2.3 m/s for the rest of the months of the year. Hence in islands and coastal areas wind mills were erected for pumping and electrification purposes. Bangladesh power development board (BPDB) is taking charge of wind mill and hybrid wind power generation and aiming to contribute to 10% power requirement of the nation. [10]-[11].

3.3 Biomass Energy

The biomass sources are cattle dung, poultry wastages, farming residues, rice husks, wood, jute sticks, municipal wastes, *etc.*, which are utilized for power generation. Around 25,000 biogas plants and 0.2 million upgraded ovens are under operation [10]-[11].

3.4 Biogas Energy

Biogas is a bio-fuel formed out of the biological breakdown of organic materials in the absence of oxygen. Animal waste, plant waste and kitchen waste are used for biogas generation. Around 13,500 biogas plants are completed by the NGO Grameen Shakthi. The IDCOL has a plan to erect 25% of biogas plants in the northern side of the country [10]-[11].

3.5 Hydro Energy

Kinetic energy of water flow is utilized in hydro power plants. Hydro power plants of large type (>10 MW) and small type (<10 MW) are common in Bangladesh. A 230 MW hydro power plant was constructed in Karnaphuli. Micro hydro plants are also in Chittagong and nearby hill areas [10]-[11].

The power generation by hydro, solar PV, wind and bio-mass from 2008 to 2018 is illustrated in Figure. 7. The losses, poor power factor, blackouts are some of the general problems faced by the power sector in the country.

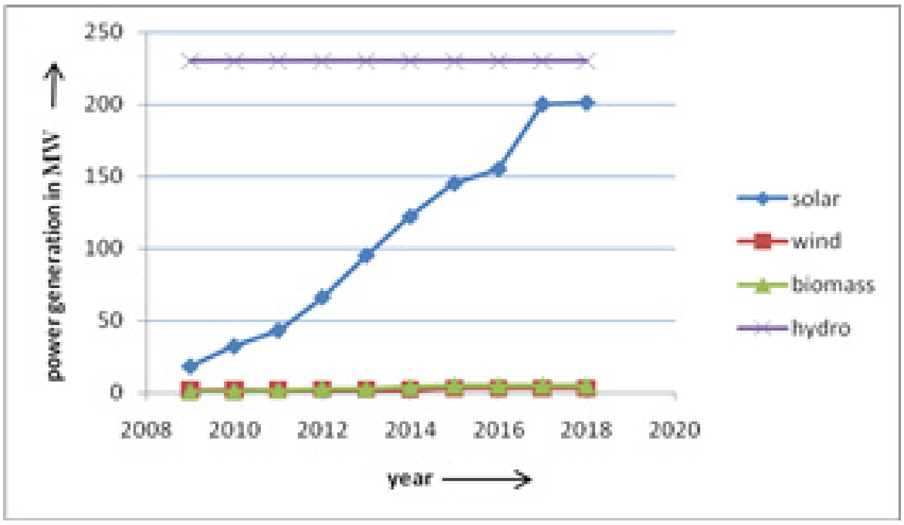

Fig. 7. Bangladesh's source wise renewable energy generation during 2009-2018 [12].

The renewable energy sources are pollution free, free of charge and abundant in nature. Its intermittent nature is the major drawback. To provide uninterrupted supply storage devices can be used.

4. INTRODUCTION TO ENERGY STORAGE DEVICES

Energy storage devices are categorized into two types based on power capacity and run time. They are, devices having high energy with slow discharge and devices having high power with fast discharge. High energy devices like pumped storage devices, compressed air storage devices and electrochemical batteries can be used from few kilowatts (domestic purposes) to several megawatt power requirements (managing of energy distribution, backup system, seasonal reserving purpose). Employing high power storage devices (super capacitors, magnetic energy storage devices and flywheels) for fast charging and discharging needs (power systems having critical pulse loads, transportation systems and power grids) will lead to good results where high efficiency is expected [13].

According to the form by which energy storage is carried out, storage devices can be categorized as mechanical, electrochemical, electrical, chemical and thermal storage devices as portrayed in Figure 8. Mechanical storage devices were further split up into kinetic energy storage devices (flywheel) and potential energy storage devices (pumped hydro and compressed air system) [14].

In all devices storage occurs by the conversion of electrical energy into storable form and when needed, stored energy can be reconverted into electrical energy as in Figure 9.

Based on the time of discharge storage devices are classified into three types. Devices having few seconds or few minutes of storage are called as short-term devices. Devices having few minutes or few hours of storage are called medium-term devices and long term devices will have storage duration of several hours to few days. Short duration storage technology is appropriate for improving the quality of power during transient's occurrence by keeping voltage stable. Medium term storage technology is useful in power system for frequency regulation, managing energy and energy jam in grids. The long term storage technology is suitable to fill the space between the supply and demand for a day to few days [14]-[15].

The worldwide utilization of various energy storage devices is illustrated in Figure 10. The pumped hydro storage system enjoys 99% global bulk storage. Compressed air storage system stands in the second position [16].

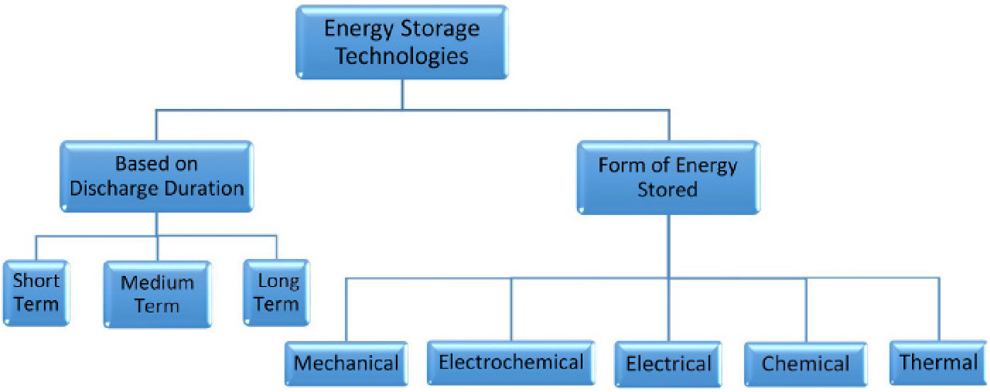

Fig. 8. Taxonomy of energy storage technologies [14].

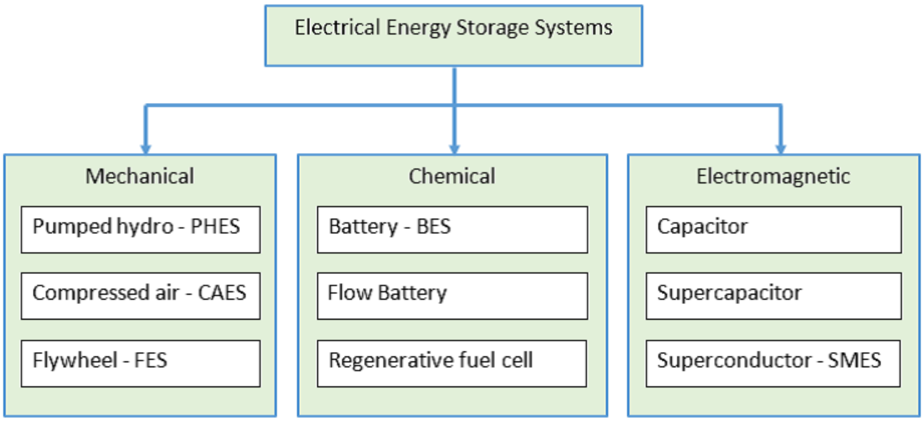

Fig. 9. Energy storage systems classification.

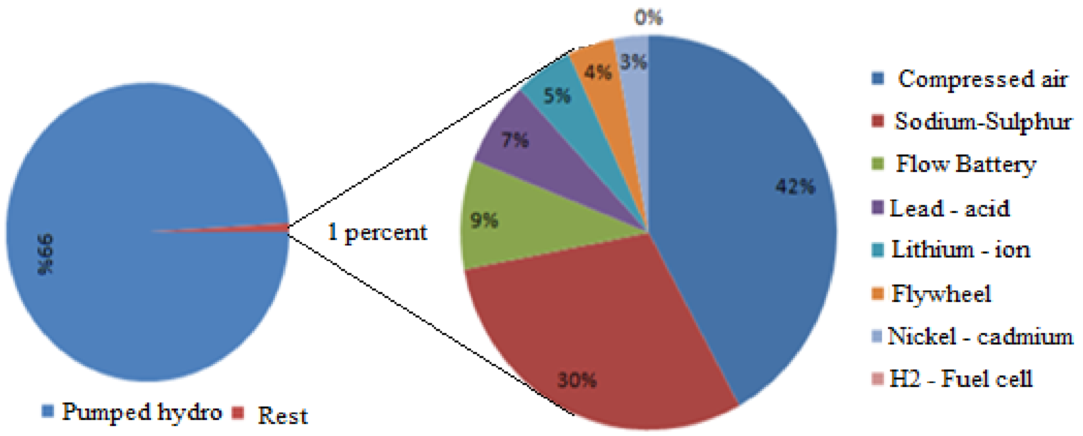

Fig. 10. Global electrical energy storage [16].

4.1 Pumped Hydro Storage (PHS) System

The system needs two water reservoirs as demonstrated in Figure 11. The water pumped during off-peak time is stored in a reservoir called upper reservoir and the water discharged during peak time is stored in the lower reservoir.

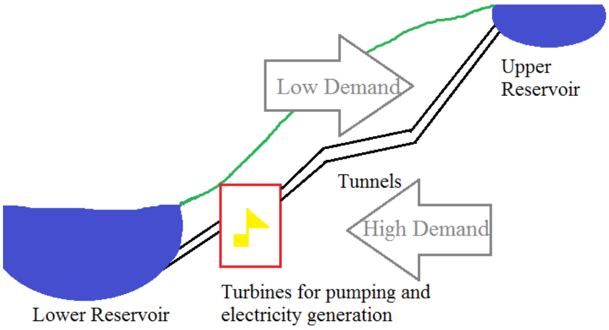

Fig. 11. Pumped storage system [29].

The stored energy computation is carried out based on the volume of the stored water and the height difference of the two reservoirs. Power rating of the unit depends upon the water pressure, rate of flow through turbine, power rating of pump/turbine and number of units of generator and motor [17]-[18].

4.1.1 Special features

- Efficiency 70-85%
- Life time >40 years

4.1.2 Applications

- Energy management purpose during time shifting like spinning reserve and supply reserve.
- Frequency control
- Supply reserve

4.1.3 Limitations

- Initial investment high
- Long construction time

4.1.4 Recent trends

- Usage of flooded mine shafts
- Usage of underground caves and oceans as basin
- Forming hybrid systems with solar and wind power generating units

4.2 Compressed Air Energy Storage (CAES) System

During low load period of power grid CAES compress air to high pressure by the use of electrical energy, and the high pressure air may be stored in scrap mine, seabed gas tank, run out oil and gas wells, new gas wells and rock cave. During high load period of power grid the air under compression is released to run steam turbine for electricity generation [17]-[18].

4.2.1 Special features

- Effective functioning during partial load conditions
- Fast change of mode from generation to compression
- Lengthy storage period
- Low principal investment
- Efficiency of 70-89%
- Rating 50-300 MW

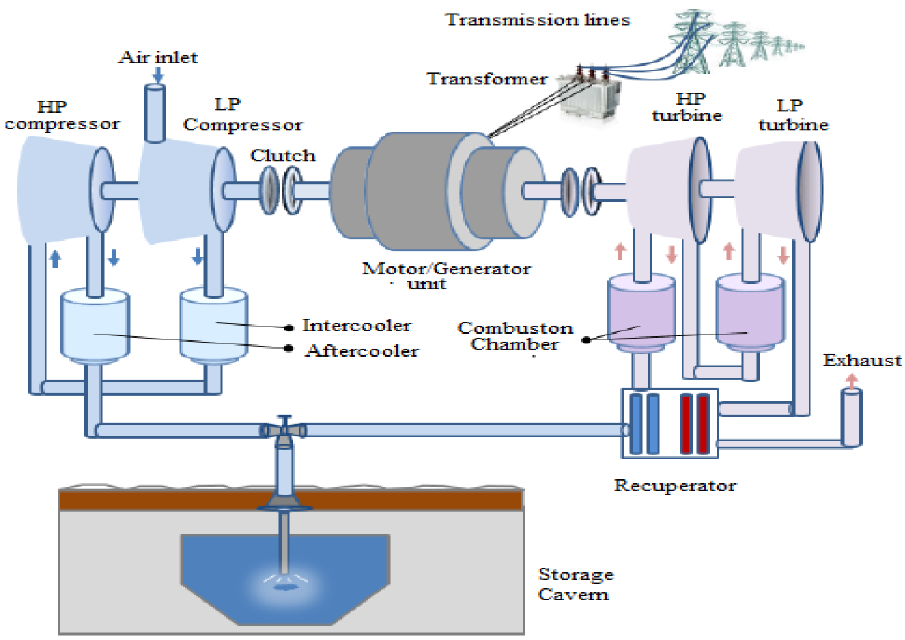

Fig. 12. Compressed air storage system [16].

4.2.2 Applications

- To top up power grids at the time of peak load
- During power outage can be utilized as backup supply

4.2.3 Limitations

- In depleted gas reservoirs the gas residues, water and oxide gases may make disturbances in the erecting surface.
- In rock caves the pressure drop may occur due to the oxygen loss, microbial growth and reservoir permeability reduction.
- Fuel is necessary for combustion process which in turn increases the cost of operation and emission of greenhouse gases.

4.3 Flywheel Energy Storage (FES) System

In this system the storage of kinetic energy is carried out by a rotating mass and hence called as mechanical battery. The renewable energy or off peak load electricity is used to rotate the rotor mounted in an empty cylinder at excessive speed and store the energy as rotational energy as in Figure 13. During energy storage the rotating device performs the work of a motor and during discharging of energy it functions as a generator [19]-[20].

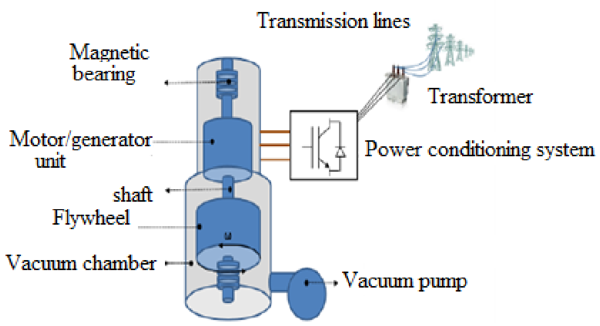

Fig. 13. Flywheel storage system [16].

4.3.1 Special features

- Less maintenance
- High reliability
- High efficiency (>85%)
- Long life time (420 years)

4.3.2 Applications

- Swapping between medium and large power (KW to MW) for short duration in seconds
- Railway power systems
- Power frequency regulation
- Renewable energy systems power quality progress

4.3.3 Limitations

- High cost of acquisition
- Less storage capacity
- Fast rate of discharge

4.4 Capacitor and Super Capacitor Energy Storage (SCES) System

A capacitor is formed by two electrodes separated by dielectric material (ceramic, glass or plastic). When voltage is applied between electrodes, energy storage occurs in the electrostatic field. Capacitors are fast charging devices. Super capacitors have two electrodes with carbon surfaces as shown in Figure 14.

A porous membrane separates the electrodes, and performs the function of an electronic insulator as well as ionic conductor. The capacitance value depends on the effective area of electrodes (A), distance (d) between the electrodes and the dielectric constant of the electrolyte (ε).

Super capacitors capacitance will be 100-1000 greater than capacitors ($C = \varepsilon A/d$) capacitance. The energy stored is given by $E=.5CV^2$, is 1V for aqueous and 3V for organic electrolyte [20].

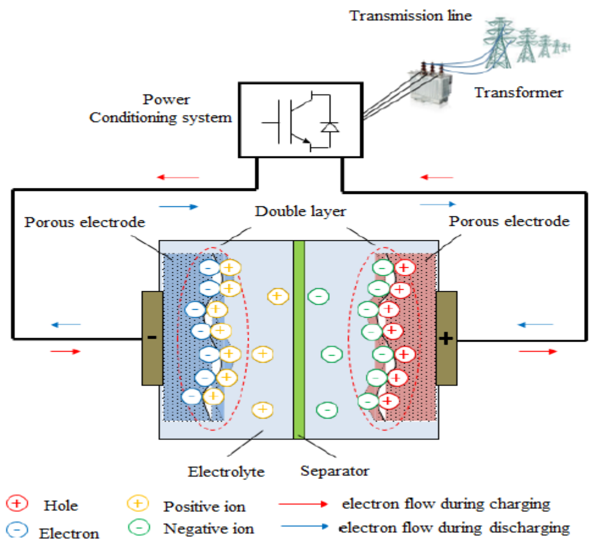

Fig. 14. Super capacitor storage device [16].

4.4.1 Special features

- High efficiency
- High life cycle
- Low environmental effects

4.4.2 Limitations

- Capacitors have low energy density
- Self-discharge rate is high

4.4.3 Applications

- Used in places where short-time and high-power fast discharge is needed
- For the storage of regenerative braking energy in transport sector

4.5 Superconducting Magnetic Energy Storage (SMES) Systems

In SMES electrical energy is stored by the passage direct electric current through coil (inductor) fabricated using superconducting material as in Figure 15.

The current circulates in the coil indefinitely causing zero loss. Since SMES contains inductor energy can be stored in its magnetic field also. The inductor acts as superconductor by keeping it immersed in helium liquid kept in a vacuum-insulated cryostat. Niobium-titanium is used as conductor and the coolant may be liquid helium (4.2 K) or super fluid helium (1.8 K). The three major units of SMES are superconducting unit, cryogenic unit and a unit of power conversion. Considering coil inductance as L and the flow of current through the coil as I, the energy (E) stored in the coil is $.5LI^2$ [19]-[20].

4.5.1 Special features

- High efficiency (> 97%)
- Fast response (few milliseconds)
- High life cycle

4.5.2 Limitations

- Storage time is short
- The rate of discharge determines the output of the system.

4.6 Thermal Energy Storage (TES) Systems

TES utilizes materials that can be kept at high or low temperatures in shielded containments. Energy recovered (from hot or chill condition) is utilized for generation of power. For storage, required energy is supplied either by heating or cooling process as input. If the operating temperature is lower than the room temperature then the TES is called as low temperature TES. If the operating temperature is higher than the room temperature then the TES is called as high temperature TES.

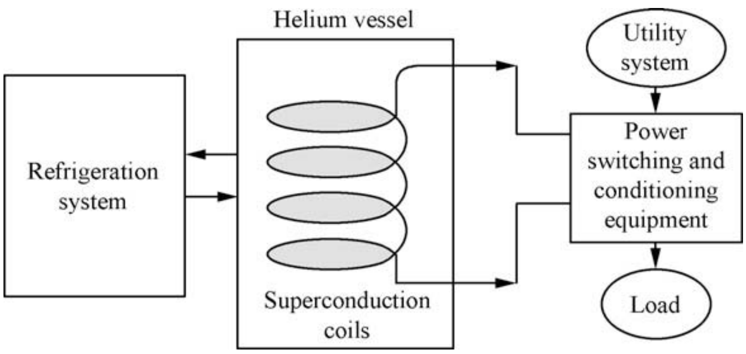

Fig. 15. SMES system [20].

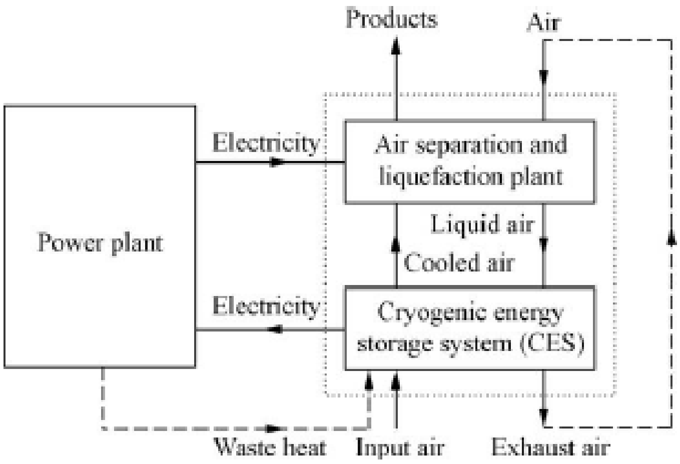

Fig. 16. CES TES system [20].

4.6.1 Low temperature TES

Aquifer low temperature thermal energy storage TES (AL-TES): At the time of off peak load, water is cooled to refrigerating temperature and at the time of peak load the stored energy is utilized. The energy storage is based on the temperature difference between the cold water in the storage tank and the hot water coming out of the heat exchange unit. This TES is useful for cooling commercial and industrial buildings during peak time.

Cryogenic TES: Cryogen (nitrogen or air in liquid form) is produced during off-peak time or from alternate energy source. During peak time cryogen is heated by the heat from the surroundings and used for power generation using cryogenic heat engines. CES have good energy density, low capital cost and environmental friendly [20].

4.6.2 High temperature TES

Molten salt storage and room temperature ionic liquids (RTILS): RTILs use natural salts at a relevant temperature range and melting temperature of 25˚C where pressure is immaterial.

Concrete storage: This method makes use of concrete or ceramics for storing energy at high temperature for parabolic trough collectors utilizing man made oil as heat transfer agent [14]. Thermal energy storage units are employed for cooling purposes in industries (< 18˚C) and buildings (at 0-12˚C). For heating purposes in buildings (at 25-50˚C) and industries storage (> 175˚C) [21].

4.7 Chemical Energy Storage

4.7.1 Hydrogen energy storage (HES) system

A HES system is constituted by a fuel cell, a storage tank for hydrogen and an electrolyzing unit. The electrolyzing unit converts water into hydrogen and oxygen by the usage of electricity by electrochemical process. For power generation both hydrogen and oxygen flow into the fuel cell, where both the gases react leading to water formation, the heat discharge during the reaction produces electricity.

4.7.2 Synthetic Natural Gas (SNG)

It is also called as methane synthesis. It is another form of chemical storage of electricity. Following the splitting of water by an electrolyzing unit, hydrogen, carbon dioxide and methane are allowed to react in a methane reactor. Then SNG produced is stored in pressure tanks or send to gas grid. The SNG units are suitable for places where CO_2 and surplus electric energy are available [14].

4.8 Battery Energy Storage (BES) System

The battery is formed by single or more electrochemical cells. Every cell in the battery includes a liquid or solid electrolyte, a positive electrode (anode) and a negative electrode (cathode) [20].

All secondary batteries and flow batteries store electrical energy in chemical form. Cells can be arranged in series or in parallel to get the voltage or power rating as needed for storage system.

4.8.1 Types of batteries

Lead acid battery: It consists of lead anode, lead dioxide cathode and aqueous sulphuric acid as an electrolyte.

Nickel-cadmium battery: It consists of Cadmium hydroxide anode, nickel hydroxide cathode with a separator and soluble electrolyte.

Sodium sulphur battery: It consists of fluid sodium anode, fluid sulphur cathode and ceramic electrolyte.

Redox flow battery: A rechargeable battery having two electrolytes each with a Redox couple. Energy expansion can be done by increasing the quantity of electrolyte and power increase can be done by the increase of cell dimensions [16]-[19]. The BES structure is described in Figure 17. Comparison of different batteries performance is listed out in Table 3.

Lithium-ion battery: It consists of carbon anode, lithium cathode and lithium salt electrolyte.

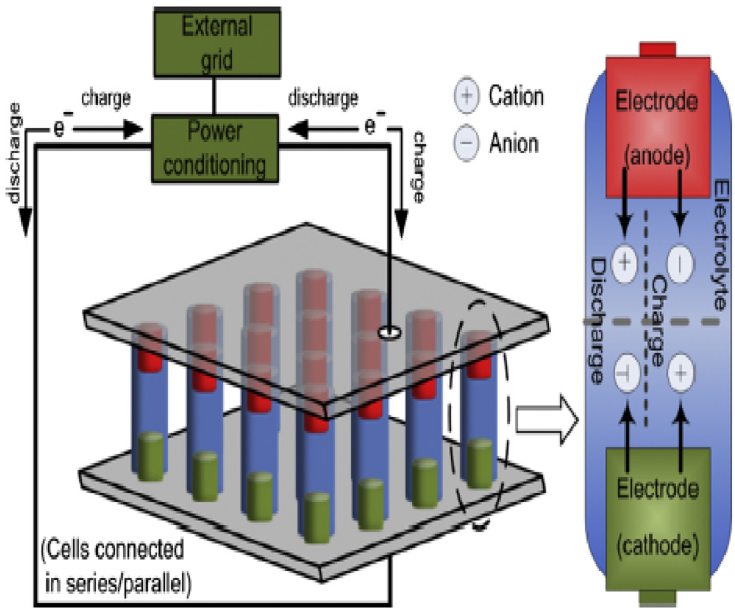

Fig. 17. BES system [15].

Table 3. Comparison of batteries performance [23].

Device	Merits	Drawbacks
Lead-acid battery	Cheap, trouble free replacement, easy availability in the market, suitable for upgrading the quality of power and uninterruptible power supply applications	Requires high maintenance, short cycling capability, less power and energy density, charging is slow, ratio of energy to power is less, noxious components
Sodium - Sulphur	High power and energy density, cheaper source for power quality improvement and peak saving purpose	Needs heat source, costly
Nickel- Cadmium	moderate energy density, cycling capacity is low, good mechanical resistance, less maintenance, best for power tools, emergency lighting, generator start , telecom and handy devices	costly, toxic, memory effect
Lithium-Ion	Moderate power density, 100% efficient, good cycling capacity, fast response during charging and discharging actions	Significant expense, debases at high temperature
Vanadium Redox Battery	High round trip efficiency (RTE), suitable for upgrading the quality of power and uninterruptible power supply applications, incorporation of renewable sources	
Redox Flow battery	Density of power and energy in this device is reasonably good, can be used for large scale requirements	Cost is high, standardizing is intricate

4.9 Fuel Cell (FC)

It is an electrochemical energy conversion device in which electrical energy is produced from the supply of fuel from anode side and oxidant from cathode side as shown in Figure 18. The reaction between the fuel and oxidant occurs in the presence of electrolyte. The reactants flood inside and the product of the reaction flood out and the electrolyte stay in the cell. Fuel cell operates continuously till the supply of fuel and oxidant is stopped [22]-[26].

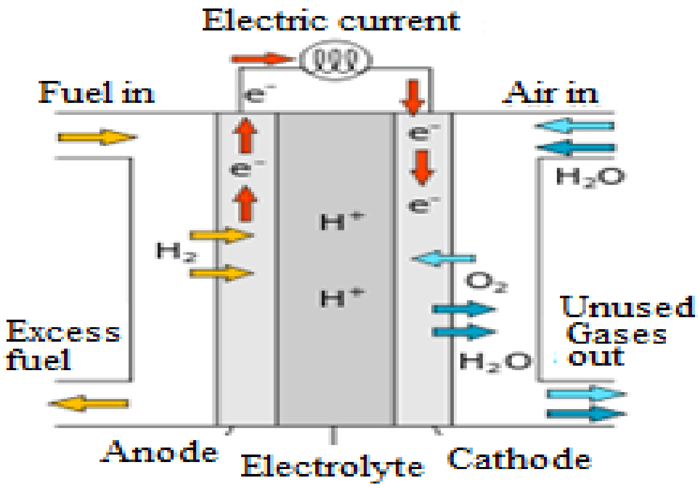

Fig. 18. Basic structure of fuel cell system [28].

Table 4. Fuel cell specifications.

Fuel cell	Fuel	Oxidant	Cell Voltage in V
Alkaline fuel cell	Pure H2	O2 in atmosphere	1.0
Phosphoric acid fuel cell	Pure H2	O2 in atmosphere	1.1
Solid oxide fuel cell	H2, CO, CH4	O2 in atmosphere	0.8 – 1.0
Molten carbonate fuel cell	H2, CO, CH4	O2 in atmosphere	0.7 – 1.0
Proton exchange membrane fuel cell	Pure H2	O2 in atmosphere	1.1
Direct methanol fuel cell	CH4OH	O2 in atmosphere	0.2 – 0.4

5. STORAGE DEVICES USED IN BANGLADESH

In order to provide continous power supply from renewable power generation system storage devices are used. In Bangladesh storage batteries are used along with home solar energy units and in wind turbines. In Banglaesh, lead acid batteries are used as energy storage devices for energy generated from renewable energy sources. For industrial applications either tubular plate type or flat plate type batteries are used.

The robustness of tubular plate batteires make its utlization higher than flat type batteries. Local manufacturer's contribution plays a major part in the fabrication of tubular plate batteries. The companies taking part in battery fabrication are Rahimafrooz, Rimso, Hamko, Navana, Pannaand, and few others and their share in fabrication are cleary plotted in Figure 19. However, 70% of the raw materials are imported [27-29].

Rahimafrooz batteries limited (RBL) is the biggest battery manufacturer of Bangladesh manufacturing around 300 types of quality batteries for industries and automotive purposes by having technical association with Lucas batteries of UK, Hawker batteries, Invensys and Hawker batteries, Eltek batteries of Norway and AEES of France [27].

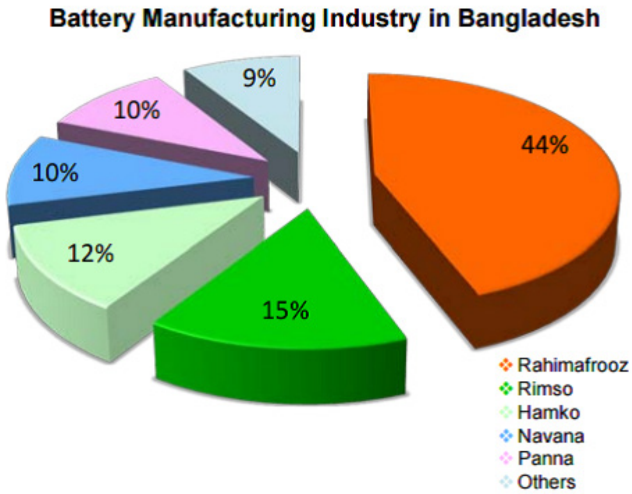

Fig. 19. Battery manufacturing industry in Bangladesh [27].

6. CONCLUSION

This paper briefly discussed the installed capacity for power generation from various sources in Bangladesh. In response to global warming and depleting fossil fuel sources renewable energy penetration need to increase in installed capacity. To overcome intermittency in various renewable energy resource based energy supply systems storage devices can play very important role. The need for renewable energy sources and the types of widely used renewable sources in Bangladesh were analyzed. The need for storage devices and the types of storage devices along with their pros and cons were explained. Finally, the storage device widely used in Bangladesh and the leading manufactures' are listed. The paper provides information on wide range of options for storage technology which can help in taking decision towards diversifying current storage practices in Bangladesh.

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Duck Curve Problem Formulation and Solving Strategies by Utilizing PVr, PEVs, Load Shifting and ANFIS for Greening Bangladesh

Md. Ariful Islam*,[1] and Jai Govind Singh*

Abstract – *The installations of solar photovoltaics (PVs) in the distribution system, including rooftop photovoltaic (PVr) have been growing dramatically, which changes the shape of the daily demand profile in a way that makes it look like a duck. The duck curve is basically formed due to the huge unbalance of demand and high penetration of solar energy for a specific daytime period. This concern in the duck curve makes an outsized omission between the peak and off-peak and it leads to a recurrent ON and OFF of the thermal generators by escalating their start-up cost (SUC). As a solution, a considerable curtailment of solar energy from the existing system does not justify the installation cost of solar PV and its energy storage devices. This study is a futuristic case study for Bangladesh, where a high growth rate of Plug-in Electric Vehicles (PEVs) (20-25%) and rooftop solar PV (8%) for decarbonization may lead the load profile becoming not only a duck shape but also an inevitable blackout. To address these outgrowths, this study utilized the combined contribution of PEVs (energized by Lithium-ion battery), solar PVr, load shifting and Time of Use (ToU) based electricity pricing. Using PEVs may add up the system's total electrical load, but its optimal battery power management will give a smoother net load profile with better system stability. ToU based electricity pricing is a new electricity tariff standard for Bangladesh the new electricity tariff will encourage the consumer to be aware of using electricity properly, benefiting not only themselves but also the utility.*

Keywords – *duck curve, load shifting, plug-in electric vehicle (PEV), solar PV, ToU.*

1. INTRODUCTION

Nowadays, the world is heading towards renewable energy because of the limited reserve of fossil fuel and the fossil fuel-based electricity generation which harms the environment. Among all renewable energies the solar energy is the most popular as it is maintaining ever-decreasing technology and installation costs [1], [2]. In some countries, government incentives are ramping up this growth. Bangladesh is closely related to all above mentioned issues.

Bangladesh is a country of a hastiest booming economy globally with an average GDP growth rate of 6.5% since 2004. With the increased economic capability and modernization of technology, the use of electrical and electronic devices has increased drastically by the consumers. The increased load creates an extra burden on the electrical grid and that extra load is supposed to be impossible to be covered by the utility alone. So, there are several reasons behind the leaning toward non-dispatchable renewable energy for providing the extra power supply to the consumer level [3].

Firstly, natural gas (NG) is used for power generation as the primary energy source in Bangladesh. In addition, the current reserve of NG will support the country for the next 10-12 years [4]. Other resources are less to be described here. Bangladesh is sensitive to the world decarbonization agenda and is trying to minimize the use of fossil fuel because it has two limitations- i) the reserve limitations and ii) environmental limitations. Secondly, Bangladesh is following Sustainable Development Goals (SDGs) to have clean energy by utilizing non-dispatchable renewable energy sources and heading towards renewable energy. Solar energy has high potential for Bangladesh, but the installation of sufficient solar PV to have an extra power supply for consumers is not possible due to insufficient space. So, the installation of rooftop solar PV (PVr) is getting popular in Bangladesh. The first solar home system (SHS) was installed in Sylhet by a private organization in the mid of 1980s. Now, it has become very popular and has become the most effective SHS program in Bangladesh. All SHS units (4.5 million) are installed by the government's financial institution called Infrastructure Development Company Limited (IDCOL) [5]. The government stated that 10% (2000MW) of total generation should come from renewable energy sources by 2020. To fulfill this target we can get 20MW from rooftop solar system as most of the rooftop of residential or commercial infrastructure is partly or completely empty [6]. The government has mandated some rules to be followed by the consumers: for residential use of electricity, the consumer has to install 3% of solar PV of total household load on the rooftop and for industrial (light and fan) use, it has to be 7% of total installed load [7]. Moreover, there are some upcoming plans by which the consumers will be able to sell their extra generation

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of electricity to utility. This advantage will encourage the consumers to have more power generation by solar PV.

Undoubtedly, this is a positive change in the energy sector with environmental benefits, but this sudden increase in solar energy has some negative sides too, which should be considered before the problems get severe. Solar radiation is not the same throughout the day. More solar power production in rooftops of homes reduces the demand for dispatchable power of the utility sides. The generation of solar energy gets its peak at solar noontime and this generation necessitates on shutting down the other dispatchable energy sources [8]. The utilities observe that i) demand spikes: morning and evening, before declining at night, ii) problem of managing "Net Load", iii) forced ramp up of dispatchable plants for a morning peak, then dispatchable plants are shut down and are brought back all online (quickly) when the sunsets. There are some associated problems like i) the dispatchable generators having the qualifications of sudden ramping, stopping and starting are expensive, ii) in some cases such expenses are also not known to the utilities iii) sudden ramping, stopping and starting cause extra stress on power grid [9].

Moreover, the conventional generators could not support this high and sudden requirement of the power generation's ramping up. Consequently, a significant investment in the power grid is needed to meet this high peak demand. Ultimately, grid investment passes to the customers as electricity price/bill increases. Again, over current flow during peak-hours can adversely affect the transmission lines and reactive power control devices. An immense valley in the load curve also means less electricity utilization by the consumers from the utility [10].

In Ref. [11], some researchers of the National Renewable Energy Laboratory (NREL) investigated integrating a large scale of renewable energy into the electrical grid. They found a strange shape of load curve while integrating a large-scale solar power generation in the electrical grid. Later, it was named the, "duck curve" by the California Independent System Operator (CAISO). So, it is mainly familiar as the California duck curve, shown in Figure 1. We can say that Duck curve is nothing but a particular shape of the load curve, where the difference between valley and peak is very high [12]. This specific shape of the load curve is formed because of asynchronous between the excess generation of solar power and, at the same time, the least demand for electricity from consumers [13].

Along with the California duck curve, many more countries are suffering from duck curve issues. They are familiar as, 'French Duck Curve', 'German Duck Curve', 'Australian Duck Curve', 'American Samoa Duck Curve' [15]. As rooftop solar PV is getting popular and obligatory in Bangladesh, soon Bangladesh could see a 'Bangladeshi Duck Curve'. This paper will investigate a probabilistic duck curve formation and its probable solution by utilizing existing resources from Bangladesh's perspective.

There are many studies where researchers tried to show the influence of duck curve in the power system. The NREL showed a repairable negative impact of the over generation of solar power in the power system [16]. Some studies show how to avoid duck curve formation by the curtailment of solar energy from solar PV, but this curtailment does not justify the installation cost of solar PV in the system [17]. One study in [18] tried to solve the duck curve problem by utilizing pumped storage hydroelectricity and renewable energy. A study showed in [19], utilized PEVs with a distributed power management algorithm to flat the duck curve. In Ref. [20], it has been shown that shiftable loads can contribute to flattening load profiles. In Ref. [21], demand response and storage systems were utilized to solve the duck curve problems. Ref. [20] tried to solve the duck curve issues by increasing energy efficiency by avoiding RE. Some studies showed that ToU based electricity price and tariff provoking could motivate more consumers to utilize battery storage system at their own cost [23].

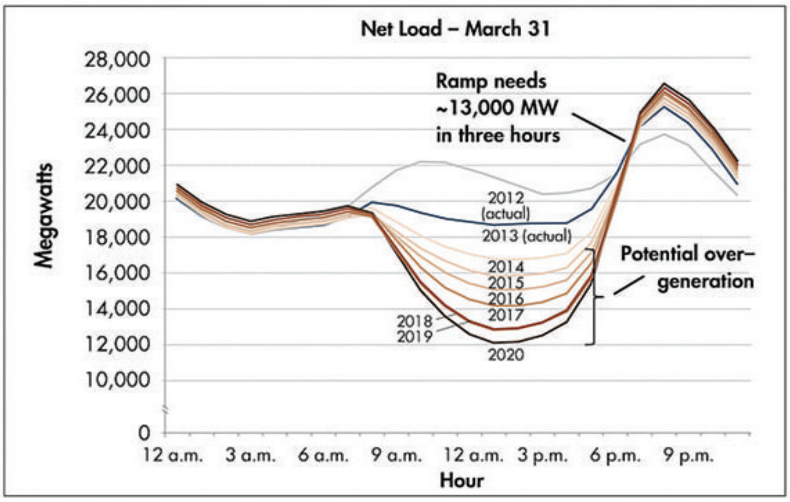

Fig. 1. The duck curve graphic California ISO and J. Lazar [14].

The duck curve has a deep valley which denotes less use of energy during that particular time. A storage system is necessary to utilize their energy. But energy storage system is expensive and not encouraged by the user. It is widely known that Plug In Electric Vehicle (PEVs) are getting better attention than any other transport mode due to its multi-purpose use in the smart grid [24]. It is an electrical load and can be used as an energy storage device [25]. To use PEV as a load and battery storage, it must have two-way energy transfer: from the grid to vehicle (G2V) and vehicle to grid (V2G). Recently, one study is carried out where it has been shown that simultaneous operation of both G2V and V2G can considerably flatten the load profile and contribute to grid stabilization [26].

Sometimes storing energy is also not sufficient for this solution. In this regard, demand response can be a useful add-on. ToU based electricity price can encourage the consumers to shift their load according to peak and off-peak hours [27].

So, flattening the Duck curve is an ultimate solution to all the above stated problems. There are some technical challenges those may be faced while flattening the Duck curve like i) how to flatten the Duck curve to reduce grid investment, ii) how to improve the load profile with PEVs capabilities, iii) how to interface load shifting, and iv) appropriate control strategy for the operation.

In this paper, to flatten the Duck curve both PEV and demand response were used. To use the PEV as a load and storage device, a flexible control strategy that helped PEV to perform V2G and G2V operation was used [26]. However, this study is a country-based operation, so the availability of PEV is a prime concern. In Bangladesh, PEV is getting popular due to legionary advantages like reducing the use of fossil fuel (imported), reducing GHG emissions by increasing the sustainability of the environment, cheaper in cost, least sound pollution, and lower government tax in purchasing PEV [28]. The automotive battery market size has grown three times in 2017 (estimated $954 mn) compared to 2013 ($358 mn) [29]. Even the Compound annual growth rate (CAGR) of the lithium-ion battery market is 7.2% more than the forecast period (the base year 2019 and study period 2018-2025) [30].

An artificial intelligence based neuro-fuzzy inference system is utilized for the management of battery power. In this case, ANFIS performs well because of its user interface and battery power management capability. Due to this paper's page limit, the advantages of using ANFIS over other controllers are not considered in this work. A ToU based electricity tariff is proposed to shrink the battery wages by shifting some shift-able loads from high peak time to less peak time.

This paper is arranged in the following sections: system description (solar integration and formation of duck curve, load shifting, modeling of battery,) is shown in section 2, section 3 shows battery power management of PEV, section 4 shows control strategy, section 5 shows simulation results and discussion, and the conclusion is shown in part 6.

2. SYSTEM DESCRIPTION

In this paper, two PEVs available at home were considered and used to flatten the Duck curve considerably. Charging and discharging were taking place in the car parking of the house. This study's main objective is to make the load power curve much flatter by ensuring the proper flexibility of connection of PEV with the grid by means of the appropriate use of controller (ANFIS) and use demand response effectively by means of ToU based tariff. Figure 2 shows the home, which is considered with standard loads available in Dhaka city. Converters were used for connecting DC loads.

When PEV was plugged-in, the battery got connected with the help of DC blocking filter, bi-directional DC to DC converter, bus for linking DC voltage, AC/DC converter and a R-L filter. The charging and discharging of the battery depend on the direction of the current. The battery's charging was indicated by -ve battery current and the discharging state was indicated by +ve battery current. The DC/DC converter was used as a buck-boost converter to boost any weak voltage to a certain level. The smoothening was done by L (inductive) filter. The AC/DC converter was used to convert the AC to DC and DC to AC according to battery and grid demand. The converter had multi-functions like- working as a rectifier while charging and inverter while discharging.

2.1 Integration of Solar in the Home System and Formation of the Duck Curve

In this study, a 3kW solar panel, which would effectively produce 2.9kW power during the solar noon (1000W/m^2 irradiance standard value and 25°C temperature), was considered. This 2.9kW solar power turns the load curve into a duck curve. This particular configuration of the solar panel is considered only for analysis purpose. The solar power generation from sunrise to sunset is shown in Figure 3.

The figure shows that sufficient solar production starts at 9h and declines producing solar power just after 15h. During that period, the produced solar energy after getting integrated into the system turned the load curve into an unusual shape. The new curves' peaks and valleys got a new shape which looked like a "Duck" that's why the new load curve was named as "DUCK CURVE". The duck curve is depicted in Figure 4. For the analysis purpose, all the waveforms were segregated into six periods.

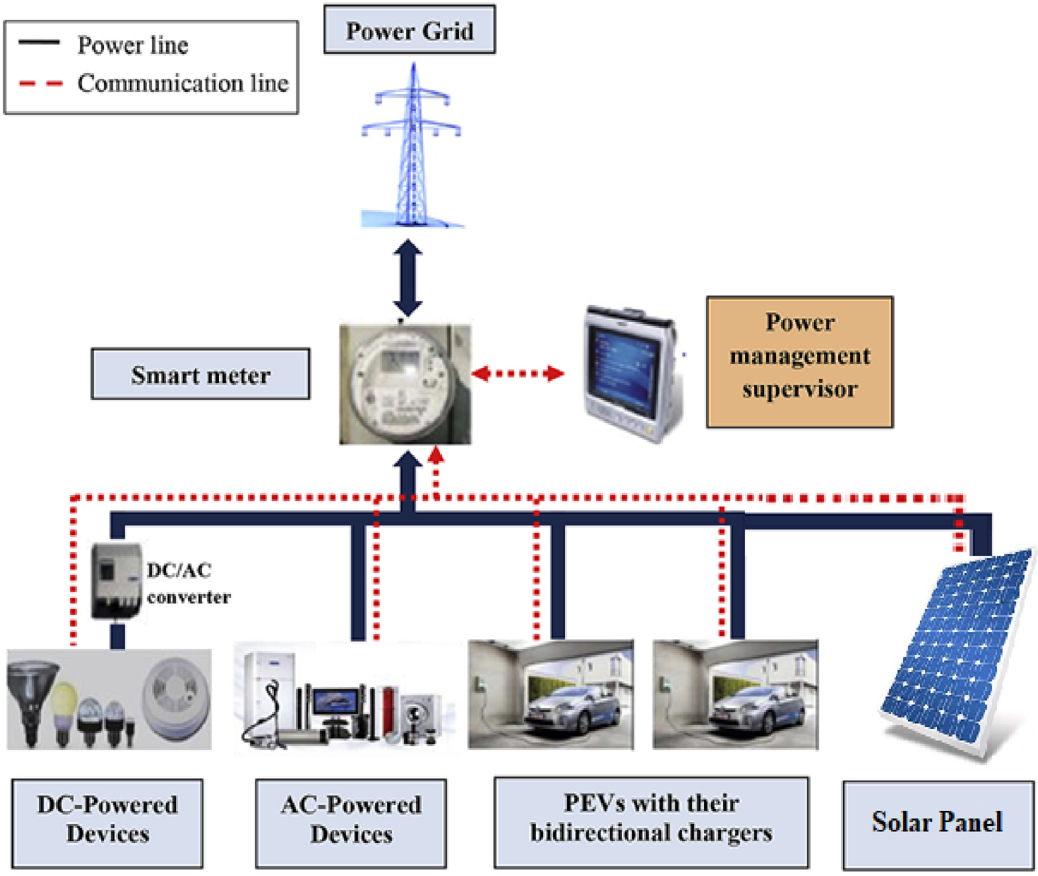

Fig. 2. Outline of home equipment.

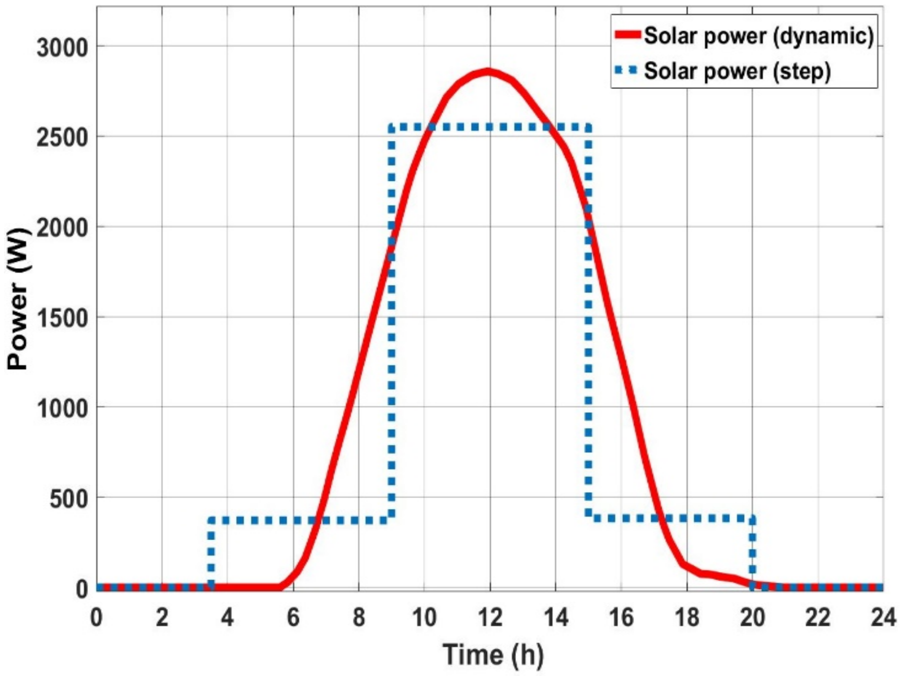

Fig. 3. Solar power generation from sunrise to sunset.

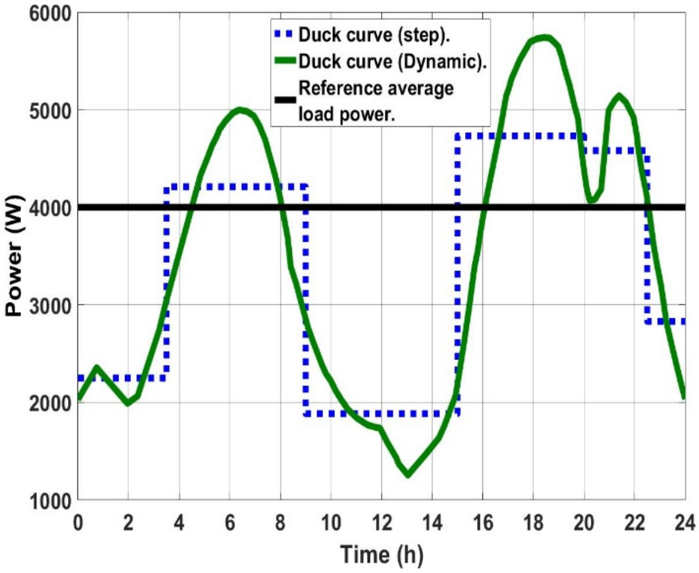

Fig. 4. Formation of duck curve by adding solar.

2.2 *Load Shifting by Time of Use (ToU) based Tariff*

ToU based tariff could play an important role in making the power system well balanced. The advantages of using ToU tariffs are that the utility can avoid constructing additional expensive power plants. The demand side is well managed, and consumers can lower their electricity bills as they are informed about the electricity price of different times of the day. In this regard, a smart meter was mandatory as it provides real time data of energy consumption to the utility as well as to the consumer.

Table 1. Exiting tariff for different consumption hour [31].

	Time of day	Energy rate (Tk./kWh)
Tariff Type	Flat rate (0h-24h)	8.00
Type-1	Off-peak hour (0h-17h)	7.20
Type-2	Peak hour (17h-24h)	10.00

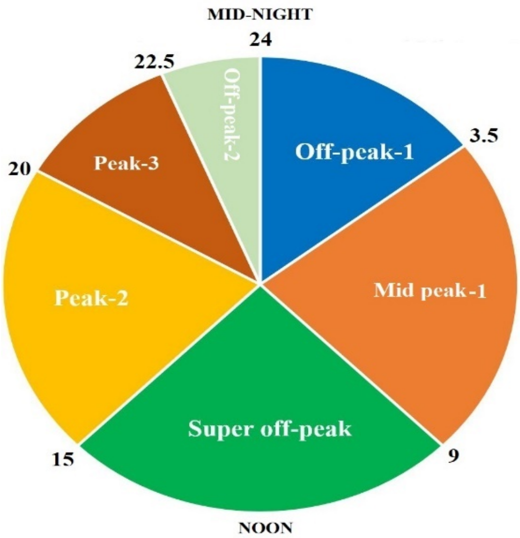

Fig. 5. Different load condition for 24 hours.

The updated electricity tariff provided by Dhaka Power Distribution Company Limited (DPDC) was collected [31]. For this study, Medium Voltage (MT) residential electricity tariff MT-1 was considered, which is shown in Table 1. The flat rate (type-1) is applicable for comparatively smaller load sized residents where the peak and off-peak rate is suitable for a relatively higher load size. But this existing tariff was not effective for flattening the probabilistic duck curve and need more segregation of the current tariff. For the dynamic pricing analysis, the duck curve (with and without PEV) was segregated into six periods. To attract the consumers for load shifting and at the same to facilitate the utility a ToU based electricity pricing was proposed, which is given in Table 2. Different load condition is shown in Figure 5.

Table 2. Proposed pricing for different consumption hour.

Time of day	Energy rate (Tk./kWh)
Off-peak hour-1 (0-3.5h)	5.00
Mid Peak hour-1 (3.5h-9h)	7.00
Super Off-peak hour (9h-15h)	3.00
Peak hour-2 (15h-20h)	10.00
Peak hour-3 (20h-22.5h)	10.00
Off-peak hour-2 (22.5h-24h)	5.00

Table 2 depicts the proposed electricity tariff along with the power used in a different time. Moreover, it shows that most energy surplus is taking place from 9h to 15h, so to attract consumers to use more power during this period, the price was considered as lowest. The reason behind choosing such a price was the consumer's unavailability and the wastage of most energy. So, offering as much as the lowest price during that period encouraged consumers to fulfill their maximum demand and utilize the surplus power. By using smart load management, some shift-able loads were shifted to that period. For this analysis, some available shift-able loads were considered, which are listed in Table 3.

Segregation of different peak and off-peak hours is depicted in Figure 5. In Figure 7 the negative sign indicates energy shifting from peak hours to off-peak hours and the positive sign indicates energy shifting from off-peak hours to peak hours.

After load shifting, the Duck curve in Figure 6 turned into the shape of Figure 8. The total electricity price of different periods is also shown in Figure 8.

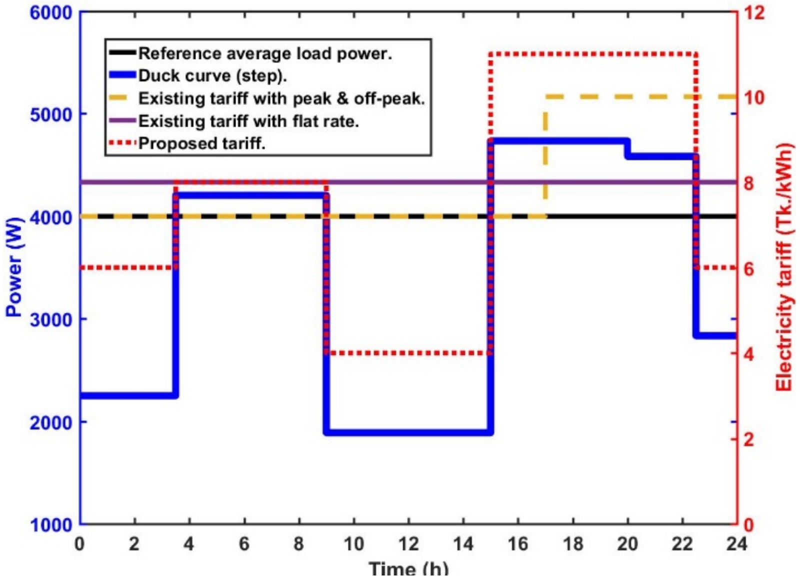

Fig. 6. Power and electricity tariff plot for different consumption hours.

Table 3. Some shift-able loads and their energy consumption.

	Shift able appliances	Power ratings (W)	Daily usages (h)	Energy Consumptions (Wh)
1.	Water heater	1800	1	1800
2.	Washing machine	600	1	600
3.	Electric iron machine	1000	0.5	500
4.	Air conditioner (2 units)	1500×2 =3000	3	9000
5.	Water pump	1100	1	1100
6.	Microwave oven	600	0.5	300
7.	Food blender	400	0.5	200
		Total energy consumption (Wh) =		13500

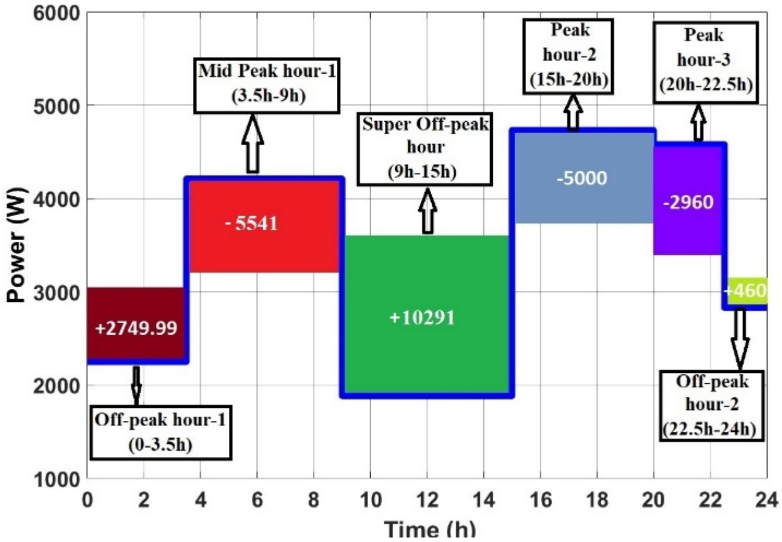

Fig. 7. Load-shifting (according to peak and off peak hours).

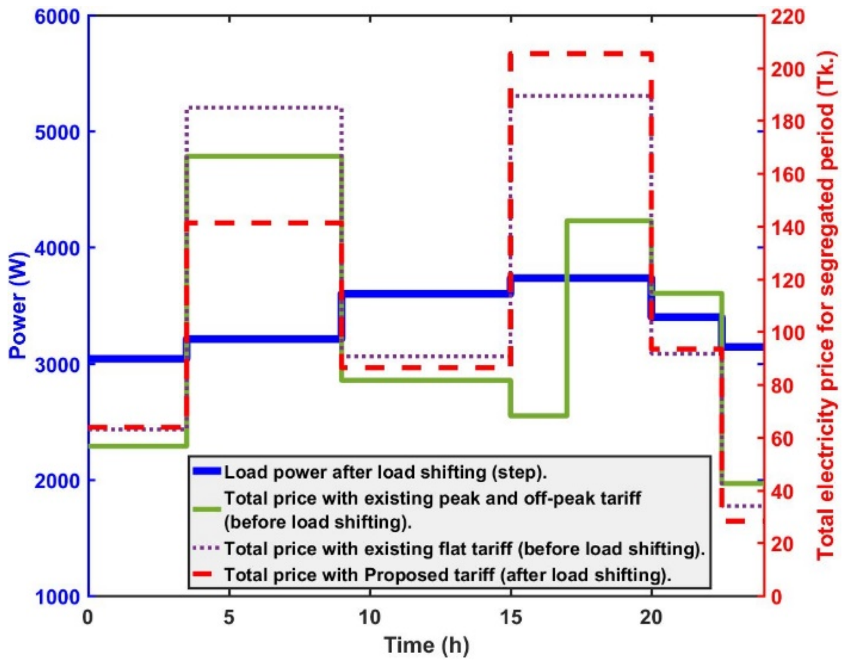

Fig. 8. New shape of load curve with total electricity price for each period.

2.3 *Modeling of the battery*

The battery used in the vehicle was Li-ion. In this paper a very classical model of the battery was used and all specifications are well described in [26]. One extra concern in this paper was to ensure better battery life by maintaining the battery SoC level to a certain percentage. Where State of Charge (SoC) is the level of charge of an electric battery relative to its capacity. The units of SoC of battery is measured as percentage (0% = empty; 100% = full). In this study, a fixed range of SOC percentage was considered to maintain battery health and avoid overcharging and deep discharging.

$$SoC_{min} \leq SoC \leq SoC_{max}$$

Where

$$SoC_{min} = 0.2 \text{ and } SoC_{max} = 0.8.$$

3. POWER MANAGEMENT OF PEV BATTERY

To perform the V2G and G2V operation an exact control strategy and bidirectional arrangement were necessary. In this study, a well-developed control strategy for PEV battery power management was utilized from [26]. The main difference between the [26] and this study was in terms of controller choice. The existing system in [26] was constructed with conventional PI controller where this study replaces this PI controller with a modern AI (artificial intelligent) based ANFIS controller. The whole system is redrawn with the ANFIS controller in PI controller replacement and shown in Figure 9. In this study, a brief description of the newly added parts was given.

Power production by each PEV was possible with the help of different power converters and power control of each PEV was ensured by controlling these converters.

Control of current: To have the reference battery current "$I_{bat\text{-}ref}$" from the battery charging/discharging an ANFIS controller was utilized. The -ve battery current represents the charging state while +ve battery current represents the discharging state. The following equation given the expression of the controller:

$$V_{m-bat} = V_{bat} - controller(I_{bat-ref} - I_{bat}) \quad (1)$$

Where, $V_{m\text{-}bat}$ is the modulated voltage of DC/DC converter, the battery voltage is V_{bat} and the battery current is I_{bat}.

Control of the converter: The main purpose of using DC/DC SMPS (switched-mode power supply) was to convert the battery voltage to a certain DC voltage level, which was suitable for inverter input. Otherwise, it was not possible to maintain a proper DC bus voltage. The duty ratio for DC/DC SMPS is given by the following equation:

$$m_{bat-ref} = \frac{V_{m-bat}}{V_{DC}} \quad (2)$$

Control of DC bus voltage: An ANFIS controller was used to control DC bus voltage by maintaining a proper "$I_{bat\text{-}ref}$". Then, nominal reference battery power $P_{bat-ref}$ was calculated for an adequate power exchange between the PEV and power grid. The equation of $P_{bat-ref}$ is given as follows:

$$P_{\text{bat-ref}} = P_{\text{DC-ref}} + P_D \quad (3)$$

Where, P_{DC-ref} =reference power of DC bus voltage
P_D =demand power.

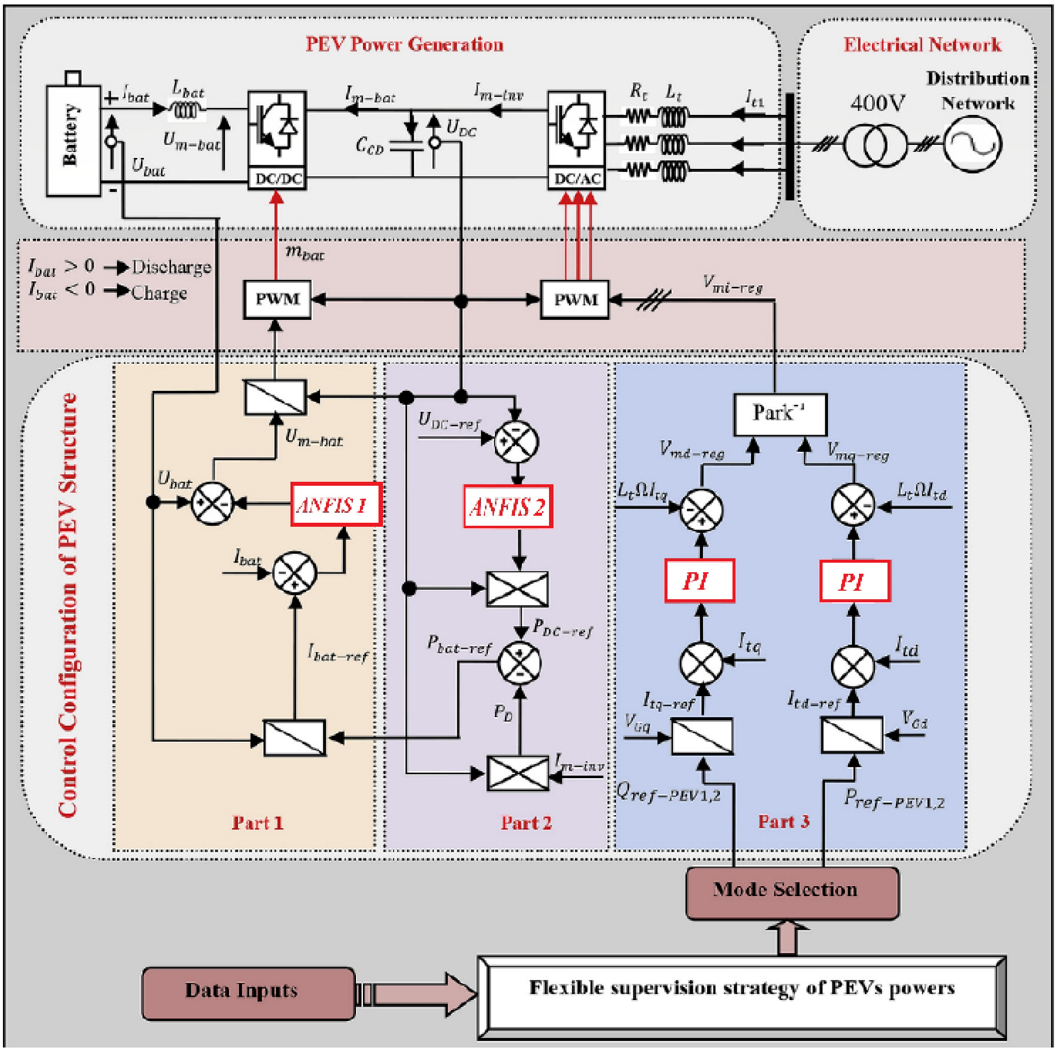

Fig. 9. Control design of each PEV structure for power production [26].

3.1 Neuro-Fuzzy Hybrid Controller Design for Battery Power Management

In terms of controller choice, ANFIS was better because it utilizes Sugeno, which gives better flexibility in the modification of MFs by means of data set. To design ANFIS, a toolbox named Fuzzy from MATLAB was utilized. The fuzzy toolbox has different features like-fuzzy inference system (FIS), MF (membership function) for input and output, rules view, rules editor and surface view.

In this study, two ANFIS (ANFIS1 and ANFIS2) controllers were designed: one for DC bus voltage control and another for battery current control. Two input variables were considered and regulated for better accuracy of the system like error and change in error. One output variable named ALC (Adapted Learner Content) was also controlled. The error was calculated by taking the difference between actual and reference value. Change in error is a ratio that was calculated from the difference and reference value.

A data set is required for ANFIS input, which was generated by the Fuzzy toolbox. Two input variables and seven (7) membership functions based fuzzy system was considered. To generate data for ANFIS1, one parameter was error in current, and another was change in error in the current. The following equation was utilized to calculate error:

$$V_{m-bat} = V_{bat} - controller\left(I_{bat-ref} - I_{bat}\right) \tag{4}$$

Change in error in current was calculated by taking the ratio between error current and reference battery current. The following equation as utilized for estimating the change in error:

$$Change\ in\ error = \frac{\left(I_{bat-ref} - I_{bat}\right)}{\left(I_{bat-ref}\right)} \tag{5}$$

To generate data for ANFIS2, one parameter was an error in bus voltage, and another was a change in error in bus voltage. The following equation was utilized to calculate error:

$$Error\ in\ bus\ voltage = V_{\mathrm{DC-ref}} - V_{DC} \tag{6}$$

Change in bus voltage error was calculated by taking the ratio between error in bus voltage and reference bus voltage. The following equation was used for calculating the difference in error:

$$Change\ in\ error = \frac{(V_{\text{DC-ref}} - V_{DC})}{(V_{\text{DC-ref}})} \tag{7}$$

With the help of above mentioned Equations 4, 5, 6, and 7, two different data sets were generated. In the ANFIS toolbox the prepared data set was uploaded and after training the new FIS file was generated. The Figure 12 shows all the steps of training the data by the toolbox. The training error is shown in Figure 13 and ANFIS structure with input and output is shown in Figure 14. The objective of utilizing ANFIS was to adjust the voltage/current level to a particular value from any range of error value of voltage/current produced by a system's malfunction.

The training procedure began with the suitable training data set. 70% data from each data set was utilized for training purposes and the rest of 30% data was utilized for testing purpose. The training data set contained enough reference values for better output. The input data set was in the matrix form. The final membership function with training data was formed at the end of the training process (trn-fismat). The trained data set was justified against the testing data set to check the proposed system's rationality.

The prototyped model was initiated with default membership function (7*7), where "Triangular-shaped (trimf)" membership function was used. The produced FIS system containing 49 rules was produced by genfis1 algorithm. To establish the relationship between the input and output and to compensate error, the whole training procedure was gone through the neural network.

The equation of root means square error (RMSE) was utilized for error investigation and the equation is shown below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(z_k - \hat{z}_k)^2} \tag{8}$$

The equation of Mean Average Error (MAE) is as follows:

$$MAE = \frac{1}{n}\sum_{k=1}^{n}|\ z_k - \hat{z}_k\ |\ , \tag{9}$$

Where, the total forecasted number is n, $\hat{z}_k$ is the forecasted time series, and z_k is the main series

The overfitting issue was solved by setting an appropriate training epoch.

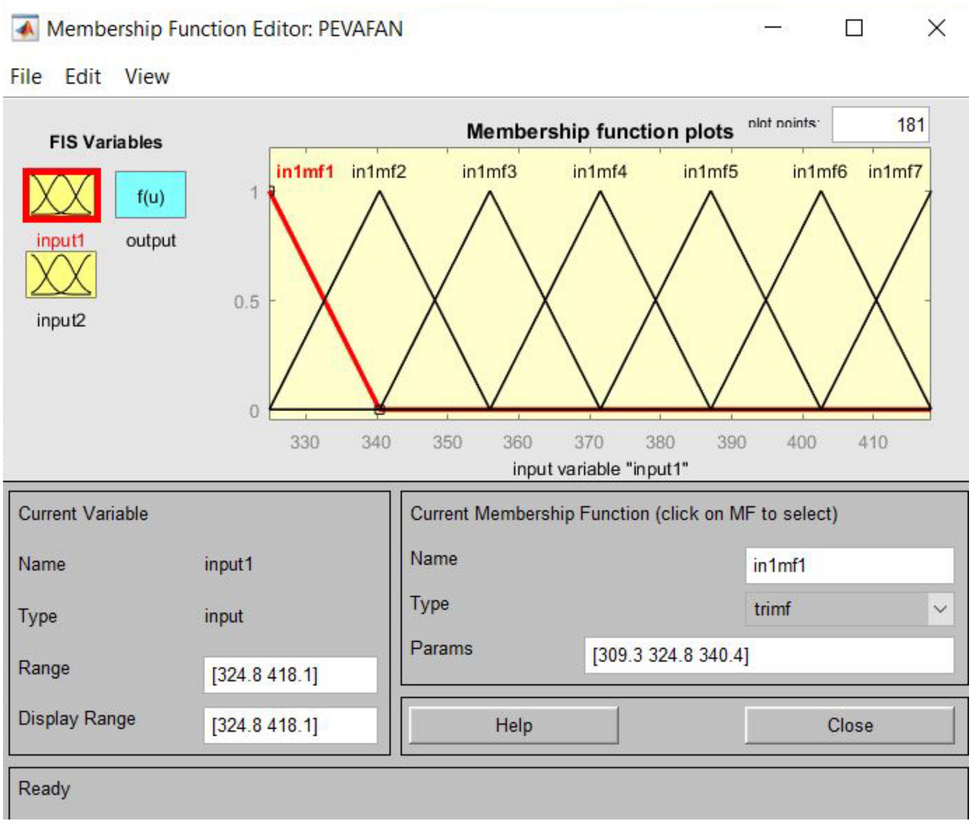

Fig. 10. Input membership function 1.

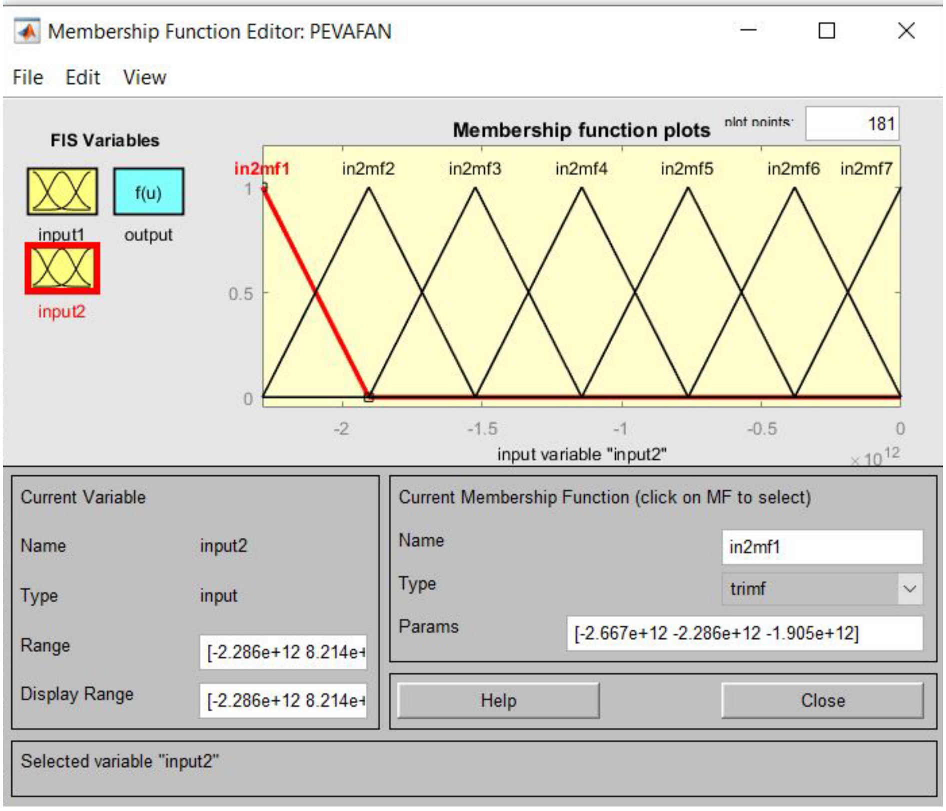

Fig. 11. Input membership function 2.

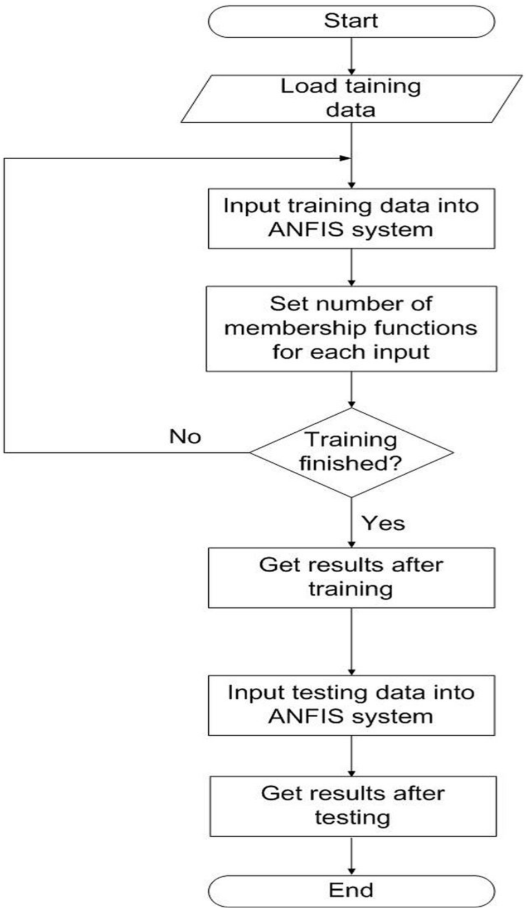

Fig. 12. Different steps of ANFIS training for battery charging [32].

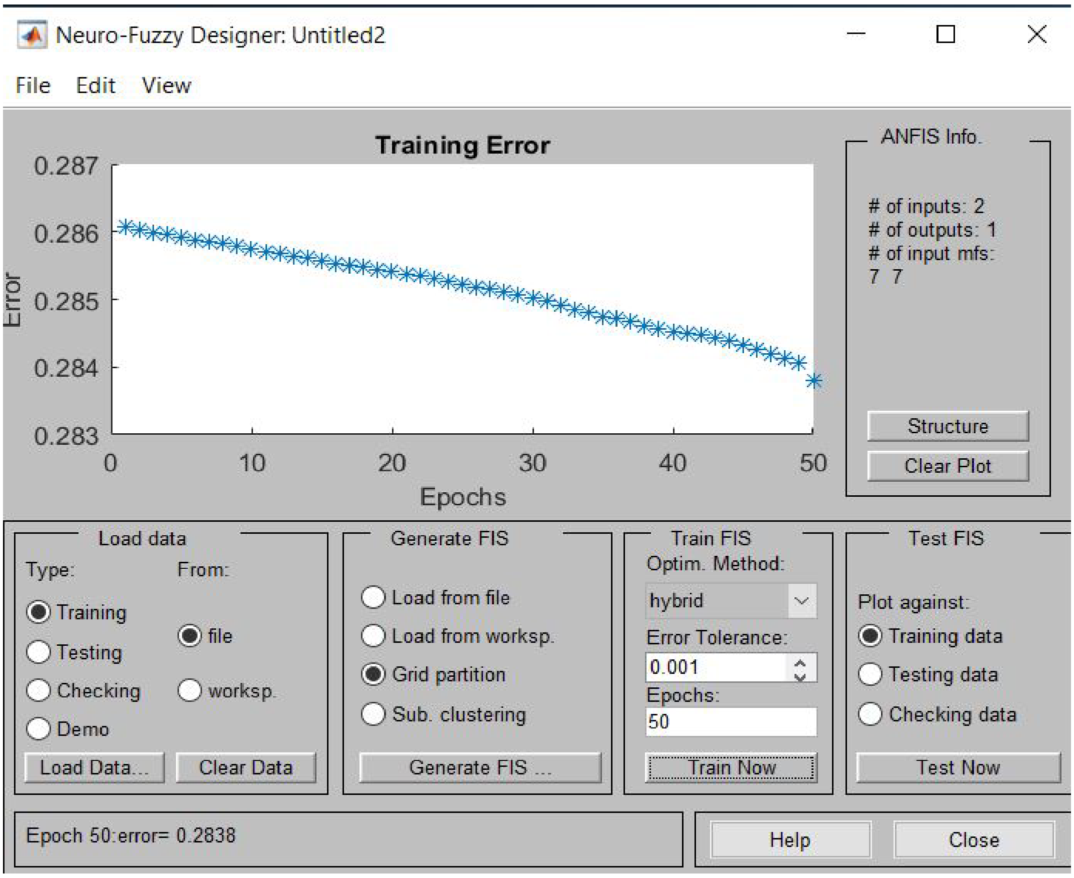

Fig. 13. Training error of ANFIS.

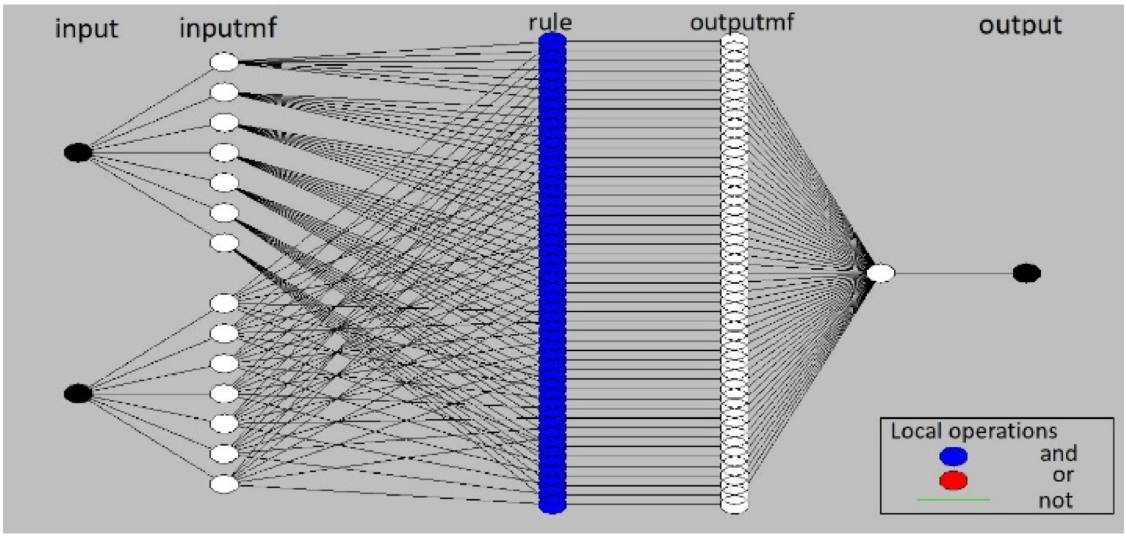

Fig. 14. ANFIS structure showing input(s) and output.

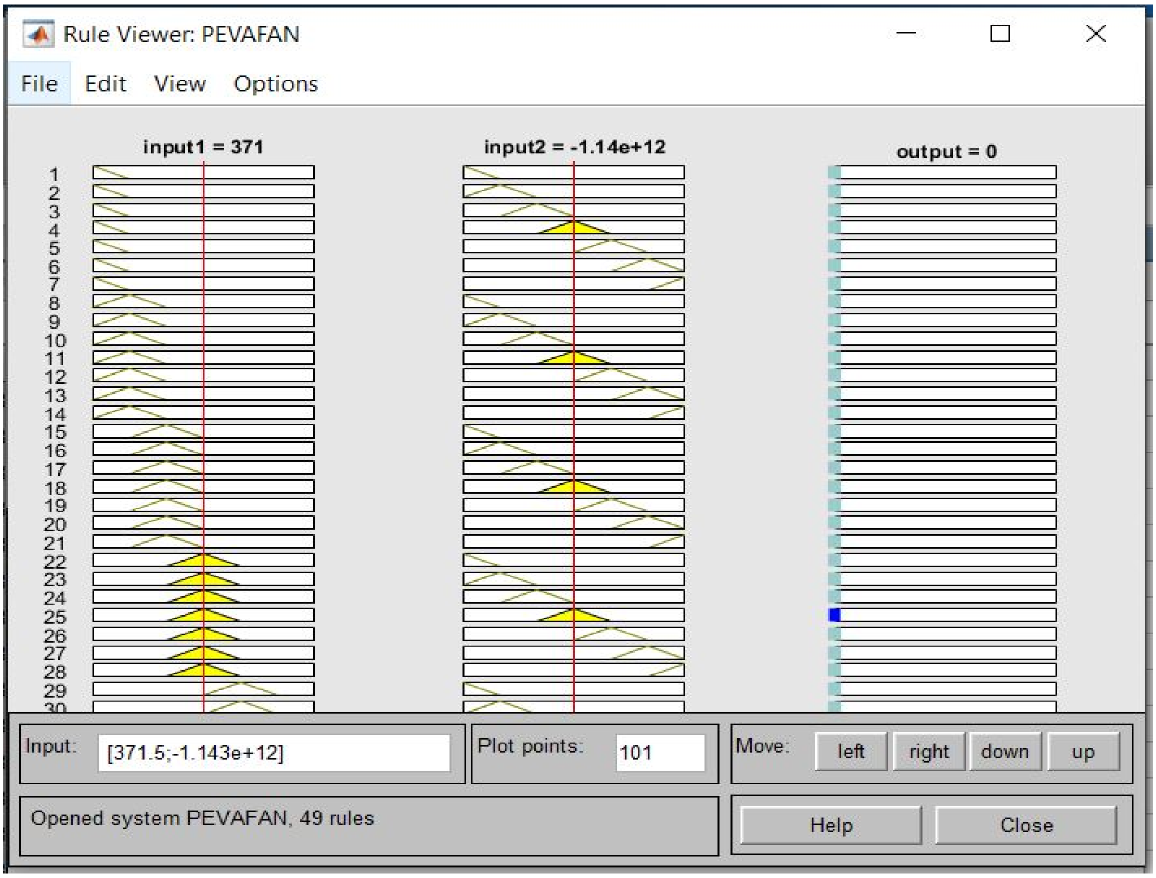

Fig. 15. Rule view of ANFIS.

4. CONTROL STRATEGY

To perform an optimal power flow between the PEV and grid, a control algorithm shown in Figure 16 was necessary. In this work, a very effective control strategy was inherited from [26]. The whole control strategy is well described in [26]. The following equation calculated in the controlled power flow that should be absorbed/injected to the grid from PEV:

$$P_{diff}=P_L-P_R \qquad (10)$$

Where, P_{diff}=absorbed or injected power,
P_L=load power,
P_R=reference load power of considered home.

The following equation given the reference power:

$$P_R = T\sum_{t=1}^{T}(P_L + P_{PEV1} + P_{PEV2}) \qquad (11)$$

Where, T is the connection time of each PEV.

5. SIMULATION RESULTS AND DISCUSSION

To validate the effectiveness of proposed system, a simulation of Duck curve smoothening was carried out. In this study two PEVs were considered. PEV1 had a battery size of 14kWh and for PEV2, it was 11kWh. The PEVs SOC limit was 0.2 to 0.8. So, that the PEV could have better battery life for a longer period than as usual.

Figure 17 shows that PEV1 was connected to the grid during the following periods [0h, 7.30h], [12h, 15h], and [19h, 24h], but it was not connected to the grid during these periods [7.30h, 12h] and [15h, 19h]. In the same figure, PEV2 was connected to the grid during these periods [0h, 11h], [12.30h, 15h], [17h, 21h], [21.30h, 24h] but not connected during these periods [11h, 12.30h], [15h, 17h], [21h, 21.30h]. During their connected period they either could perform G2V or V2G operation according to their demand/capability and the proposed algorithm justified this operation. When they were not connected to the grid in those periods, they were used for traveling.

The total number of PEVs was counted from their connection status at home parking.

"$N=CS_{PEV1} + CS_{PEV2}$"

The working mode 4.2 was available for the time intervals [0 h, 4 h], [6 h, 7:30 h], [12:30 h, 14:30 h], [20 h, 21 h] and [22 h, 24 h]. In mode 4.2, both PEV1 and PEV2 were in the charging phase. Mode 4.1 was activated when discharging was necessary (Figure 14).

Mode 7.2 was activated in the time interval [4 h, 5:15 h] where mode 7.2 was activated in the time interval [18 h, 18:40 h]. The total power exchange was provided by PEV2 that might have "SoC_{min}" or "SoC_{max}" [Figure 14].

During the periods [5:15 h, 6 h] and [18:40 h, 20 h], mode 5.2 was activated and SoC of each PEV was SoC_{max}. Again, in the mode 5.1 both PEVs had SoC_{min}. So, no power exchange was possible in mode 5 [Figure 14].

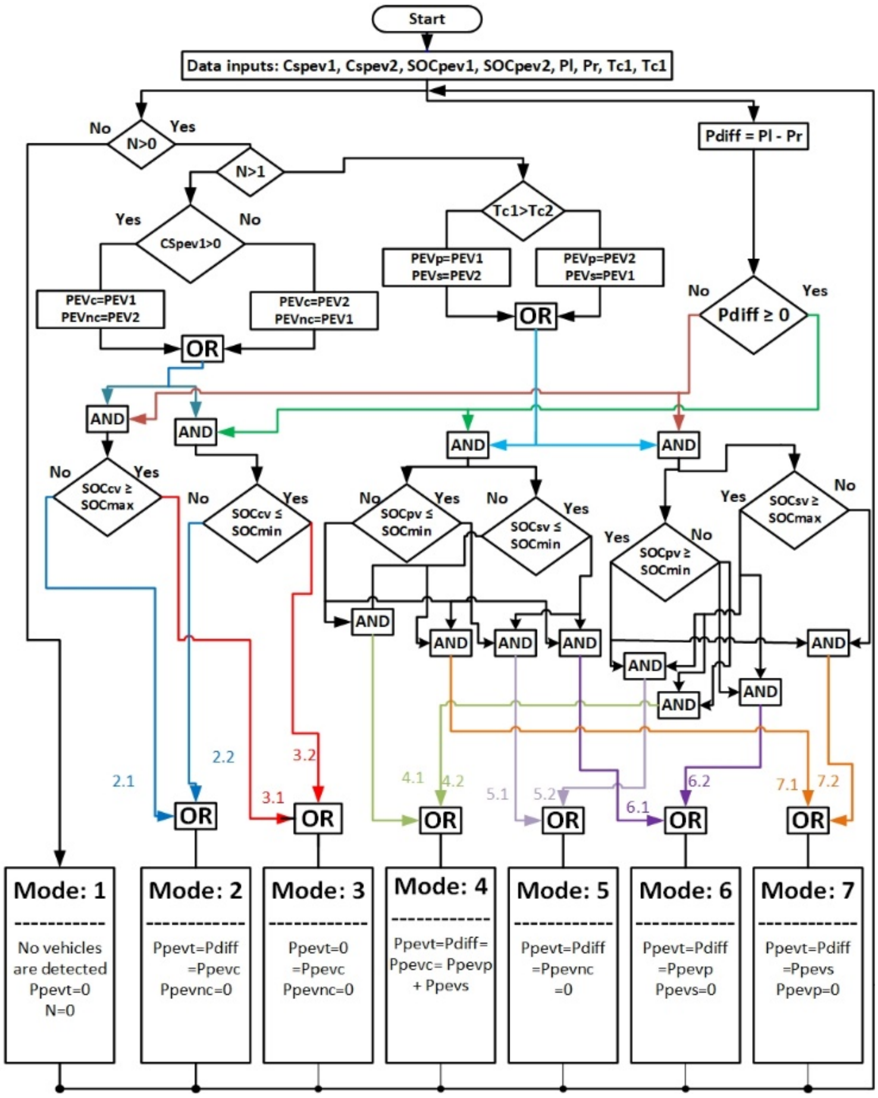

Fig. 16. Adaptive supervision system of PEVs powers [26].

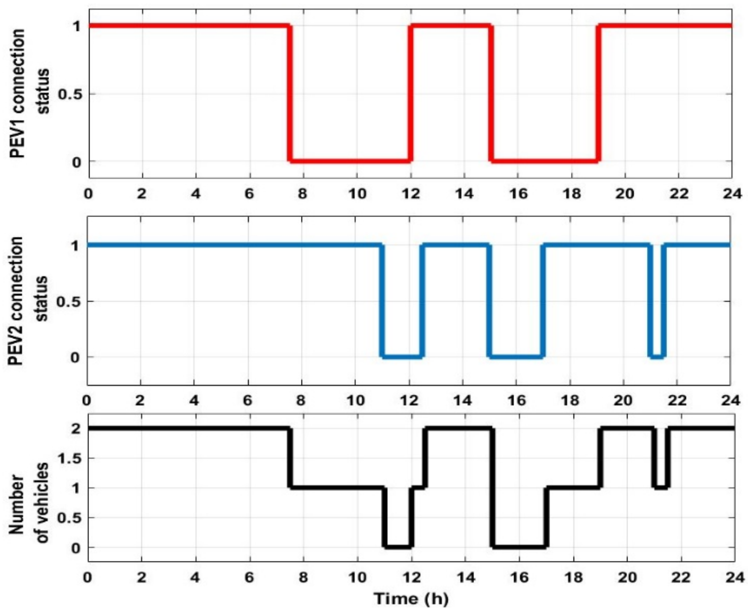

Fig. 17. Various connection states for each PEV.

Mode 2.2 was activated in the intervals [7:30 h, 8:30 h] and [21 h, 21:30 h], where at first interval SoC of PEV2 was at its maximum and at second interval PEV1 was kept charging. Mode 2.1 worked during the time intervals [8:30 h, 10 h] and [12 h, 12:30 h]. In the modes 2.1 and 2.2, both PEVs performed G2V operation. [Figure 14].

Mode 3.1 and 3.2 were detected during the intervals [10, 11 h] and [17, 18 h], respectively. In the first interval, PEV2 was detected with "SoC_{max}" and in the second interval with "SoC_{min}". [Figure 14].

In the time [11, 12 h], and [15, 17 h], mode 1 was detected and no PEV was connected to the grid.

Mode 6.2 worked at [14:30 h, 15 h] and mode 6.1 worked at [21:30 h, 22 h]. In these modes, power exchange was contributed by the priority vehicle (PEV2). [Figure 14].

The comparison of different load power curves is shown in Figure 19. The load curve (pink dotted line) that was converted to the Duck curve (green line) was considerably flattened (red dotted line) by proper load shifting (blue line) and implementing appropriate control strategy for PEV. But some certain periods of duck curve (blue line) could not be flattened due to the unavailability of PEVs.

5.1 Load Factor

Load factor (average-load/peak-load) was a proper way to compare this study's outcome with the work [26]. The average load value was 4985W and peak load value was 5833W. So, the load factor of the work [26] was 4985/5833=0.85. The average load value was 4000W and the peak load value was 3960W. So, the load factor of this study was 3960/4000=0.99. A higher load factor is better because of the higher utilization of resources. Different value of load data and load factor are shown in Table 4.

5.2 Cost savings by a consumer

By controlled charging of PEVs and load shifting, the consumer was benefitted financially. Table 5 shows the cost of controlled/uncontrolled charging of PEV and load shifting on a daily and annual basis. This table it is clearly shows that by controlled charging of PEV and proper load shifting, a single house could save 22728.23Tk. per annum compared to the existing flat tariff and 29442.07Tk. per annum compared to existing peak and off-peak tariff. So, these cost savings encouraged the consumers to flatten the Duck (load) curve.

Table 4. Different values for load factor.

Parameters	Average load (W)	Peak load (W)	Load factor	Load factor improved (%)
[26]	4985	5833	0.85	16.47
Proposed method	3960	4000	0.99	

Table 5. Cost comparison for the different tariffs.

Parameters (Electricity cost)	Daily cost (Tk.)	Annual cost (Tk.)	Total cost savings per annum (Tk.)
Part 1. Uncontrolled charging of PEV before load shifting with existing flat tariff	653.84	238650.02	22728.23 (comparing part 3 with part 1)
Part 2. Uncontrolled charging of PEV before load shifting with the existing peak and off-peak tariff	672.23	245363.86	29442.07 (comparing part 3 with part 2)
Part 3. Controlled charging of PEV after load shifting with proposed tariff	619.51	215921.79	

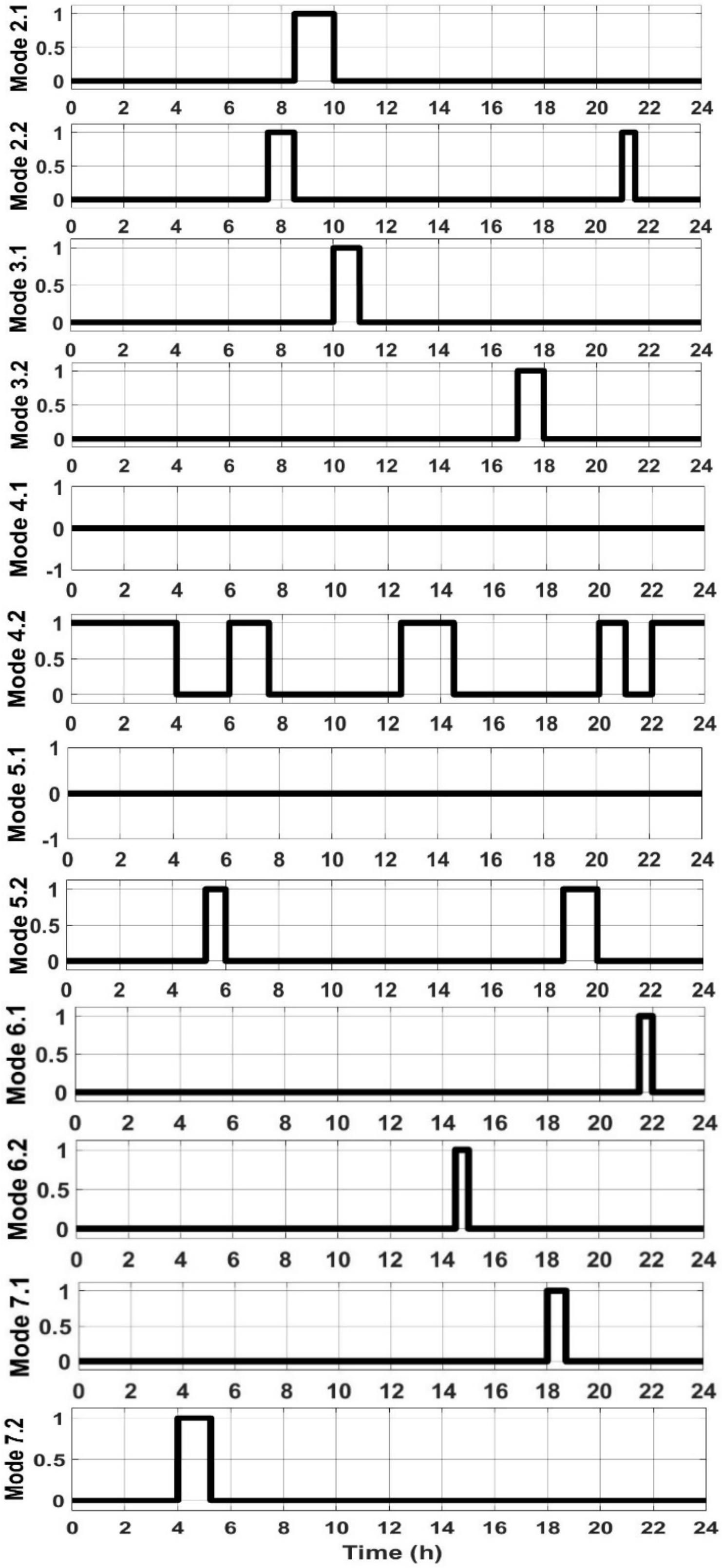

Fig. 18. Different modes with active hours.

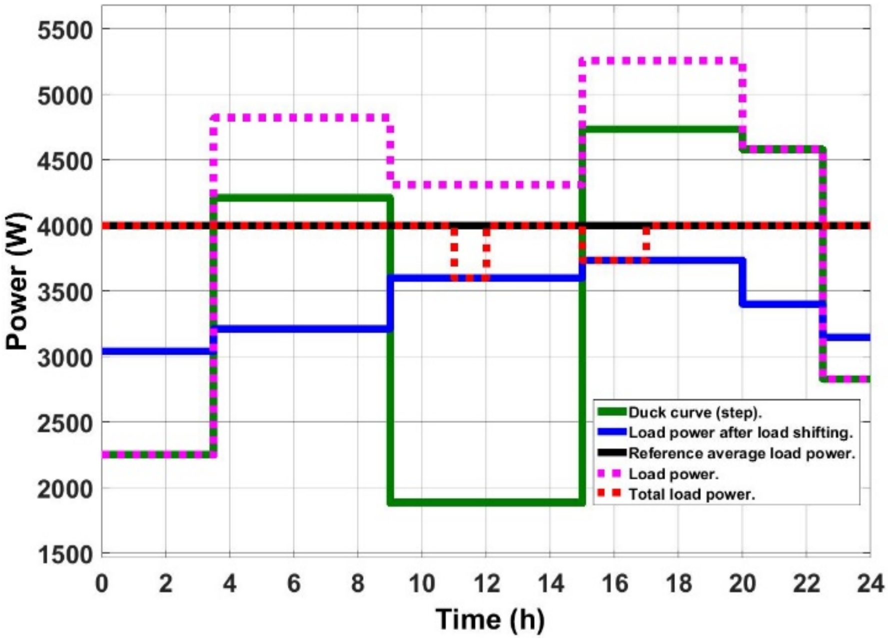

Fig. 19. Comparison of load power curves.

Table 6. Different results of THD using different controller.

Parameter's Name	THD (%) at T=10	THD Improvement (%)	THD (%) at T=15	THD Improvement (%)
PI controller [26]	27.81	18.27	28.67	26.75
ANFIS controller	22.73		21.00	

5.3 Total Harmonic Distortion (THD)

In this study, the ANFIS controller was used instead of the conventional PI controller and found that total harmonic distortion (THD) was improved too. THD of this study was a byproduct parameter.

Table 6 above informs the calculation of THD for both periods and it was clearly seen that harmonics were much improved by replacing PI controller with the ANFIS controller.

6. CONCLUSION

In this study, we anticipate a likely technical problem in Bangladesh with solar rooftop penetration. It can be shown by shape of the load curve assuming the shape of a duck curve. The solution methods both in supply side and in demand side were discussed in the perspective of Dhaka city (capital of Bangladesh). A proper load shifting and a flexible control strategy of two PEVs were used as example to sort out the duck curve problem. Proper load shifting was possible by considering ToU based electricity pricing. Segregation of load power into six periods of time within 24 hours gave a better opportunity to shift the necessary shift-able loads from peak hours to off-peak hours. This considerably flatten the load profile. However, to utilize the energy and resources completely, an energy storing device was important. In this regard, existing PEVs used by the consumers were considered as a good storing device. So, in case of charging and discharging the PEVs, a flexible control strategy with seven operating modes was investigated in this study. This control strategy ensured the bi-directional flow of power between the PEVs and the grid, and the power management was measured by ANFIS controller. The regulated charging of PEVs and required power injection into the grid were made possible by both control strategy and ANFIS controller to avoid the huge energy consumptions during the peak hours. Different simulation results justified the whole procedure. Finally, the combination of proper load shifting with ToU based tariff and regulated charging of PEVs considerably flatten the Duck curve as expected.

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Using Plasmonic Metal Nanoparticles to Enhance Solar Cell Efficiency – Bangladesh Making Significant Progress in Renewable Energy Technology

S. M. Nayeem Arefin*, Shahriar Islam*, Jawad Hasan*, Mustafa Mohammad Shaky*, Fatema Fairooz* and Mustafa Habib Chowdhury*,[1]

Abstract *–The booming economy of Bangladesh in recent times has created a significant need for energy. Consequently, the increasing demand for power generation has led Bangladesh to become more reliant on fossil fuels. This paper highlights the current situation of the power sector in Bangladesh, proposes practical steps that can be taken to tackle the increasing energy demands and discusses the current state of research taking place in Bangladesh regarding the development of photovoltaic solar cells and the potential for thin-film solar cells to effectively harness solar energy. The use of different kinds of plasmonic metal nanoparticles (NPs) such as core-shell NPs, NP dimers made of metallic alloys and hybrid bow-tie shaped NPs with thin-film solar cells are discussed. These nanoparticles are found to significantly improve the efficiency of thin-film solar cells. The societal, environmental, and health impact of shifting from traditional fossil fuel-based energy resources towards harnessing renewable energy, primarily solar energy using thin-film solar cells is also discussed. The paper concludes with a discussion on the economic sustainability of using such proposed high efficiency thin-film solar cells so that such technologies may help lead Bangladesh towards a cleaner, greener and more secure future.*

Keywords *– Bangladesh, plasmonics, renewable energy, solar cells, thin-film solar cells.*

1. INTRODUCTION

Bangladesh has recently emerged as a country with a thriving economy with one of the highest gross domestic product (GDP) growth in 2019 [1]. It is expected that this growth will continue and so the demand of power will increase exponentially. Unfortunately, Bangladesh is still predominantly dependent on fossil fuels to produce electricity. This dependency will create major problems as the natural gas reserve in Bangladesh is estimated to dry out by 2026, as reported by British Petroleum (BP) [2] and the severe impact on the environment of the fossil fuel will make the situation even more difficult.

Solar energy harnessed by photo-voltaic (PV) devices has the potential to address the problem as it provides a greener alternative to the traditional fossil fuels and its cost can be compensated over an extended period of time as it requires almost no cost after installation. Solar energy is abundant in nature and Bangladesh is particularly blessed with a suitable geographic location to harness solar energy for energy applications in large industrial scales [3].

However, two of the major challenges of current photovoltaic (PV) technology is the relatively high cost of production, installation and the relatively low energy conversion efficiency of PV devices such as solar cells. Commercially available solar cells have an efficiency that is less than 30% [4]. It is absolutely crucial to reduce the cost of the solar cell and increase solar cell efficiency in order to have large scale implantation in Bangladesh. It is observed that a significant portion of the cost of a solar cell made of crystalline silicon (Si) is the material cost of Si itself as it comprises almost 40% of the total cost of a solar cell [5]. Thin-film solar cells (TFSC) have the potential to reduce this cost significantly as it uses a very thin layer of Si (not more than 3 μm) compared to 1st generation solar cells (substrate thickness around 180 μm) and thus saves a lot of the expensive bulk material [6]. However, this reduction of material also reduces the volume of the absorbing layer and thus the efficiency (*i.e.*, electricity generation capacity) is also reduced. To increase the light absorption and current generation efficiency of TFSCs, different light trapping technologies such as anti-reflection coating, surface texturing *etc.* have been studied [7]. Among them, the usage of various metallic nanoparticles (NPs) has shown favorable results in increasing the opto-electronic performance of solar cells through harnessing the unique phenomenon of surface plasmon resonance (SPR) [8]. These metal NPs (*e.g.*, silver, gold, aluminum, copper, *etc.*) are characterized by localized surface plasmon resonance (LSPR) modes that come into play when these nanostructures are excited by sunlight (*i.e.*, stimulated by an incident electromagnetic radiation). This leads to increased light absorption and scattering by such metal NPs (called plasmonic metal NPs) at certain resonant frequencies (or wavelengths) [9], [10]. These plasmonic metal NPs can be coupled to solar cells to increase the light absorption and current generation efficiency of such "plasmonic" solar cells [10], [11].

Along with homogenous metallic NPs, various hybrid NP systems have shown promising results in significantly increasing solar cell performance [12]-[14].

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Recent studies highlight a number of such hybrid nanostructures that include: (i) NPs consisting of a plasmonic metal core that is surrounded by a thin dielectric/insulating shell layer; (ii) single or multiple "plasmonically coupled" metal NPs made up of alloys of different plasmonic metals; (iii) hybrid bow-tie shaped NPs that can be used to confine light into a small region on the surface of the solar cells where spherical metal NPs can be selectively placed to significantly enhance the TFSC performance. All these techniques contribute to significantly improve light absorption and current generation efficiency of the solar cell. Thus such "plasmonic solar cells" with a higher current conversion efficiency can lead to fewer solar cells needed to produce a specified amount of electricity, and thus potentially significantly reducing the price and increasing the accessibility of the "green energy" in developing nations like Bangladesh.

2. PRESENT SITUATION AND PROSPECT OF SOLAR ENERGY IN BANGLADESH

2.1 Current State of the Power Sector and Solar Energy Potential of Bangladesh

The majority of electrical power generated is through the use of non-renewable energy sources like natural gas and other fossil fuels. With the rising energy requirement than ever before, as Bangladesh strives towards her development goals by opening new industries in different sectors, providing a reliable electrical energy supply is of the utmost priority. It is of critical importance to highlight, analyze, and predict the current trends of electrical energy generation in Bangladesh. Figure 1 highlights the current electric energy generation capacity sorted using different types of resources from 2018-19 [15]. From Figure 1, it can be clearly observed that the overwhelming generation of electricity depends on the use of non-renewable energy sources (92.51%) and renewable energy generation makes up a very small percentage (1.37%) in the total generation capacity. For the year of 2019 in Bangladesh, electrical generation capacity using gas as the fuel accounted for 57.36% (10877 MW) of the total installed generation capacity followed by oil (furnace oil and diesel) with a percentage of 32.239% (6140 MW), imported power with 6.12% (1160 MW), coal with 2.76% (524 MW), hydro with 1.21% (230 MW) and lastly solar PV which only accounted for 0.16% (30 MW) of total generation capacity [15]. The current annual production of gas in Bangladesh is at 0.97 Tcf (trillion cubic feet) (2018) with 11.47 Tcf of reserves remaining [16]. Considering the yearly growth and production rate, natural gas reserves in Bangladesh will last up to 2026 [17]. In order to tackle this problem, coal generation power plants are expected to play a key role in power generation in Bangladesh [18]. This can bring about adverse effects on the environment, and decrease the already low air quality in the country. In 2019, Dhaka city has repeatedly been ranked as the city with the worst air quality, with an air quality index (AQI) score ranging from 242 to 252 [19].

The geographical location of Bangladesh gives it a distinctive advantage if PV solar cells can be used to harness solar energy for electricity generation. This is because Bangladesh has roughly 300 days a year with an average of 7 to 10 daylight hours with an average Global Horizontal Irradiance of 5 kWh/m^2 in these days [22]. A study conducted estimates that the total grid-connected solar PV potential in Bangladesh could be up to 50 GW [20], which is many folds above the current and even future energy demands of Bangladesh. Hence, among the different forms of renewable energy sources available, solar energy has the highest potential and feasibility for energy production in Bangladesh and can potentially replace fossil fuels in the future to meet the country's energy demands.

Currently, PV solar cells account for a very small percentage in generation capacity for the national supply grid in Bangladesh (0.16%) [15]. However, there has been a growing market for PV cells in the form of microgrids. Despite the relatively high cost of PV solar cells, it has successfully been adopted for generating electricity in rural areas. These rural PV solar systems are also referred to as microgrids (small electrical grids to supply electricity in places where the national grid cannot reach). Rural areas in Bangladesh and most other developing (or third-world countries) still lack access to reliable electricity which impedes socio-economic development and growth in these areas [21].

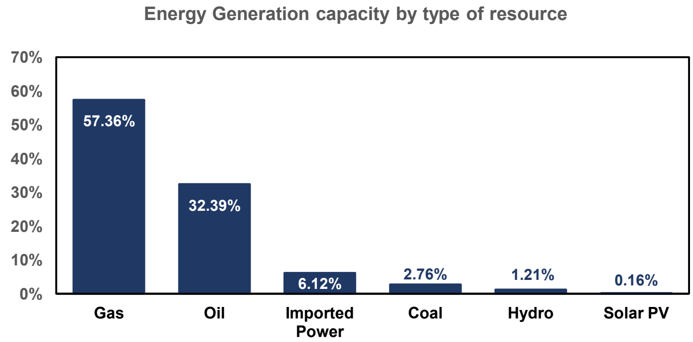

Fig. 1. Energy generation capacity of Bangladesh in 2018-2019 by type of resource [15].

2.2 Current Research and Development Work on Solar-Cells in Bangladesh

Significant efforts have been made in theoretical and practical research and development (R&D) work based on PV cells and solar energy in Bangladesh. A significant portion of these works directed their focus on the development of rural electrification, local transportations, *etc.* Research groups also focused their study on the improvements of PV cells and modules, which will help people both in Bangladesh and globally. Improvements of critical modes (oscillatory stability) within the power system can be achieved via the integration of PV systems to the current power system [23]. Additionally, replacing the existing grid with a smart grid with PV integration can minimize the power shortage problem in Bangladesh [24]. Unlike the conventional solar tracking algorithms and techniques, Ahmed and Rony (2014) suggested a sensor-less and simple mathematical algorithm that uses linear quantization techniques to derive the sun's optimal azimuth and altitude that can be used to track the sun [25]. Similar work has been done to determine the optimum angle for maximum incident power under the climatic conditions of Bangladesh [26]. Later, an idea of using reflectors (fixed directed mirrors or aluminum foils) to concentrate sunlight onto PV panels was proposed by Ahmed *et al.* (2014), so that each of the panels receives more power individually [27]. Furthermore, Hasan *et al.* (2018) propound the use of proton exchange membrane fuel cell (PEMFC) with an upgraded PV system to solve black out problems in base transceiver station (BTS) at telecom sites in Bangladesh [28].

The use of plasmonic NPs to enhance the performance of TFSCs has also gained traction in Bangladesh over the last few years. Works have been done towards increasing the opto-electronic performance of TFSCs using various NPs (Ti and Pt) placed on top of an ARC (anti-reflection coating) or spacer layer (TiO_2) [29]. The use of textured surfaces like back reflectors, ring shaped apertures and gratings have been investigated to explore their light trapping and guiding properties [30], [31]. The possibility of integrating plasmonic nanostructures (Au and Ag) of various shapes with organic solar cells has also shown potential towards increased light absorption compared to basic organic solar cells [32].

2.3 Current Thin-film Solar Cell (TFSC) Technologies

Research has been conducted on various methods through which the opto-electronic performance of thin-film solar cells can be increased, namely, utilizing a metal layer to create a reflective surface on the back surface of the solar cell, employing nano-pyramidal surface textures on the front and back of the solar cell, and using plasmonic metal NPs [10], [33], [34]. The difference in refractive index between silicon and air is very high which leads to the reflection of a significant portion of the incident radiation from the interface of the two mediums (silicon and air), which is known as strong Fresnel reflectivity [35], [36]. To reduce this phenomenon, the use of anti-reflection coatings (ARC) on thin-film solar cells have been proposed [37]. While these ARCs improve the performance of thin-film solar cells, their fabrication is complex and costly due to the expensive equipment involved and the precise control that is required during synthesis, thereby increasing the cost of fabrication substantially [38]. Attempts have been made towards increasing the opto-electronic performance of solar cells using nanostructures like nanopillars, which reduces the Fresnel reflectivity by acting as an additional medium between air and the substrate [39]. But this method leads to an increase in surface recombination and a reduction in the amount of charge carries which ultimately contributes to less current generation [38]. Approaches towards employing surface textures like surface grating has been reported to aid in increasing the optical absorption of solar cells. However, these surface textures are usually fabricated on the micron scale (10-15 microns in thickness) which is considerably large when comparing with the thickness of TFSC and is therefore not suitable for use in 2nd generation TFSC [40]. Furthermore, surface texturing using NPs with high aspect-ratio results in higher surface defects thus increasing the chances of recombination of electron-hole pairs [41].

2.4 Plasmonic Thin-film Solar Cells (TFSCs)

A promising method of increasing the performance of TFSCs is using the LSPR property exhibited by plasmonic metal NPs when incident electromagnetic radiation (*e.g.*, sunlight) matching the plasmon resonance wavelength excites the metal NPs [42]. This research group has conducted extensive computational studies based on Finite-Difference Time-Domain (FDTD) simulations of the effect of using different plasmonic metal NPs and nanostructures to enhance the opto-electronic performance of thin film "amorphous Silicon" (a-Si) solar cells [9]-[13]. The results from these studies showed that TFSCs coated with a layer of homogenous metal NPs exhibit increases in the absorption of light into the solar cell substrate and subsequently results in higher photocurrent generation. It was also shown that the extent of light absorption into the solar cell substrate was influenced by the size and shape of the plasmonic metal NPs [10], [11]. The next sections outline some of the recent research that was conducted by this research group investigating the use of different plasmonic hybrid/multi-particle NP structures such as core-shell NPs, plasmonic NPs made of alloys of different metals and hybrid bow-tie shaped NPs to increase the performance of TFSCs.

3. PLASMONIC NANOSTRUCTURES AND CONFIGURATIONS

3.1 Simulation Setup and Parameters

Commercial grade simulation software such as FDTD Solutions and DEVICE developed by the Lumerical Inc. were used by this research group to perform the simulations with the following configurations and parameters:

Optical Absorption Enhancement Factor (g): Optical Absorption enhancement factor is the ratio of the power absorbed by Si TFSCs with the presence of the different types of plamonic NP and the power absorbed by Si TFSCs without any NP [12]. This unitless ratio gives an idea of how much more or less light is absorbed by the absorbing layer of the solar cell due to the effect of the plasmonic NPs. In the simulations, two detectors (power and field monitors) were placed at two different locations in the absorbing substrate of the solar cell, and the difference of the power recorded between the two detectors was used as the power of the light absorbed in the TFSC. Industry standard test conditions (STC) like temperature (300K) and air mass coefficient (AM 1.5G) were maintained for all simulations.

Short circuit current density (J_{SC} in A/m^2): Short circuit current density gives the idea about how much electricity is produced within a specific region of a solar cell and is calculated as discussed previously [12]-[14].

Open circuit Voltage (V_{oc} in volts): The open circuit voltage was determined to calculate the normalized open circuit voltage and output power of the solar cell and is calculated as discussed previously [12]-[14].

Fill factor (unitless): The fill factor (FF) determines the maximum output power capacity of a photovoltaic cell and as such is used to calculate the output power of a photovoltaic cell. It is the ratio of the power at maximum power point by the product of short-circuit current (J_{SC}) and open circuit voltage (V_{oc}).

Analysis of Electromagnetic Near Fields (NF): The near-field enhancement is the ratio of the electro-magnetic (EM) field distribution in a TFSC in the presence of the plasmonic NP and in a TFSC without the presence of the plasmonic NP [12]-[14]. It is a pictorial representation of the enhancement of the EM field in the vicinity of the plasmonic NP when incorporated in the TFSC.

3.2 Studies of plasmonic core-shell nanoparticles in TFSCs

Apart from homogenous plasmonic NPs (made of a single metal), various composite plasmonic NPs (made of two or more materials) such as core-shell NPs (where the core is the inner material and shell is outer layer material) has shown promising results in improving TFSC performance. From the early 90s, researchers have started to synthesize multilayer NPs to improve and tune their optical and chemical properties based on different applications. Subsequently these NP got coined into the term of ‘core-shell’ [43], [44]. Core-shell NPs have some distinctive advantage due to the nature of their composition. Figure 2 shows a composition of core-shell NP where the core is made of metal and shell is made of a dielectric (insulating) material.

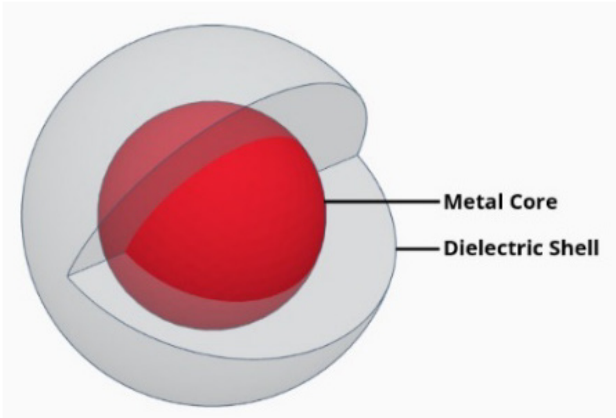

Fig. 2. Meta core-dielectric shell nanoparticle composition.

3.2.1 Advantages of using core-shell NP in photovoltaic applications

For PV applications, metal core and dielectric shell NPs are particularly suitable due to its metal-dielectric interface which can support surface plasmon resonance (SPR) even when embedded inside the light absorbing substrate of the solar cell [9]. So, with core-shell (metal core and dielectric shell) NPs, the particles can be placed on the top as well as inside of the absorbing substrate. Moreover, the dielectric shell can provide much needed chemical and electrical isolation which is crucial for the stability of the NPs as the metallic NPs show the tendency to get oxidized easily [12]. Additionally, by changing the material (*i.e.*, metal), size of the core, thickness of the shell layer, and shape of the particle, the amount of light absorbed and scattered by these plasmonic metal NPs can be tuned as well as the wavelength of the plasmon resonance peak. The high permittivity of the shell provides electrical isolation which is particularly helpful for the metallic core to avoid becoming a new center of electron-hole recombination while still providing LSPR [45]. Furthermore, a new configuration was proposed namely ‘sandwich configuration’ that comprises both homogenous and core-shell NPs where the core-shell NP is embedded inside the absorbing substrate and a homogenous metallic NP is placed on the top of the substrate, as shown in Figure 3 [12]. It is observed that this particular configuration can significantly increase the performance of the TFSC.

3.2.2 Results and Analysis of Using Core-Shell NP

Figure 4 shows the optical absorption enhancement (g) and short-circuit current density (J_{sc}) comparison between different nanostructure configurations with respect to that of a bare silicon substrate. The percentage increases outlined in Figure 4 are all done with respect to the bare silicon substrate (traditional solar cells that contains no plasmonic NPs). The inset outlines the two parameters considered. It can be seen that highest optical absorption enhancement (g) (42.30%) and J_{sc} (36.33%) is observed for sandwich configuration. This percentage increase corresponds to a g value of 213.45 and a J_{sc} value of 9.321 mA/cm^2, when compared to that of a bare Si substrate with no plasmonic NPs (g=150, J_{sc}=6.837 mA/cm^2) [12]. The percentage increase of other performance parameters such as V_{oc} (0.66%), FF (0.14%) and efficiency (36.4%) were also found to be the highest for sandwich configuration, when compared to the bare Si substrate [12]. This means 42.30% more light will be absorbed by the Si absorbing layer and 36.33% more current will be produced and 0.66% greater open-circuit voltage difference will be generated resulting in 0.14% increase in the FF, which ultimately translates to a 36.4% increase in efficiency exhibited by the Si solar cell embedded with the sandwich configuration of the NPs in comparison with bare Si solar cell. This can lead to potential overall improvements in the opto-electronic performance of the solar cell. It is to be noted that the efficiency values presented are percentage increase in efficiency of the different plasmonic metal NP coupled Si solar cells when compared to a bare Si solar cell. This might not reflect the true efficiency of any real device because the p-n junction, doping concentration and contacts were not considered in the simulations.

Figure 5 shows the optical near-field enhancement image for the “sandwich” configuration of the core-shell NP embedded inside the Si absorbing layer and the homogeneous NP on top of the Si absorbing layer of a TFSC. It is seen that strong EM field enhancement is occurring in the vicinity of NP on the top and also the core-shell NP inside the substrate as seen by the substantial regions in yellow and red colour that represents EM field enhancements of well over 10-fold compared to a bare Si substrate.

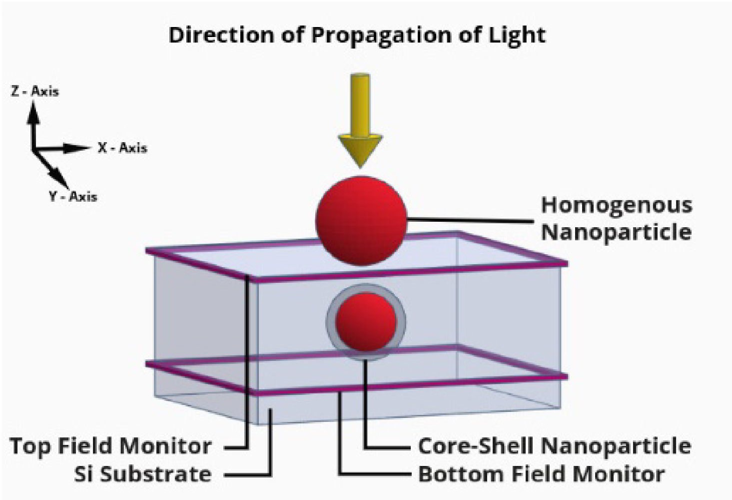

Fig. 3. Simulation setup showing frequency domain field and power monitor placements for “sandwich” configuration of homogenous NP and core-shell NP coupled to a solar cell.

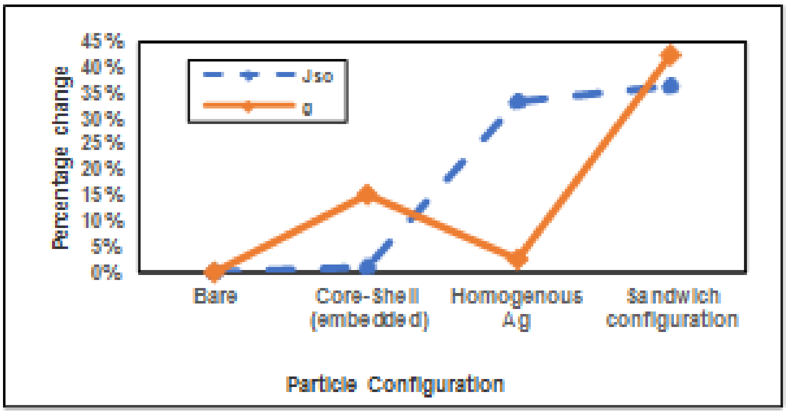

Fig. 4. Optical absorption enhancement (g) and short-circuit current density (J_{sc}) comparison between different nanostructure configurations with respect to that of bare Silicon substrate [12].

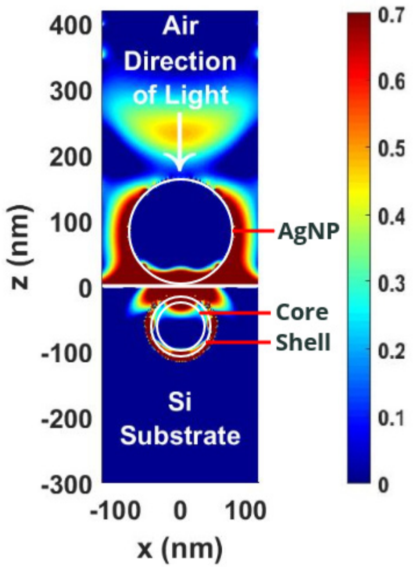

Fig. 5. Optical nearfield enhancement as a result of incorporating homogenous plasmonic NP on top of the substrate and a plasmonic core-shell NP embedded inside the substrate, in "sandwich" configuration.

3.3 Studies of Plasmonic Alloy Bimetallic Nanoparticles in TFSCs

The second set of recent investigations conducted by this research group includes FDTD simulation studies by placement of two plasmonic NPs placed side by side with a clearly defined inter-particle spacing whereby the material of the NP is composed of either an alloy (comprising a mixture of more than one kind of metal) or a homogeneous metal. These two metal NPs are placed on top of a Si absorbing layer of a TFSC as shown in Figure 6. A hybrid bimetallic NP system represents two metallic NPs considered as a single entity [46]. Alloys are created when two or more different metals are combined to form a new material by independently varying the composition of each metal in the alloy [47].

3.3.1 Motivation of alloy bimetallic for solar cell application

The justification for using alloy NPs was to be able to harness the favourable optical and chemical properties of different plasmonic metals within one NP and thus utilize a broader section of the solar irradiance spectrum to enhance the performance of TFSCs [14]. In some instances, two different metallic NPs (of either alloys of single metal) were placed next to each other to better harness multiple wavelengths of the solar spectrum as well as attaining the most stable condition in terms of chemical reactivity and optimized optical properties. It is well known that plasmonic coupling can occur efficiently between neighbouring metal NPs thus leading to strong optical absorbing properties. Varying the combination of metal, composition of each metal in a NP, interparticle distance between metals in bimetallic entity showed that multiple regions of the solar irradiance spectrum has been utilized which were previously not possible and significant enhancements were observed in the Si TFSCs modified by such bimetallic hybrid NPs systems [14].

3.3.2 Results and analysis of using alloy bimetallic NPs with Solar Cells

The graphical representation in Figure 7 shows the percentage change for optical absorption enhancement (g) and short-circuit current density (J_{sc}) for different NP configurations that were incorporated on top of the Si absorbing layer of TFSCs. From the simulation results plotted in Figure 7, it can be observed that an alloy bimetallic NP configuration comprised of two alloy NPs in close proximity where each of the alloy NPs consist of Gold (Au) -the inert metal, with composition of 10% mass and Aluminium (Al) –chemically instable yet with excellent optical properties, with composition of 90% mass. There is a significant change in g (17%) and J_{sc} (25%) for single alloy NP in comparison to bare Si configuration. The alloy-alloy bimetallic/ dimer NP system when coupled to the Si absorbing layer of a TFSC showed the maximum increase in the values for g (22%) and J_{sc} (51%) in comparison to bare and single alloy configuration [14]. A similar trend is also observed for V_{oc} (0.43%), FF (0.09% increase) and efficiency (53% increase). This significant percentage change is observed when two alloy NPs are placed in the bimetallic/dimer configuration due to the plasmonic hybridization [14].

3.4 Studies of Bow-tie Hybrid Nanoparticles in TFSCs

In order to observe and improve the optoelectronic performance of the thin-film silicon (Si) photovoltaic cells, recently this research group performed computational studies on the use of different configurations of hybrid bowtie-based plasmonic metallic nanostructures [48], [13]. Figure 8 shows the

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bow-tie configuration where the hybrid nanostructures were designed with two triangular cross-sectioned pyramidal nanostructures (equilateral triangle cross-section in x-y plane) and one spherical NP in such a way that both of the triangular NPs were facing each other with one of the apex of their vertices and a spherical NP placed in between. These nanostructures were studied by varying the side lengths and pitch sizes of the triangular NPs, while keeping their height of the triangular NPs and the diameter of the spherical NPs constant.

The main goal of this study was to design pyramidal NPs that can concentrate a significant portion of the incident light (*e.g.*, sunlight) between their apex points (like a magnifying glass concentrating sunlight at a specific point on a paper). The design involved placing a single spherical NP at the point where the light from the sun was concentrated by the triangular NPs. This is done to expose the spherical NP to a maximum amount of incident light (both the direct light hitting the spherical NP and the light concentrated by the triangular NPs). When there is significant spectral overlap between the plasmon resonance of the spherical NP and the scattering resonance of the pyramidal NPs, a high concentration of the incident light occurs in and around the hybrid NPs which can then be plasmonically coupled to the absorbing (Si) substrate of the TFSC below. Increased absorption of this incident light by the absorbing Si substrates can lead to increased electron-hole pair production in the absorbing layer.

These studies involved designing hybrid plasmonic nanocomplexes comprised of: (i) two Al triangular and one Ag spherical NPs, which was named Al-Ag-Al nanocomplex and secondly, (ii) two Ag triangular and one Au spherical NPs, which was named Ag-Au-Ag nanocomplex. The idea was to match/overlap the maximum scattering intensity of the plasmonic triangular NPs with the plasmon resonance (extinction spectra) of the plasmonic spherical NPs that are placed in between the triangular NPs [13]. Figure 9 highlights the percentage increase in J_{SC} values of different NP configuration obtained from FDTD simulations. The results from the graph show that these hybrid bowtie-based plasmonic nanostructures coupled to Si substrate show superior performance in the light coupling efficiency and electrical current generation within the Si absorbing layer of the TFSCs when compared to the bare Si substrate and Si substrate coupled to only spherical NPs[13], [48]. Among the two bowtie nanocomplexes considered, the superior results were obtained with Al-Ag-Al nanocomplex in J_{SC} (5.81% increase), V_{OC} (4.53% increase), FF (0.87% increase), and efficiency (11.58% increase).

It is to be noted that the recent plasmonic solar cell research of this research group described above are simulation results, and steps are being taken to practically implement such “plasmonic solar cells” for testing. It is expected that fabrication of such plasmonic solar cells will not pose a major technological challenge due to the advanced stage of fabrication technology of Si due to its widespread use in the electronics industry. In general, wet chemistry method can be used to manufacture metallic NPs while Stöber process has been shown to be capable of synthesizing dielectric shell layers [49]. The NPs can be embedded by depositing a silver film through thermal evaporation, followed by thermal annealing in nitrogen to create NPs, while the substrate layers (above and below the NPs) can be created through plasma enhanced chemical vapor deposition [50].

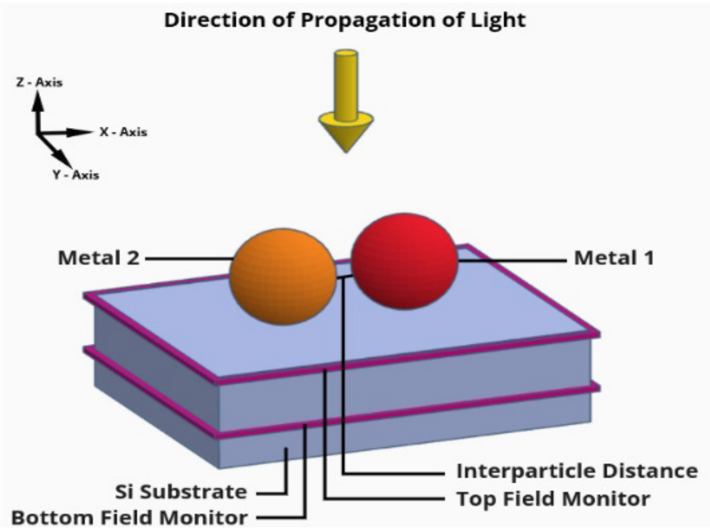

Fig. 6. Simulation schematic showing the plasmonic alloy bimetallic nanoparticle configuration.

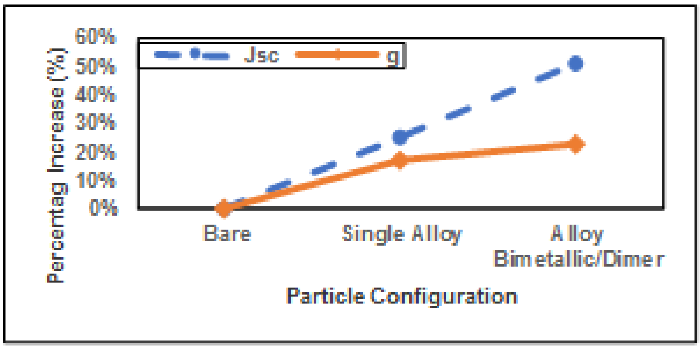

Fig. 7. Percentage change comparison for optical absorption enhancement factor (g) and short circuit current density (J_{sc}) for different nanoparticle configurations [14].

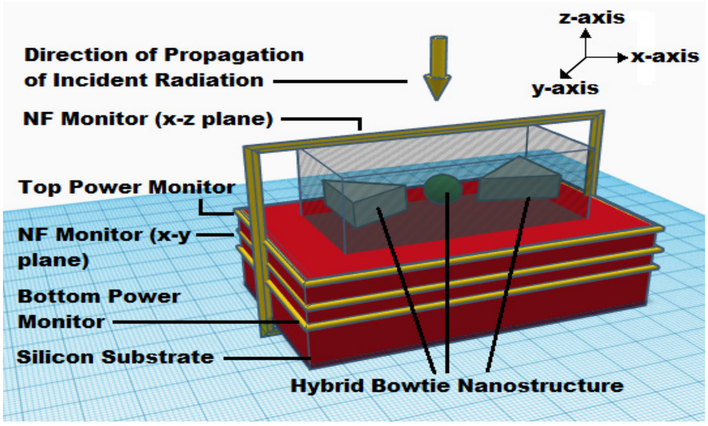

Fig. 8. Simulation setup for optical absorption enhancement and near-field analysis of the bow-tie hybrid nanostructure.

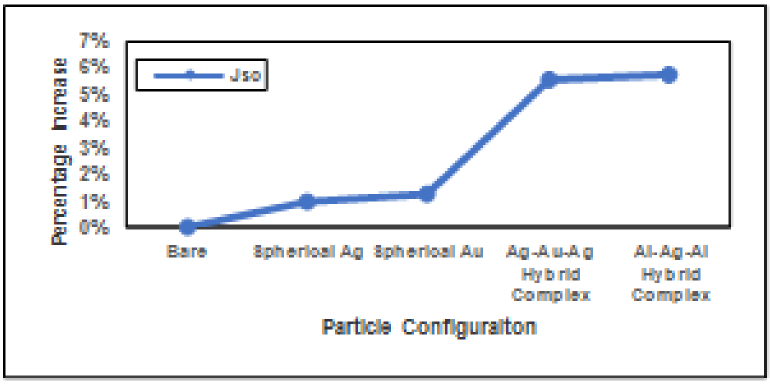

Fig. 9. Percentage change comparison for short-circuit current density (J_{sc}) for different nanoparticle configurations [13].

4. IMPACT OF HIGHER EFFICIENCY THIN-FILM SOLAR CELLS ON SOCIEY, HEALTH AND CULTURE IN BANGLADESH

The continuous rise in the quantity of greenhouse gases (GHG) have led to an increase in the Earth's average temperature, the rise of sea-levels and is causing global climate change. A significant source for GHGs can be attributed to power generation plants (mainly fossil fuel powered plants) operated around the world [51]. According to 'Global Climate Risk Index 2020' report published by Germanwatch, in the period from 1998 till 2018, Bangladesh ranked seventh in the long-term climate risk index. The power generation plants are responsible for 52% of carbon dioxide (CO_2) emissions of the country [52]. If emission levels from these plants are not brought down, adverse environmental, health and security issues may arise in Bangladesh. With the current rate of use of natural gas for energy generation and plans to further increase usage to meet the increased energy demands, natural reserves of gas are projected to be depleted by the next decade [17]. While it may be true that gas-fired power plants are more environmentally friendly than coal-fired power plants, due to diminishing natural reserves [17], substantial investments should be made in the renewable energy sector to mitigate the health hazards and environmental pollution created due to the use of fossil fuels.

The operation of solar panels during their lifetimes (raw materials extraction and manufacturing) produce several magnitudes lower CO_2 emissions than fossil fuel power plants [53]-[56]. Also, no harmful pollutants are released during its operation. Second (2^{nd}) generation or thin-film solar cells (TFSCs) require a lower amount of materials than crystalline solar cells and so TFSCs are more ecologically friendly than traditional soar cells. Due to reduction of thickness of the light absorbing layer of TFSCs, they also tend to be elastic, increasing the flexibility in the location for deployment. This can lead to reduction in space requirement for deployment and more robust structures to withstand adverse environmental conditions like cyclones and nor'westers that are common in Bangladesh. Increasing the efficiency of TFSCs by the proposed incorporation of different plasmonic metal NPs can potentially reduce the cost and amount of PV cells required to power specific rural, urban or industrial areas of Bangladesh.

In order to tackle the problems of power generation (of Bangladesh) stated throughout this paper, the government would be advised to follow in the steps of countries (Germany, Iceland, Kenya, Morocco, China, U.S.A. *etc.*) that have been successful in adopting renewable energy practices [57]. The policies used to realize their energy goals need to be scrutinized, evaluated and possibly be modified to suit the current situation (socio-economic and political) of Bangladesh. Extreme remote and rural areas in Bangladesh (*e.g.*, Chittagong Hill Tracts) still have no access to electricity (5%) due to the high cost and challenges involved in connecting these remote areas to the national grid [58]. Hence, using stand-alone power systems (*e.g.*, solar homes) or using microgrids appears to be one of the practical solutions to deliver electricity to these areas. Lack of access to electricity in remote areas of the country have impeded the development and growth in these areas and is a hurdle that needs to be overcome for Bangladesh to fully transition into a developing country.

Facilitating electricity in these rural areas can bring about development and growth. It can also lead to the development of communication pathways (cell phone towers, roads, radio, *etc.*), thereby connecting the remote populace to the rest of the country and the world (via the internet). It also works to reduce the feeling of alienation and neglect of the people living in such remote areas of Bangladesh (*e.g.*, indigenous minority tribes living in the hill tracts and the people living in the alluvial land areas) where it is almost impossible to have access to grid electricity. The proposed access to electricity will make such rural and minority communities feel as being accepted as a citizen with equal facilities as the vast majority of people living elsewhere in the country. This can prevent or discourage such estranged communities from indulging in terrorism and other illegal measures to express any form of dissent.

Efforts should not only be made to provide electricity to these remote and rural areas via microgrids but also the possibility of using such grids to provide electricity in areas which have an unreliable electrical connection (frequent outages, faulty transmission lines, *etc.*) should also be explored. The biggest hurdle in adopting PV solar panel technology is the high initial cost investment needed. The cost of these PV crystalline solar cells can be reduced substantially if TFSC technology is used. Increase in TFSC efficiency using the proposed plasmonic NPs can potentially further reduce the cost of operation and installation of the solar cells. Implementation of solar energy can give rise to a cultural movement and massive paradigm shift of the minds of the common people. Hence, Bangladesh can also have bright prospects to be a part of a multi-billion-dollar solar cell industry and become a market leader like it is in the ready-made garments (RMG) industry. This revolution can pave Bangladesh towards a greener and sustainable future because this will not only protect the environment and provide electricity but also create new employment opportunities for large number of people.

5. IMPACT OF HIGHER EFFICIENCY THIN-FILM SOLAR CELLS ON THE ENVIRONMENT AND ECONOMIC SUSTAINABILITY IN BANGLADESH

The majority of carbon dioxide (CO_2) emissions in Bangladesh (52%) can be attributed to the power sector [52]. Many countries have invested heavily in renewable energy sources to reduce their carbon footprint and meet their carbon goal according to the Paris Climate Agreement 2016. In 2018, 26.1% (26614 TWh) of the world's electricity production was generated from renewable energy sources and globally, the new installed capacity of renewable sources was greater than the installed capacity of traditional sources and nuclear power combined [17]. Since 2008, the price for PV solar modules have gone down by a factor of about 5 [59], while their efficiency has been improved, making PV solar cells widely adopted globally for power generation.

According to PSMP (Power System Master Plan prepared by the Government of Bangladesh) 2016 [18], proposed plans to increase the generation capacity in Bangladesh point to an alarming scenario where the dependence of foreign imports of fuel for power generation would increase, thereby decreasing the energy security in Bangladesh and lead to an increase in the already high carbon dioxide emission (CO_2) from the power sector due to the increase in fossil fuel power plants. Adopting a scenario more geared towards the use of renewable energy sources such as PV solar systems would be better for the environment as PV solar systems have lower CO_2 emissions (approximately 40g CO_2 eq/kWh for PV systems compared to an approximately 1000g CO_2 eq/kWh for coal, 640g CO_2 eq/kWh for natural gas-fired combustion turbine (NGCT) and 460g CO_2 eq/kWh for natural gas-fired combined-cycle systems) [53]-[56]. This would also decrease the dependency on foreign imports of fuel (such as coal, natural gas) and therefore can potentially increase energy security in Bangladesh.

Traditional or 1st generation PV solar cells are the predominant type of solar cells that are available in the market. Crystalline (monocrystalline and polycrystalline) Si (with a typical thickness of the cut wafers of approx. 180 μm) makes up the bulk of the material used in these 1st gen cells and is the main contributor to the high price [60]-[62]. To find an alternative to using high quantities of Si, the 2nd generation of solar cells (also called TFSCs) were developed. The absorbing layer in TFSCs are usually only a few microns (μm) thick and so a considerable amount of expensive material can be saved in their fabrication. The primary focus of this paper is on enhancing the opto-electronic performance of a-Si (amorphous silicon) TFSCs by utilizing the plasmonic properties of different kinds of metallic nanostructures coupled to the solar cells. Potentially higher efficiency and thus lower amounts of expensive absorbing materials used can lead to more affordable solar panels and also can significantly reduce the amount of space needed to mount the solar modules. This can potentially lead more widespread adoption of renewable energy with significantly lower carbon emissions compared to fossil fuels and can also save much needed agricultural land for installing such solar panels on a large industrial scale.

For PV solar cells to become a major sustainable competitor in the power generation market, the materials involved in the manufacture of these cells must be abundant, affordable and have a much lower environmental impact than its traditional counterparts. Additionally, the engineering complexity of fabrication should be such that the costs associated should not be prohibitive for widescale deployment in developing countries like Bangladesh. Hence, the cost of one unit of electrical energy generated via PV systems must be equal to or lower than the cost of one unit of grid electricity. While 1st generation crystalline PV cells now cost much lower than they did in the past, it is still relatively expensive for widespread deployment and use in developing countries like Bangladesh. That is why extensive research is being done in developing efficient TFSCs (2nd generation cells) which are significantly cheaper than crystalline Si solar modules [63]. As with the advancement of technology, the price of solar electricity is getting lower but significant work remains to be done to reduce the price even further, for example, via the potential use of plasmonic nanostructures as described in this paper. Despite the relatively limited availability of raw materials (*e.g.*, Te, In, Ge, Cd, Ga, *etc.*) involved in fabrication of PV devices, the growth of TFSCs market should be sustainable to provide Terawatts of renewable energy by the mid-21st century [63].

6. CONCLUSION

This paper outlines the current state of the energy sector of Bangladesh and its challenges to meet the increasing energy demands resulting from thriving economic growth. It also underlines the extent of Bangladesh's reliance on fossil fuels and its ramification on the environment and society. Being fortunate to have favorable solar irradiance due to the geographic location, Bangladesh is well positioned to implement large a scale PV industry to address the current and future energy demands provided that the cost of PV cells can be reduced. To this end, thin-film solar cells have been proposed that require less absorbing material (*e.g.*, silicon) and thereby potentially reducing their fabrication cost. However, due to the reduction of the absorbing layer, the light absorption and current generation efficiency of TFSCs decreases. To overcome this challenge, the use of plasmonic metal nanostructures like core-shell NP, alloy-bimetallic NP and, hybrid-bowtie NP configurations to increase TFSC efficiency have been outlined. The optimal configuration of each NP configuration mentioned above has been shown (via numerical simulations) to significantly increase the opto-electronic performance of TFSCs. The proposed benefit of such higher efficiency combined with low cost of these cells can facilitate both small and large scale deployment of TFSCs. This in turn can aid in bringing electricity to remote areas and rural communities of the country that are outside the current coverage area of the national grid. This in turn can aid in significant infrastructure development, education improvement, economic growth, clean environment and better health of the people thus fulfilling the promise of a "golden" Bangladesh.

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Energy Cost Saving Prospects in Buildings Using Various Window Glazing in Dhaka

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Abstract – *Energy saving is one of the opportunities in residential and commercial building sectors. Proper selection of window glasses reduces the energy consumption in the built environment. The objective of this work is to ascertain the best glazing and it's orientation to save the high air-conditioning costs in buildings of the Dhaka in Bangladesh. This article presents the experimental results of solar optical characteristics of four different glasses such as clear, tinted bronze, tinted green, and bronze reflective glasses. Burnt brick buildings were modeled with four different glasses and analyzed for air-conditioning cost-saving prospects. The results reveal that among the four window glazing processes; the bronze reflective glazing has 45.66% and 26.42% higher energy cost-saving potential compared to the tinted bronze and tinted green glazing, respectively. The bronze reflective glazing gives the highest air-conditioning demand and hence cost savings with the lowest payback periods (0.95 in SE) and adequate daylight factors. The four window glazing materials have also shown better daylight factors than the recommended values. The southeast orientation was observed to be the optimal orientation for the placing of glazing for maximum air-conditioning cost savings followed by the southwest and south. The results of this article can be used for the design of energy-efficient buildings.*

Keywords – *Air-conditioning, cost-saving, building physics, window glazing, energy-efficient glasses, payback period.*

1. INTRODUCTION

Globally building sector is responsible for a minimum of 40% energy consumption and there is a continuously increasing demand for energy in forthcoming years for its operations and maintenance. Heating and cooling of the space consume around 60% of the total energy consumption in buildings, which is the largest portion of energy usage [1]. In Bangladesh too buildings are responsible for major power consumption which is about 50%, with a near consistent rise of 8% over the coming years as per SREDA [2]. In hot climatic regions, cooling demand in residential and commercial buildings is an important concern for its functional requirements and to maintain thermal comfort. Energy demand in buildings would continue to rise unless appropriate actions to improve the energy efficiency are taken up immediately because of urbanization, increasing gross built-up area, and standard of living. Solar passive buildings with energy-efficient designs of systems consume around 30% less energy as compared to conventional buildings [3]. Building components such as walls, roofs, floors, and glazings are responsible for the heat gain. In passive building design, the building envelope is the most significant and basic element to save energy. Suitable design and materials selection of the components is an efficient measure to reduce the energy consumption in the buildings. Optimization of building materials and components specifications is an important aspect to achieve energy conservation. Such building enclosures help in resisting or reducing the heat gain. Glazing placed in an optimum tilt angle to the vertical external wall curtailed the intensity of solar radiation in the buildings [4], [5] Investigations concluded that installing windows at an inward tilt position is an effective and inexpensive technique in reducing the solar heat gain in the buildings for hot climatic conditions. The effect of external wall thickness on the thermal comfort of the building is studied and reported that houses that have thick walls will be comfortable all year round as opposed to houses with thin walls [6]. Radiation control coatings applied on the opaque outer surfaces of the building had shown a reduction in solar heat gain. DOE Simulations for the warm climatic zones reported a 60% reduction in the heating and cooling loads. The reduced loads, economize the size of the air-conditioning system to be installed by 50% or more [7]. Dynamic thermal modeling of industrial buildings (Retail shed) in China, and Australia with reflective coatings over the external surfaces such as walls, roofs, and glazing's had shown a minimum of 30% reduction in the cooling load. The study concluded that the use of reflective coatings as a passive measure to control heat gain in the buildings can potentially save operational energy as high as 25% [8].

Numerous experiments and simulations have been conducted to mitigate solar radiation through building

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components, Taleb and Al-Watter designed the windows to reduce solar radiation transmission in the building enclosures and reported analytical models to compute the solar radiation [9]. Detailed mathematical calculations were reported to compute the glazing properties such as overall heat transfer coefficient, solar heat gain coefficient, and solar optical properties for different window systems in various climatic conditions [10]. Thermal insulation of external walls improves the thermal resistance to heat gain and significantly reduce the energy consumption of cooling and heating. Thicker thermal insulation diminishes cooling and heating load and improves the energy-saving effects [11], [12]. Optimum economic insulation thickness of various building components was computed considering comprehensive interaction among the external walls, roof, and windows for various window-to-wall ratios. A suggested combination of the insulation thickness with optimum WWR had shown significant energy savings [13]. Thermal insulation provided to the external walls, roofs, and floors mitigates heat gain through them and improve the thermal performance of the built environment [14], [15]. Thermo economic analysis is carried out to optimize the insulation thickness of external walls in different climatic regions of Turkey [16]. Aerogel based super insulation materials were investigated for the optimum thickness of the insulation and its environmental impacts to abate the greenhouse gases. These insulating materials had shown a reduction in the cooling loads along with a reduction in the CO_2 and SO_2 emissions [17].

The window-to-wall ratio (WWR) is defined as the ratio of the glazed area to the gross exterior wall area. WWR is an important parameter that affects the energy performance in the building. Window area has an impact on building the heating load, cooling load, and natural daylighting. The impact of Window to wall ratio on thermal and visual comfort for various interiors of the residential building studied, it had shown a substantial reduction on the cooling and heating energy consumption in hot summer and cold winter zones of China [18]. In a solar passive building, the area of the window to the external wall area in the south orientation was optimized to achieve the highest energy efficiency in Turkey for five different cities [19]. Thermal analysis of various buildings and glass materials with different WWR has been carried out to obtain a feasible combination to minimize the external cooling load in the building [20]. The efficient utilization of natural daylight for illumination will show the reduction in artificial daylight energy consumption. The natural daylight availability of global solar radiation was estimated with the help of different models for different climatic zones [21]. Single pane glazing can be retrofitted with reflective glasses [22] and double pane windows to reduce the heat gain and cooling load. Thermal and cost analysis of the air-filled reflective double glazing had shown a substantial reduction in heat gain. Double glazing showed significant net annual energy savings at a low payback period of 1.42 years [23]. The heat gain through the various float and tinted glasses was determined for buildings of different Indian climatic zones [24]. Energy-efficient window and wall building materials were proposed based on the heat gain using Energy plus simulation tool for Indian climatic regions [25], [26]. Heat transfer characteristics of five homogeneous and composite building materials were reported using the admittance method [27].

The above-discussed literature reveals the importance of the control of heat gain in the building through its components. The literature reveals a significant gap in the research on thermal and visual comfort potential of glazing for buildings in Dhaka (23.81^0N 90.41^0E). Heat gain in the building is the most critical parameter to determine the air-conditioning energy and cost-saving prospects of the building. In the present study, four different window glazing are studied for solar heat gain/loss and energy-saving prospective. The spectral properties of the glasses are measured experimentally and these results are used in the mathematical model to compute the solar heat gain/loss and air-conditioning cost savings. This work aims at proposing the best energy-efficient window glazing for buildings in the Dhaka taking peak climatic conditions. This work proposes thermal and visual comfort potential of four different window glazing types (clear glass, tinted bronze glass, tinted green glass, and bronze reflective glass) for the buildings of Dhaka climatic conditions. The results of this work are significant in selecting a suitable glass for reducing cooling loads in the built environment.

2. METHODOLOGY

Figure 1 shows the flow chart of the procedure followed to obtain optimum air-conditioning cost-saving potential of glazing with adequate daylight factors. Solar gain through the glazing can be computed with the help of solar optical properties of the glasses. The solar spectral characteristics of different glasses were obtained by striking light at zero angle of incidence onto the glass surface in the Perkin Elmer Spectrophotometer with the spectrophotometric method [28]. Figure 2 shows an integrating sphere spectrophotometer interfaced with UV Win Lab software used in the experimentation.

The solar spectral characteristics of four 5 mm thick glasses like clear glass, tinted bronze, tinted green, and bronze reflective were measured for the light spectrum range of 300-2500 nm. These spectral characteristics of the glasses were further deduced to obtain solar energy transmittance and reflectance in British Standard [29], [30]. Spectral transmission and spectral reflectance were measured in specular mode and diffusive reflectance mode respectively. Spectral absorption of glasses obtained from the summation rule. The spectral transmission and reflection properties of the glasses have been depicted in Figure 3 and Figure 4 respectively. The solar optical properties of window glazing have been presented in Table 1. The U-value of the glazing is 5.70 W/m^{2}K.

The solar energy transmittance and reflectance for single-pane glazing can be computed using Equations (1) and (2). In Figure 4, the graph shows the least spectral transmission for bronze reflective glass and the highest spectral transmission for clear glass among four glasses.

Solar transmission is the fraction of the solar radiation transmitted through the glazing that is incident on the glazing and is calculated using the following formula.

$$T_{SOL} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \tau(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \Delta\lambda} \quad (1)$$

Solar reflectance is a fraction of the solar radiation reflected from the glazing that incident on glazing and is calculated as follows.

$$R_{SOL} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \rho(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_\lambda \Delta\lambda} \quad (2)$$

The percentage of solar transmission and solar reflectance can be calculated by multiplying with 100 using Equations (1) and (2).

Solar absorption can be calculated using the following formula.

$$A_{SOL} = \left(100 - T_{SOL} - R_{SOL}\right) \quad (3)$$

Burnt clay facing brick is a construction material, which is used to make the building walls in Dhaka (23.81^{0}N 90.41^{0}E), a city in Bangladesh. Thermo-physical properties of burnt clay facing brick are as per the Bangladesh standards (BDS 1250:1990) [31].

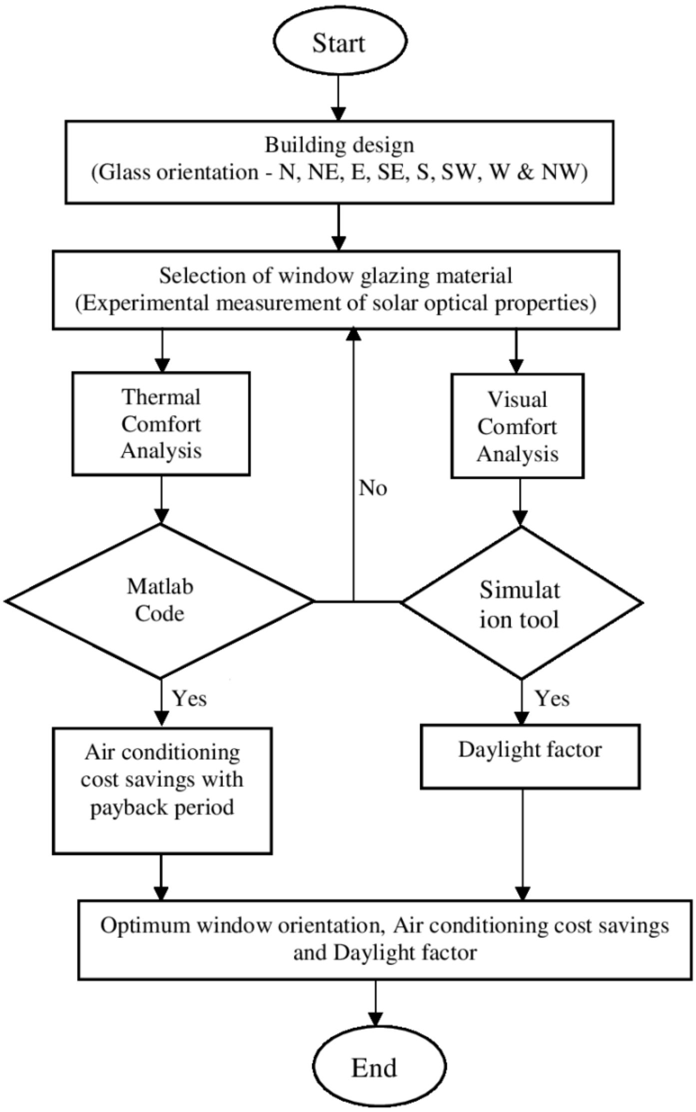

Fig. 1. Flowchart of methodology.

Fig. 2. UV-Vis-NIR Perkin Elmer (Lambda 950) spectrophotometer.

Table 1. Solar optical properties of glasses of 5mm thickness.

Window glass	Transmittance T_{SOL} (%)	Reflectance R_{SOL} (%)	Absorbance, A_S (%)	SHGC (%)
Clear glass	82	8	10	84
Tinted Bronze glass	56	6	38	65
Tinted Green glass	47	6	47	58
Bronze Reflective glass	41	6	53	48

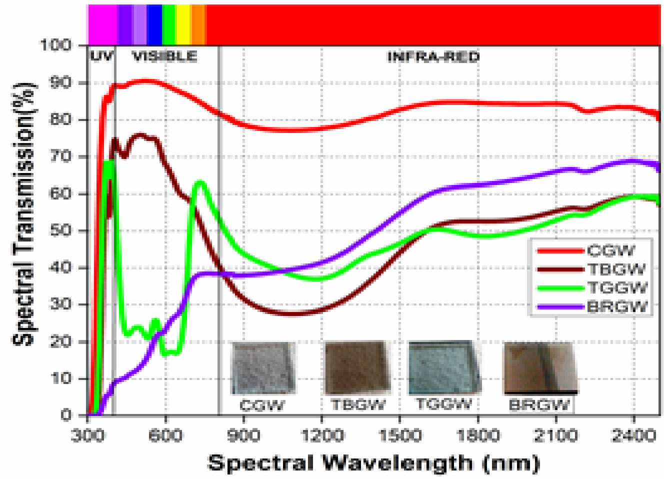

Fig. 3. Spectral transmission of glass materials.

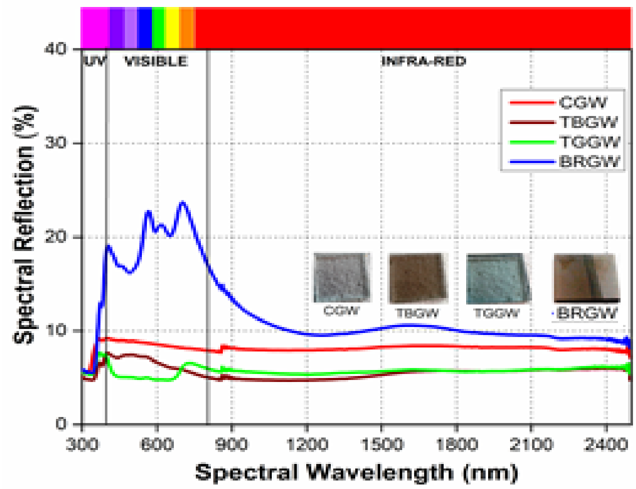

Fig. 4. Spectral reflection of glass materials.

3. ANALYTICAL METHOD TO FIND THE SOLAR HEAT PASSING THROUGH GLASS WINDOWS

To determine the solar heat gain through the glass, it is required to find the three radiation components such as direct, diffuse, and ground reflected radiations falling on building surfaces. The solar radiation reaches the earth in the form of electromagnetic waves (300 nm - 3000 nm). The 2-3 % quantum of radiation exists in the ultraviolet zone (0.30 mm–0.38 mm), 47% in the visible zone (0.38 mm–0.78 mm), and nearly 51% of the radiation in the near-infrared region. To find the solar heat gain passing through the glass window it is necessary to account for these radiation factors in each zone. The total solar radiation that enters the building through the glazing is the sum of direct normal radiation (I_{dir}), sky-diffuse radiation (I_{dif}), and ground reflected radiation (I_{grr}). Solar radiation in the wavelength range of 300 nm to 2500 nm was considered to compute the heat gain through the glazing. The total solar irradiance (W/m^2) that reaches the earth is related to solar geometry, which includes several angles. Solar azimuth and altitude angles depend on the fundamental angles such as solar declination, latitude, and hour angle. In this work, the warm and humid climatic condition was considered, i.e. Dhaka (23.81^{0}N 90.41^{0}E), a city in Bangladesh and analyzed for heating and cooling costs. The analysis was carried out, between 6:00 am to 6:00 pm (LAT), and 7:00 am to 5:00 pm (LAT) for peak summer and winter days, respectively. The room setpoint temperatures are 24^{0}C and 21^{0}C, respectively for summer and winter as per ASHRAE (2001). Building model of dimensions 5 m X 5 m X 3.2 m was considered and four glass windows were placed at a 40% window to wall ratio (3.2 m X 2 m). The building models are considered as commercial/office buildings that use the air-conditioning system (cooling and heating systems) during diurnal hours. Thermal and cost assessment was carried out for this climatic region, in eight cardinal directions to compute the solar heat gain/loss and energy savings. Total solar radiation admitted in building through the glazing is calculated as per the following procedure at given latitude as per ASHRAE clear-Sky and intermediate sky models [32].

Declination angle is the inclination of the earth's axis measured from the perpendicular to the sun's rays. It can be computed by Equation (4).

Declination angle

$$d_{an} = 23.45 \sin \frac{360(248 + n_{da})}{365} \tag{4}$$

Solar altitude angle

$$\sin \beta_a = \cos l \cos d_{an} \cosh_{an} + \sin l \sin d_{an} \tag{5}$$

Solar azimuth angle

$$\cos \phi_a = \frac{\sin \beta_a \sin l - \sin d_{an}}{\cos \beta_a \cos l} \tag{6}$$

Surface solar Azimuth angle

$$\gamma_a = \phi_a - \psi \tag{7}$$

The surface azimuth measured from the south for the orientations N, NE, E, SE, S, SW, W, and NW is 180^0, -135^0, -90^0, -45^0, 0^0, 45^0, 90^0, and 135^0, respectively.

Angle of incidence

$$\cos \theta = \cos \beta_a \cos \gamma_a \cos k - \sin \beta_a \sin k \tag{8}$$

Terrestrial solar radiation on a clear atmosphere day is given by

$$I_{DN} = \frac{A}{\exp(B/\sin \beta_a)} \tag{9}$$

Where, the constants A, B, and C are used for calculating solar radiation per hour in Dhaka climates as per ASHRAE (2001).

Total solar radiation passing through a single glazing window can be obtained from Equation (10).

$$I_{SRSGW} = \left((I_{DN} \cos \theta) + (C I_{DN} \frac{1 - \sin k}{2}) + ((C + \sin \beta_a) I_{DN} \rho_g \frac{1 - \sin k}{2}) \right) . \left(T_{SOL} + \frac{U}{h_o} A_{SOL} \right) . A_G \tag{10}$$

Where

$$U = 1/(1/h_o + L/K + 1/h_i)$$

Where (h_i, h_o are considered as per standards (CIBSE, 2006 [33])).

The results obtained were compared with results found in the literature Ishwar *et.al.* (2011) on this subject for validation purposes. The validation of the MATLAB program was carried out for a 3 mm clear glass window in New Delhi climatic conditions. The deviation of the validation results was within ±1%. Hence, the program was considered to be reliable for studying other glasses [34].

3.1 Cost Analysis Methodology

The procedure is followed to find the total cost savings per year through all window glasses.

The savings in yearly net cooling and heating cost of glass windows in eight directions were determined for the warm and humid climatic region of Dhaka. For computing net cost savings annually, the following procedure has been followed [35].

The mean diurnal incident total solar radiation onto the glazing during any season can be computed by Equation (13). For computing incident solar radiation on glazing in both summer and winter seasons, the following months are considered in the study: i.) Summer season is from April to August ii.) Winter season is from September to March. The number of days in each month are also considered for computing average daily incident total solar radiation onto the glazing.

Total solar radiation in the summer months:

$$Q_{sol,\text{summer}} = (q_{ds_{April}} X30) + (q_{ds_{May}} X31) + (q_{ds_{June}} X30) + (q_{ds_{July}} X31) + (q_{ds_{August}} X31) \quad (11)$$

Total solar radiation in the winter months

$$Q_{sol,\text{winter}} = (q_{dw_{Sep}} X30) + (q_{dw_{Oct}} X31) + (q_{dw_{Nov}} X30) + (q_{dw_{Dec}} X31) + (q_{dw_{Jan}} X31) + (q_{dw_{Feb}} X29) + (q_{dw_{Mar}} X31) \quad (12)$$

Then the decrease in annual cooling load and the increase in annual heating load due to the different glasses becomes:

$$\textit{Cooling load decrease} = Q_{sol,summer} X\ A_G\ X\left(SHGC_{CGW} - SHGC_{SGW}\right) \quad (13)$$

$$\textit{Heating load Increase} = Q_{sol,winter}\ X\ A_G\ X\left(SHGC_{CGW} - SHGC_{SGW}\right) \quad (14)$$

The unit cost of the electricity and natural gas considered is \$0.075 kWh and \$0.45/therm, respectively. The coefficient of performance of the cooling system and efficiency of the furnace is taken as 2.5 and 0.8, respectively.

1Therm=29.31 kWh, the corresponding decrease in cooling costs and the increase in heating costs are

Decrease in cooling costs = (cooling load decrease) (unit cost of electricity) / (COP) (15)

Increase in heating costs = (heating load increase) (unit cost of fuel) / (Efficiency) (16)

The net annual cost savings = Decrease in cooling costs – increase in heating costs (17)

Simple payback period = (Implementation cost) / (Annual cost savings) (18)

Implementation cost = (Unit price of glazing (\$/m^2) X (Glass area (m^2)) (19)

4. RESULTS AND DISCUSSION

4.1 Incident Solar Radiation and Radiation Passing through a Glazing

Figure 5 presents the solar radiation falling and passing through four glazings on a peak summer day (May 15th) of the Dhaka region as per standards [36]. The results have shown the least incident radiation in the south orientation among eight orientations studied. It is also observed that heat gain through the south-oriented glazing is the least compared to the other orientations.

Figure 6 presents the solar radiation falling and passing through four glazings on a peak winter day (Dec 21st) of the Dhaka region. The results have shown the highest incident radiation in the south orientation among eight orientations studied. It is also observed that heat gain through the south-oriented glazing is the highest compared to the other orientations. The heat gain/loss through CGW is significantly high and contributes to the higher cooling and heating costs. Though the incident radiation is the same for all the glazing, their heat gain/loss is different for different window glazing. The glazing which is the best in the summer season observed to be the worst in the winter season. Therefore, it is necessary to identify the best window glazing to save cooling and heating cost collectively. For this purpose, air-conditioning cost-saving prospective of various window glazing has been carried out.

4.2 Annual Air Conditioning Cost-Saving Prospects of Window Glazing in Buildings within the Dhaka Climatic Zone

Figure 7 presents the air conditioning cost-saving prospective of various window glazing of the Dhaka climatic zone. The energy-saving prospective of tinted and reflective window glazing compared to clear glazing has been reported in this work. The results have shown the highest air-conditioning cost savings in southeast orientation compared to other orientations for all window glazing. Bronze reflective glass window reported the highest energy cost savings compared to other window glasses studied. Bronze reflective window glazing saves 45.66% and 26.42% more air-conditioning cost savings compared with tinted bronze and green glass windows, respectively. The SE orientation is followed by SW, S orientations are recommended for the highest cooling and heat cost savings in buildings. The North and NE orientations are not recommended to place glazing due to their lowest air-conditioning cost-saving prospective.

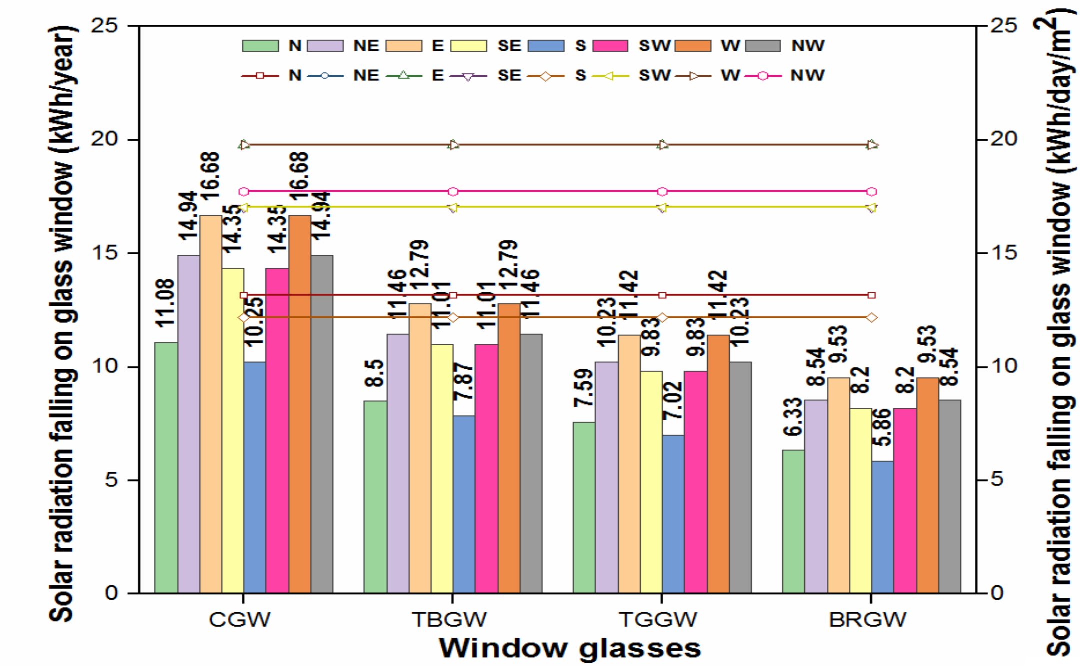

Fig. 5. Solar radiation falling and passing through window glazing of the Dhaka region on a peak summer day.

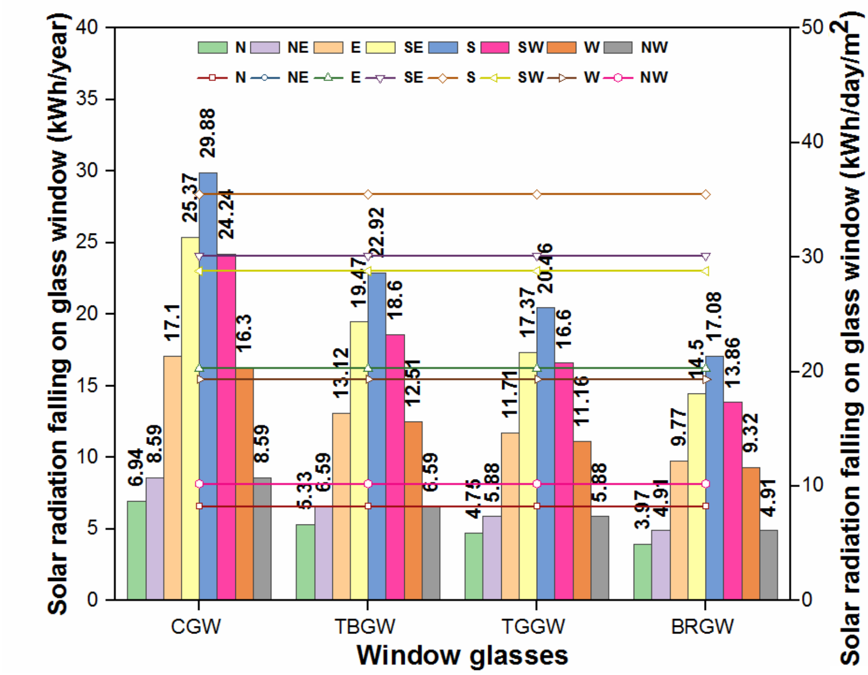

Fig. 6. Solar radiation falling and passing through window glazing of the Dhaka region on a peak winter day.

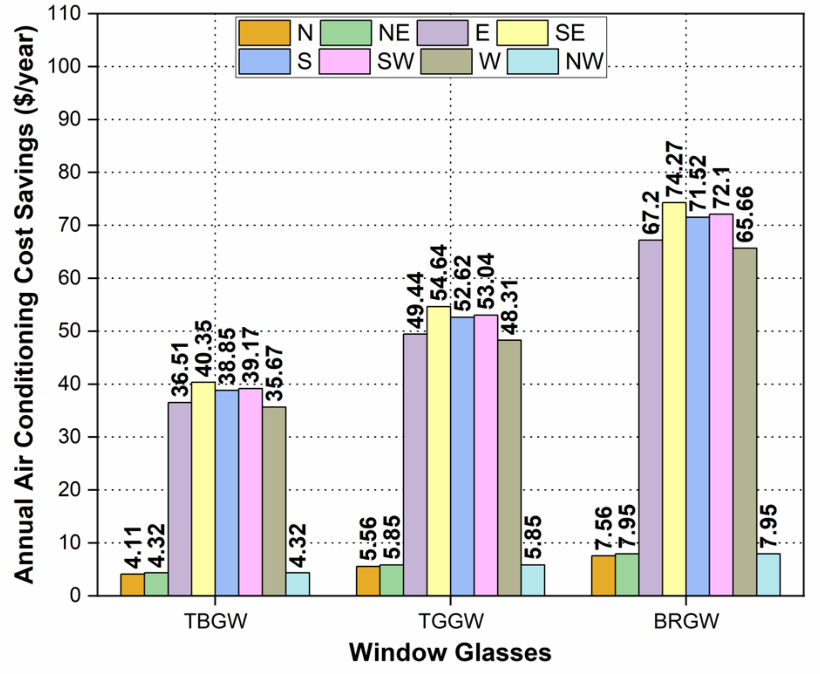

Fig. 7. Annual air conditioning cost savings of buildings using various glass windows compare with a clear glass window.

4.3 Payback Period of Various Window Glazing in Dhaka Climatic Region

Figure 8 shows the payback period of various window glazing compared to the clear glazing in Dhaka Region. From the results, it is observed that the payback period of bronze reflective window glazing is the shortest compared to the other studied glass windows. The SE orientation has been observed to be the best for the shortest payback periods of 0.95 years compared to the other studied orientations. The SE orientation followed by South and Southwest orientations is preferable for the shortest payback periods. The North and NE orientations are not recommended to place glazing due to longer payback periods.

4.4 Daylight Factor of Various Window Glazing in Dhaka Climatic Region

Figure 9 shows the average daylight factors of various glazing materials. The average daylight factor (ADF) is the measure of the level of illuminance in the indoor room following the external daylighting. The average daylight factor was evaluated for Dhaka climatic condition in Design builder and Energy Plus simulation tools from 7 am to 5 pm on peak winter day and 6 am to 6 pm on peak summer day for four best directions of air-conditioning cost savings (SE, E, W, and SW). For office inquiry rooms, living rooms, bedrooms, library stack rooms, and in most of the rooms, the minimum recommended average daylight factor is 0.625 as per the standards [29]. All four glass materials in all four directions (SE, E, W, and SW) have shown better daylight factors than the recommended levels on both peak summer and winter days. The south gives the best daylighting in winter whereas, the East gives the best daylighting in summer. The daylight factor of the bronze reflective glass window (BRGW) ranges from 92% (On peak summer day) to 204% (On peak winter day) higher than the recommended daylight factor values in the southeast orientation. From the results, it is observed that all four window glazing studied give adequate daylight factors.

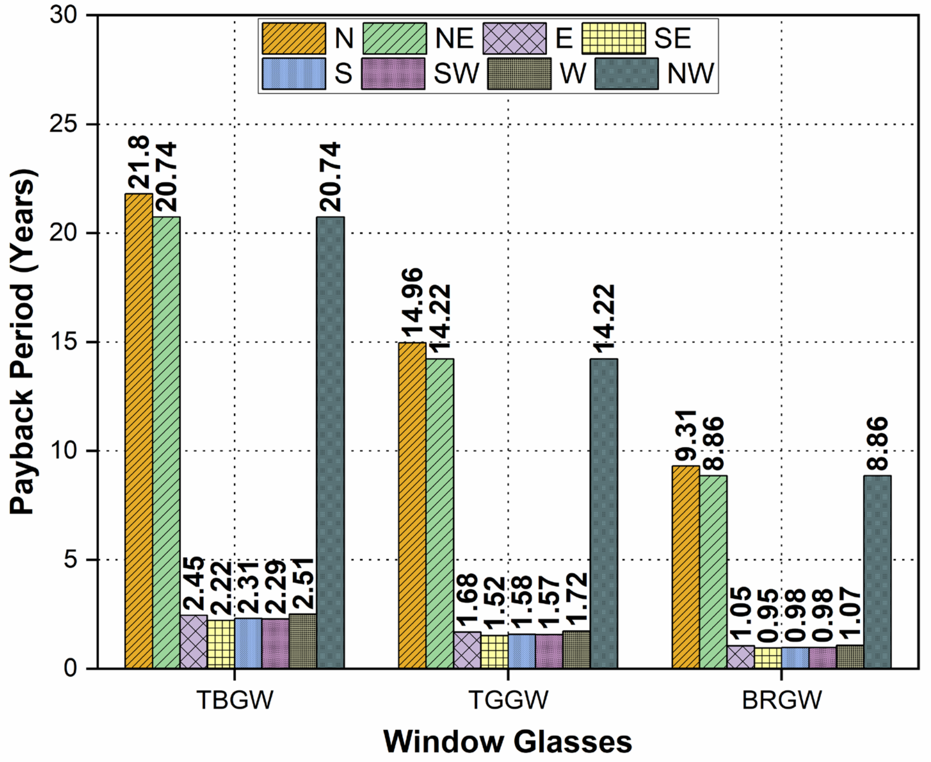

Fig. 8. Payback period of various window glazing.

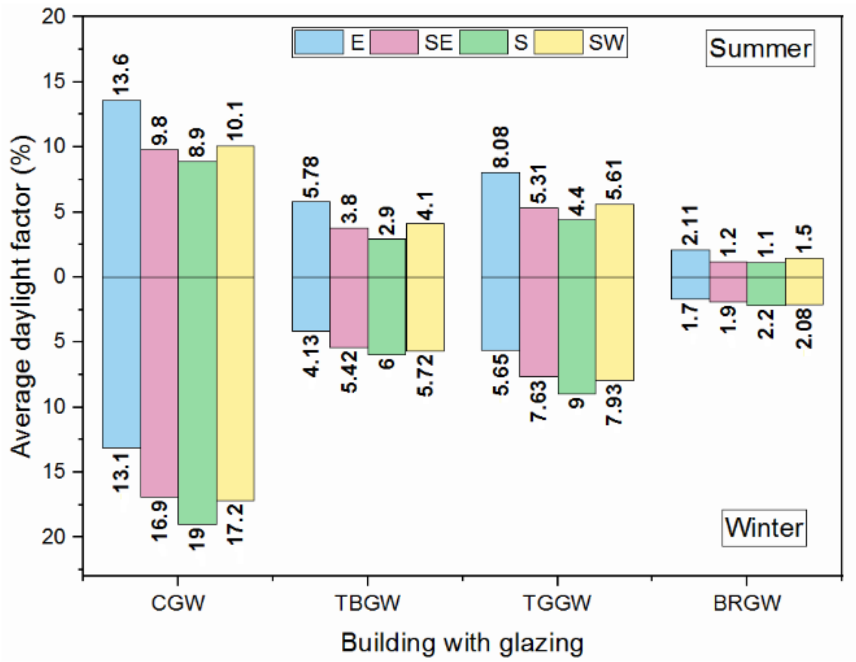

Fig. 9. Average daylight factors of various window glazing.

5. CONCLUSION

The objective of this work is to ascertain the best glazing and it's orientation to save the highest air-conditioning costs in buildings of the Dhaka climatic region, Bangladesh. From the results, it is concluded that

- The use of bronze reflective glazing for buildings contributes to the higher air-conditioning cost savings of about 45.66% and 26.42% compared to the tinted bronze and tinted green glazing, respectively. The bronze reflective glazing gives the highest air-conditioning cost savings with the lowest payback periods (0.95 in South East) and adequate daylight factors.
- The southeast orientation for glazing is observed to be optimal for increased energy

cost savings followed by southwest and south. The north and northeast orientations for glazing lead to higher energy costs and therefore they are not recommended for energy saving.

- The four window glazing materials of the building have shown better daylight factors than the recommended values. The bronze reflective glazing is responsible for the highest air-conditioning cost savings with adequate daylight factors inside the building.

The results of the paper can be extremely useful in designing the most energy-efficient buildings.

NOMENCLATURE

A_G	Area of the glass (m^2)
A	Solar radiation in absence of atmosphere (W/m^2)
B	Atmospheric extinction coefficient (W/m^2)
C	Dimensionless coefficient for sky radiation
d_{an}	Declination angle (^{0}Deg)
h_{an}	Hour angle (^{0}Deg)
k	Angle of window glass from vertical (^{0}Deg)
l	Latitude (^{0}Deg)
n_{da}	Number of days
I_{DN}	Solar radiation at normal incidence (W/m^2)
h_o	Outside surface heat transfer coefficient (W/m^2K)
h_i	Inside surface heat transfer coefficient (W/m^2K)
I_{TSRSGW}	Total solar radiation through single glass window (kW)
$Q_{Sol,summer}$	Solar radiation in summer months (kW)
$Q_{Sol,winter}$	Solar radiation in winter months (kW)
q_{ds}	Daily average solar radiation in summer month (kW)
q_{dw}	Daily average solar radiation in winter month (kW)
T_{SOL}	Solar transmittance (%)
R_{SOL}	Solar reflectance (%)
A_{SOL}	Solar absorbance (%)
$S\lambda$	Relative spectral distribution of the solar radiation (W/m^2)
U	Thermal transmittance (W/m^2K)

Greek letters

λ	Wavelength (nm)
$\Delta\lambda$	Wavelength interval (nm)
β_a	Solar altitude angle (Deg)
θ	Solar incidence angle (Deg)
Φ	Solar azimuth angle (Deg)
γ_a	Surface solar azimuth angle (Deg)
Ψ	Surface azimuth angle (Deg)
ρ_g	Ground reflectance factor
(λ)	Spectral transmission (%)
(λ)	Spectral reflection (%)
$\alpha(\lambda)$	Spectral absorption (%)

Abbrevations

BRGW	Bronze reflective glass window
CGW	Clear glass window
NIR	Near infrared
SG	Single glass
SGW	Selected glass window
TBGW	Tinted bronze glass window
TGGW	Tinted green glass window
UV	Ultra-Violet Region

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A System Dynamic Energy Economic Assessment Model for Road Transportation

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Abstract *– The road transport sector is highly dependent on conventional energy resources that account for approximately 20% of a country's primary energy. This figure will certainly increase in the upcoming years due to the growth in population, leading to an increase of vehicles in the country, therefore increasing the consumption of fuel. Limited, poorly managed public transportation and the increase in the number of registered cars has led to an increase in emissions produced that contribute to environmental factors including air pollution and noise, as well as carbon dioxide (CO_2), and other greenhouse gases. This paper evaluates the economic impact of implementing energy efficiency strategies in the transportation sector using a system dynamic model and associated scenario analysis that can be applied to Bangladesh. Transportation data was collected and analyzed using Stella, a visual programming language for system dynamics modeling, to develop the energy economics evaluation model. Hence, the economic effect of various alternative scenarios for emission reduction and fuel consumption enhancement was identified and evaluated. It was estimated that the economic savings that would be achieved by adopting the 70/30 and 50/50 scenarios on private vehicles for the year 2027 were $74, 800, 00 and $124,700,000 respectively. Therefore, a significant reduction of approximately 60.35% is expected in financial terms. This demonstrates that along with emission and fuel consumption reduction, the proposed strategies will also achieve substantial financial savings.*

Keywords *– Bangladesh, economic evaluation, emissions, energy efficiency, road transport, system dynamics.*

1. INTRODUCTION

Worldwide, 98% of the energy consumption by transport is based on oil [1] that makes the transport sector heavily dependent on the price and availability of oil with consequent environmental impact. To achieve economic savings from fuel consumption policymakers introduce interventions targeting domestic oil prices when international oil prices rise. This allows domestic oil prices to correspond to global market prices. Freezing gasoline prices goes against encouraging public transportation use. Demand for public transportation may increase if oil prices increase, especially if the public transportation system is accessible and well established [2]. Thus, increasing gasoline prices via taxes or user fees can be methods adopted to incentivize public transportation [3]. Any country wishing to achieve emission reductions and economic savings should address the feasibility of these measures. Environmentally approachable and sustainable road transport is a key feature of the Bangladesh transport policy from 2013 [4]. The following literature gives a bird's-eye view of the existing literature about road transport research.

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Economic development is another factor in the growth of road transportation. This in turn increases energy consumption, however; enhancing energy efficiency can reduce transportation energy consumption, and pollutant emissions [5]. Chapman [6] assessed new technologies, including alternative transport fuels, to decrease the dependence on petroleum, and suggested that technological innovation is expected to be the only solution to the climate change problem. Wang *et al.* studied the present practical developments of dynamic traffic assignment (DTA) models in environmentally sustainable road transportation applications in 2018. Gasoline prices and national fuel tax policy changes also affect road transportation energy consumption to certain extent. Financial credit and employment implications of policies influencing road transportation energy consumption in China have been studied. An increased energy utilization rate can reduce road transportation energy consumption and pollutant emissions, as can the price of gasoline and national fuel tax policy changes [7].

Ansari *et al.* [8] carried out a review study that analyzed the development of continuous approximation (CA) models for transportation, distribution, and logistics problems to synthesize current innovation and to recognize present research gaps. They focused on major principles and key results from CA models. Asadabadi and Miller-Hooks [9] studied the problem of optimal continuing transportation investment planning to shield from and alleviate the effects of climate change on roadway operations. The solution proposed by Asadabadi and Miller-Hooks enables the estimation of options relating to where, when, and to what level to make infrastructure investments. Yıldız *et al.* [10]

developed a technique to optimize the location and capability of charging stations to assure the ease and speed of charging electric vehicles in urban areas and evaluated the electric vehicles demand in the transportation sector.

Factors including government policies, economic growth, employment, energy consumption, and environmental impact have been put into the system, and their interactive relationships were studied. It was found that road transportation energy consumption was affected by both market conditions and government policies [10], [11]. Based on the recommendations derived from J. Chai's study, the Chinese government should enhance and develop buses as public transportation to resolve city congestion and to encourage green transport. He suggested the government introduces strategies to discourage purchasing of private vehicles, such as strengthening the automobile credit market regulation, improving the control of automobile credit funds, managing private car parking, collect congestion charges and plan low emission zones and travel times. Road transportation energy consumption in China is expected to reach around 226181.1 ktoe by the end of 2015, and about 347,363 ktoe by 2020, [12].

Sun *et al.* [13], evaluated the coordinated development of economic, social, and environmental benefits taking four Chinese autonomous municipalities as examples, realizing the construction of urban public transportation infrastructure will cause a revolution in urban living. This will most importantly increase the flow of population, which will raise the urbanization rate, increase urban employment, leading to urban social development and progress. "Transportation infrastructure is an important basic condition of regional economic development. It generally confirms the universal knowledge that one of the basic functions of transportation infrastructure is promoting economic development. Also, the urban public transportation infrastructure has proven to be an effective way of tackling environmental problems, which were brought by the expansion of urban scale and the use of private transport".

Timilsina and Shrestha [14] did a comprehensive study of climatic change in Asia, focusing on the transportation sector. They pointed out the need to identify key factors that drive CO_2 emission so that the preparation of policies and strategies will be much easier. The transport sector contribution to the total national CO_2 is continuing steadily for Bangladesh according to their study. They stated that, even though the rail system was a vital mode of transportation in Bangladesh, the road transportation sector is contributing a lion's share in the CO_2 emission.

Alam *et al.*, [15] analyzed the future energy requirements for Bangladesh based on Long-range Energy Alternatives Planning (LEAP). They identified that the imported energy demand from the transportation sector will increase by more than 10 times in a span of 25 years as per the Business as Usual (BAU) scenario.

The United States Agency for International Development (USAID), [16] in one of their studies reported that for the road transport sector, GHG emissions are approximately 14% for Bangladesh. According to them, the transport sector energy consumption reduction has to be a major priority, to reduce GHG emissions as well as to achieve significant reduction in fuel consumption. In their report, the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) feature are noticeably reinforced.

Ahmad *et al.*, [17] estimated the major GHG emissions – CO_2, N_2O, and CH_4 from transportation in Bangladesh. In addition, by using a co-integrating econometric model, they projected the future transportation performance for the country. According to their study, the road transportation sector in Bangladesh is currently undergoing a phenomenal change and the likely GHG emission growth rate in the projected study period is more than 17% per year. Rahman [18] emphasized the importance of public transportation in Bangladesh and the need to decrease emissions as well as fuel consumption to significantly reduce the national transport energy consumption.

The referred literature emphasized the importance of developing the transportation infrastructure to reduce dependence on private vehicles and to encourage the use of public transportation facilities. Decreasing climate change in Asia can be achieved by giving precedence to the transportation sector, and by studying the future energy requirements for Bangladesh and GHG emissions produced by the transportation sector. Therefore, this study is a vital topic for Bangladesh transportation sector. However, it was noticed that no studies on this subject was previously carried out in any of the Gulf Corporation Council (GCC) countries or in Bangladesh, despite the fact they all struggle with limited and poorly managed public transportation systems. Through this study, authors are trying to fill the above gap by developing an economic model and analyzing the associated benefits by demonstrating the results in one of the GCC countries, Kuwait. The referred literature emphasized the importance of developing the transportation infrastructure to reduce dependence on private vehicles and to encourage the use of public transportation facilities. Even though Kuwait is not a highly industrialized country, the per capita CO_2 emission stands among the top ten countries in the world, and the transportation sector accounts for 14% of the share [3]. The backbone of Kuwait's economy is the export of oil, which provides 80% of the country's income [2]. However, the recent increase in the internal consumption of oil is very alarming, as it consumes 24% of the oil produced in the country. As the above figure is mainly distributed between power generation and transportation sectors [19], any reduction in the transportation sector's fuel consumption will not only improve the country's rank in the per capita CO_2 emission but also will enhance Kuwait's oil reserves. These factors show the importance of this study for the region. Hence, a detailed study was carried out to identify the impact of the reduction of private vehicles on the environmental parameters, specifically CO_2 emission. The main contribution of this study and novelty are as follows:

- A System dynamic modeling (SDM) methodology is suggested to identify the fuel consumption reduction and associated emission reductions, so as to develop a suitable public transportation system.
- In this study, the authors predict the possible growth rate of GHG emission, especially CO_2, until 2027, along with the projected number of vehicles, which is not performed previously in the GCC region.
- The results are based on the three different scenarios carried out in this study. This can be used as a reference for calculating the impact on associated parameters in other sectors.
- The economic benefits and the associated environmental gains are predicted as the major outcomes of this study. It will be thought-provoking to the policymakers to consider a category, which was not previously studied.

To carry out this study, a detailed methodology based on system dynamic modeling (SDM) is developed. The methodology consists of two parts. In the first part, various parameters such as the type of vehicles, daily distance covered, average fuel consumption, etc. are collected through a survey. In the second part, the actual analysis of the data through system dynamic modeling to measure the impact of the pollutants such as CO, CO_2, HC, and NO is done. Data are collected for one year. The methodology is presented below.

2. METHODOLOGY

The economic benefits are evaluated by using the following methodology, as illustrated in Figure 1. Data on transportation in the study area were collected, from various sources such as the Ministry of Interior (MOI), Ministry of Electricity and Water (MEW), statistical books, relevant literature as well as from other government sources. In addition to this, the project team collected data using a survey consisting of 17 questions, which was distributed to participants. The present population of the study area was collected, and the population growth for the next ten years was forecast. The number of commercial and non-commercial vehicles in the study area between the years 2006 to 2017 were also collected. The data collected were screened and verified for the correctness and accuracy. The sampling plan used was simple stratified cluster sampling to give equal opportunity for all sectors of data.

To ensure the quality of data collected based on the survey, statistical tools such as coefficient of variation, standard error, standard deviation, etc. were determined. The population growth will lead to an increase in vehicles, consequently producing an alarming increase in CO, CO_2, HC, and NO emissions. This was then projected for the next ten years using System Dynamic Modeling (SDM) growth rate to estimate the private vehicle population. The fuels that were considered in the study are petrol and diesel. The projected number of vehicles was then used to carry out three different scenario analyses. The do- minimum (base case) scenario- where the number of cars operating in the future is projected using SDM. Based on the existing growth rate, the amount of fuel consumed by the private car transport sector and the corresponding emission levels have been simulated. The system dynamic model applicable to the interaction of the social sector, fuel, and energy sector, environmental sector, and their impact on the overall road transport sector in terms of economics and atmospheric pollutants were developed.

2.1 System Dynamic Model Development

The system dynamic model (SDM) applicable to the economic evaluation of the road transport sector was developed. The various parameters considered for building the SDM are presented below in figure 1. POP - Total Population, BR - Birth Rate, DR - Death Rate, IMR - Immigration Rate, OMR – Out-Migration Rate, BN - Birth Normal, DN - Death Normal, IMN - Immigration Normal, OMN – Out-Migration Normal. In this segment, population of the base year, birth rate, death rate, immigration, and outmigration are considered.

The size of the population is predisposed by both the net birth rate and the net migration rate. The net birth rate equals the total number of births per year, minus the total number of deaths. Likewise, the net migration rate equals the number of immigrants minus the number of out-migrants. The number of births and deaths in addition to net immigrants can be defined as a percentage of the yearly population. Thus, the population model can be defined as stated below:

$$\text{Population}(t) = \text{Population}(t-dt) + (\text{Birth\_Rate} + \text{Immigration\_Rate} - \text{Death\_Rate} - \text{Out-Migration\_Rate}) * dt \quad (1)$$

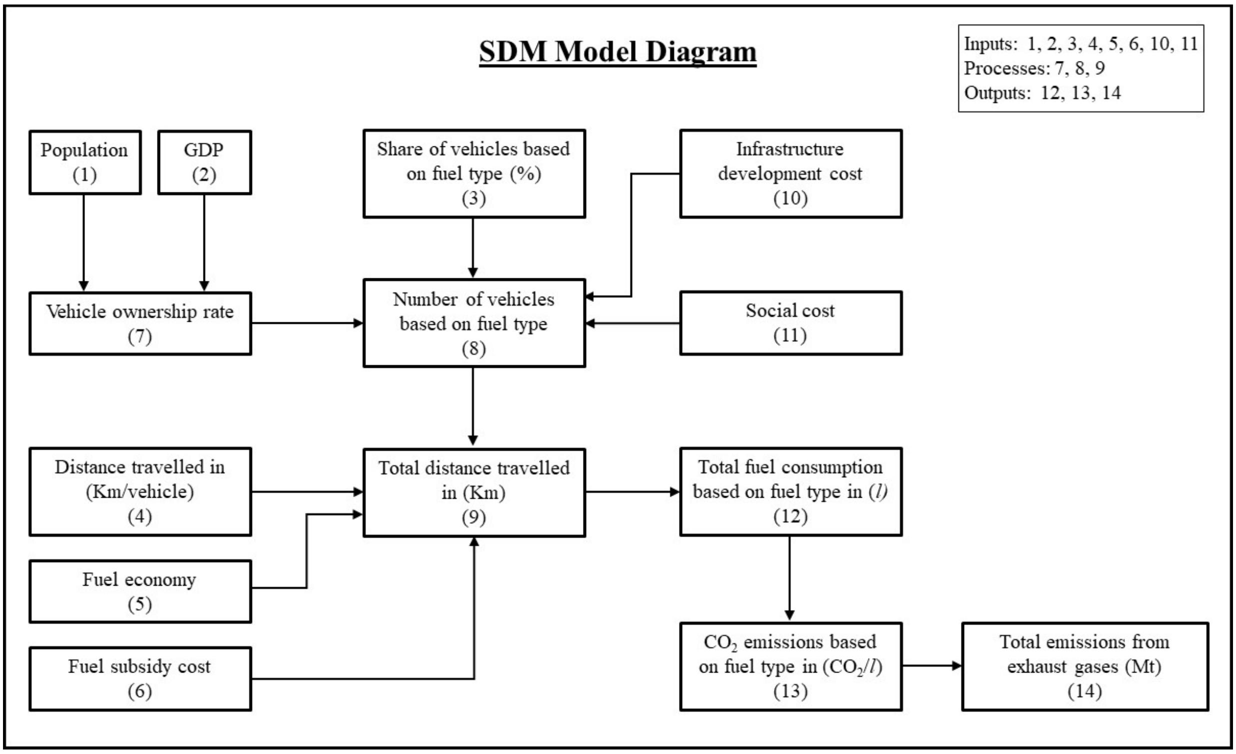

Fig. 1. Model diagram of system dynamic parameters for the energy economics assessment for the transport sector.

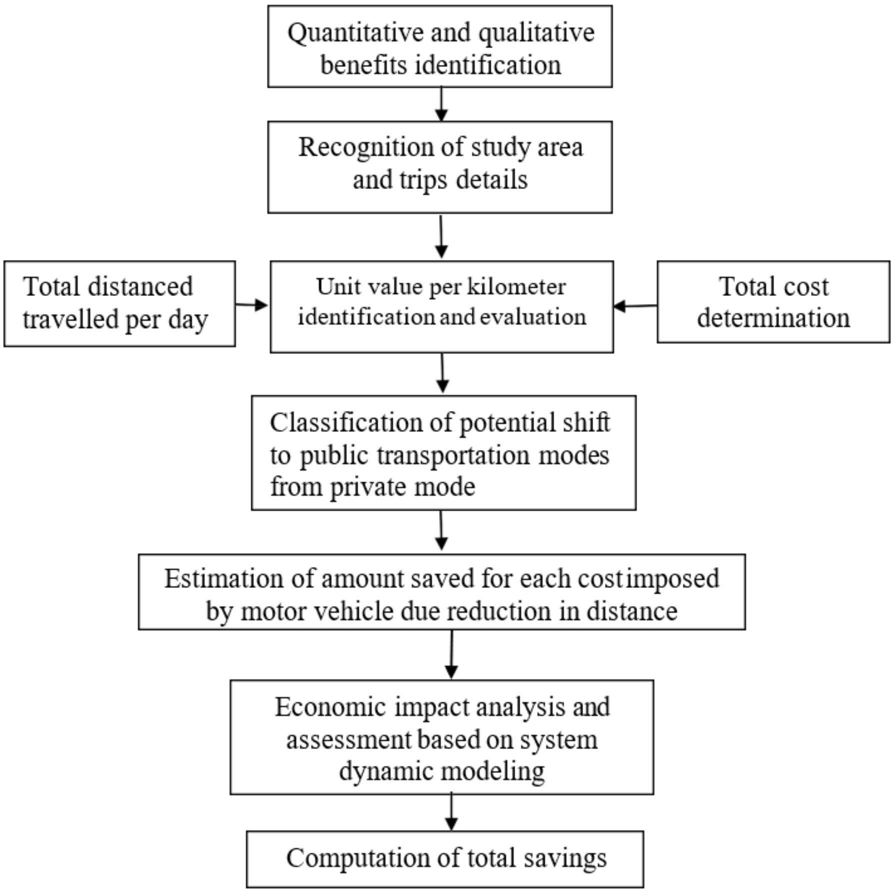

Fig. 2. Flow diagram showing the system dynamic modeling methodology.

The base year population for the study area is taken as 2,217,258 as per the data available from the government. The Birth Rate is inspired by the number of births per 1000 Population, Birth Rate Normal, and Initial Population. Birth Rate is established by multiplying the Birth Rate Normal by the population. Birth Rate Normal is expressed in terms of several births per 1000 of the population. The population growth rate is taken as 3.44 [20] in the year 2017 and is expected to reach 2.63 in the next ten years. The death rate normal is described as the number of deaths for every 1000 population. It is expected to be 2.2 per 1000 population as per data and is expected to reduce further due to improved health services that would be fundamental to the study area. In the study area, the total immigrant population was 1,375,468 in 2000, whereas it was 2,931,401 in 2015. This implied that there is high migration to the study area every year, by which the immigrants comprise of nearly 69% of the total population. Figure 2 depicts the flow diagram explaining the system dynamic modeling methodology and Figure 3 presents the system dynamic model developed for the energy economics assessment for the transport sector.

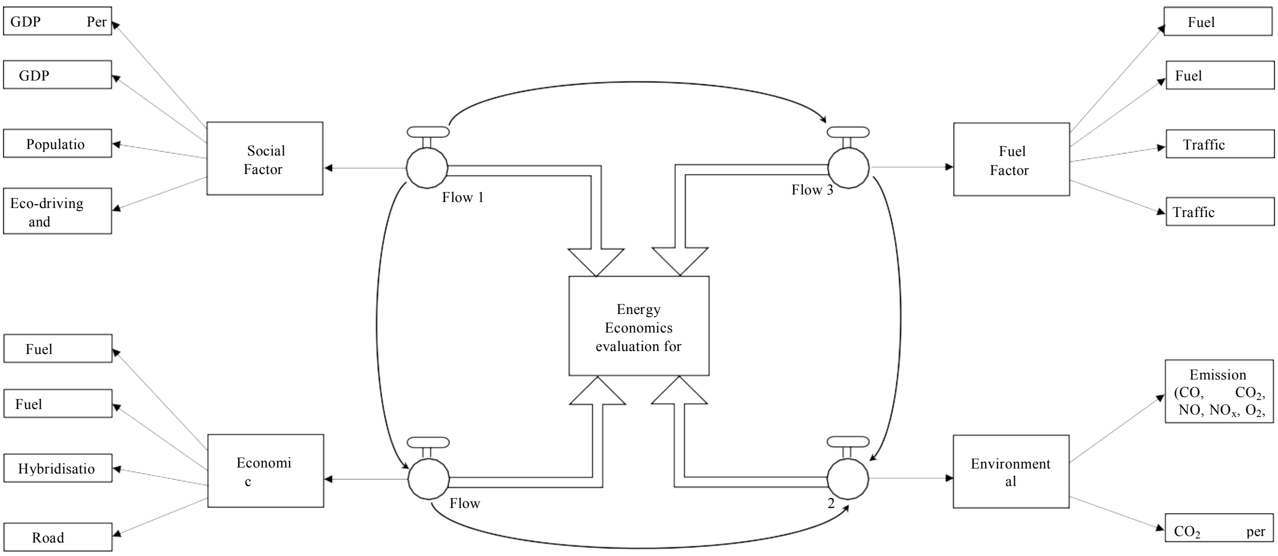

Fig. 3. System dynamic model for the energy economics assessment for the transport sector.

3. MODEL RESULTS AND SCENARIO ANALYSIS

Among the three scenarios analyzed in this study, the do- minimum (base case) scenario, where the assumption is, the normal situation. Scenario II, the 50:50 scenario, which is replacing 50% of private vehicles with public transport facilities, and scenario III, the 70:30 scenario where 30% of the cars on the road will be replaced with public transport. The effect of the road transport sector is considered in two major fields – fuel consumption or energy requirement and GHG emissions. Hence, the outcome was investigated for these two fields in the below three scenarios.

3.1 Do-Minimum (base case) Scenario

Under the base case scenario, it is assumed that the prevailing patterns will remain in the future. The current vehicle exhaust emissions (base case) were derived from the measurements taken during the one-year study. To measure the concentration of CO, CO_2, HC, and NO in vehicle exhaust emissions, two types of tests were applied: the first type in which, the vehicle is in a state of idle, and the second type in which, the vehicle is in the state of accelerating. This data was projected using population increase to forecast emissions until the year 2027.

Based on the number of vehicles operating in the study area for the year 2015, the number of cars until 2027 is estimated, and CO, CO_2, HC, and NO emissions expelled from the cars' exhaust is calculated for each year. Hence, the major emission parameters of CO, CO_2, HC, and NO in terms of parts per million (ppm) and fuel efficiency parameters such as fuel consumption of vehicles were identified for the present scenario. Based on this, the forecasted values till 2027, including the CO_2 per capita are identified and presented in Table 6. The existing growth rate, the amount of fuel consumed by the private car transport sector, and the corresponding emission levels have been simulated. This is presented in Table 1. Table 2 shows the estimated annual cost of fuel while applying the do-minimum scenario.

Table 1. Predicted emissions based on private vehicle population.

Year	Population forecast	Forecasted vehicle population	Emissions (x 10^6) (ppm)				Metric tons per capita
			CO	CO_2	HC	NO	CO_2 per capita
2016	4411124	1708589	2910.43	246173	74.2285	137.134	55807.25
2017	4590028	1798615	3530.22	253640	88.9292	310.979	55258.92
2018	4791651	1894360	4145.04	262549	64.8367	433.847	54793.06
2019	5002837	1996133	5398.84	288882	108.715	475.841	57743.67
2020	5222177	2105223	4614.69	304877	87.4339	327.515	58381.13
2021	5448511	2220438	4435.94	325862	79.0747	315.311	59807.47
2022	5672497	2340437	4972.92	335459	100.92	397.148	59137.75
2023	5890626	2464412	5409.41	352921	106.133	454.917	59912.32
2024	6108252	2594971	5796.45	372564	108.997	484.076	60993.56
2025	6322733	2734216	6128.28	394823	118.39	490.694	62445.07
2026	6553190	2880854	6234.48	415845	119.379	488.722	63456.81
2027	6801274	3035658	6555.37	437952	125.747	522.103	64392.57

Table 2. Prediction of the estimated annual cost for fuel consumption.

Do-Minimum Scenario		
Year	Total volume of fuel consumption liter/month	Petrol Price X Total volume of fuel consumption (liter/month)
2016	391573870.5	46336241.34
2017	279374884.8	33059361.36
2018	294246716	34819194.73
2019	460258854.9	54463964.49
2020	583372659.6	69032431.38
2021	578322858.2	68434871.56
2022	510204409.9	60374188.51
2023	532636613.3	63028665.91
2024	587151647	69479611.56
2025	650984418.5	77033156.19
2026	689504480.8	81591363.56
2027	707447253.2	83714591.63

The number of private cars until the year 2027 is estimated based on the number of vehicles operating in Kuwait for the year 2015. CO, CO_2, HC, NO emissions expelled from the cars is calculated for each year. For do- minimum scenario, the results showed that the trips taken by private cars form a major share and the corresponding CO_2 per capita based on this has been estimated as 64,392.57 metric tons per capita for the year 2027 as shown in Table 1. Inevitably, with the increase in the number of vehicles, the fuel consumed increases. The demand for fuel by private vehicles reaches to approximately 391,573,871 liters per month in 2016. This figure is established by calculating the monthly fuel consumed by the participants in the survey using fuel efficiency details and monthly kilometers reading of surveyed vehicles.

The liters of fuel consumed in a month for each participant is then calculated using the equation:

$$\text{Liters of fuel consumed in a month} = \textit{(Fuel Efficiency/100) x (Monthly Kilometers Driven)} \quad (2)$$

This will give the monthly amount of fuel in liters consumed for each vehicle. The average liters for each month are computed, and then by projecting the current vehicle population to the year 2027, the growth in vehicles is forecasted, thereby, the amount of fuel consumed by vehicles in 2027 is calculated. Fuel consumed is established to be 707,447,253 liters per month in the year 2027. The average quantity of diesel consumed by buses in each month is multiplied by the computed number to determine the quantity of diesel consumed by buses in 2027. Based on the existing scenario, the monthly petrol consumption from vehicles in Kuwait is 400 million liters per month. The cost of fuel consumed by private vehicles is determined by multiplying the amount of fuel consumed monthly by the price of petrol. The average price of petrol is established to be $0.039/liter. This is the average of the three types of fuel, Super, Premium and Ultra that are being used in the study area. The cost of diesel is $0.031/liter. These numbers are multiplied by the corresponding quantity of fuel, and the total cost of fuel is established for buses and private vehicles.

3.2 50:50 Scenario

The second scenario is 50:50, which is replacing 50% of the operating vehicles with buses. The hypothesis considered is that one bus will replace 40 cars. This is shown in Table 3 below.

To achieve the 50:50 scenarios, 50% of the vehicles are replaced with buses. Introducing the metro in the country, and promoting utilization of the services by providing smooth, time-saving commutes can achieve this increase and act as an incentive for 50% of private vehicle owners to replace their daily private vehicle trips by public transportation. This reduces the increase of private cars by 50% by the year 2027 compared to the do-minimum scenario.

The total cost of fuel consumed monthly for both buses and cars are determined. The average quantity of diesel consumed each month (liters/month), was multiplied by the computed number of buses to determine the volume of diesel consumed by buses. Table 4 shows the savings yielded from the 50/50 assumption, the base case monthly cost of petrol was compared to the monthly cost of fuel for 50% of cars and 50% of buses. Savings of 45% were found to be achieved. The total cost of fuel for 2027 was $150,338,987 when this scenario was adopted, where else it was $274,809,891 in the do-minimum scenario, as shown previously in Table 3.

The total volume of fuel consumed by cars, based on this scenario, is 353,723,627 liters per month for the year 2027, which is half of the fuel consumption in do minimum scenario (707,447,253 liters per month). Also, a reduction of 50% is observed in fuel consumed by petrol-driven cars. Table 4 shows the expected savings from scenario II.

3.3 70:30 Scenario

The third scenario is 70:30, where 30% of the cars on the road will be replaced with buses. These two scenarios will further encourage the use of public transportation, decreasing the number of vehicles on the roads in Kuwait, consequently leading to an overall drop in fuel consumption. This, in turn, will reduce energy consumption and emission levels.

In scenario III, 30% of cars have been converted into buses, therefore, giving the 70:30 hypotheses, restricting the growth of cars for the year 2027. In this scenario, public transport has been developed and enhanced to encourage 30% of car owners to replace their daily private vehicle trips to utilize public transportation. This is shown in Table 5. The decrease in private cars leads to a reduction in fuel consumption, as displayed in Table 6. The total cost of fuel consumed in 2027 was $200,127,347 for scenario III, showing a 27% saving was achieved compared to $274,809,891 in the do-minimum scenario.

Adopting one of the presented scenarios can achieve vast financial rewards. This is illustrated below in Table 7. Implementing the simpler policy, the 70:30 hypotheses for the year 2019 can achieve savings of $48,587,794 and eventually savings of $74,682,541 for 2027.

Table 3. Predictions based on 50/50 scenario (Scenario II).

Year	Number of Cars	50% of Cars	Convert 50% of Cars to Buses
2016	1708589	854295	21357
2017	1798615	899308	22483
2018	1894360	947180	23679
2019	1996133	998067	24952
2020	2105223	1052612	26315
2021	2220438	1110219	27755
2022	2340437	1170219	29255
2023	2464412	1232206	30805
2024	2594971	1297486	32437
2025	2734216	1367108	34178
2026	2880854	1440427	36011
2027	3035658	1517829	37946

Table 4. Expected savings from 50/50 scenario (Scenario II).

Year	Base Case - Monthly Cost of Petrol ($)	Monthly Diesel Consumption by Buses (50/50), (liter/month)	Diesel Price ($)	Monthly Petrol Consumption by Cars (liter/month)	Petrol Price ($)	Total Cost ($)
2016	152,107,978	22,956,150	7,159,024	195,786,935	76,053,991	83,213,015
2017	108,523,964	16,378,447	5,107,724	139,687,442	54,261,984	59,369,707
2018	114,300,971	17,250,313	5,379,623	147,123,358	57,150,484	62,530,107
2019	178,788,855	26,982,830	8,414,771	230,129,427	89,394,427	97,809,199
2020	226,612,761	34,200,419	10,665,624	291,686,330	113,306,382	123,972,003
2021	224,651,154	33,904,372	10,573,298	289,161,429	112,325,577	122,898,875
2022	198,190,350	29,910,905	9,327,910	255,102,205	99,095,173	108,423,084
2023	206,904,202	31,226,001	9,738,031	266,318,307	103,452,101	113,190,132
2024	228,080,722	34,421,963	10,734,711	293,575,824	114,040,361	124,775,072
2025	252,876,741	38,164,181	11,901,747	325,492,209	126,438,371	138,340,118
2026	267,839,971	40,422,433	12,605,998	344,752,240	133,919,985	146,525,983
2027	274,809,891	41,474,334	12,934,042	353,723,627	137,404,946	150,338,987

Table 5. Scenario III: 70:30- Private vehicle replacement with public transport systems.

Year	Number of Cars	30% of Cars	70% of Cars	Number of buses after converting 30% of cars
2016	1708588.92	512576.676	1196012.2	12814.417
2017	1798614.754	539584.4262	1259030.3	13489.611
2018	1894359.563	568307.869	1326051.7	14207.697
2019	1996132.838	598839.8515	1397293	14970.996
2020	2105222.841	631566.8524	1473656	15789.171
2021	2220438.327	666131.4982	1554306.8	16653.287
2022	2340436.858	702131.0575	1638305.8	17553.276
2023	2464411.941	739323.5824	1725088.4	18483.09
2024	2594970.579	778491.1736	1816479.4	19462.279
2025	2734215.974	820264.7922	1913951.2	20506.62
2026	2880854.134	864256.2403	2016597.9	21606.406
2027	3035657.703	910697.311	2124960.4	22767.433

Table 6. Predicted savings from 70/30 assumption (Scenario III).

Year	Base Case: Monthly Cost of Petrol Consumed by Cars ($)	Monthly Diesel Consumption by Buses (70/30) (liter/month)	Diesel Price ($)	Monthly Petrol Consumptio n by Cars (liter/month)	Petrol Price ($)	Total Cost ($)
2016	152,107,978	13,773,690	4,295,416	274,101,709	106,475,586	110,770,999
2017	108,523,964	9,827,068	3,064,634	195,562,419	75,966,776	79,031,410
2018	114,300,971	10,350,188	3,227,774	205,972,701	80,010,678	83,238,452
2019	178,788,855	16,189,698	5,048,862	322,181,198	125,152,199	130,201,060
2020	226,612,761	20,520,251	6,399,374	408,360,862	158,628,934	165,028,308
2021	224,651,154	20,342,623	6,343,979	404,826,001	157,255,807	163,599,785
2022	198,190,350	17,946,543	5,596,747	357,143,087	138,733,244	144,329,992
2023	206,904,202	18,735,601	5,842,819	372,845,629	144,832,941	150,675,759
2024	228,080,722	20,653,178	6,440,828	411,006,153	159,656,504	166,097,332
2025	252,876,741	22,898,509	7,141,048	455,689,093	177,013,718	184,154,769
2026	267,839,971	24,253,460	7,563,600	482,653,137	187,487,977	195,051,577
2027	274,809,891	24,884,600	7,760,424	495,213,077	192,366,922	200,127,347

Table 7. Projected financial savings by adopting the scenarios

Year	Savings from 70/30 scenario ($)	Savings from 50/50 scenario ($)
2016	41,336,980	68,894,964
2017	29,492,555	49,154,257
2018	31,062,519	51,770,864
2019	48,587,794	80,979,656
2020	61,584,457	102,640,759
2021	61,051,366	101,752,276
2022	53,860,359	89,767,263
2023	56,228,443	93,714,070
2024	61,983,390	103,305,647
2025	68,721,975	114,536,623
2026	72,788,390	121,313,987
2027	74,682,541	124,470,904

3.4 Discussion

From the analyzed scenarios, by implementing the simpler policy, the 70:30 hypotheses for the year 2019, savings of $48,587,794 and $74,682,541 for the next ten years can be achieved. The economic savings adopting the scenarios on vehicles for the year 2027 were $74,682,541 and $124,470,904 respectively. Therefore, for the year 2027, a considerable reduction of approximately 60.35% is expected in financial terms. At the same time, it is evident that the projections of emissions until the year 2027 vary considerably, spanning around 9,133 metric tons per capita for the next ten years from 2018. This study adds to a notable and needed outlook on how innovative economic policy measures are vital that provide increased energy efficiency in the road transportation sector, and consequently help to downsize CO_2 emissions.

By the assessment of these scenarios, it can be identified that the fuel consumption and corresponding GHG emissions are the major parameters that affect the energy economics of any developing country. The average fuel consumption for a private car in Asia is approximately 10 liters per kilometers [17]. This is comparatively high in comparison with first world countries, for which the value is nearly 5-6 liter per kilometers. Hence, even by improving technology to increase efficiency in private vehicles used in the country, a realistic minimum of a 1% efficiency increase can be achieved in road transportation. This also includes the public transportation segment modes. If the study includes the latest hybrid vehicles and electric vehicles, which produce very low emissions, the energy economics enhancement will be much higher. In line with this, the use of compressed natural gas (CNG), alternative fuels like biodiesel, are other options that were not considered for this study, but are essential to consider in the future. Particularly CNG utilization in public transportation will result in a reduction of fuel consumption and GHG emission reduction.

The predicted population in the study area for the year 2027 is 6,801,274 and the corresponding vehicle population is 3,035,658. These numbers make the transport state of affairs in the study area extra perilous if suitable actions are not taken to restrain the swift surge in the population and corresponding travel and fuel demand. Contemplating the prevailing socio-economic circumstances, including the future energy demand and travel scenarios, developing countries should focus more on developing public transportation facilities including rail transportation. These energy-efficient mass transportation methods will restrict the use of small, private vehicles, which consume high quantities of fuel and emit considerable GHGs.

4. CONCLUSION

Public transport infrastructure development faces multiple barriers in many countries. Endorsing the harmonized development of socio-economic and environmental benefits of road transportation infrastructure is of immense significance to sustainable development. Since it is clear that the other energy-consuming sectors might not be able to compensate for emissions from the road transportation sector; the three scenarios that were evaluated here reveal the development of emissions portfolios that affect attaining and endeavoring environmental protection and climatic change.

The results of this study recommend that a well-tailored transportation policy suitable for each region/country have substantial effect on the national energy demand situation. Road transportation has been prioritized by the government in the previous decades and was improved by substantial investments in the road network. Presently the road transport in the region is dominant with the energy-intensive transportation systems, which are hugely dependent on private vehicles, and hence produce high GHG emissions and high consumption of fuel. It should be noted that the apprehensions about the diminishing quantity of natural resources, ambiguities in international and regional political scenarios and increasing fuel demand has triggered a swift surge of fuel prices that has caused an immobilizing effect on the economy. The road transport sector, which is, accountable for approximately 20-25% of collective general energy consumption, is a significant factor in this situation.

From a regional outlook, the economic evaluation indicates that future dynamics in the transportation energy demand is important as road transportation structure in the region is highly dependent on private vehicles. Developments that are taking place in the electric vehicle technology were not considered in the study. Once the electric vehicle technology is established, the present scenario will surely change. Similarly, the impact of mass mobility, especially the metro rail feasibility is another feature that needs to be investigated. When these two scenarios come into existence, there will be a total change in the present economic and emission characteristics.

Public sector - multi-modal transportation systems- bonding energy-efficient public transportation approaches with less private travel needs blend well with sustainable future. We understand the limitations of this research and suggest some ideas for future research in the same sector, such as multi-modal mass transit and electric vehicle inclusion. Even if energy efficiency features in the road transportation sector have numerous dimensions, this study relies on one dimension- energy economics, which is important.

Finally, this study is based on SDM and does not comprise concerns such as fuel demand price elasticity, economic change related to different scenarios, technological change of vehicles and use of alternative fuels in the vehicle. Moreover, this study does not assess likely choices such as travel demand management, vehicle capacity, and governmental regulatory opportunities. The methodology employed in this study has focused primarily on system dynamics and hence it is static in nature. Their implication can be augmented by incorporating demand dynamic interfaces, GHG emissions and related environmental implications, fuel price as well as international supply politics, which are likely to be included in upcoming studies.

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Active Seismic Structures, Energy Infrastructures, and Earthquake Disaster Response Strategy - Bangladesh Perspective

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Abstract – *Bangladesh is situated at the juncture of the three tectonic plates and the active interaction of these plates resulted in several major active faults in and around Bangladesh, especially along its northern and eastern margins. Some of these faults are regional scale, and capable of generating moderate to great earthquakes. The rate of plate motion, presence of seismogenic gaps in the active faults, and the time since the last rupture of these faults indicate a high probability of impending earthquakes. The country and its neighboring surroundings have experienced high-magnitude earthquakes in the past and caused substantial damage of the infrastructures and lives. Although the possibility of damages arising from a seismic hazard is on the rise due to the dynamic and intensified development of engineering and energy infrastructures, human casualties may decline because of a better understanding of the earthquake mechanism, possible area of seismic hazard, recurrence interval, and the improvement of the monitoring system capabilities. However, due to the lack of a comprehensive seismic zonation map and site-specific probabilistic seismic hazard maps, the human casualty, and property losses, specifically, energy infrastructure will be disastrous. Therefore, the professionals, scientific and technological community of the country should cooperate and make joint efforts to overcome all the scientific and technological hurdles to seismic disaster management of Bangladesh. By considering the importance of the energy sector in the country's rapid economic growth, an in-depth seismic vulnerability assessment of the energy infrastructures is needed to be performed immediately.*

Keywords – *active faults, disaster response strategy, energy infrastructures, seismogenic gaps, seismic zoning map.*

1. INTRODUCTION

Earthquakes, a natural disaster have long dynamically affected the earth's landscape and caused shifting of the large river courses, serious injury to living creatures, drastic changes to the living environment, catastrophic damage to the economy and infrastructures, and even large-scale human migration. In the last few years, earthquakes, an unpredictable but impending threat for Bangladesh sparked much discussion regarding the possible disastrous consequences. Export driven economic growth of Bangladesh in recent years powered by not only the private sector but also by the public sector which has undertaken several mega engineering and energy infrastructure projects with huge investments, and therefore, the continued rise of GDP year-on-year. However, the country's economy faces a double blow in 2020 from short-duration disaster and long duration pandemic the cyclone Amphan, and COVID 19, respectively. These two incidents expose the high vulnerability of the country's economy against natural disasters. Moreover, all major earthquakes had occurred in and around Bangladesh long before the establishment of the country's energy infrastructures (*i.e.,* gas production facilities, processing plants, transmission and distribution pipelines, and oil refinery). It is worth to be mentioned that after 1950, no major to the great earthquake has occurred along the seismogenic gaps, locked thrust, and active faults in and adjacent to Bangladesh. Hence, the sustainability of these energy infrastructures in the case of major earthquakes is unknown.

The country is historically exposed to a number of natural disasters (*e.g.,* Floods, Riverbank erosion, Cyclones, Landslides, Tsunami, and Earthquakes) that disrupt the economy significantly in the past and causes substantial damage of the infrastructures and lives. However, with the advancement of science and technology, almost all the natural hazards can be predicted well before their strike, except earthquakes. This unpredictable natural disaster poses an extraordinary risk for the whole country. Bangladesh and its neighbouring countries have experienced high-magnitude earthquakes in the past [1]-[8], and the consequences were devastating. Among such seismic events, the Chittagong earthquake of 1762 (R 8.5+), Sirajganj earthquake of 1787 (MM X), Cachar earthquake of 1869 (R 7.5), Bengal earthquake of 1885 (Mw 6.8), Great Indian/Assam earthquake of 1897 (Mw 8.1), Srimangal earthquake of 1918 (Mw 7.6), Meghalaya earthquake of 1923 (Ms 7.1), Dubri earthquake of 1930 (Mw 7.1), Bihar-Nepal earthquake of 1934 (Mw 8.1), Assam earthquake of 1950 (Mw 8.6), and Nepal earthquake of 2015 (Mw 7.8) are well known.

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The maximum felt intensity of these seismic events is localised in the tectonically uplifted region of the Bengal Basin [2]. If such a magnitude earthquake occurs at present in or adjacent to Bangladesh, the devastation may get intensified manifold because of the huge population density in the poorly-planned urban areas. Recent earthquake occurrences and their colossal damages in neighbouring countries, like Nepal (7.8 Mw, 2015/4), Myanmar (6.9 Mw, 2016/4), and India (6.7 Mw, 2016/1) further exacerbate this issue. Bangladesh itself experienced several small to moderate shocks during this time, in which Mw 4.9 in Madhabpur (2017/11), Mw 4.7 in Rangamati (2016/6), Mw 4.6 in Sarankhola (2015/4), Mw 4.5 in Chhatak (2017/4), and Mw 4.5 in Sylhet (2020/1) are the noticeable one. It is thought-provoking to see that except for the Sarankhola earthquake, the rest of them belong to the high seismic prone area, as demarcated in the earthquake zonation map of Bangladesh (Figure 1).

The geodynamic development and multifaceted neotectonic evolutions of the Bengal Basin result in several active faults in and around Bangladesh, especially along its northern and eastern margins. Some of these faults are regional, and capable of generating moderate to great seismic events. The rate of motion and recurrence interval indicates that the probability of earthquakes from the existing active faults is high [8], [9]. A general increasing trend of seismic/earthquake activity has been observed in and around Bangladesh in recent years [9], [10]. This apparent increase of seismicity in the Bengal Basin indicates either new faults propagation from the preceding seismically undisturbed zones or the reactivation of some earlier faults in pre-existing seismically active zones. Considering the above risks, Bangladesh needs to devise preparation and disaster response meticulously that will contemplate every possible aspect of the potential earthquake damage, specifically the energy infrastructures. It is necessary to prepare a comprehensive seismic hazard map and all engineering constructions and energy infrastructure, specifically large-scale ones, need to strictly follow this hazard map guideline during the construction and subsequent operation/maintenance. This review study is aimed to address the current state of seismic vulnerability, and highlighting the possible disaster response strategies for energy infrastructures in Bangladesh's perspective.

2. TECTONIC SETTING OF BANGLADESH

Bangladesh constitutes a major portion of the Bengal Basin, which is the largest peripheral collisional foreland basin in South Asia [8], [11]. Hence, the geology of Bangladesh is an integral part of the geology of the Bengal Basin. Geographically, the basin also covering parts of the Indian States of West Bengal, Assam, Tripura, and Mizoram. The Bengal Basin is surrounding by four major geotectonic units, which are the Indian Shield to the west and the Shillong Plateau to the north, the Indo-Burman Ranges to the east and the Bay of Bengal to the south [12] (Figure 1). The Bengal Basin (Bangladesh) has been divided into three major geotectonic provinces: i) Geotectonic Province 1– the Stable Shelf to the northwest, ii) Geotectonic Province 2 – the Foredeep Basin at the center, and iii) Geotectonic Province 3 ¬– the Folded Flank to the east [8], [13]-[15].

Active tectonics and earthquake geology in these provinces and their adjacent regions are directly related to the oblique collision of the Indian Plate with the Eurasian Plate to the north and the Burmese Plate to the east (Figure 1). The collision developed the Himalayan Orogen to the north, and Indo-Burman Orogen to the east [7], [16], [17]. Based on recent seismic studies, it is presumed that subduction has clogged below the Himalayan arc and is only actively continuing below the Burmese–Andaman arc [18]-[20]. Due to plate convergence and resistance to subduction below the Eurasian Plate, tectonic deformation and seismic activity occur in the Indian intra-plate region, including the stable shelf in the western part of Bangladesh. To the north, tectonic loading is accommodated along the Dauki Fault zone, which is a set of high angle, deep-seated reverse faults [21], [22]. To the east, the collision results in westward migration of accretionary prism complexes and the deformation front as well [7], [8], [12], [16]. The cumulative effects of these complicated neotectonic evolutions around the Bengal Basin result in several active faults in and around Bangladesh.

Geologically, the earthquakes are not isolated events for Bangladesh, rather a part of events that have been mainly occurring along these active faults located at the juncture of three tectonic plates - the Indian, the Eurasian and the Burmese plates. Recent geodetic measurement shows that the motion of the Indian Plate is ~6 cm/yr in the northeast direction, which results ~4.5 cm/yr rate collision with the Eurasian Plate, and ~4.6 cm/yr rate collision with the Burmese Plate [23]. This contractional motion is taken up by stress accumulation and strain partitioning mainly along some major active faults, which are broadly distributed over a series of reverse and strike-slip structures. The probability of an earthquake from such an active fault depends on the rate of motion and the time since the last rupture (i.e., the recurrence interval).

3. MAJOR ACTIVE FAULT IN AND AROUND BANGLADESH

Tectonically active faults of regional-scale capable of generating moderate to strong earthquakes are present mainly in the north and eastern part of Bangladesh and its neighbouring surroundings [8], [9], [11], [24-27]. In Bangladesh, the major active faults are - about 320 km long east-west trending Dauki Fault, located along the southern edge of the Shillong Plateau; the 150 km long

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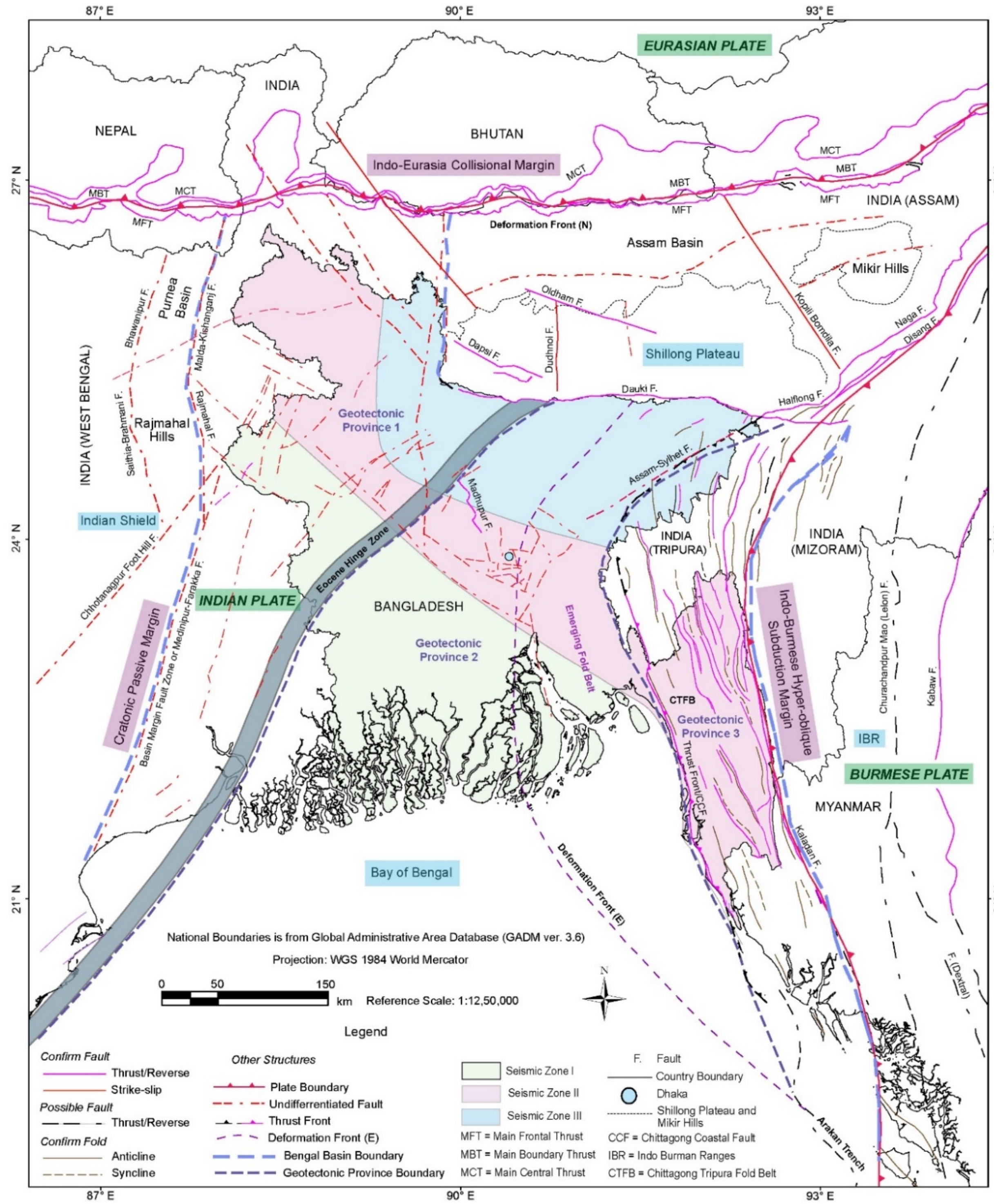

Fig. 1. Simplified tectonic map of the Bengal Basin (Bangladesh) and its surroundings (modified after Hossain *et al.* [12]) superimposed on the tectonic zonation map of Bangladesh [28]. All major active faults in and around Bangladesh have been labeled on the map. Other seismogenic features potential to major earthquakes are also labeled. BNBC [28] divides Bangladesh into three seismic zones with coefficients representing peak ground acceleration (PGA). The PGA of 0.25g (Z=0.25) for Zone III, 0.15g for Zone II, and 0.075g for Zone I. Note: g is the acceleration due to gravity, Z represents design basis earthquake (DBE). Among these three zones, Zone I is seismically less active, zone II is moderately active and Zone III is seismically most active.

Madhupur Fault trending approximately north-south located at the western edge of the Madhupur Tract; the Assam-Sylhet Fault of about 150 km length trending northeast to southwest located in the southern edge of the Surma basin; and the Chottogram-Coastal Fault (CCF), which is a plate boundary fault of about 800 km long, running parallel to the Chittagong-Arakan coast and reaches inland up to the Tichna anticline near

Bangladesh-Tripura border; and ~450 km long west verging Kaladan Fault, which mostly follows the course of the Kaladan River along Bangladesh-Myanmar border. In the adjacent surroundings, major active faults are - east-west running Main Frontal Thrust (MFT) to the north; WNW-ESE running Oldham Fault also to the north of Shillong Plateau; the Dapsi Fault strikes WNW across the western Shillong massif; the NE-SW running Hafflong-Disang Fault to the northeast; Kabaw and Sagaing faults progressively towards the east of Bangladesh. All these faults had generated devastating earthquakes in the past and can potentially generate a large seismic event in the near future.

The Dauki Fault is an intra-plate active reverse fault with a dextral strike-slip component. The continuous active subsidence of the southern footwall of the Dauki Fault has resulted in the Surma basin [29]. Geomorphic indices suggest that the fault is tectonically more active in the eastern part than in the western portion [30], [31]. The flexural seismic event has been identified along the Dauki Fault near Jaflong (Sylhet) and is inferred to be AD 840-920 [26]. Another rupturing event in the Dauki Fault was estimated to be AD 1548 [25], [26]. It is also assumed that the 1897 Assam earthquake that occurred along the Oldham Fault also caused a slip along the Dauki Fault. Although it was previously thought that the interval between these giant plateau-building earthquakes exceeds 3,000 years [21], the paleoseismic signature indicates a recurrence interval of 350-700 years [26]. The Madhupur Fault is constituted of a series of en-echelon faults, and flanks the western side of the uplifted Madhupur High [9], [12]. It is believed that this fault resulted either from the torsion of the region or from the effect of compressive shear along the western edge of a possible buried anticline or possibly a combination of both [8], [32]. This thrust fault is east-dipping and is considered as an important structure for the seismic hazard assessment of the central part of Bangladesh. The cyclic avulsion history of the Brahmaputra River with a periodicity of about 1800 years is most likely related to the uplift of the Madhupur High due to slip along the Madhupur Fault [33]. The Assam-Sylhet Fault also known as Hail Hayalua Lineament is a major fault, which is probably the southwest extension of the Naga-Disang Thrust [34]-[38]. In November 2017, a shallow focus (30.3 km depth) earthquake with Mw 4.9 occurred at a distance of 27 km SSW of Habiganj, Bangladesh is probably related to the Assam-Sylhet Fault.

The CCF is a dextral strike-slip fault with an appreciable thrust component and is a resultant product of thin-skinned and thick-skinned tectonics [39]. This fault is seismically less active. Maurin and Rangin [39] suggest that the CCF can be interpreted as a deep-seated basement reverse fault with a dextral strike-slip component. The Moheskhali earthquake with 5.2 Mw occurred in Moheskhali Island in July 1999 is a proof of seismic slip along the CCF. This earthquake was strongly felt all over Bangladesh and caused significant damage locally [40]. Moreover, the occurrence of any large seismic event in the offshore area along the east coast of the northern Bay of Bengal is likely to produce a great tsunami [41]. In 1762, one of such large earthquakes (R 8.5+) occurred along the Arakan coast (i.e., Arakan subduction zone) known as Chittagong/Arakan earthquake [2], [4], [7], [41], [42]. The ~450 km long west verging Kaladan Fault mostly follows the course of the Kaladan River [39], [43], [44]. This fault marks the eastern boundary of the CTFB and extends from the Arakan coast in the south to the northern-most part of the CTFB and the IBR contact [4], [7], [12], [39]. Although the Kaladan Fault shows dextral strike-slip as well as west verging thrust components, it is generally considered as a thrust fault, and seismically the fault is sparsely active. While Mw 6.2 earthquake in December 1955 along the Kaladan Fault near the Bangladesh-Myanmar border region is a proof of seismic slip, mainly shallow focus and low-intensity earthquakes are observed along this fault [4].

Besides, the main active faults in the central part of Bangladesh are Madhupur, Dhaleswari, Padma, and Meghna. Around the Dhaka City, few other active faults are also present, which include the Bangshi and Turag faults to the west, Tongi Khal Fault to the north, Balu, Sitalaykha, Banar, and Arial Khan faults to the east, and Buriganga Fault to the south [8], [12]. The 1812 Dhaka earthquake (MM VIII), the 1845 Sirajganj earthquake (Mw 7.1), the 1846 Mymensingh earthquake (Mw 6.2), the 1885 Bengal (Manikganj) earthquake (Mw 7), the 2001 Dhaka earthquake (Mw 4.5), the 2008 Mymensingh earthquake (Mw 5.1), and the 2008 Chandpur earthquake (Mw 4.5) caused damage, especially in Dhaka City [2], [8], [45]. Among these, the 1846 and 2008 Mymensingh earthquakes probably occurred along the Old Brahmaputra Fault, the 1885 Manikganj earthquakes probably occurred along the Madhupur Fault, and the 2001 Dhaka earthquake possibly occurred along the Buriganga Fault. In the eastern part, medium to small-scale thrust faults with strike-slip components are present in the CTFB area. These faults are mostly parallel to the strike of the anticlines, and mostly affected the folds of the CTFB regions [8], [15], [27], [39], [46]-[49]. Few moderate magnitude earthquakes are recorded, which may be connected with these faults of the CTFB region. Among such events, the Bandarban earthquake in 1997 (Mw 6.1), and the Barkal earthquake in 2003 (Mw 5.7) are well known [8].

In the western part of Bangladesh, several faults and lineaments have been identified that have the potential to generate earthquakes of Mw 3.5 and above [45]. Major active faults are the Jangipur–Gaibanda Fault, and the Katihar-Nilphamari Fault. The Eocene Hinge Zone is also identified as a seismically active tectonic element, which is reportedly triggered two earthquakes of magnitude Mw 7.3 and Mw 6.2 in 1842, and 1935, respectively [2], [8], [45]. Although this part of the country is not subjected to any direct seismic event with high magnitude, the younger unconsolidated fluvial sediments are even prone to liquefaction under favourable ground shaking from distal seismic events. The 1737 Kolkata earthquake, the 1787 Sirajganj earthquake (MM X), the 1842 Rajshahi earthquake (Mw 7.3), the 1897 Assam earthquake (Mw 8.1), the 1934 Bihar-Nepal earthquake (Mw 8.1), and the 1935 Pabna earthquake (Mw 6.2) had widely affected the western part of the Bangladesh and adjacent Indian region [1], [2], [8], [45], [50].

4. SEISMOGENIC GAP, LOCKED THRUST, AND SEISMIC HAZARD MAPS

Among all these active faults, the presence of three important seismic gaps in three major active faults - the eastern segment of the Dauki Fault, northern segment of the Chottogram-Coastal Fault, and Bhutanese segment of the MFT causes major apprehension to the earthquake geologist [8], [11], [51]. In general, a seismic gap is a locked segment of an active fault, which is supposed to produce a significant seismic event that has not been slipped in a long time, in comparison to other segments along the same fault [8], [16]. It is worth mentioning here that the eastern segment of the Dauki Fault has not been slipped in the recent past, but was it to slip in a single earthquake, its potential maximum magnitude would constitute a significant seismic threat to nearby densely populated areas and energy infrastructures of Bangladesh, India, Bhutan and Nepal [52]. Disturbingly, the other two seismic gaps in the rest two major active faults are also close to Bangladesh, compared to the other segments of these faults. Therefore, a possible high-intensity seismic event in any of these seismic gaps will cause catastrophic consequences for a large part of the country [11]. Moreover, the faster convergence rate and presence of seismogenic gap along the East Himalayan deformation belt (Bhutan Himalaya) can produce earthquakes with great magnitudes analogous to those of oceanic subduction zones [5], [53], [54]. On top of that, the deformation to the east along which the Indian Plate subducting beneath the Burmese plate at the rate of 13–17 mm/year appeared to be loading the locked shallow megathrust (Deformation Front- E) that connects CCF, Kaladan, and Kabaw Faults (Figure 1). As in the case of other subduction zones, the accumulated strain from this locked thrust will likely be released in future large earthquakes [16], [51]. The three seismogenic gap and locked shallow-mega thrusts to the north and to the east will significantly control the seismic activity within Bangladesh and its surroundings in the future [11].

Despondently, in producing the earthquake zonation map of Bangladesh [28], [55]-[57], these three seismogenic gaps and locked shallow-mega thrusts have not been considered yet. Even, none of the probabilistic seismic hazard maps of Bangladesh [57]-[61] comprehensively considered these seismic gaps, and therefore, we are completely unaware of the possible consequences. Besides, the basement rock in most parts of Bangladesh is covered by an enormous thick pile of Tertiary soft sedimentary rocks, and therefore, it is necessary to accurately estimate the attenuation of seismic waves through these soft sediments. In the absence of specific attenuation laws for Bangladesh geology, an attenuation relationship for the country has been developed by Islam *et al.* [62], but required validation and further improvement with consideration of local geological structures and tectonic deformation.

5. SEISMIC VULNERABILITY OF THE ENERGY INFRASTRUCTURES

It is a point to be noticed that all major earthquakes had occurred in Bangladesh and adjacent regions long before the establishment of the energy infrastructures (gas production facilities, processing plants, transmission and distribution pipelines, and oil refinery) across Bangladesh. Moreover, it has to be emphasized here that after 1950, no major to great earthquake have occurred along the seismogenic gaps, locked thrust, and active faults in and around Bangladesh as mentioned earlier sections. Therefore, it is difficult to determine how sustainable will be these energy infrastructures if major earthquakes that have witnessed in the past occur during the present times. It is speculated that the Dauki, Assam-Sylhet, CCF, Kaladan, and Madhupur faults which have already generated great earthquakes are capable of doing the same in the near future [7]-[9], [11], [25], [26]. Moreover, recent studies also suggest that the locked shallow megathrust (i.e., Deformation Front- E; Figure 1) is also highly potential for a major earthquake [16], [51], [63], [64].

Now if we look to the map of the gas fields, gas processing plants, gas transmission networks, oil refinery, Moheshkhali Floating LNG (MLNG) Terminal, and Matarbari LNG Terminal, all these energy infrastructures belongs to the eastern and southeastern part of the country (Figure 2). Moreover, Chittagong and its adjacent area are heavily industrialized and several export processing zones also present in this area. If we compare the energy infrastructures map (Figure 2) with the tectonic zonation map of the country (Figure 1), it is clear that most of these infrastructures are belongs to the Zone II and Zone III (Figure 2). Interestingly enough, the major gas transmission pipelines pass transversely over the CCF, Assam-Sylhet, and locked shallow megathrust (Figures 1 and 2). Since these pipelines are essential for the economic lifeline of the country, it is very important that the pipelines withstand the shaking from a major earthquake. However, no such study is yet performed. On the other hand, the Ruppur Nuclear

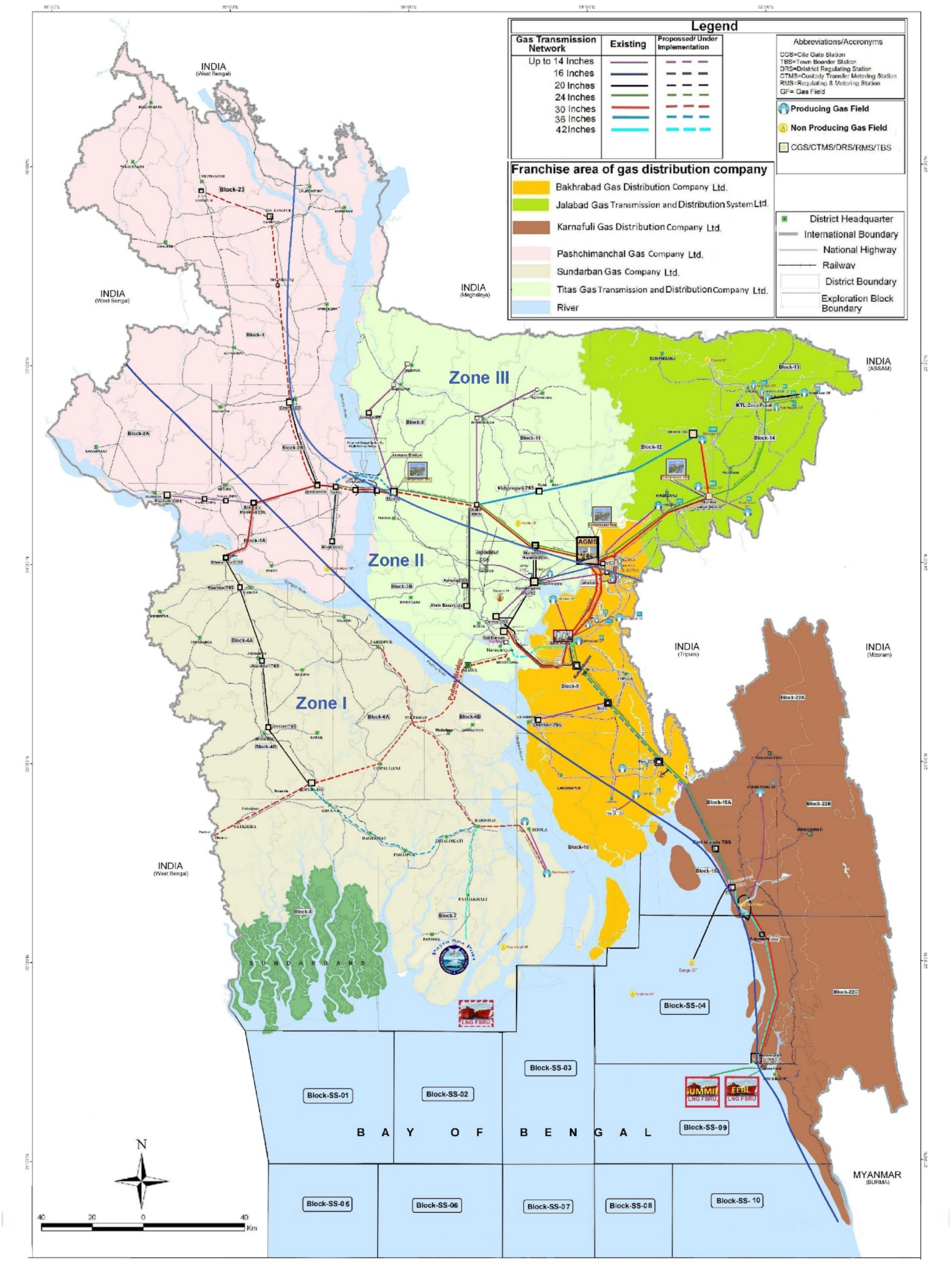

Fig. 2. Energy infrastructures (gas fields, gas production facilities, processing plants, gas transmission network, and oil refinery) map of Bangladesh [66]. The three earthquake zones [28] are marked (solid blue lines) on top of the map to show the spatial distribution of the energy infrastructures.

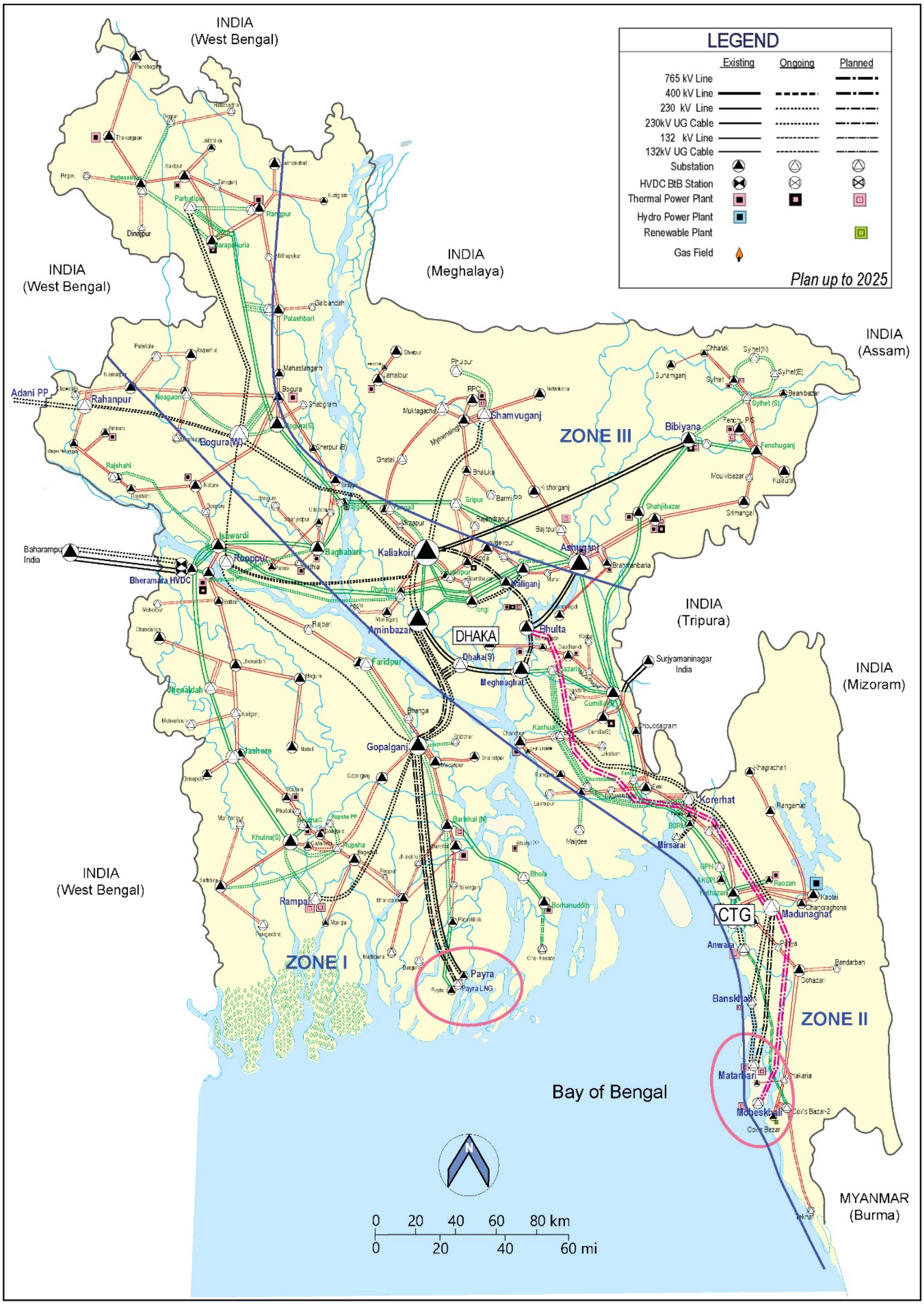

Fig. 3. Map of the Power Grid Plan 2020-25 of Bangladesh [67]. The three earthquake zones are marked (solid blue lines) on top of the map to show the spatial distribution of the power grid infrastructures. Red ellipses mark the three under construction power hubs [65] in which in Matarbari and Maheskhali located in the south-east, and Payra is located south-west of the map.

Power Plant of Bangladesh, which is under construction, belongs to the southern edge of the Zone II.

In addition, the concentration of major power grid infrastructures of Bangladesh is located in seismic Zone II, except the Asuganj hub, which is situated in the south-eastern corner of the seismic Zone III (Figure 3). As part of the Power System Master Plan 2016 [65], the Bangladesh government is setting up three new energy hubs in three locations to boost the country's power generation capacity over the next two decades. Two of them are located in Matarbari and Maheskhali of Cox's Bazar district (south-east Bangladesh), and the other one is located in the Payra of Patuakhali district (south-west Bangladesh). These power hubs will use imported coal and liquefied natural gas (LNG), and therefore, situated in the coastal areas. These hubs will house 21 mega power plants with a total generation capacity of 28,600 MW in which the Maheskhali hub will have eight mega power projects with a generation capacity of 12200 MW, the Matarbari hub will house seven plants with 6200 MW capacity, and the Payra hub will house six plants with 10200 MW capacity. Although, the Matarbari and Maheskhali Island located in the seismic Zone II [28] (Figure 3), Carlton *et al.* [59] did probabilistic seismic hazard analysis (PSHA) of this offshore area found that the area is a highly seismic region due to presence several active faults (*e.g.,* CCF, Kaladan faults) (Figure 1). Furthermore, Cummins [41] suggests that the occurrence of any large seismic event in this part of the offshore area is likely to produce a great tsunami. As the uninterrupted power supply is the backbone of an economy, hence it is very important that the power grid infrastructures of Bangladesh withstand the shaking from a major seismic event. However, a comprehensive study is yet to be performed.

Historically, energy infrastructures, specifically gas and oil pipelines underwent damages across the globe due to major earthquakes in the past. Ground fissures and lateral spreading due to liquefaction triggered by the 1971 San Fernando earthquake (Mw 6.6) results in major damage to pipelines. Underground ductile steel pipes are subjected to substantially damaged due to faulting and lateral spreading of the ground [68]. Interestingly, although there were no reports of liquefaction, landslides, or faulting during the 1985 Michoacan earthquake (Mw 7.6), there were reports of damages to water pipelines. Later it has been determined that the damage in the pipelines was mostly due to amplification of the propagated surface wave through clay deposits [69]. During the 1989 Loma Prieta earthquake (Mw 6.9), the gas mains and service lines of Pacific Gas and Electric Company underwent damages due to liquefaction and ground fissures [70]. During the 1994 Northridge earthquake (Mw 6.7), a total of 1400 pipeline breakages were reported across the San Fernando Valley due to high liquefaction, and led to fire breakouts at several locations across the valley [70], [71]. During the 1999 Izmit earthquake (Mw 7.6), the highest damage was reported from the water supply distribution system in Adapazari due to the crossing of pipelines over the right lateral strike-slip fault. Similar damage was also observed in a pipeline crossing the North Anatolian Fault [72]. During the 1999 Chi-Chi earthquake (Mw 7.6) in Taiwan, several buried gas pipelines were bent as a result of ground deformation due to the movement at a reverse fault [72]. The 2011 Great East Japan Earthquake (Mw 9) also known as Tohoku Earthquake is a classic example of the triple disaster of earthquake, tsunami and nuclear accident [73], [74]. About 20,000 people were dead or missing and around 500,000 people were forced to evacuate due to the tsunami and subsequent meltdown of the Fukushima Daiichi nuclear power plant triggered a nuclear emergency. The direct economic loss from this triple disaster is estimated at $360 billion.

From the above discussion, it is apparent that energy infrastructures, specifically gas transmission pipelines in the north-eastern, eastern and south-eastern parts of Bangladesh are vulnerable to possible seismic hazard. From the historical observation of pipelines damage related to the earthquake as discussed earlier, it is observed that most damages in the pipelines have occurred due to local site effects (ground condition or rock types) and/or crossing over active faults. As mentioned earlier that the pipelines in Bangladesh have not yet experienced any major to great earthquakes, and therefore, have not undergone any damages related to local site effects and faulting. However, it can be logically argued that the upper ground surface of the north-eastern, eastern, and south-eastern parts of the country is vulnerable to local site effects and thus the pipelines crossing through these areas are equally at risk.

6. SEISMIC VULNERABILITY ASSESSMENT AND ITS IMPLEMENTATION

Now the important questions are: what should be done in preparation, and what makes us well prepared for seismic disasters? It is worth remembering that what we cannot do normally, cannot be done well during the emergency period. Good preparation will enable us to respond successfully to seismic disasters. In this connection, we need to do nationwide collaborative research involving geologists, seismologists, urban planners, and civil engineers to develop a comprehensive probabilistic seismic hazard map for the whole country. Earthquake geologists can play a vital role in interlinking the earthquakes and the underlying geology. The things that to be noticed are where an earthquake can possibly occur (major active faults), segmentations in the major faults (seismogenic gap), the geological setting of specific focus areas (collisional or subductional plate boundary zone), the possible surface effects of an earthquake (liquefaction and lateral spreading), identification of the past seismic events recorded geomorphologically (paleoseismicity for recurrence interval), and how to apply all these knowledge to comprehensively evaluate possible seismic hazards and their impact on the present-day society [75], [76]. A number of researches have been done on structural geology and tectonics by taking into account all the relevant geological/seismological attributes [2], [7], [8], [9], [11], [16], [24]-[26], [29], [39], [41]. Recently, a comprehensive tectono-structural framework map of Bengal Basin (Bangladesh) has been published, which documents all active faults in and around Bangladesh ([12]: Main Map). During the development of the future earthquake zonation map and probabilistic seismic hazard maps of Bangladesh, these studies need to consider and new research should be performed.

In addition, to evaluate the seismic vulnerability of the energy infrastructures, specifically gas pipelines, it is essential to estimate the seismic hazard potential of the upper ground surface (soil) within which the pipeline is laid. Geologically, basement rock in the eastern part of Bangladesh is covered by a huge thickness of Tertiary sedimentary rocks. The upper surficial parts of these rocks are made of soft sediments (soil), which is susceptible to liquefaction. According to Honegger and Wijewickreme [77], liquefaction induced lateral spreads tend to cause more damage to pipelines than liquefaction itself. Studies suggest that lateral spread is generally common at places close to river banks, and coastlines. Raghukanth and Dash [78] report the occurrence of lateral spreading along the banks of Brahmaputra due to the 1897 Assam Earthquake. The gas pipelines in Bangladesh also cross the Meghna, Jamuna, and many other small rivers that flow from the north, north-east, and east. By taking into consideration of the past studies and damage reports [78], it could be said that at several points, the pipelines in Bangladesh may be susceptible to damage from lateral spreading triggered by a possible earthquake. However, to understand the possible extent of damage, no such studies are performed yet. Therefore, assessment of lateral spreading of soils needs to be performed using empirical (for regional assessment of lateral ground deformation) as well as mechanistic (for site-specific assessment of lateral ground deformation) approaches [77], [79]. The empirical approach is good for estimation of Liquefaction Severity Index (LSI) for lateral spread occurring along gently sloping sediments deposited during Late Holocene, which is the case of Bangladesh.

7. DISASTER RESPONSE STRATEGIES

Considering the above risks we, therefore, need to devise our preparation and disaster response meticulously that will contemplate every possible aspect of the potential earthquake damage. We should immediately record and preserve detailed drawings, photos, images, and technical reports of all energy infrastructures. It is also imperative to make a disaster response master plan immediately by considering the possible worst-case scenarios. The plan also needs to be updated and evaluated based on the spatial extent of energy infrastructures, and the current state of scientific and technical advancement in every five years interval. This disaster response master plan needs to consider the following major issues: a) Up to date records of the available competent energy infrastructure professionals in the country. b) Immediate after a major earthquake, geotechnical and engineering professionals must need to conduct quick temporary safety assessment checks and related measures for partly damaged energy infrastructures; inform the associated risk to the concerned authorities or organizations accordingly. c) Making short notice availability of heavy logistics, accessories, and other emergency supplies. d) Repair and reconstruction should be based on economic feasibility, the urgency of demand, and considering the importance of national energy interest. It is essential to devise policy by involving local experts and professionals for repair, reconstruction, maintenance, and management of the energy infrastructures.

Besides, all major engineering constructions, specifically large-scale ones, need to strictly follow the probabilistic seismic hazard map guideline during the construction and subsequent operation/maintenance. Following any disaster, it is indispensable to compare the pre and post-disaster aerial photos immediately to pinpoint the relevant disastrous impacts in the affected areas. Repair and rescue workers in remote areas heavily rely on maps in the planning of their post-disaster operations, and therefore, pre-disaster maps need to immediately update based on the post-disaster aerial photos. Archiving relevant maps and aerial photos to make them readily available for disaster response is the strategic responsibility of the Power Division and its utility companies, Petrobangla and its subsidiary companies, Geological Survey of Bangladesh (GSB), Bangladesh Space Research and Remote Sensing Organisation (SPARRSO), and Survey of Bangladesh (SoB). Post-disaster aerial photo surveys can be done by the Bangladesh Air Force (BAF) and the photos need to be immediately transferred to the GSB, SPARRSO, and SoB for processing and interpretation. The total process needs to be completed in the shortest possible time, and necessary information needs to be disbursed to relevant authorities. Regular emergency drills are necessary to train the professionals/employees of the energy sectors and emergency response workers to be well prepared for seismic disasters.

To the end, it is indispensable to study the earthquake resilience of critical infrastructures as a part of the comprehensive Disaster Risk Reduction (DRR) [80] for Bangladesh. Critical infrastructures are the organizations, facilities, and assets (physical or virtual), whose incapacity or impairment would have a debilitating impact on national security, economic security, public health safety, significant disruptions to public order, or other dramatic consequences [81]. As mentioned earlier, the current development of Bangladesh is characterized by high economic growth rates, and critical infrastructures are constantly

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expanding. Therefore, possible major seismic events, and their associated critical infrastructure impacts and recovery trajectories are needed to be carefully assessed. It is also important to understand the interlink and dependence of critical infrastructures [82]. Focusing on critical infrastructure protection and management should be a part of the core strategy of the DRR when investing and extending these infrastructures to improve their resilience.

8. CONCLUSIONS

Taking into account past energy infrastructures damage reports, it is to remember that the cost of the damage and number of fatalities primarily depend on the intensity of the earthquake, depth of the hypocentre, distance of the relevant infrastructures from the epicentre, geology of the area, and quality of the engineering constructions. We need to keep in mind that earthquake is a natural calamity; it does not kill people directly; rather engineering and energy infrastructure damages during an earthquake kill people. The cumulative effects of very high population densities, the vulnerability of the existing poorly constructed energy and engineering infrastructures, the potential for liquefaction and seismic-wave amplification within the thick pile of soft sediments, and the low seismic attenuation of the Indian Shield may results catastrophic damage in Bangladesh during a major earthquake. The destruction or partial damage of engineering and energy infrastructures can be possible to control largely by implementing guidelines based on a comprehensive seismic zonation map and site-specific probabilistic seismic hazard map during construction. For existing energy infrastructures, an in-depth seismic vulnerability assessment study is needed to be performed immediately. More than anything, it's crucially important to make all the energy infrastructures professionals and relevant authorities understand that earthquake disaster risk is real, and to convince them to act accordingly in order to make earthquake-resilient energy infrastructures for Bangladesh.

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Energy Security and Disaster Risk Governance in Energy Sector of Bangladesh

Khan Ferdousour Rahman*, Indrajit Pal*[,1], and Afshana Parven[#]

Abstract – *Bangladesh is prone to various hydrometeorological hazards due to its geophysical location. The exposures and resulting impacts of these natural hazards are aggravated by persistent social, economic and environmental status. Compounded with the country's current dependence on imported fossil fuels and other challenges, this study seeks to stimulate discussions around the complementarity of energy sector as well as its linkages with disaster risk governance and promote good governance in the sector that integrates energy policies, disaster risk governance and climate change impacts. The energy sector plays a critical role in all stages of the disaster management cycle; especially considering that all societal service systems rely on the energy sector for everyday activities, as well as for emergency response and recovery (e.g., telecommunications, health, and infrastructure). Addressing the resilience of energy systems as a component of disaster risk governance, and in response to climate change, requires considering all the components of the power supply value chain. These components should be deployed in line with relevant national policy frameworks (i.e., national development plans, energy policies, building policies, among other regulations and planning instruments), availability of technical capabilities, and financial resources, among others. However, this has been observed that energy-related measures are poorly considered in the early stages of the disaster risk governance cycle. Therefore, this study proposes to promote the resilience of the energy sector in Bangladesh through comprehensive measures. With that in mind, efforts have been made to identify challenges, gaps and recommend plausible measures for solutions.*

Keywords – *disaster risk governance, fossil fuels, natural hazards, power supply value chain, resilience.*

1. INTRODUCTION

Disasters leave adverse impacts on humans, natural ecosystem, social systems and human wellbeing. The natural and anthropogenic hazards may lead to disasters, which cause short and long term impacts on social and economic development of the country. The shocks and stress due to the disasters gradually erode assets of citizens, increase social and economic inequity, and often divert critical resources from development towards creating humanitarian goods and services for the affected people [1]. In recent decades, Bangladesh has achieved commendable success in economic and social indicators [2]. Bangladesh is one of the rapidly developing countries in South Asia [3]. The average annual GDP growth rate was 5.7% between 1996 to 2016, with a peak of 7.1% observed in 2016 [4].

One of the key indicators to measure overall economic as well as social development of the nation is energy, which has determinant influence on Human Development Index [5]. Bangladesh is ranked 136 with the Human Development Index (HDI) 0.608 which is significantly good while comparing to World HDI value 0.728 [6]. The country has been dependent on fossil fuels for its electricity generation and a continued reliance will require an increase in fossil fuel imports to satisfy the growing electricity demand, as domestic reserve is inadequate [7].

Energy sector is one of the most essential elements for achieving national vision of reaching developing country status by 2021 and developed country by 2041. Energy demand in Bangladesh has significantly increased over the past decades. A large number of Bangladesh's power plants are heavily dependent on expensive imported fossil fuel energy resources. Thus, the power supply adversely affects the socio-economic development of the country. On the other hand, a recent study titled "Bangladesh Power Review: Overcapacity, Capacity Payments, Subsidies and Tariffs are set to Rise Even Faster" by the Institute for Energy Economics and Financial Analysis (IEEFA) finds that the power sector of Bangladesh is heading towards financial disaster due to the current plan to increase power capacity based on a switch to expensive imported coal and liquefied natural gas (LNG).

In the context of disaster and development, United Nations International Strategy for Disaster Reduction (UNISDR) have identified three key variables "disaster reduction, social and economic development, and sympathetic environmental management" [8]. Apart from the sudden shocks of natural or/and anthropogenic events, there are number of underlying factors partially or fully responsible for increased vulnerability *e.g.*, growing urban population and increased density, weak local governance, insufficient participation by local stakeholders in planning and urban management, coordination challenges during emergency services, adverse effects of climate change, *etc.* [9][, 10].

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Capacity building through the creation of skilled and trained professional manpower is one of the major components in Disaster Risk Reduction, which also caters to the need of reduction of impacts of climate change through holistic developmental adaptation [11].

The enhancement of resilience to disasters through the modernization of energy systems requires monitoring and verification to determine and evaluate the real reach of their impacts. Each phase of intervention requires a set of indicators that allow evaluators to measure performance in relation to a baseline scenario. It should also be used for policy learning, guiding changes or modifications based on progress or changes in conditions. The objective of this paper is to identify key elements that would allow the integration of energy sustainability and disaster risk governance (DRG) strategies in Bangladesh.

2. BANGLADESH ENERGY PROFILE

Bangladesh is located in the heart of the Ganges-Brahmaputra-Meghna Delta in South Asia and borders India on 3 frontiers: west, north and east, Myanmar on the south-east, and the Bay of Bengal on the south. The country has an insufficient energy reserve; small amounts of oil, coal and countable natural gas reserves [12].

Disasters are frequently occurring phenomena in Bangladesh, a land of about 160 million people within its 147,570 sq. km territory. The country is exposed to several geological, hydrological, meteorological as well as human induced hazards. According to the UN World Risk Report, Bangladesh is one of the world's most disaster exposed countries. Bangladesh is one of the four countries among the highest risk countries in Asia with the risk index of 18.78 (World Risk Index 2019). It is susceptible to annual flooding, frequent cyclones, and potentially large earthquakes along with the creeping hazards like drought, saline intrusion, air quality, land degradation *etc.* The country's exposure to hazards is compounded by its population's exposure, vulnerability and lack of resources. The mostly agrarian economy and the high population density leave large sections of the population exposed to various geophysical and hydrological hazards.

The energy is prerequisite for social and economic development of Bangladesh for achieving sustainable energy systems to protect natural life-support systems on which humanity depends, and to eradicate poverty. Bangladesh has limited alternatives and will continue to rely primarily on this energy source to fuel its development [13]. Energy demand in Bangladesh is rising swiftly, which is outstripping the production and transmission and distribution capability and leads to increased power disruption and poor quality of power supply [14]. Bangladesh imports to meet most of its oil needs and remains heavily dependent on biomass for domestic energy production, particularly in rural areas [15]. Domestically produced natural gas provides majority of Bangladesh's commercial energy.

The Ministry of Power, Energy and Mineral Resources (MPEMR) are responsible for overall sector policy formulation, investment decisions and regulation of the energy sector in Bangladesh. Two independent divisions, the Energy and Mineral Resources Division (EMRD) and Power Division of MPEMR is responsible for developing the oil, gas, and coal sectors to diversify energy supply and improve energy security and subsequently implementing the power sector reforms and ensuring adequate power generation capacity.

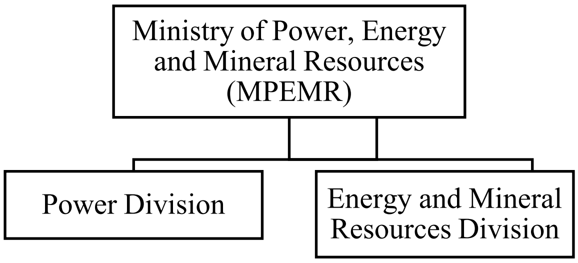

Fig. 1. Broad organizational structure of MPEMR.

Bangladesh has established two energy regulatory bodies, the Bangladesh Energy Regulatory Commission, established in 2003 to oversee tariffs and operations in electricity, gas, and oil; and the Sustainable and Renewable Energy Development Authority (SREDA), established in 2014 to promote renewable energy and energy efficiency.

2.1 Energy Scenarios 2016-2030

In the wake of heavy reliance on domestically produced natural gas, gradually diminishing gas reserves, and electricity shortages, the Bangladesh Power System Master Plan 2010 (PSMP 2010) laid out an energy sector vision for 2030. This vision included active development of domestic primary energy resources, establishment of a power system portfolio based on fuel diversification, and building of an infrastructure necessary for a stable power supply. The PSMP envisioned a fuel composition of 50% coal, 25% natural gas, and 25% other fuels/energies by 2030, with coal consumption consisting of both imported and domestically produced coal. This composition is in stark contrast to the composition in 2013 with natural gas constituting 76% of primary energy and 87% of electricity production. While coal consumption was less than 1 million Tons of Oil Equivalent (ToE) in 2013 and coal fired power plants in operation was only 250 MW in 2016, several coal fired plants are at various stages of construction and preparation. However, increased domestic coal mining and production met resistance among the local population. This was one of the factors that motivated the initiation of the Power Sector Master Plan 2015(PSMP 2015) in late 2014.

The Government of Bangladesh (GoB) has made plans to expand the energy sector consistent with Bangladesh becoming a middle income country by

2021, and by 2030 it expects to move further up the ladder. To achieve this status projection of electricity has been made to 2030 and beyond. According to the PSMP 2015, the peak electricity demand will be over 25,000 MW, and 100% of the country will be electrified. In 2015, the total consumption of commercial energy was around 32 million ToE. To achieve the target of 2030 this will have to be increased several fold to beyond 100 million ToE (Power Cell, Power Division, MPEMR).

2.2 GoB Priority

2.2.1 Energy Sub-sector

- Formulating a long-term strategy about how the growing needs of primary fuel will be met in the next 25 years and achieving Vision 2041.
- Exploring domestic gas resources, both on shore and off shore, to address the growing shortage of natural gas.

Diversifying energy supply through (1) energy imports, both LNG and coal and supporting infrastructure, (2) energy conservation measures and Demand Side Management (DSM), and (3) renewable energy sources, biogas, and Improved Cooking Stoves (ICS).

2.2.2 Spinning reserve constraints:

- Curbing increasing electricity cost and improving financial viability of the power sub-sector, through fuel diversification, economic dispatch and improving energy efficiency.
- Enhancing reliability and network quality of power supply to meet rapidly increasing power demand and higher quality of power supply.
- Increasing capacity for power transmission and distribution to keep pace with the increasing generation capacity.
- Improving power sector efficiency by (1) reducing technical and non-technical losses, and (2) improved operation and maintenance (O&M) of power plants.

2.2.3 Cross-cutting Issues

- Improving energy (gas) and power tariff setting mechanism to cover the 'true' cost of energy and power supply and reduce the burden of power subsidies on the national budget.
- Pursuing DSM in both energy and power sub-sectors, through regulatory reforms.

(Source: Power and Energy Sector Strategy Paper, 2018)

2.3 Energy Sources in Bangladesh

In Bangladesh the sources of energy consumption are Bio-mass (wood, animal and agricultural residues, municipal waste *etc.*) which contributes about 65% of the total energy consumption and the remaining 35% stands for commercial sources which are natural gas, oil, coal and hydro-electricity [16]. The major commercial energy sources consist of natural gas (from which almost half is used for electricity generation), petroleum, coal and hydro-power [17].The shares of natural gas, petroleum, coal and hydropower to total commercial energy consumption is 70.8%, 25%, 2.4% and 1.8%, respectively [18]. The petroleum and coal are mostly used for transportation and industrial purposes.

2.3.1 Natural Gas

Domestic natural gas production is less than 3,000 MMcfd (million cubic feet per day), but the demand is more than 3,500 MMcfd. From existing reserves the supply cannot be increased, and, therefore, the gap between demand and supply will widen as the demand in 2030 is projected to be more than 5,000 MMcfd. Considering a modest exploration program where the probable and possible reserves can be brought into supply, the production of gas would still fall to 2,000 MMcfd in 2030.

Table 1. Gas sector: Basic information.

Gas Reserve	1st July, 2018 (in TCF)
No. of Field	27
Total Gas Initially in Place (GIIP)	39.8
Proved (1P)	20.9
Proved + Probable (2P)	27.81
Proved + Probable + Possible (3P)	30.82
Cumulative production	15.94
Remaining Reserve (1st July, 2018)	11.92

Source: Reservoir and Data Management Division, Petrobangla, 2018.

2.3.2 Use of Coal

Local demand for coal is met up mainly by local production and partly by imported coal. At present, total coal reserve in the country is amounted to be7962 million MT (Table 2). Till date, about 8.88million MT of coal has been utilized. About two thirds of that coal is used in power plants and the rest is used in other purposes (brick field, households *etc.*). The coal policy which was prepared long back did not materialize. There was huge public protest against extraction of coal through open-mine system due its possible huge impact on environment and livelihood in the coal-belt.

Table 2. Coal reserve in Bangladesh.

Name of the Coal Field	Reserve in Million MT
Barapukuria, Dinajpur	390
Khalaspir, Rangpur	685
Jamalganj, Joypurhat	5450
Fulbari, Dinajpur	572
Digipara, Dinajpur	865
Total	7962

Source: Mines and Minerals Development Report, 2019

A 1320 MW (2x660) power plants are currently being set up in the southwest region of Bangladesh, near to the Sundarbans. Bangladesh and India have been jointly constructing this power plant. The $2 billion cost of building the Rampal power plant is likely to rise to $5 billion after river dredging and for subsiding coal. The cost will also be influenced by the price of coal. In 2010, a total of 930 acres of land were acquired to implement the project at Rampal of Bagerhat - some 14 kilometers away from the Sundarbans, a World Heritage site declared by the UNESCO. The environmental concerns have been raised by right-based groups both nationally and abroad.

2.3.3 Import of Petroleum

Petroleum constitutes a major share of fuel costs for power production and dependence on it has increased overtime. Costs for diesel and HFO have been increased significantly over the years. A large number of newly established power plants are based on imported petroleum which caused a huge import bill. There is a plan to reduce dependence on petroleum-based power plants. As part of that there is initiative to commission large scale power plants soon.

2.3.4 Renewable Energy

The expansion of the potential of wind energy is crucial in order for Bangladesh to achieve its national vision of providing electricity to all of its population by 2020 [19]. Despite having a huge coastline and relatively large area only 100 MW of huge demand is projected to come from wind power sources. The bulk of this generation is planned to be deployed in the coastal area and adjacent islands [20]. The contribution of renewable energy is at an early stage (0.01% of total energy generated). Major part is solar energy which is mostly in off-grid. The incremental contribution of hydropower, as per plan is rather discouraging. The implementation phase of biogas program in Bangladesh is also in progress since 2006 with support from the development partners.

2.3.5 Nuclear Power

Bangladesh is in the stage to become the 33rd nuclear power-producing nation after the successful construction work at Rooppur, Pabna [21]. The Rooppur Nuclear Power Plant (RNPP) is expected to generate additional 2400 MW (2x1200)of power to the national grid at a cost of US$ 12.65by the year 2024 [22].

3. DISASTER AND ENERGY SYSTEM CHALLENGES IN BANGLADESH

Energy is an essential factor for sustainable development and poverty alleviation, as recognized by a wide variety of regional and international development instruments (SDG 7, 8, 9, 11, 12 and 13). The effects of disasters and climate change on energy systems vary from affectations to infrastructure (*e.g.* generation plants, transmission and distribution networks), to disruptions in supply, and changes in demand patterns. The cascading impacts of disasters on energy system decelerate the achievements in sustainable development, especially when financial protections are missing and when DRG still follows a silo approach.

In the case of Bangladesh, gas and electricity infrastructure are the critical elements, but others are becoming important as the gas reserves of the country dwindle. In electricity infrastructure, there is generation, transmission and distribution. For gas, it is exploration, development, transmission and distribution. It has been the fact that for many years governments have struggled to provide energy security through a mix of policies that tempered demand and increased supply. Poor energy management caused severe impacts on agriculture, industry, food security and poverty. Additionally, a number of interlinked issues and challenges have appeared in recent years [23].

Table 3. Imported quantity for refined petroleum products and crude oil during 2009-2019 (quantity in M.ton).

Year	Imported Refined Petroleum Products						Imported Crude Petroleum Products	
	Gas Oil	JET A-1	MOGAS	SKO	HSFO	LUBE	ALC	Murban
2009	2343758	256576	98064	141103	0	7248	612913	425614
2010	2186597	339998	90197	107758	0	4745	620238	654832
2011	2955798	318202	95824	153598	665260	4980	627535	583960
2012	2618685	339699	95824	20380	670899	4852	682039	583494
2013	2608746	310884	97641	28376	1005104	0	592054	591091
2014	2903928	334079	35596	0	869124	0	592865	714746
2015	2974749	338315	33842	0	414451	0	697667	395006
2016	3130052	354430	150601	0	481673	0	728307	579848
2017	3716349	393918	32837	0	563856	0	497907	667861
2018	3457987	307777	32550	0	341329	0	597338	482260
2019	3410937	426745	115603	0	274915	0	592711	573717

Source: Bangladesh Petroleum Corporation 2020

Table 4. Renewable energy generation capacity (MW).

Technology	Off-Grid	On-Grid	Total
Solar	291.12	47.53	338.65
Wind	2	0.9	2.9
Hydro	-	230	230
Biogas to Electricity	0.68	-	0.68
Biomass to Electricity	0.4	-	0.4
Grand Total	294.2	278.43	572.63

Source: SREDA, 2019

Bangladesh has an insufficient energy reserve; small amounts of oil, coal and countable natural gas reserves. The country suffers an internal energy struggle, as about 93% of the country's power producing thermal plants is gas-based, but the gas is also needed for the industrial sector. Therefore, the country has to continuously make some compromises between power production and developing the industrial sector [12]. About 62.9% of Bangladeshi generated electricity comes from natural gas, while 10% is from diesel, 5% comes from coal, 3% of heavy oil, and 3.3% is of renewable sources [24].

Despite the fact that the Bangladeshi energy sector uses and covers varied products; electricity, petroleum products, natural gas, coal, biomass and solar, yet the policy and decision makers are mostly pre-occupied with electricity, as it is the most common used form of energy in the country. Thus, because there is a continuous and rapidly widening gap between electricity supply and demand, therefore it is a major challenge for the energy sector in Bangladesh. The lack of investment is also a major contributing factor to Bangladesh's energy crisis [25]. Establishment of a stable, economical, clean, and safe energy supply system is faced with significant challenges in few aspects such as severe resource constraints and low energy efficiency, natural gas and coal dominated energy consumption and environmental pressures; and imperfect market systems and weak emergency response capacity. The country does not have adequate storage facilities. Therefore, the future of energy security of Bangladesh appears bleak with gas resources depleting fast and no coal extraction in sight, while poor energy supplies could potentially stun the country's economic growth.

Due to the adverse weather system, Bangladesh becomes the worst victim of natural disasters like tropical cyclone, tidal bore, flood, tornado, river bank erosion, earthquake *etc.* occur in Bangladesh that causing colossal loss of lives and properties. The power sector is both extremely vulnerable to natural hazards and a priority for any country's recovery and reconstruction. Severe weather events, particularly storms, are among the main causes of power outages around the world [26]. The cost of power infrastructure disruptions is substantial in developing countries. The share of power outages due to natural shocks can vary from anywhere between zero and 100 percent [27].

Table 5 presents a summary of the vulnerabilities; it categorizes the importance of considering a given disaster when designing an asset to avoid physical damages or service interruptions. During a natural hazard, three main types of incidents can lead to system breakdowns: transmission and distribution grid failure, generation plant failure, and fuel and maintenance supply chain failures.

In order to understand the legal procedure relating to any aspect of a nation, it is crucial to look into the country's regulatory structure and hierarchy. Therefore, Figure 2 shows the structure and hierarchy of the laws in Bangladesh to construct a comprehensive regulatory idea about the energy sector for the country.

The Energy Action Plan (2009-2013) of the country included a series of actions, measures, programs and targets to be met to achieve greater energy efficiency and conservation awareness, together with reductions in CO2 emissions. The Bangladeshi Energy Strategy of 1996 with its actualization in 2002 is the main document of the promotion of renewable energy (RE). It focuses on energy supply in rural areas. In December 2009 the Renewable Energy Policy for Bangladesh was ratified. It was intended to integrate this policy paper into the New Energy Policy (NEP). The NEP was developed in 2006 by the "Renewable Energy and Energy Efficiency Programme" in cooperation with the UNDP. In the Intended Nationally Determined Contributions (INDC), the GoB announced to install 3000 Mega Watts of solar energy and continue to promote off-grid solar energy as well as ICS. It looks like the GoB is following a parallel strategy: on the one hand, increase power generation based on coal, on the other hand offer projects in the field of on-grid and off-grid solar electrification and stoves to be supported by development partners. The Private Sector Power Generation Policy adopted to attract private investment for installing new power generation capacity on build-own-operate (BOO) basis. The Renewable Energy Policy provides incentives for RE. The Power Division of MPEMR has announced and published the Country Action Plan for Clean Cookstoves (CAP) in November 2013. The target of CAP is to disseminate cookstoves to over 30 million households in the country by 2030.

Table 5. Power sector vulnerability to natural disasters.

Type	Earthquake	Cyclone	Flood	Tsunami	Wildfire	Drought	Extreme Heat
Thermal plants	High	High	Medium	High		High	Medium
Hydropower plants	High	Low	Medium	Low		High	Medium
Nuclear Plants	High	Medium	Medium	High		High	Medium
Solar (PV)	Low	High	Medium	Medium		Medium	Very lw
Wind	High	Medium	Low	Medium		Very low	Very low
T&D lines	Medium	High	Low	Medium	High	Medium	Medium
Substations	High	High	High	Medium	High	Low	Medium

Source: Nicolas, et al., 2019

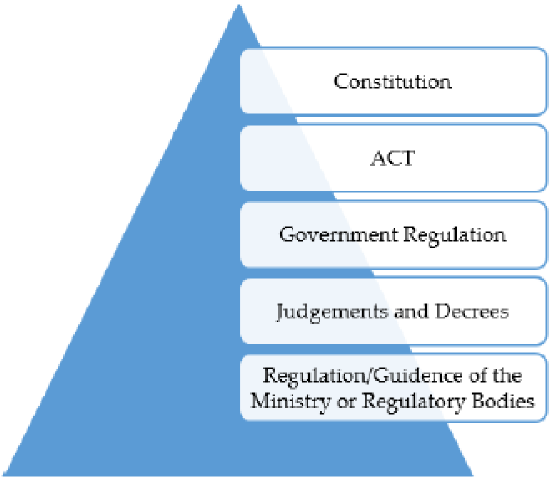

Fig. 2. Hierarchy of laws in BD. *(Source: Karim, et al., 2018).*

Table 6. Public expenditure in power and energy sector (in Crore Tk.)

Division	Year	Non-Development Expenditure	Development Expenditure	Total Expenditure
Power	2009-10	4	2024.54	2028.54
	2010-11	5	6189.92	6194.92
	2011-12	6	7179.65	7185.65
	2012-13	6	8868.01	8874.01
	2013-14	7	7843.99	7850.99
	2014-15	11	8030.78	8241.78
	2015-16	18	15558.46	15576.46
	2016-17	29	18136.89	18165.89
	2017-18	63	22757	22820
	2018-19	43	22893	22936
	Total (FY10-FY19)	192	119682.20	119874.20
Energy and Mineral Resources	2009-10	33	1367.64	1400.64
	2010-11	214	990.02	1204.02
	2011-12	39	746.02	785.02
	2012-13	40	1629.82	1669.82
	2013-14	35	1832.38	1867.38
	2014-15	33	1879.71	1912.71
	2015-16	51	2008.34	2059.34
	2016-17	43	2435.90	2478.90
	2017-18	95	1346	1441
	2018-19	165	1820	1965
	Total (FY10-FY19)	748	16055.80	16803.80

Source: Bangladesh Economic Review, 2018

4. ENERGY SECURITY CONTEXT AND RESILIENCE

Access to and promotion of sustainable energy remains persistent challenges in Bangladesh. The country continues to be heavily dependent on imported fossil fuels, which impacts national finances, restricting investment capacity and development opportunities, while posing major threats to environmental damage and long-term ecosystem resilience. An important opportunity to overcome some of these issues is exploring and exploiting the country's potential for green growth, along with measures to promote low emission and climate resilient development initiatives, which can result in lower investment and operation costs and create economies of scale, thus facilitating financing opportunities [28].

Bangladesh is ranked 114th out of 128 countries in the2019 (having score of 41.1) World Energy Trilemma Index by the World Energy Council. Conceptually, 'energy trilemma' involves the complex trade-offs among three core dimensions, *i.e.* energy security, energy equity and environmental sustainability. A large number of countries of the developing economy, including in Bangladesh, domestic energy (*e.g.* for cooking, heating or lighting) is still obtained from the energy-inefficient and toxic burning of biomass such as wood, charcoal or agricultural waste which is traditionally a women's work [29]. Women are the major consumers of energy in rural areas as they are responsible for gathering fuel for cooking and heating. More than 100 million people in Bangladesh, about 63 percent of the population, live in rural areas, where annual per capita commercial energy consumption averages less than 100 kilograms of oil equivalent (kgoe), considerably lower than the average international levels [30].

Bangladesh is standing at historical crossroads with respect to energy policy. Past decades of relatively abundant natural gas supported a set of policies that are not sustainable in future decades. The country still faces widespread poverty and the potential of conflict to arise as a result of energy shortage. The major challenges in the power sector of Bangladesh are: (i) providing universal access to power; (ii) providing good quality and reliable power supply; (iii) ensuring gas availability for generation; (iv) long-term energy security and fuel diversity; (v) cost recovery and financial sustainability of power sector agencies; and (vi) mainstreaming renewable energy [31].

It is a challenging task for Bangladesh to meet its increasing demand of energy while its economy is rapidly growing. Though prices of oil, coal, and fossil fuels around the world have been volatile, the price trend in Bangladesh demonstrates a persistent rise in the immediate past. This is further exacerbated by depleting reserves of natural gas. Cumulatively, these two effects heighten Bangladesh's energy needs. In the country as electricity is the most widely used form of energy, so future economic growth significantly depends on the availability of electricity [32]. However, consequently, due to scarcity of natural gas, oil and coal resources, nuclear power surfaces as a palatable strategic option for Bangladesh's future development agenda [22].

4.1 Components of a Resilient Energy Sector

To achieve the resilience of energy systems for disasters and climate change is a complex process. Resilience building can be better attained through the multi-sectoral synergies between adaptation and mitigation. Both types of approaches, as well as other pertinent measures, should necessarily take local conditions, such as priorities, governance frameworks, available funding, infrastructure, capabilities, access to information, and awareness.

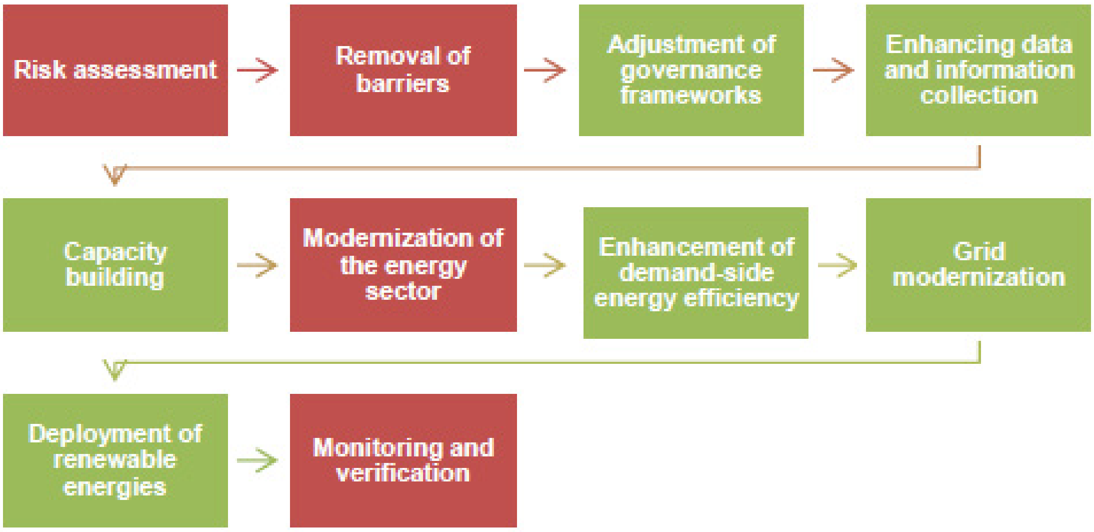

Fig. 3. Components of a resilient energy sector.
(Source: Flores and Peralta, 2020)

According to GFDRR, DRG should be founded on five pillars: risk identification, risk reduction, preparedness, financial protection, and resilient recovery [33].

Table 7. Pillars of action of disaster risk governance.

Serial	What the Pillar is?	How to Achieve?
Pillar-1	Risk Identification	Improved identification and understanding of disaster risks through building capacity for assessments and analysis
Pillar-2	Risk Reduction	Avoided creation of new risks and reduced risks in society through greater disaster risk consideration in policy and investment
Pillar-3	Preparedness	Improved capacity to manage crises through developing forecasting and DRR capacities
Pillar-4	Financial Protection	Through financial protection strategies of governments, private sector and households
Pillar-5	Resilient Recovery	Through support for reconstruction planning

Source: GFDRR, 2013.

5. CHALLENGES AND WAY OUT FOR ENERGY SECTOR IN DISASTER RISK GOVERNANCE

5.1 Adjustment of Policy and Govenance Framework

Governance frameworks refer to modern energy policies and plans that include measurable RE and energy efficiency (EE) targets, assign responsibilities, establish timetables and communication and accountability mechanisms, allocate resources (financial and non-financial), and be based on conceptual budgetary provisions. They should promote multi-stakeholder participation and provide moments for policy learning. Modern energy policies must be accompanied by a regulator responsible for creating an enabling environment for all stakeholders, and to ensure transparency, accountability and fair-conditions. The most relevant challenge of adjusting governance frameworks is coordination among a diversity of institutions and regulations.

5.2 Enhancing Data and Information Collection

Data and quality information are required to guide decision making, to monitor and verify future scenarios and improvements. Inadequate or insufficient baseline data could hinder efforts to make reliable assessment, identify and reduce risks, as well as to assess the effects and impacts of disasters on infrastructures (including that of energy systems), ecosystems and populations. Inadequate baseline data could also result in over or underestimations of the efforts needed. The generation and dissemination of information requires strong institutions providing leadership and guidance for the generation and use of resources, as well as a platform to keep it available to stakeholders. The analysis of DRG frameworks also evidenced the importance of updated and readily available data and information for decision making.

5.3 Capacity Building

The incorporation of new technologies and activities demands specialized skills and knowledge. Local and regional capacities must be created and/or improved to face the challenges posed by the modernization of energy systems in view of increasing resilience to disasters. Although the country is permanently supported by multiple capacity building initiatives, important knowledge gaps and barriers to institutional effectiveness remain, including duplication of efforts, high staff mobility, loss of institutional memory and expertise, and lack of coordination, which often hinder effectiveness. To address this situation government institutions and related stakeholders must develop shared databases, networks, and collaboration frameworks to guide institutional structure and operation.

6. MODERNIZATION OF THE ENERGY SECTOR

6.1 Enhancing Demand-Side Energy Efficiency

Efforts to address the challenges of the energy sector cannot rely exclusively on the incorporation of RE. Demand-side EE and other energy saving measures are crucial, as they consist of the most cost-effective and fastest way to lessen the environmental and socioeconomic costs associated with energy systems. Demand-side EE is achieved when less energy input is used to deliver the same service or when the same amount of energy input delivers more services. This concept is relevant in light of climate change challenges in two ways: (i) the less energy used, the fewer emissions produced, and (ii) cost effective EE achieves environmental benefits at low cost, and thus could reduce the economic costs of achieving climate change policy goals [34].

6.2 Incorporation of Renewable Energies

RE deployment is a widely discussed topic and the overall potential for RE sources is high. Although estimations point out that the global energy supply will remain dominated by fossil fuels over the next decades, countries should seek to develop and disseminate cost-effective and efficient low or zero-carbon emitting technologies [35]. Nowadays, RE cost-effective supply is in continuous growth due to an increase in the investments and advancement in technologies and features. While the cost of RE technologies has decreased in recent years (*i.e*., between 33 and 80 per cent depending on the technology), they are still not comparable to subsidized fossil fuel energy sources. However, if we take into consideration the associated socio economic and environmental externalities of conventional energy generation, the opportunity cost to switch the energy paradigm is exposed. Proper integration between energy and land use and zoning policies should be done.

6.3 Grid Modernization

Due to the broad availability of RE resources and the wider need to decentralize generation systems (*i.e.,* to enhance energy access), adjustments in their design and technical features are required if full RE potential is to be achieved. Additionally, after a disaster takes place, the bulk of the damage is absorbed by infrastructure (*i.e.,* especially overhead power lines, utility poles, transformers, as well as power generation stations), making the adjustments more imperative.

7. DISCUSSIONS AND RECOMMENDATIONS

Resilience is not a one-dimensional issue- there is a need for holistic solutions that cut across sectors. To be resilient, infrastructure of tomorrow must cope with, and adapt to a complex, extensive and evolving mix of hazards, risks and threats. Assessments of multi-hazards risks should be an essential component of every project across its entire life cycle - integrated from the planning and design phase - and not just added on as a last-minute feature. Having early-stage conversations such as meeting about risk management in future infrastructure projects makes it easier to customize a resiliency strategy-knowing which assets to protect, understanding the function of those assets and the potential cost of losing those assets from shocks like natural disasters and extreme weather [36], [37].

The occurrence of natural hazards and their impact on electric power system functioning has been experienced by many countries worldwide, particularly in relation to earthquakes, cyclone, tsunami and floods. Several countries such as Chile, China, Haiti, Indonesia, Italy, Japan, Mexico, the Philippines, Turkey, and the United States have experienced severe earthquakes that resulted in serious damage to their energy supply infrastructure, in addition to the loss of lives and property. Drought/water stress can also pose a substantial risk in the energy sector, particularly for hydropower.

It is evitable to experience disruptions in the power system at various stages during major disasters, but adequate mitigation measures and response plans can help the system to return to its original functionality. Risk governance at various levels, starting from power generation sector to the local government, need to function in line with the preparedness and crisis management plans. Resilience not only depends on equipment, building codes, seismic micro zonation maps of the city for resilience planning and technology but more on the organization and pre-defined emergency preparedness of well-structured electricity companies [38].

8. CONCLUSION

Increasing risk of natural and anthropogenic hazards and climate-induced extreme events necessitates the improvement of disaster risk management (DRM) and governance mechanism at multi-stakeholder level across jurisdictions. DRG through integrated approach with development provides opportunities for stronger incentives when DRM visibly contributes to improved economic and resilient society. Power and energy sectors of Bangladesh cannot get free flow of urgently required private sector investment without stronger and truly functional regulator. The BERC and SREDA must be manned by qualified and experienced professionals. These statutory authorities must function absolutely independently creating level playground for public and private sector companies. It must police enforcement and compliance of acts, laws, policies and regulations through stakeholders' engagement and efficiency auditing.

The GoB policies in the energy sector will be critical to the country's national security, economic development, and environmental sustainability. Bangladesh's energy and power sector needs to shift its activities from the 'emergency management' (initiated in early 2010s) to 'market-led' management (needs to be initiated towards 2021-2030). It needs to reduce lack of transparency, accountability, efficiency, irregularities and corruption. It is high time to pay attention to the primary energy sector particularly to gas and renewable generation and energy efficiency from an economic and environmental perspective to minimize debt and fiscal impacts. The potential for private investment in generation, transmission, and demand management should be fully pursued as the government proceeds with the implementation of its ambitious scheme to establish industrial and export zones. Finally, developing countries like Bangladesh face enormous challenges in attaining the UN SDGs. The energy sector is central to realizing these aspirations. It is precisely for this reason that Bangladesh should chart a course that can lead to a more efficient, clean, affordable, and sustainable power and energy system.

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Coastal Hazards in Asian Countries in the Context of Climate Change

Nandini Sanyal*,[1] and Sakib Rahman Siddique Shuvo*

Abstract – *The paper carried out a comparative assessment of coastal hazards and their resultant impacts on communities and physical systems/resources in the countries located in the Asian coastal regions and maritime areas. Only those natural hazards were considered in the assessment which pawned from climate change-induced phenomena. At the outset, the coastal countries including Bangladesh are grouped into three categories based on their exposure to natural hazards, the degree of vulnerability of the communities, socio-economic contexts and technological advancements to cope with the challenges. Then the state, nature, pattern of coastal hazards, and their resultant consequences have been analyzed. Secondary research materials, especially the National Communication (NC) reports of the countries submitted to the United Nations Framework Convention on Climate Change (UNFCCC) were used to undertake the study. The results suggest that the pattern of impacts and their consequences are somewhere identical and, in many areas, different that suggest cross-country understanding combined with local knowledge is crucial for taking effective policies for adaptation or mitigation planning in respective countries.*

Keywords – *Asian coastal hazards, climate change impact, National Communications to UNFCCC, vulnerability.*

1. INTRODUCTION

Coastal regions are the place where global and local events and processes make the interface, sometimes overlie and intermingle when variables like climate, hydrology, geomorphology, water currents, biological habitats are considered and put together in the context. Sometimes, natural hazards cause disturbance in all of these functions and processes and destabilize the whole system. Therefore, proper understanding of the coastal environment and associated hazards is important so that informed actions can be taken towards reducing vulnerabilities of coastal regains. This paper took efforts to examine vulnerabilities of Asian coastal countries in the contexts of climate change. The countries which are surrounded by the seas and which possess significant coastal regions such as India, Bangladesh, Sri Lanka, Maldives, Pakistan, Myanmar, Thailand, Malaysia, Indonesia, Philippines, Cambodia, Vietnam, Singapore, Japan, South, and North Korea were taken into consideration for the assessment. The article is written primarily depending on secondary information and a detail review is undertaken for examining the vulnerabilities of coastal communities of these aforementioned countries due to natural hazards induced by climate change. The National Communication reports of respective countries that were submitted to UNFCCC to meet their signatory obligation were examined to make a comparative and critical assessment.

The work aims to provide a continental scale overview of the vulnerabilities and sectoral impacts of coastal hazards induced by climate change. The climate-vulnerable countries are currently giving efforts in planning and developing diversified approaches like reforming institutions, mainstreaming adaptation projects into regular development programs, developing fiscal frameworks and necessary instruments to address the challenges posed by climate change induced hazards and disasters. A deep understanding of the pertinent issues from different countries combined with local knowledge may help countries to set up their appropriate strategies in this regard. This paper, in this backdrop, made a comparative assessment on the ways countries conceptualized their risk and vulnerabilities from climate change-induced challenges and at the same time learnings received by them while implementing programs to reduce vulnerabilities of different forms.

2. PEOPLE, ENVIRONMENT, AND HAZARDS IN COASTAL REGIONS

The coastal environment plays vital roles in supporting people's lives and livelihoods by facilitating them with different types of endowments in almost all the Asian countries which possess significant coastal areas. These coastal endowments may be classified as biotic and abiotic resources. These resources are generated from coastal ecological systems and depend on the complex physical processes. The physical processes include tidal systems, offshore currents, and waves, geomorphological processes like erosion and accretion phenomenon that develop various kinds of coastal landforms like offshore islands, beach environment, and dunes, spillover fans, and tidal channels, lagoon wetlands. Human communities interact with all these physical systems/processes in a very intricate manner to make their living and ensure their physical, social,

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cultural, and economic wellbeing [1]. Besides, several large, medium, and small-sized cities have also developed in the coastal areas in Asian countries because (i) the water-based communication facilities for supporting trade and commerce are better in those areas, (ii) various types of livelihoods supporting options exist there. More than half of the world's population live in the coastal areas and the rate of concentration is increasing [2].

The complex and interconnected human-nature interface in the coastal areas evolved based on the long-term knowledge, understanding, and familiarity of the coastal communities with the systems and resources they are settled in. People are even familiar with the unusual physical threats and risks that sometimes cause the collapse of the composition, and they generally know how to cope with those uncertainties. However, in recent times, climate change induced threats make those century-old, known patterns of risks and threats more strange, and people become unfamiliar with those to deal with [3]. Some of these threats are slow and progressive like sea-level rise, salinity intrusion, while some others are strong, sudden and rapid like cyclones with strong winds, water surge, tidal bore etc. [4]. Both the types of hazards cause the coastal systems collapsed and resources degraded or destroyed. Impacts of these destructions radiate into different sectors/areas of life, causing immediate and far-reaching, short and long-term chain-of-effects on coastal communities. It is observed that one impact triggers many new forms of consequences, and finally, communities find it difficult to return to their original state. In these circumstances, communities sustain by exercising and accommodating a continuous form of adaptation mechanism to cope with new conditions [5].

3. COASTAL HAZARDS IN THE CLIMATE CHANGE CONTEXTS

Asian coastal countries assessed their vulnerability in the context of climate change and reported to UNFCCC by submitting their National Communication (NC) papers. These documents thoroughly examined the physical and social contexts and showed how climate change exacerbated the existing hazard conditions and focused on the upcoming threats that climate change may cause to happen. Most of the countries refer to IPCC's (Intergovernmental Panel on Climate Change) predictions about climate change and accordingly presented their vulnerabilities, impacts, and response from formal and informal sectors. Countries like India, China, Thailand, Bangladesh, Maldives, Malaysia, Indonesia, Singapore, Republic of Korea, carried out assessments primarily focusing on sectoral impact scenarios. The studies were concentrated on the four areas closely related to the national economy, namely, water resources, agriculture, terrestrial ecosystem, and coastal regions, including offshore marine ecosystems. Countries like India, Thailand, China urged that the projections should be appropriate for scales (e.g., regional, local) to ascertain and understand the intricate dynamics of impacts. However, some countries depend on the PRECIS model to understand regional-scale climate change projections, and most of them started working on climate change induced impacts in the 1990s. It is important to note that the early assessments (reflected in the Initial National Communication, INC reports) of the impacts of climate change were mostly qualitative studies focused on the sensitivity of social and physical systems under incremental scenarios. In recent years, the study has been carried out based on the quantitative models linked up with projected outputs of the global climate models (GCMs) under greenhouse gases (GHGs) emission scenarios.

The types of coastal hazards reported by the countries are almost identical; these are sea-level rise, cyclonic disturbances with strong wind/gusts, coastal flooding or water surges, salinity intrusion in both soil and water, coastal erosion, increase in the sea surface temperature and resultant coral bleaching. However, sea-level rise is considered by the most of the Asian coastal countries as one of the severe threats, since sea-level rise will have long term and big impacts on the country's economic production, livelihoods security, environment, infrastructure, public health, and threaten the achievements of poverty reduction, food, and energy security, sustainable development, as well as the fulfillment of the Sustainable Development Goals.

The global disaster and emergency database managed by *Universite Catholique de Louvain*, Belgium, has become a vital source of information in present times in this regard. Data retrieved from this source separately on the number of people killed and the number of affected from the recent disasters for respective countries and graphically presented in Figure 1a and Figure 1b. Both the Figures depict that the hazards that Asian coastal countries are facing are mainly related to climate. It emerges from the Figures that storms, *i.e.* the cyclonic disasters, are more deadly for almost all the countries (Figure 1a). The mortality rate appeared higher from cyclonic events as it takes place with strong winds, huge rain and often accompanied by water surge, requiring huge number of emergency evacuation.

On the other hand, a flood is a slow-occurring phenomenon and lasts for a longer duration cause great suffering and leave millions of people in trouble in almost all the countries, though the death toll could be less (Figure 1b). However, the risk of losses from a particular hazard depends on three factors, *i.e.* hazard, elements at risk and vulnerability [6]. These elements at risk could be human, property, infrastructure etc. On the other hand, vulnerability indicates the likelihood of any community to be affected by any upcoming crisis that can damage its life, property, infrastructure and other kinds of resources on which their life and livelihood depend [7]. Thus the degree of vulnerability of the countries in question to specific hazards varies with the

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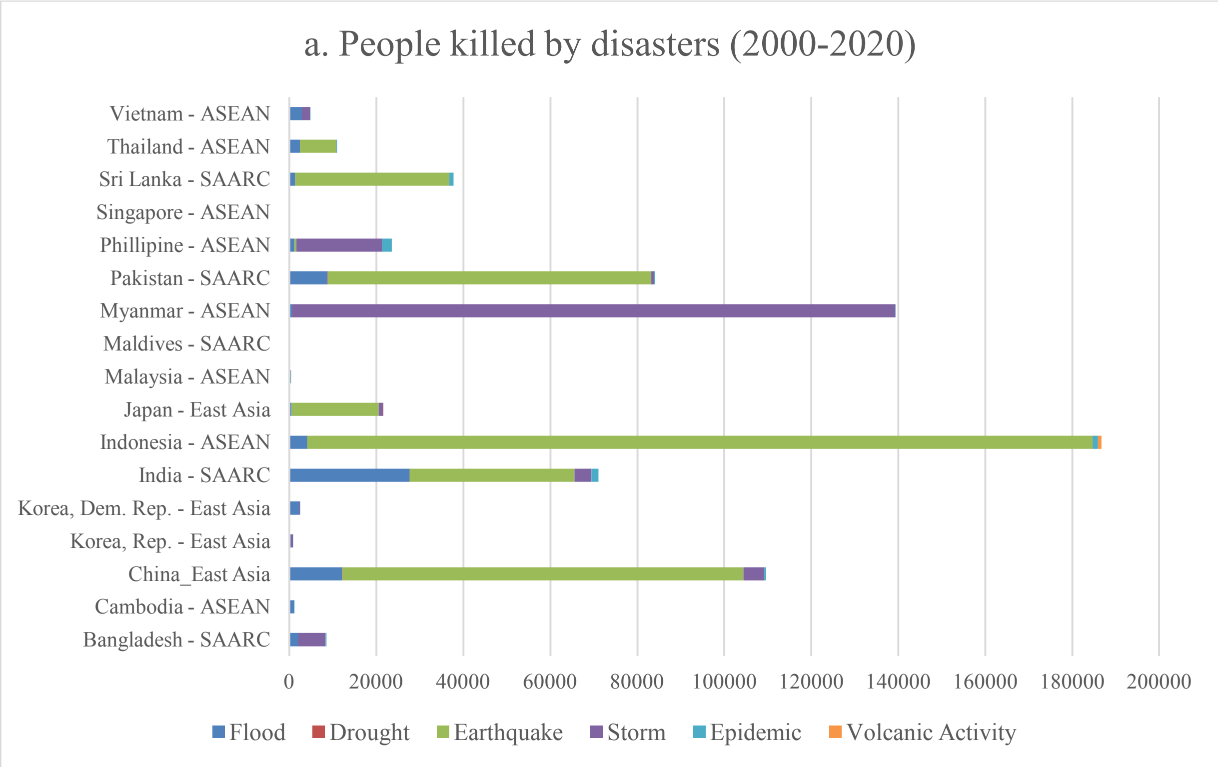
variation of (i) the physical location of the countries, (ii) the socio-economic context of the country within which the community operates themselves and (iii) technological advancement of the country and the strength of the overall governance by which they can better handle the risk factors. Depending on these elements the studied countries were grouped into three distinct categories for this exercise (Table 1), *i.e.*

- The most vulnerable countries
- The countries with moderate vulnerability, and
- Less vulnerable countries.



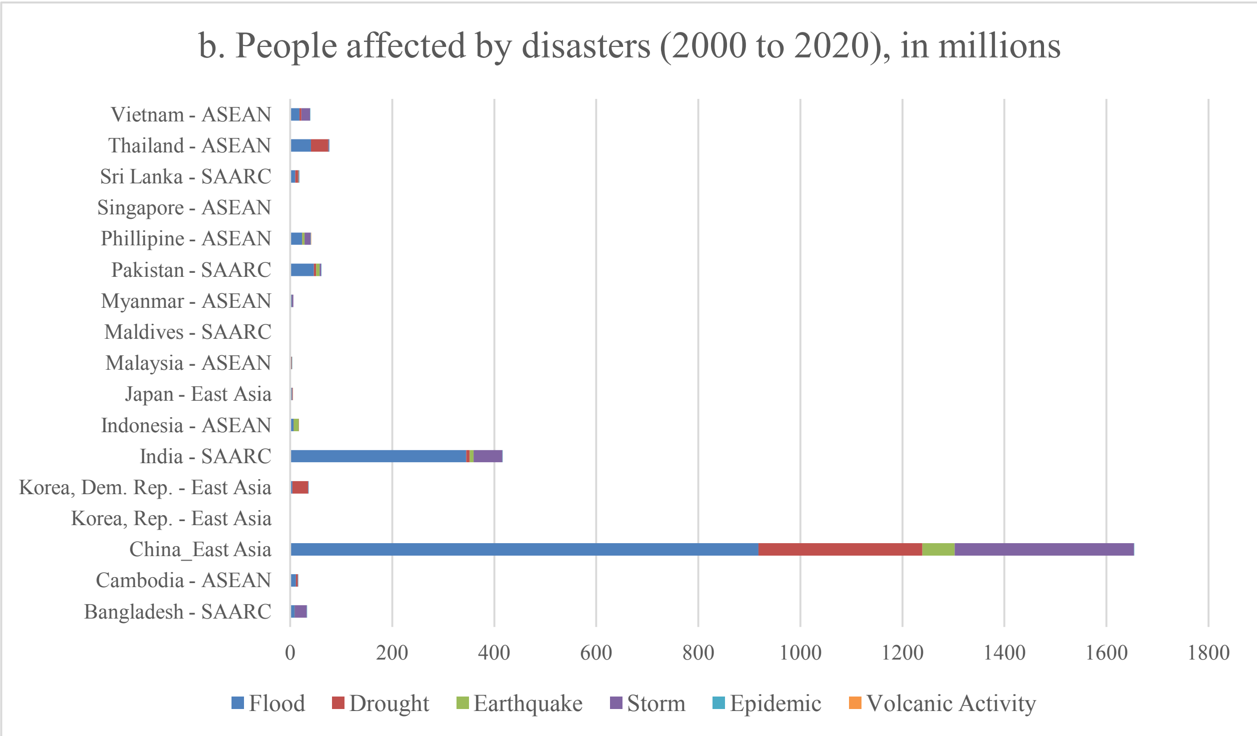


Fig. 1. (a) People died in disasters from 2000 to 2020 (b) People affected in disasters from 2000 to 2020.

Table 1. Types of natural hazards in Asian coastal countries and categories based on exposures to hazards (as reported in UNFCCC National Communication documents).

Groups of countries	Characterizing the hazards and impacts
Group – 1: Most vulnerable countries (*Indonesia, Malaysia, Philippines, Vietnam, Bangladesh, Maldives, Srilanka*)	• The proportion of coastal areas is high compared to the total land areas in these countries that means more people and large parts of economic activities are exposed to the threats of natural hazards. • Sea-level rise related coastal inundation, typhoon impacts, wave action, changes in the storm intensity, coral bleaching as an impact of seawater temperature increase. Oil and gas exploration, transportation, the transmission may be affected. Increased rainfall may cause landslides in some mountainous coastal areas.
Group – 2: Moderate vulnerable countries *(China, India, Thailand)*	• The proportion of coastal areas is less compared to the total land areas in these countries. The impacts are generally concentrated in local coastal regions, not pervasive like Category 1, most vulnerable countries. • Storm surge, sea-level rise related coastal inundation, coastal erosion, saltwater intrusion, death of coral caused by increased seawater temperature, destruction of mangroves, high waves, changes in the pattern of precipitation.
Group – 3: Less vulnerable countries *(Myanmar, Cambodia, Pakistan, Singapore, Japan and both South and North Korea)*	• Two different characteristics differentiate these countries from Group 1 and 2; Firstly, these countries have fewer coastlines like Myanmar, Pakistan and Cambodia. Secondly, some countries are technologically advanced to cope with coastal hazards like Japan, Singapore and Korea. • Flood is the main problem; coastal erosion, salinity intrusion, destruction of coastal forests also happens.

Reflecting on the categorization mentioned above, a comparative assessment of hazard proneness of the Asian coastal countries is given in the following sections.

4. VULNERABILITIES IN ASIAN COASTAL COUNTRIES AS REPORTED IN THE NATIONAL COMMUNICATION REPORTS

4.1 Most Vulnerable Countries

The countries that are most likely to be affected by coastal hazards are mainly the South East Asian (ASEAN) archipelago countries and some of the countries from South Asia. The archipelago countries composed of thousands of islands that include the Philippines, Indonesia, Malaysia, Vietnam; and the countries from South Asia such as Bangladesh, Maldives, Sri Lanka fall into this category. These countries suffer the most from coastal hazards compared to other Asian coastal countries. It is important to mention that although the Maldives does not have any record of great sufferings from coastal hazards but the country is highly susceptible to sea-level rise induced inundation. This reason made the rationale to include the Maldives into the most vulnerable countries.

The Southeast Asian archipelago countries such as the Philippines, Indonesia and Malaysia are situated in the narrow strait between the Indian and the Pacific Ocean in their west-to-east arch and having Australia and Asian landmass in their south and northern parts. This spatial location and geometric form make the region highly vulnerable to typhoon risks generated mainly in the Pacific Ocean. There is a tendency that the typhoons that are spawned in the Pacific generally follow this narrow path. However, in addition to typhoons, sea-level rise, an increase of seawater temperature, landward intrusion of saline water, change in the physical processes, and coastal and marine ecosystems are some significant physical hazards that these countries face. In general, these south East Asian countries have a humid equatorial climate marked by high temperatures and heavy annual rainfall. The countries located in the region experience ascending air and widespread equatorial cloudiness. The length of the discontinuous coastline of these countries is quite extensive because scores of islands form these, and many of the islands are having rugged surface terrains. The long coastline *vis-à-vis* large coastal areas caused to increase in the vulnerability of the human communities, ecosystems, coastal infrastructures to coastal hazards. The settlement clusters of these countries, in the form of cities and urban places, are mostly developed in coastal areas. For instance, the Philippines has 32,400 kilometers of coastline exposed to the sea, and about eighty percent of the provinces and sixty-five percent of the cities and municipalities are located in the coastal areas [9].

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Table 2. Land erosion along the Malaysian coastlines [8].

State	Eroded Coastline (km)	Category 1		Category 2		Category 3	
		Critical Erosion		Significant Erosion		Acceptable Erosion	
		No. of Areas	Aggregate Length (km)	No. of Areas	Aggregate Length (km)	No. of Areas	Aggregate Length (km)
Johor	64.7	0	0	30	38.1	42	26.8
Kedah	26.8	4	1.9	28	13.6	90	11.3
Kelantan	19.8	2	2	2	2.5	43	15.3
Melaka	3.7	1	0.2	6	1.7	3	1.8
Negeri Sembilan	9.8	6	5.5	9	4.1	2	0.2
Pahang	61.8	2	1.5	14	16.9	58	43.4
Pulau Pinang	16.3	7	4.7	13	5	31	6.6
Perak	95.1	1	0.3	21	33.8	105	61.2
Perlis	0.1	0	0	0	0	2	0.1
Selangor	76.4	2	4.8	16	18.6	156	51.2
Terengganu	48.7	8	12.3	20	15.4	115	21
Sarawak	492.5	7	18.6	78	144.8	566	329.1
Sabah	429.3	3	3	63	79.1	1120	347.2
Labuan	4.4	1	0.6	9	2.5	11	1.3
TOTAL	1,349.30	44	55.4	309	376.1	2,344	916.5

In the National Communication papers, the Philippines and Malaysia [8],[9] mentioned that sea-level rise, increased sea surface temperature, storms, heavy rainfall, increased tropical cyclonic activities and associated storm surges are major threats in the coastal regions. The Philippines has shown concern that these hydro-meteorological irregularities may impact on freshwater availability, disrupt agricultural activities and food production, destabilize physical and biological systems (*i.e.*, coral bleaching, loss of sea-grass, mangrove area loss) in the coastal and marine areas. The bleaching and degradation in the coral ecosystems (by expelling the single-celled *zooxanthellae* living within coral polyps) as a consequence of sea temperature increase is a significant worry for the Philippines and Malaysia since coral reefs provide fish catch opportunities and thus ensured livelihoods security for millions of people in these the countries. Malaysia mentioned that eighty-five percent of the reefs are threatened by this phenomenon as coral bleaching reached 40-60% in 2016. Malaysia also claimed [8] that the renowned diving sites would be eroded if more coral bleaching occurs. Malaysia mentioned that sea-level rise is expected to cause, (i) inundation of coastal areas resulting in socio-economic loss or changes, (ii) saline intrusion that will affect agriculture and (iii) changes in the salinity of coastal waters that will impact upon marine and aquatic life as well as aquaculture.

Philippines National Communication papers claimed that 1964 is the cut off the year [9], from which a rising trend in sea-level can be detected. In terms of the occurrence of typhoons, the northern parts of the Philippines receive most of the devastating typhoons compared to the southern parts of the country. These typhoons are stronger, faster, carry more moisture, track differently, and will be aggravated by sea-level rise [10]. Similar to the Philippines, S-shaped extended coastal areas in Vietnam also received seven to eight out of twelve to sixteen active typhoons or tropical cyclones in the South China Sea every year. Sea-level rise would cause serious devastations for Mekong river floodplains and delta, the Red River delta, and the central coast of Vietnam, as claimed in the National Communication paper of Vietnam [11]. In Figure 2, the flooding risk of Vietnam's largest cities has been shown.

Vietnam expects saltwater intrusion in the floodplains aggravating agricultural production, causing severe economic and social consequences. The country also stated about higher risks of saltwater intrusion into the rivers and underground water resources caused by sea-level rise resulting in severe social and economic losses. Increased coastal flooding along with sea-level rise will also affect coastal infrastructures and communities, interrupt the waste management procedures and landfill plants; climate change may have

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severe impacts on coastal ecosystems and coastal forests.

The impact scenario for Indonesia is almost identical to Malaysia, the Philippines, and Vietnam but for Indonesia, most death records are reported by non-climatic hazards like earthquakes and eruption of volcanoes (Figure 1). Figure 3 shows the likely loss of Indonesia due to sea-level rise.

While considering the South Asian region, Bangladesh, Sri Lanka, and the Maldives would face severe impacts from coastal hazards. All these countries are concerned about climate change induced sea-level rise, anticipating that inundation of low-lying areas would occur, coastal erosion and change in the coastal and marine ecosystems would cause serious uncertainties among coastal communities. However, it is imperative to mention that the coastal hazards of Bangladesh are a little different from other Asian countries. Large-scale coastal inundation problems were initially thought [13] to be the primary concern for Bangladesh, but gross inundation of coastal lands is no longer considered a serious threat in recent times. Increase of temperature and salinity, rise in the frequency and magnitude of cyclones and floods, sediment deposition in the river channel are the major threats in Bangladesh reported in the Third National Communication [14, 15, 16] report. The most characteristic phenomenon for the Bangladesh coast is the continuously changing nature of the geometric shape of the landform. This unstable nature of landform does not allow the coastal lands to settle permanently to develop topsoil and finally to establish vegetation climax and ready for agricultural production based on which people can rely on for their food and livelihoods security. Climate change induced threats is aggravating the situations further.

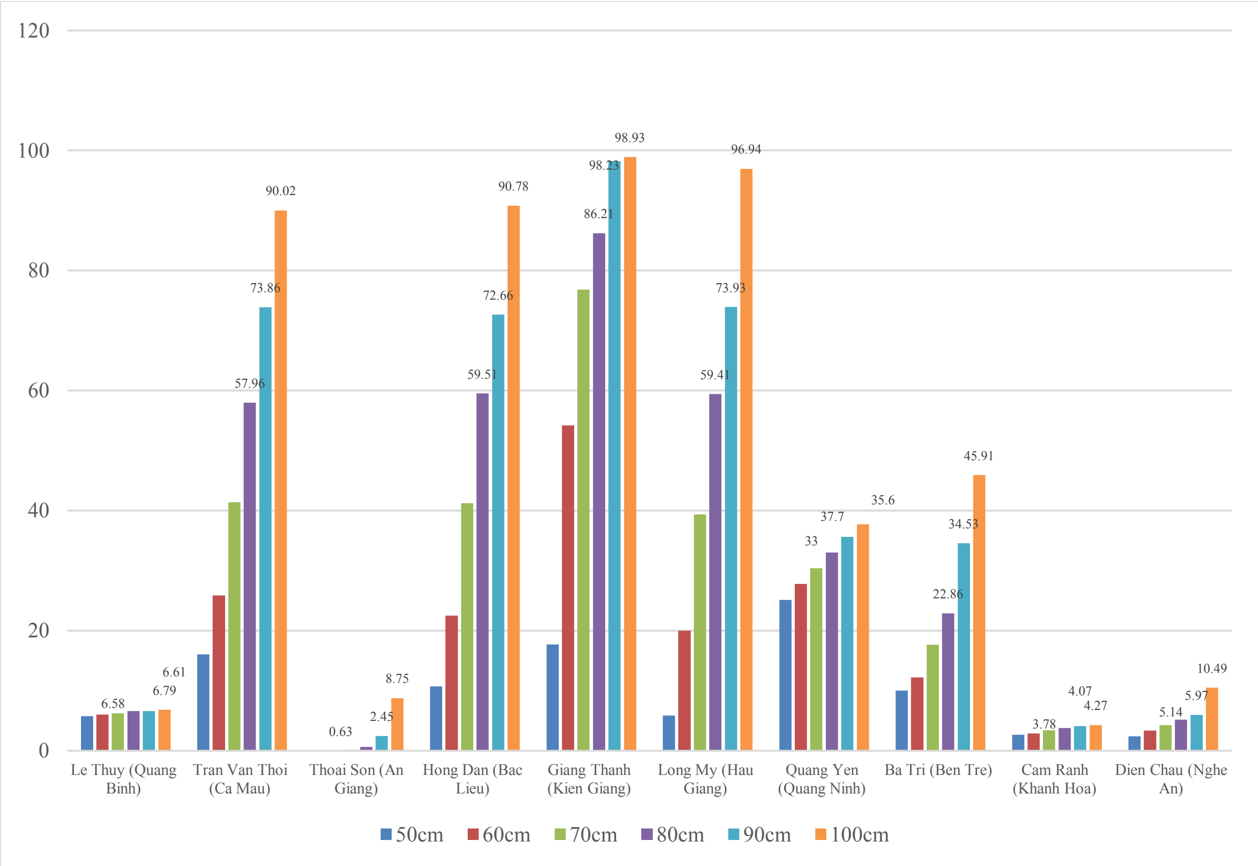

Fig. 2. Risk of flooding concerning sea level rises (% area) of the ten largest coastal regions of Vietnam [11].

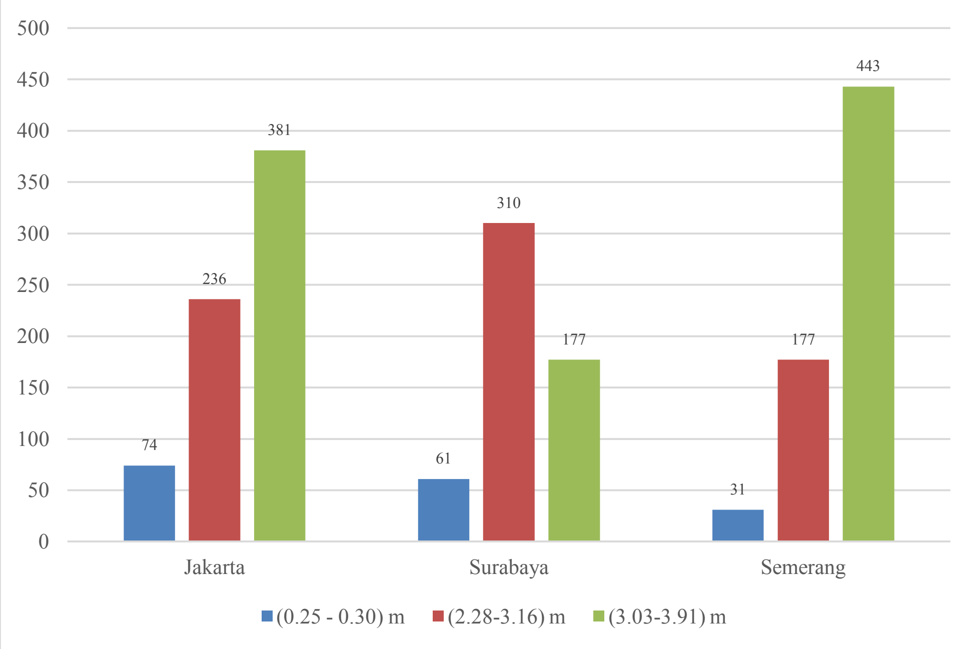

Fig. 3. Potential impact of sea level rise in three big cities of Indonesia (in '000); number of people affected due to sea level rise in three big cities of Indonesia (in '000). [12].

The Maldives, on the other hand, comprised of almost 1192 coral islands situated in the Indian Ocean is under serious threat of seal level rise [17] since almost eighty percent of the areas exist within one meter of mean sea level. The IPCC projected sea-level rise at the end of this century may cause wiping out the country from the map of the world. Beach erosion, bleaching of corals are the major coastal problems in Maldives. The Maldives is not located in a region of cyclonic disturbance, but the northern parts are affected by storms generated in the Arabian Sea and Indian Ocean [18]. Coastal erosion is a concern for Sri Lanka; the country reported that coastal erosion is taking place at a rate of about 0.03 to 0.35 meter per year [19]. Sea level rise, storms, floods, saline intrusion and coastal retreat are common hazards in Sri Lanka which will result in changes in habitat and species distribution, landward migration of coastal species and may cause coastal infrastructural damage [19].

4.2 Coastal Countries with Moderate Vulnerability

The countries that have comparatively less coastal areas are generally less vulnerable because only a part of the whole population live in coastal areas and the concentration of economic activities is less (Table 1). These countries are also prone to coastal hazards and are categorized as the second most vulnerable countries. Countries like China, India, Thailand lie in this group. The types of coastal hazards faced by these countries are almost similar to those faced by the most vulnerable (Group I) countries. Sea level rise, increased frequency of tropical cyclones, coastal erosion, flooding, saline intrusion, destruction of coastal and marine ecosystems are the major types of coastal hazards in these countries. The countries reported that these natural hazards are not new rather they existed from time immemorial. But the strength and severity, frequency of occurrence, the unpredictability of these hazards have increased significantly in recent years.

India, a country of having a coastline of about 7500 kilometers, is susceptible to different types of coastal hazards, though the types of coastal hazards are location specific. For instance, the Bay of Bengal (West Bengal) and Gulf of Kutch coasts anticipate the highest level of sea-level rise, accounted for 0.4 to 2.0 mm per year [20]. In contrast, sea-level in the coastal areas of Karnataka undergoes a relative decrease. The overall estimation of sea-level rise between 1990 to 2100 is about 3.5 to 34.6 inches [21]. India expects that a one-meter sea-level rise would cause to displace approximately 7.1 million people in India, and about 5,764 square kilometers of the land area will be lost, along with 4,200 km of road networks. Indian government expressed their concern about the future state of coastal wetlands and mangrove forests as a result of climate change induced sea level rise, the temperature increase in the coastal areas, change in the brackish water environment, and increased frequency of storm surges. The mangroves located in the mouth of Ganges-Brahmaputra in West Bengal, Mahanadi mangrove forests in Orissa, the Godavari and Krishna mangroves in Andhra Pradesh, the Pichavaram and Muthupet mangroves in the Cauvery delta of Tamil Nadu, the mangroves in the Gulf of Kutchh in Gujarat, and those in the Andaman and Nicobar islands are in great danger of coastal hazards. Besides, increased sea surface temperature causes severe bleaching of corals in Indian coastal areas. Three major metropolitan areas, such as Kolkata, Mumbai, Chennai, and eighteen urban centers, having a population of one million are located in coastal areas [20]. These urban agglomerations and

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associated infrastructures are under threat of cyclonic events. Table 3 depicts the spatial and temporal pattern of cyclonic events in the Indian coastal areas.

China is mostly concerned about sea-level rise. The sea-level rise in the Yangtze and Pearl river delta would create a severe impact on agricultural production and human habitation. In the coming 30 years, marked as critical coastal economic belts, these areas will be the most vulnerable zone and face a high risk of flooding due to rising sea level which has happened at an average rate of 3.3 millimeters/year between 1980 and 2017 [22]. Currently, the Yangtze and Pearl river delta areas are experiencing a rate of 3.1 and 1.7 mm per annum increase in the sea levels respectively [23]. The general trend of the change in sea level is that the change along the southern coast is relatively significant, while that along the northern coast small; among the coastal provinces, a significant level of the rise was recorded along the coastal regions of Hainan and Guangdong provinces, while the smallest along coastal regions in Tianjin, Hebei and Liaoning provinces. Decadal change of sea surface temperature indicates a rising trend. The increase in the temperature of coastal waters were estimated to be as 0.55, 0.35, and 0.25 degree Celsius per decade for winter, spring-autumn and summer respectively [22] which may cause coastal bleaching.

Thailand experiences cyclonic disturbances in the forms of depressions, monsoon, and typhoons in their coastal areas. Based on the historical trend analysis, the Department of Disaster Prevention and Mitigation of Thailand reported that Thailand would face an increased number of cyclonic hazards over the upcoming years (Table 4). However, Thailand expressed concerns about understanding local level climate change impacts based on the global scale modeling results [24]. Their National Communication paper mentioned that more local scale research is needed to understand the precise nature of climate change induced coastal hazards.

Table 3: Cyclonic events in Indian coasts.

The spatial pattern of cyclone incidences and the fact (data from 1877 to 1990)

- 1474 cyclones originated in the Bay of Bengal and the Arabian Sea during this period.
- 964 cyclones crossed Indian coastline; of these 3 districts in West Bengal received 174, seven districts in Orissa received 422, nine districts in Andhra Pradesh received 203 and 15 districts in Tamil Nadu received 100 cyclonic events. The remaining 65 cyclones are received by Indian west coastal areas.

The temporal pattern of cyclone incidences

- Depressions have a distinct peaks in the month of August
- Storms have two distinct peaks in June and October
- Severe storms have distinct peaks in May and November
- The total number of tropical cyclones seasonality follow the path of the depression

Average based on the facts

- 8.45 cyclones cross Indian coastline every year
- 5.15 depressions cross Indian coastline on n average per year
- 1.93 storms occur on an average per year
- 1.35 severe storms occur on an average per year

Table 4. Trends in the intensity of depressions, monsoons, and typhoons in Thailand and forecasts over the next 30 years (2013 to 2043).

Storm	1963 to 1982		1983 to 1997		2013 to 2043	
	Number	%	Number	%	Number	%
Depression	8	54	6	46	6	40
Monsoon	5	33	4	31	5	33
Typhoon	2	13	3	23	4	27
Total	15	100	13	100	15	100

4.3 Less Vulnerable Countries

The countries having significant coastal areas but comparatively better protected from coastal hazards are categorized in this group (Group 3). The countries are better protected because of their locational advantage or the countries are technologically and financially capable to put safeguard efforts for minimizing the negative consequences of natural hazards. Countries like Myanmar, Cambodia, Pakistan, Singapore, Japan and both South and North Korea fall into this category. The comparatively safer geographical position of the countries such as Myanmar, Cambodia and Pakistan and the technological and financial advancement of Singapore, both the Korean states and Japan fall into this group. For instance, the eastern parts of Myanmar are protected by Thailand and the southern adjoining Gulf of Martaban is comparatively shallower than the Andaman sea or the adjoining Bay of Bengal. This shallow depth of continental shelf areas contributes to softening the impacts of cyclones or tsunamis and give Myanmar better natural protection from coastal hazards.

Table 5 indicates that only cyclone Nargis, struck in Myanmar coast on 02 May 2008 caused 138 thousand deaths; the death toll in the rest of other coastal disasters is less. The high death toll in cyclone Nargis took place because of lack of preparation to deal with this disaster, where almost similar kind of cyclones struck in Bangladesh coast in 2007 and 2009 (cyclone Sidr and Aila respectively) causing death below 5000 people in each disaster because of better preparedness were put in place.

Table 5. Top 10 disasters in Myanmar in terms of number of people killed.

Disaster	Date	No of people killed
Storm	May 2008	138,366
Storm	May 1926	2700
Storm	May 1968	1070
Storm	April 1936	1000
Storm	May 1902	600
Earthquake	May 1930	500
Storm	May 2004	236
Storm	May 1975	200
Storm	October 1967	178
Flood	October -2011	151

Source: EM-DAT: The OFDA/CRED International Disaster Database, www.em-dat.net – Universite Catholique de Louvain – Brussels – Belgium". Data created on June 23, 2020.

On the other hand, Cambodia is protected by Thailand, Laos, and Vietnam in eastern, northern and eastern parts, respectively; only the southern parts are open to the Gulf of Thailand. But this coastal part is also protected by mountain ranges from coastal hazards. These physical barriers put Cambodia in a relatively safer position from coastal hazards. National Communication report of Cambodia also mentioned that the country rarely suffers from extreme weather events such as typhoons [25]. However, recent studies confirmed that this country is threatened by a sea-level rise which may threaten seaports, beach resorts, coastal fisheries and coastal land use patterns. Recent analysis showed that 25000 and 38000 hectares of lands will be inundated permanently if sea level rise happens 1m and 2m respectively [26]. Eighty percent of lands may go under water in the low-lying areas of Koh Kong province if sea level rise takes place by 1 meter and eleven percent in Prah Sihanouk Province. The coastal mangrove forests, grasslands and shrimp farms in these coastal plains would be destroyed as an effect of sea-level rise [26]. Large parts of Mekong river delta and Combodia's 435 km shoreline could be affected by sea level rise [27].

Pakistan also reported climate change induced vulnerates in variety of forms [24]. A small part of Pakistan (the Indus valley and port city Karachi), stretches over 990 kilometers, is situated along the Arabian sea, more specifically along the Gulf of Oman. These coastal areas are susceptible to coastal hazards like cyclones. Almost seventy five percent of the cyclones that spawned in the Arabian Sea generally end up at the Omani coast on the western Arabian sea, and the remaining twenty five percent cross Pakistan coast as reported in Pakistan's National Communication report [28]. Sea level rise becomes a significant concern for Pakistan. Pakistan anticipates that the very physical processes and sediment dynamics will be impacted as a consequence of sea-level rise, resulting in disturbances to coastal mangroves.

On the other hand, South Korea, North Korea, Japan and Singapore remain under threats of coastal hazards, but they are better prepared to face those events. Japan gives protection to both the Korean states from cyclonic hazards as Japan situates directly in the eastern sides of Korean states. Korean countries are rather worried about the rise of the water temperature and increase in the sea level in the surrounding waters of the Korean Peninsula, which will ultimately cause changes in the ocean circulation pattern and seawater characteristics resulting to the change of the marine ecosystems and impacting on the distribution of fisheries resources in adjoining coastal areas.

However, Japan is one of the worst affected countries from cyclone hazard, but the country has demonstrated tremendous success in reducing vulnerability by strengthening community capacity and making evacuation efforts efficient. This statement is also true for Singapore since the country has protected about eighty percent of her coastline from hazards by erecting hard walls and stone embankments. Mangrove forests protect the remaining areas. However, Singapore showed their concern as sea level rise may cause saltwater intrusion into their water reservoirs [29]. However, Singapore is getting prepared to deal with climate change induced coastal hazards by accommodating adaptation measures in its *Sustainable Singapore Blueprint* and took necessary steps towards its implementation.

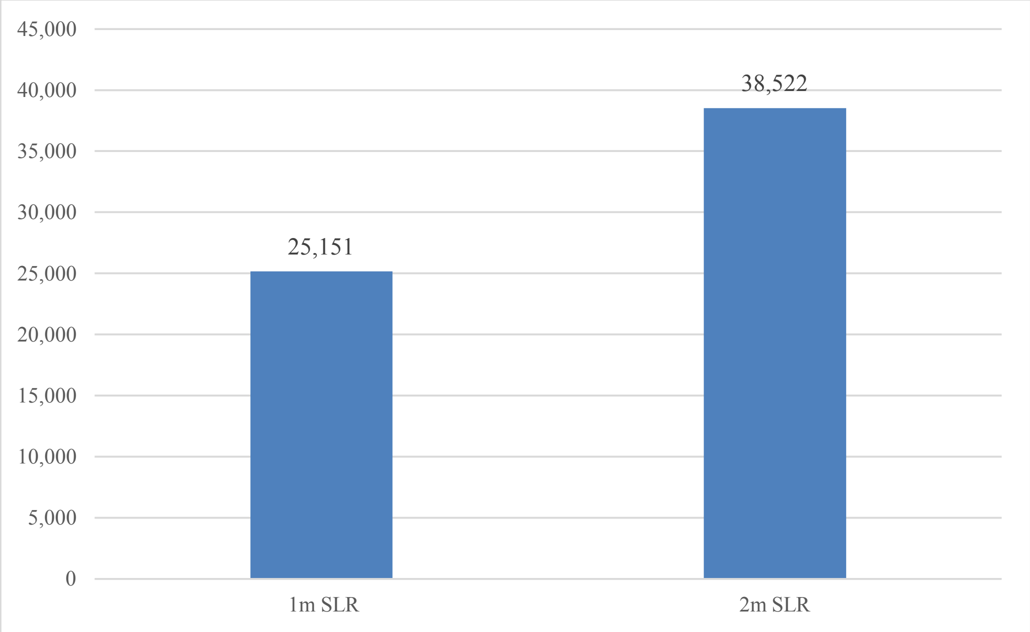

Fig. 4. Coastal areas (in hectares) under threat of inundation against 1m and 2 m sea level rise scenario in Cambodia [26].

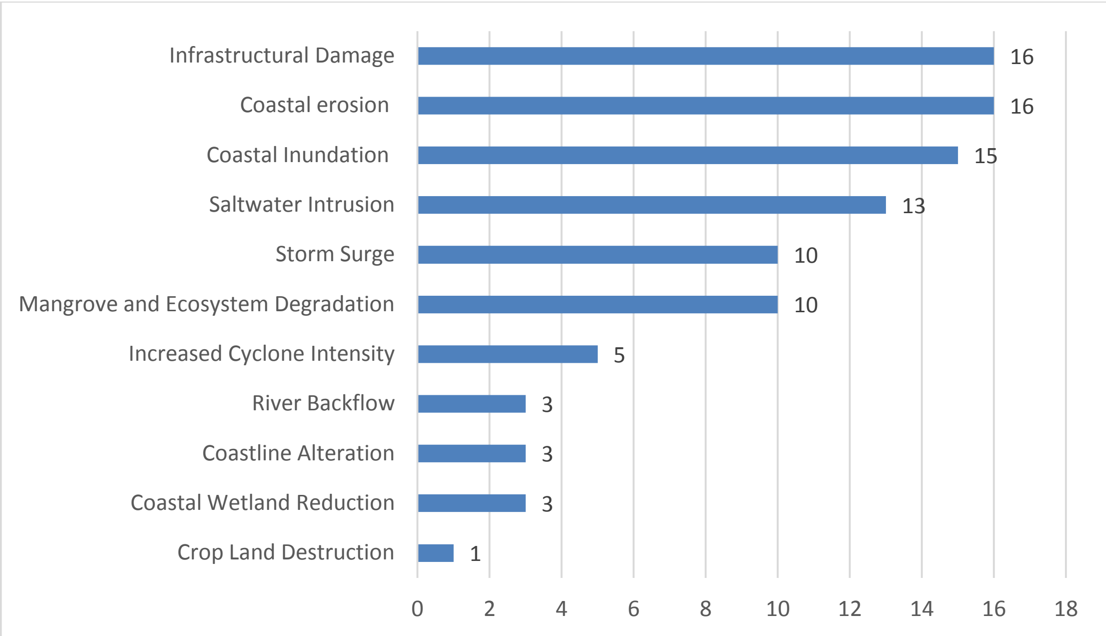

Fig. 5. Sectors of potential impacts of sea level rise and number of concerned countries.

5. CONSEQUENCES OF COASTAL HAZARDS

The review of the National Communication (NC) reports prepared by seventeen Asian coastal countries for UNFCCC gives the opportunity to make continental-scale comparative assessment on climate change induced threats and challenges. The countries reported a range of hazards those are currently occurring and also those which may occur in the upcoming years as results of change in the climate systems. The reported hazards are mostly identical but the degree of threats was reported to be variable in different countries (Table 6). It is found that cyclonic disturbances are common in all the countries which is deadly and rise in the sea level indicated by most of the countries as a potential threat (Figure 5) in the coastal systems (both economic and ecological). The countries mentioned (Table 6) that many hazards are localized but will become a potential challenge in the future under the influence of incremental changes of regional and global patterns of climatic systems. The concerns for hazards come from the fact that these will destroy infrastructure, local economy and destabilize the ecological processes vis-à-vis undermine the ecosystem services based on which coastal communities live and thrive.

6. LITERATURE BEYOND NATIONAL COMMUNICATIONS

This paper primarily focused on climate induced hazards and vulnerability that are narrated in the National Communication Reports (NCR) submitted to UNFCCC by 22 coastal countries of Asia. The results informed about the impacts and magnitude of hazards in the milieu of climate change. In addition to these documents, a rich scholarly literature is available that was not taken in the purview of this paper. However, a brief reflection from the literature that exists beyond NCRs may provide an extended understanding of the issues mentioned in the paper. For instance, a study shows that due to saltwater intrusion, oil palm production in Malaysia will be seriously interrupted [34] under the increasing trend of storms, droughts and floods [35]. The increasing trend of storm intensity and sea level rise is projected for the Philippines [32], the vulnerability in low-lying coastal areas of Vietnam is increasing [37]. Studies show that the salinity level is becoming high in coastal regions of Bangladesh which is highly affecting the economy and livelihood in those areas including sectors such as health, water and sanitation [30], [31]. Apart from coral reef destruction, increased coastal flooding is expected in the Maldives [36]. Sri Lanka is expecting sea level rise that might cause increased coastal erosion [37]. In Thailand, increasing trends of droughts are reported in eastern parts of the country [38] and prolonged droughts, decreased agricultural and fishery yields, violent flooding, sea level rise and health related issues can be seen in the future throughout the country [39]. Both India and China might experience different types of hazards in their vast coastal areas from climate induced rainfall anomalies and increased temperature conditions [40, 41].

7. VULNERABILITIES OF BANGLADESH COAST IN THE CONTEXTS OF CLIMATE CHANGE INDUCED HAZARDS

It is widely reported that coastal regions of Bangladesh are one of the major vulnerable areas of the country [42], [43] that sufferers from a range of natural hazards such as cyclonic disturbance, storm surge, flooding, waterlogging, coastal erosion, salinity intrusion etc. [44], [45]. These situations are aggravating under the influence of climate change [16] and the people living in coastal areas are becoming more exposed to hazards. Even the efforts taken by the government, development partner agencies (like UNDP and other international agencies) and non-government agencies as part of the adaptation process (such as building infrastructure, providing livelihood support etc.) are also damaged repeatedly and thus the hard-earned gains towards building resilience become undermined. These challenges are currently being critically scrutinized by the researchers and also by the government agencies [46], [47] to devise appropriate pathways so that vulnerability-reducing actions and related gains could sustain. Improvements in the allocation of business of the government agencies (e.g. incorporating the 'climate change' in the name of the ministry of environment and forest and adoption of new responsibilities), developing climate sensitive budget codes by the Ministry of Finance [48], institutionalizing climate change interventions into regular development pathways of the government [47] are some of the evidences of taking different, novel and appropriate approach in tackling climate change threats in Bangladesh. In these contexts, it is imperative to know about the problem contexts happening in other countries facing similar kinds of challenges, may be happening in different forms. For example, Vietnam considers three approaches (adaptation, mitigation and withdrawal) to tackle climate change threats while Bangladesh is based on two (adaptation and mitigation). Bangladesh may learn from Vietnam whether 'withdrawal' is appropriate or not for Bangladesh for certain coastal regions. This cross fertilization of knowledge may help Bangladesh to develop policy and necessary instruments that are appropriate for the time and need to tackle climate change related challenges more effectively and sustainably.

8. CONCLUSION

The communities living in the coastal areas in Asian countries have been dealing with coastal hazards for hundreds of years. Some countries have enhanced their capacities to reduce the degree of impacts and to better adapt with the challenges, while some countries still suffer from disaster impacts due to weaker economic conditions and exposure of a large number of people to hazards. This review assessment, in this backdrop, suggests that climate change related hazards have appeared as a new dimension to the pre-existing set of uncertainties and exacerbating the situation that has already been fragile as a consequence of socio-economic-political systems of societies [14], [49]. The countries have been putting their efforts to develop policies and improve institutional capacities to deal with the challenges. But the inadequate and incomplete understanding of the hazards (in terms of intensity, magnitude and frequency of occurrence, spatial extent etc.), risk and vulnerability may create impediments in devising appropriate policy instruments to deal with the challenges.

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Building Resilience Fighting Back Vulnerability in the Coastal City of Khulna, Bangladesh: A Perspective of Climate-Resilient City Approach

Md. Esraz-Ul-Zannat*, Md. Anwarul Abedin[+,1], Indrajit Pal[#], and M. Mashroor Zaman[^]

Abstract – *Extreme weather is becoming one of the fierce symptoms of rapidly changing climate era which is causing long and short term damage at different aspects of our day-to-day life. Extreme weather events like heavy rains cause sewers to overflow and may result in urban flooding a common scenario to the cities in developing countries like Bangladesh. With a current population of 1.4 million estimated to rise to 2.9 million by 2030, Khulna is more prone to urban flooding due to lower topography and sea-level rise due to climate change. This research aims to find the different aspects of climatic vulnerability and how the city is sustaining by gaining resilience and adaptation in the hostile climatic condition due to climate change and sea level rise. Different spatial analysis viz. land use-land cover mapping, flood mapping based on Digital Elevation Model, catchment delineation, hazard and risk mapping, physical vulnerability, etc. carried out to understand the climatic hazard condition and its impacts on different aspects. It is found that 0.25m and 0.50m sea level rise (SLR) leads to inundate 5% and 9% of the city where 4% and 6% are agriculture respectively within the city. Within this range, residential uses inundate 0.50% and 1% respectively. The city has 52% open field and greeneries and 14% waterbodies which can absorb 0.50m SLR accepting 1% inundation of the residential land uses. This research would help city decision-makers to make them more familiar with the climate resilience and adaptation options in relation to the growing concern of the city and choose the right decision.*

Keywords – *Climate change, flood mapping, hazards, risk, spatial analysis.*

1. BACKGROUND

The current population of the world is 7.7 billion and more than 50% of them live in cities and increasing with each passing year [1], [2]. According to UN projections, by 2050 more than 68% of the world's population could be concentrated in urban areas. The rate of urbanization especially in the cities of the developing countries is quite high and population in the urban areas is increasing gradually with the passage of time. The annual rate of urbanization in Bangladesh is 3.3%, significantly higher than the national population growth of 1.8% [3]. It is expected that the current urban population of about 53 million, will grow twice the size with 112 million people by 2050 [4]. The ever-growing expansion of urban cities and urban adaptation that were made have given rise to sprawling metropolises beset by a range of social and environmental problems due to the interaction between urbanization and its social and environmental impacts in respect of current and future universal challenges. Modern cities are in tremendous pressure to provide sufficient facilities to accommodate the needs of this rapidly growing trend in urban population including proper housing, sufficient scope of work and resources such as water, energy and food. Continued emission of greenhouse gases is adding extra dimension to these challenges and cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems [5]. One of the key sustainable challenges to the future of modern cities is urban resilience. Frequent and heavy rainfall, hailstorms, extreme temperatures, flooding and waterlogging, drought, cyclone and storm surges, etc. are making cities more complex urban systems and create hindrance to provide city services. Khulna, a coastal city of Bangladesh is not exceptional in this regard. Climate change and its consequences add extra dimension to this complex system [24]. Khulna City is a quintessential example in this context as it is one of the most vulnerable coastal cities in the world.

Over the past 50 years, modern cities in the different part of the world are experiencing a rapid, unplanned and uncontrolled which caused the loss of numerous permeable soils which constantly reducing the soil's ability to absorb rainwater making cities vulnerable to manage the impacts of rainstorm triggered by climate change, and consequently increasing temperature [6]. Cities in Bangladesh especially Khulna are experiencing storm water drainage problems due to a combination of proper planning, policy making, and implementation, structural and climatic factors [7]. It's likely to increase the frequency of short duration, high-intensity rainfall in the near future because of climate change [8]. Given the unplanned and inadequate condition of drainage systems in Bangladeshi cities,

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urban flooding and waterlogging are expected to intensify [9]. Urban flooding can wreak havoc in the cities and lead to significant impacts on people, the economy and on the environment. In response to the increased frequency of rainfall and the severity of flooding in cities the strategies for flood management moving away from flood proofing towards urban climate resilience. Climate resilience especially flood resilient together with technological implications have become the present aspect of critical thinking for city planners and decision-makers to manage flood risks. Flood resilience has been defined differently in various conditions and different context. Despite having different definitions, a common theme is that climate resilient cities are impacted less by extreme flood events.

For the sake of building resilient city, it is imperative to address the current gaps and challenges in the face of increasing weather extremes. So many experts focus more on the landscape and nature-based solutions in building the resilience. In this regards, these are identifying weak spots that will be affected by climate extremes, visualisation of climate information to facilitate planning processes, cooling cities by proper management of urban waterways, reducing damage caused by excess runoff water by planting trees, vaporizing water for a cooling effect, creating *wadis* (rain gardens) for water storage. Nature based solutions minimize the risk for floods, droughts and urban heat, render ecosystem services and improve the livability of cities [10]. Due to the complexity of making a city resilient, it is necessary to adopt an integrated approach along with ensuring participation at all levels to effectively transform a modern city into a resilient city. However, its way of becoming the climate resilient city should get the highest priority for Khulna City because of its importance as the political, economic, social and cultural centre of the region. So, the high vulnerability of the city to various water-related natural and man-made hazards should be minimized through a proper strategy and making it more climate resilient. This research has focused on exploring the urban flooding especially waterlogging problems triggered by climate change and sea level rise and examine the different casual factors and inter-dependencies of the different elements of the city with the given problems. In other words, how the city is behaving with the extreme climates and explore the impacts on different aspects. Opportunities especially landscape and nature-based solutions with related issues to build climate resilient city is also explored in relation to the gaps and challenges of the city.

2. VULNERABILITY AND CITY RESILIENCE IN CHANGING CLIMATE

Vulnerability is a concept which describes factors or constraints of an economic, social, physical or geographic nature, which reduce the ability to prepare for and cope with the impact of hazards. This research focused on the physical vulnerability which is appeared with hazards and disaster and triggered with climate change and sea level rise. The factors influencing the risk are not static and can be improved, enhancing the institutional and individual capacity to cope and act to reduce risk. It is important to mention that the organizational and community capacity in the context of response and recovery from disasters has paramount importance and can be linked to the concept of disaster and development including the concepts of resiliency, policy creation, and governance [26]. Climate change brings many challenges for the cities though they are fighting with numerous problems at present. In other words, climate change is making cities more vulnerable and will exacerbate the situation in the future. Frequent flooding and prolonged inundation cause damage to properties and affect livelihood, and the impacts are multiplied for densely populated areas [24]. Climate variability has contributed to the unpredictability of precipitation in many parts of the world and also to the frequent urban flooding. Climate change induced corollary effects impact every aspects of the cities especially the urban infrastructure, livelihood of the residents, natural and man-made environment [31][30].

In urban areas where ground surface is paved with asphalt and concrete, rainwater mostly remains on the surface, which is subsequently drained by networks of drainage system. However, floodwater from persistent heavy rainfall sometimes exceeds the capacity of the drainage system in many urban areas [24]. Flood risk management in urban areas relies on structural concrete infrastructure for flood prevention and management. Nevertheless, evidence shows that resilience and flood adaptive capacity of urban residents (i.e., non-structural strategy) are key to effective flood reduction and management in cities and urban areas. Effective urban flood prevention requires holistic urban infrastructure planning which takes into account technological capabilities, land use, floodwater drainage, and flood prevention strategies [25], [27]. Risk assessment is an initial step to determine the risk by analysing hazards and evaluating vulnerability conditions and exposure of the property, services, livelihoods, and the environment [29]. Building resilience of the city will be the main focus of the city decision makers to fight back the vulnerability through innovative climate-proofing solutions. A resilient city is characterized by its ability to withstand or absorb the impact of a hazard through resistance or adaptation, which enable it to maintain certain basic functions and structures during a crisis, and bounce back or recover from an event [11]. To achieve sustainable development of the city, integrated DRR and resilience must be part of urban design and strategies through multi-stakeholder alliances and broad participation [26].

In a word, a resilient city is continued to sustain enduring the extreme climates keeping functioning of the physical and socio-economic infrastructure. It means it has ability to tolerate the impacts on the city system.

When the future hazard strikes, the city will minimize the impacts on the society, economy and environment. All the component of the complex system of the city viz. technological, natural and social acts together to hinder the unexpected events. [12]. Along with the complex risk governance system, the effective early warning system required well-developed governance and institutional arrangements to support the successful development and sustainability to encourage local decision making [28]. Carefully designed sociotechnical systems and incorporating a process of continuing organizational, inter-organizational, and interjurisdictional learning may manage the risk more efficiently and effectively [32].

3. STUDY AREA

Khulna is a linear shaped city. Its shape and growth are conditioned by geo-environmental controls such as physiography, natural and man-made drainage pattern, geological structure, soil condition, fluvial factors and climatic condition along with most of economic and socio-political factors [13]. Khulna is the third-largest city of Bangladesh with an area of 46 sq.km located in southwestern Bangladesh (Fig. **1**), on the banks of the Rupsha and Bhairab River to the east. In the west of the city, Mayur River is situated. The city consists of 31 wards (Fig. **2**) starting numbering from the north and ending to the south.

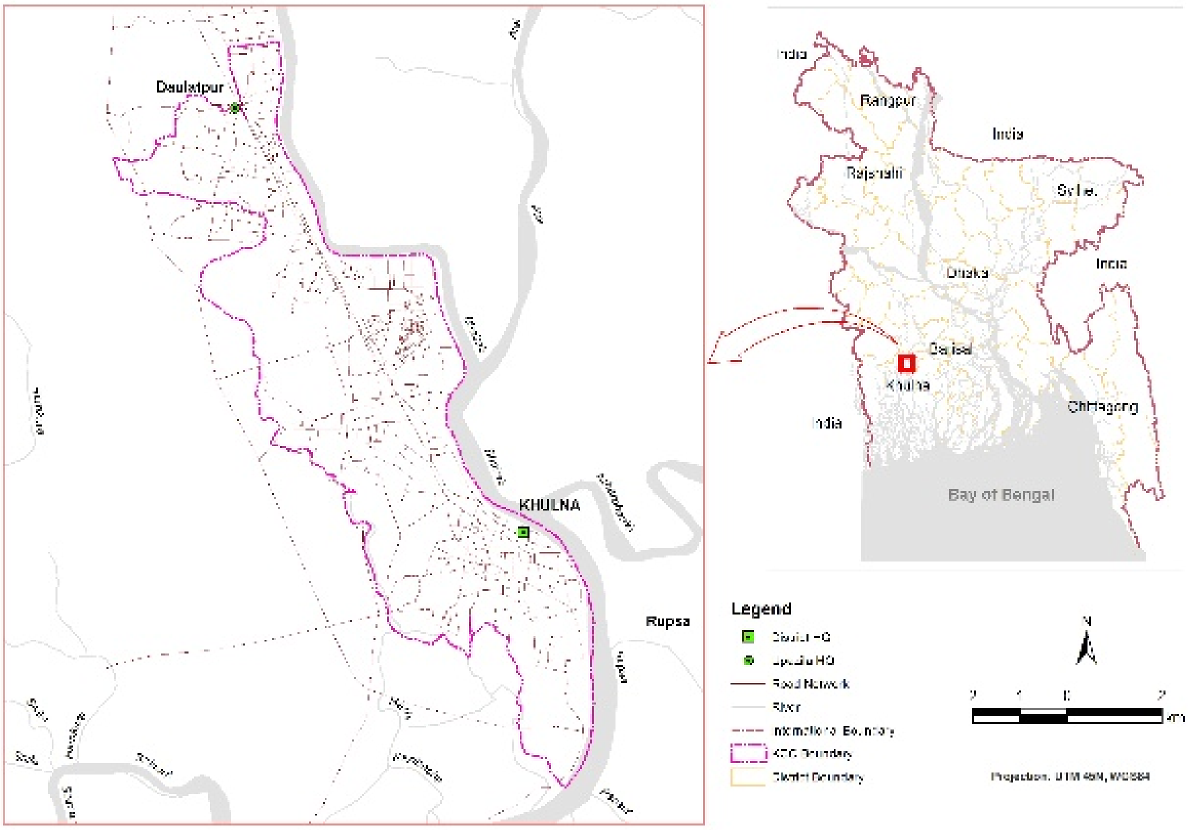


Fig. 1. Location of Khulna City.
Source: Authors, 2020

Khulna is humid during summer and pleasant in winter. The annual average rainfall of Khulna is 1,809.4 millimetres and average highest and lowest temperature is 40.5ºC and 7.0 ºC for Khulna, have been found in June and January respectively in 2013 [14]. It is also found from the Fig. **3** that monthly average of the maximum temperature for 17 years from 2000 to 2017 found highest in April and May. It is evident from the Fig. **4** that there are variations in yearly average temperature over 17 years but at present it is moving upwards. Approximately 87% of the annual average rainfall occurs between May and October [15]. Fig. **5** shows that almost in every decade, there was a major fluctuation in the occurrence of rainfall and highest amount of annual rainfall found in 1974. It is also noticed from the same figure that after 2014, rainfall showed uprising trend, and it is 2337mm in 2017.

This city is attractive to people, majority of them came from the neighboring districts due to employment opportunities. In addition, people from the coastal risk prone areas migrate to this city after disasters. The major concerns for Khulna City are frequent and increased level of floods, storm surges, the intensity of cyclones; water logging, saline intrusion, and sedimentation and river erosion, which are expected to be particularly severe due to the consequences of climate change. On the other hand, Khulna has a lot of opportunities to fight back the risk and vulnerabilities arising from the hazards. The city is surrounded by rivers and crisscrossed by a number of canals. Though the main city area is dense, another part of the city still has a vast amount of land to be developed. It is observed that city land areas that are less used for urban purposes covers a significant number of waterbodies.

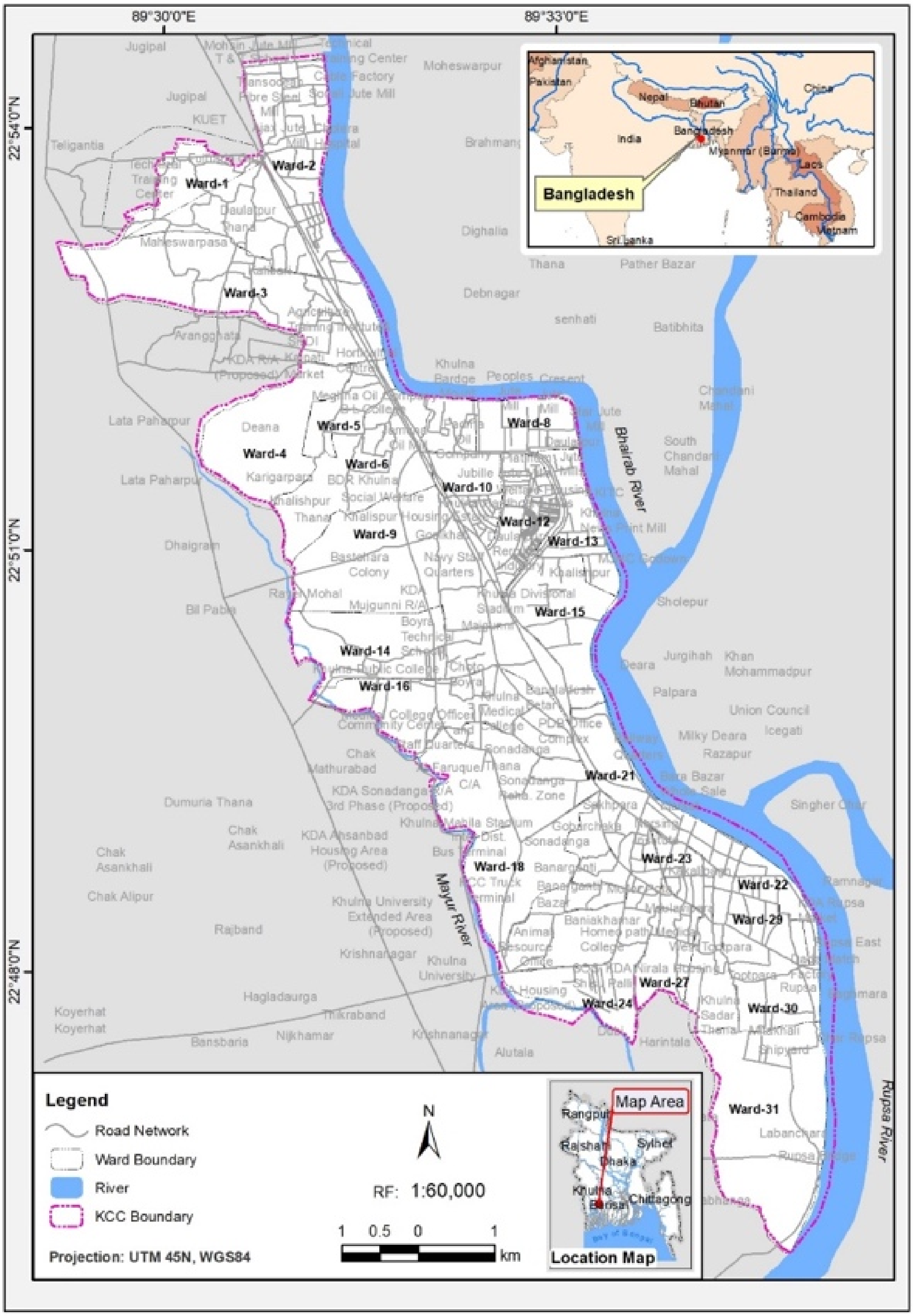


Fig. 2. Study area with respect to Bangladesh and South-East Asia.
Source: Authors, 2020

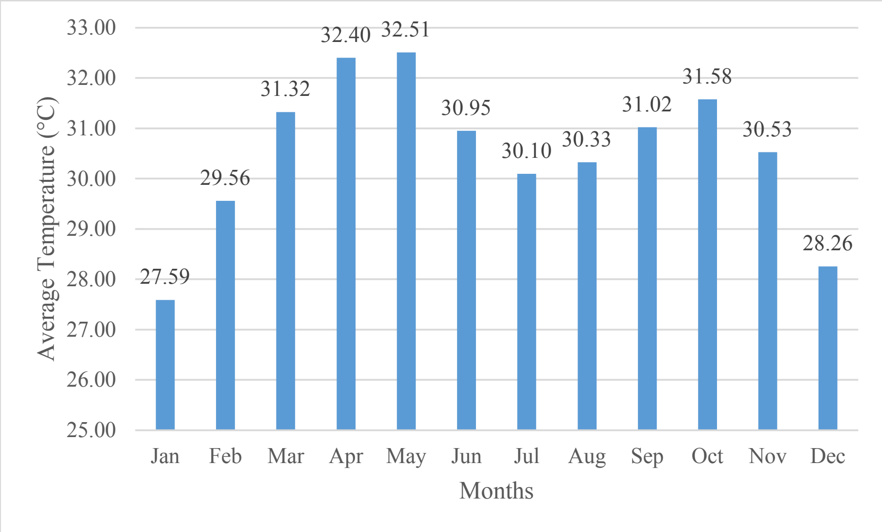


Fig. 3. Monthly average temperature distribution for 2000 to 2017.
Source: Bangladesh Meteorological Department (BMD), 2020

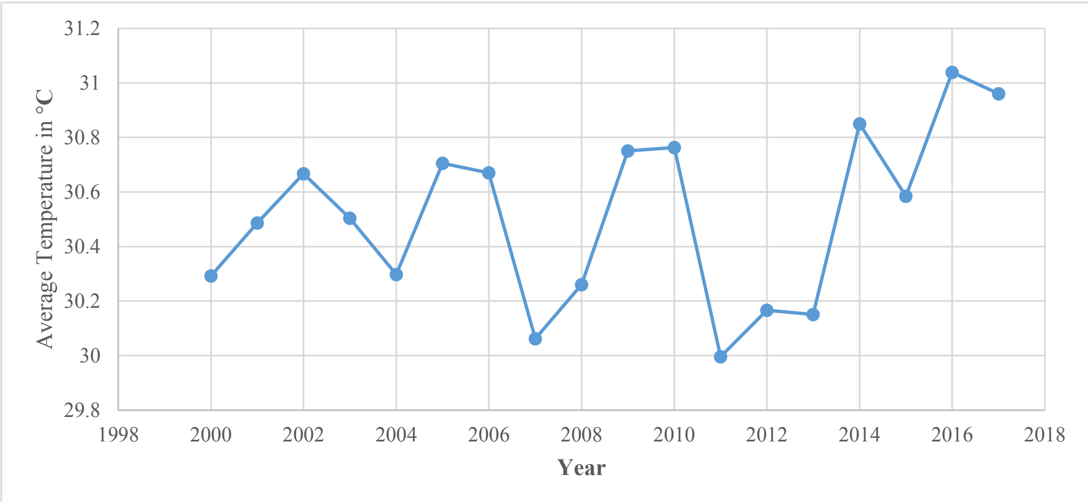


Fig. 4. Yearly average temperature distribution for 2000 to 2017.
Source: Bangladesh Meteorological Department (BMD), 2020

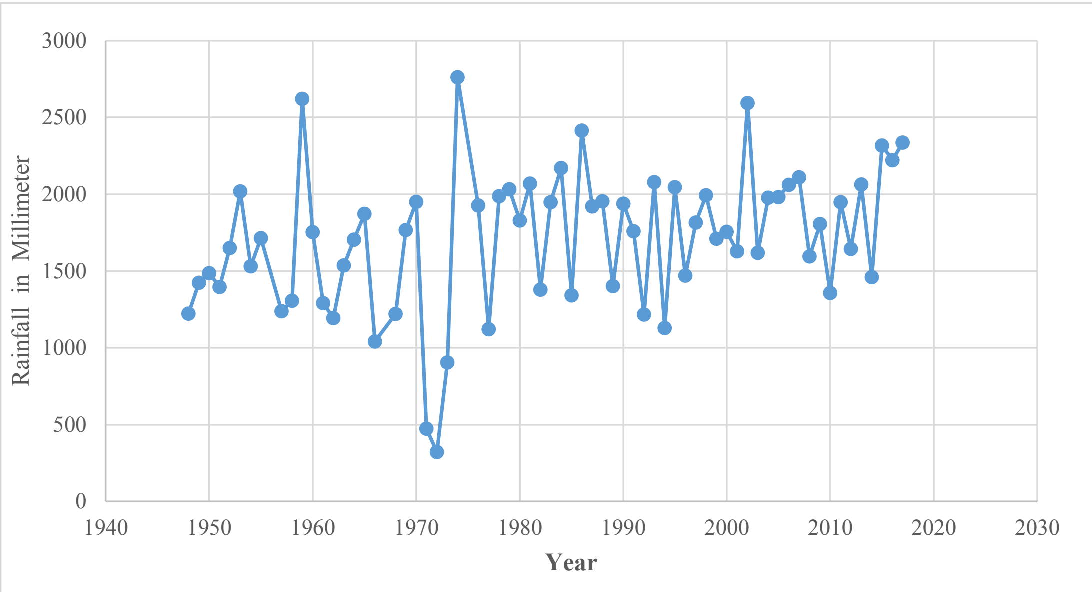


Fig. 5. Yearly rainfall distribution for 1948 to 2017.
Source: Bangladesh Meteorological Department (BMD), 2020

Population growth rate for Khulna City is comparatively slower than other major cities in Bangladesh. In 1991, population growth rate was 1.51 and it was reduced to 1.35 in 2001. During this 10-year, population increased by 16.15% whereas from 2001 to 2010 population increased by only 10.59% (948,814) [33], [34], [35]. According to population projection under KDA Detailed Area Plan (2001 - 2020), population for 2020 will reach out to1190000 where KCC will experience 25.42% population increase.

Household survey (2012) under Detailed Area Plan preparation by KDA shows that about 44% population migrated in the city from other places. Another study named Household Survey (1998) under Khulna Master Plan preparation by KDA shows that around 50% population migrated to this city. It is evident that after a major catastrophic event like cyclone and storm surge, people mostly from the hazard risk prone areas migrated to this city. Firewood is still the most dominating fuel in the KCC area where about 76% of the households use firewood as their main fuel. Among them, around 60% use firewood which indicates that majority people cannot afford LPG gas [17].

4. MATERIALS AND METHODS

This study is based on mainly secondary data sources, which were collected from sources such as government institutions, research centres and experts, development authorities, etc. More specifically KDA for planning data, Bangladesh Bureau of Statistics (BBS) for socioeconomic data, Google Earth for satellite images, Bangladesh Meteorological Department (BMD) for climatic data and other organizations. Beyond these, it required some primary data such as waterlogging observations during the raining in different parts of the city, field observations, which were collected through field survey, and interpersonal communications with the city officials of Khulna Development Authority, Khulna WASA and Khulna City Corporation. Data collected both from primary and secondary sources were checked, processed and prepared for carrying out different types of spatial analysis with MS Excel, GIS and Remote Sensing platform.

Based on topographic survey data carried out under Detailed Area Plan (DAP) in 2012 by Khulna Development Authority, high resolution (1m) DEM produced through Triangulated Irregular Network (TIN) and Natural Neighbor Interpolation technique and extracted for the Khulna City Corporation Area in ArcGIS Platform. This DEM is the major source of risk assessment and mapping due to flooding, sea level rise, and climate change, and watershed analysis. More than 200 catchments were generated using ArcGIS hydrology tools based on the generated DEM, which simplified into 60 catchments based on flow accumulation and flow direction for making the analysis process easier as catchments represents unit of analysis like drainage density, area, etc. Land use data came from the KDA Detailed Area Plan report. Land use and land cover maps generated from satellite images for 2005, 2010, 2015 and 2018. Satellite image for 2005 came from quickbird satellite. On the other hand, Google Earth images for 2010, 2015 and 2019 downloaded and further processed for maintaining accuracy. Image are classified using supervised classification method for land use and land cover mapping. Authors produced on an average of 500 training samples for each classification for ensuring better results. Overall accuracy for image classification was between 70% and 80% whereas Kappa coefficient was between 0.70 and 0.75 for all image classification of different years.

5. RESULTS AND DISCUSSION

5.1 Water System and Physiography

The physiography of Khulna is broadly characterized by tidal flood plains having lower relief and crisscrossed by innumerable river channels. Khulna City is on the natural levee of the *Rupsha-Bhairab River* (Fig. **2**) and its elevation sharply falls down to the east and gradually decreases to the west directions. Settlements along with other developments starts from the bank of the rivers. In the north south direction, the city finds its way to expand naturally on moderately elevated lands. But the western parts of the city are gradually expanding which has lower topography. The western part is enclosed by Mayur River, which is one of the major drainage channels through which a large volume of water, both, from the city and adjacent *Beel Pabla* and *Beel Dakatia* area is discharged into the river Rupsha [16]. This river is playing an important role to drain out excess water from the urban area as well as from the vulnerable *Beel Dakatia*. *Moyur River* fell into the *Passur River* at *Alutala* 10 vent sluice-gate. There are 22 existing canals besides the rivers with a number of small to large waterbodies which consists of an area of 2.5 sq.km (5.5 percent of the city area) shown in Figure 7 (a). There are more than 1000 ponds accounted for 43% waterbody and are playing a major role in managing the climate especially micro-climate and controlling the temperature and contain a huge amount of water during rain. Canals cover 10% waterbody and collects water from different watersheds and carry water to the rivers. Around 50% waterbody termed as ditches which are the retention areas for containing the rainwater. Figure 7 (b) shows the drainage networks which are man-made under covered, earthen and concrete categories. Among them, there are around 3600 concrete drains, 250 earthen drains and 278 covered drains which covers around 700km altogether. It is worth to mention that there is no underground drainage system in the city. About 68% households do not have any drainage facilities [17].

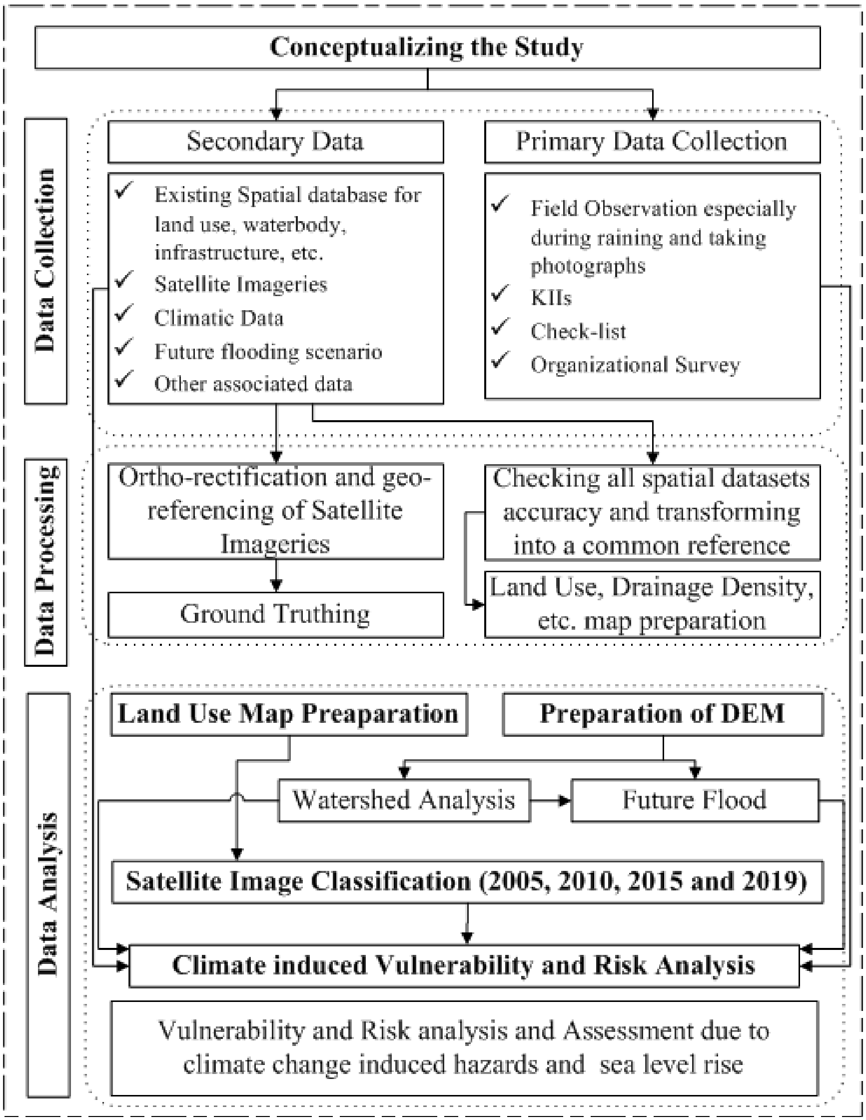


Fig. 6. Methodological flowchart.

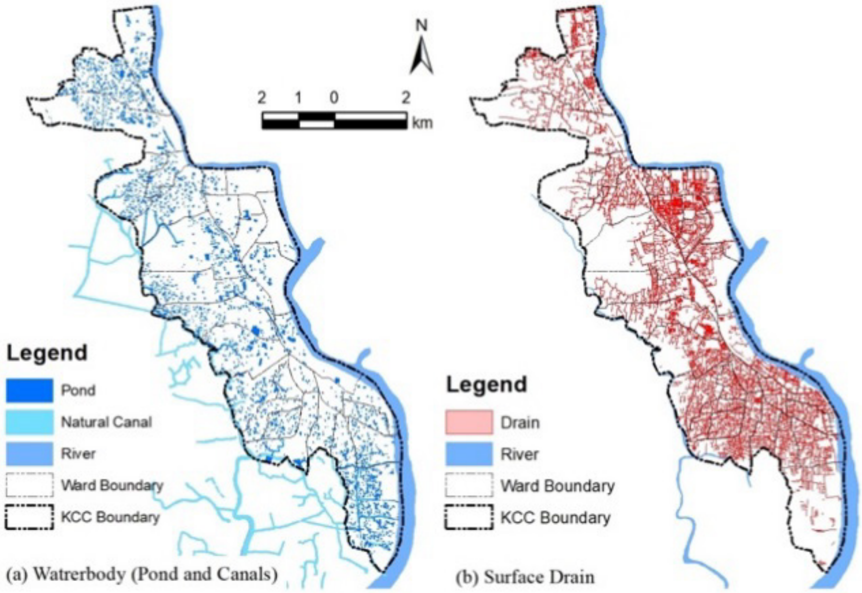


Fig. 7. (a) Waterbodies within the city (b) Drainage networks (both concrete and earthen).
Source: Authors, 2020 based on [17]

Watershed analysis in Fig. **8** shows the drainage density in 60 catchments over the city area. Through watershed analysis, 60 catchments resulted based on high resolution Digital Elevation Model. Highest amount of drainage density (31 – 40 km/ sq.km) is observed in 9 and 18 catchments at *Khalishpur* area where catchment 56 has no drains. But majority drainage networks are concentrated in the core part of the city. On the other hand, highest number of waterbodies in terms of area is found in catchment 4 and 31 where catchment 22 has no waterbodies. It is surprisingly observed that in the main part of the city, there is less number of waterbodies.

The spatial growth of Khulna City based on the topography and situated on the natural levee on either side of the *Bhairab-Rupsha* River which varies from (2.13 m to 4.27 m) above MSL and the levee extends about ½ km. to 4 km inside from the river on both sides [17]. Average topography of the city is 1.95m and only the flood plains is between 1.22 m to 1.52 m and beyond the flood plains, there exist ditches of lower topography which, is unsuitable for development. Fig. **9** shows that how the area varies with the change of elevation. Around 20% area is under 1m and 50% area falls within 2m elevation. Any rise in the sea level will affect these areas directly. It is mentioned here that rivers around the city are subject to tide. The low tide water level has been found (-) 0.92m at *Rupsha*. The high tide water level has been found (+) 3.75 m for the same area. About 25% of KCC area may have continuous gravity drainage [38]. During the high tide, river's water swells up and ingress in canals and drains through inlets and cannot escape during the low tide. As a result, the situation leads to cause temporary waterlogging in the local areas. During the monsoon, the situation become worst.

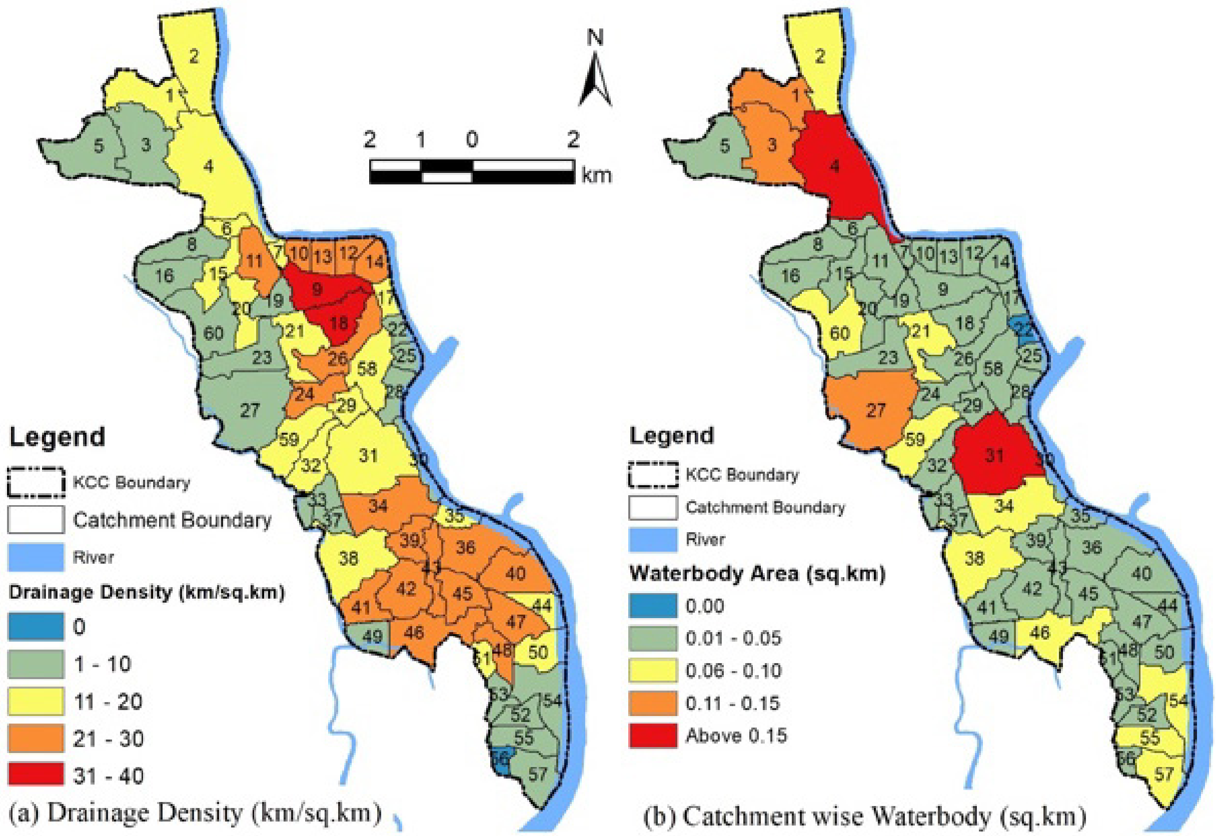


Fig. 8. (a) Catchment wise drainage density (km/sq.km); (b) Catchment wise among of waterbodies (sq.km).
Data Source: Authors, 2020

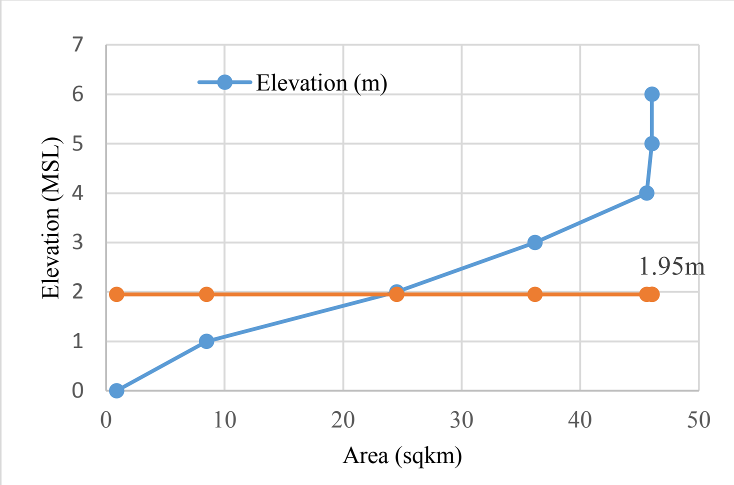


Fig. 9. Area elevation curve for Khulna City.
Data Source: Authors, 2020

Encroachments in the form of building structures in the hinterland (floodplains), connecting roads across the canals, etc. hinders the hydrological process. As a result, surface runoff finds nowhere to go and stuck in the surround areas and caused flooding. Cluster and larger developments that are poorly planned, designed without consideration of natural process or public safety, or located in areas with no real planning can have cumulative and ongoing impacts to floodplains, wetlands and the functions they provide. [18]. Lack of planning considerations and in some cases, absence of planning while establishing infrastructure in the floodplains and wetlands especially the hinterlands aggravate the flooding scenario during rainy seasons and cause permanent inundation in some areas.

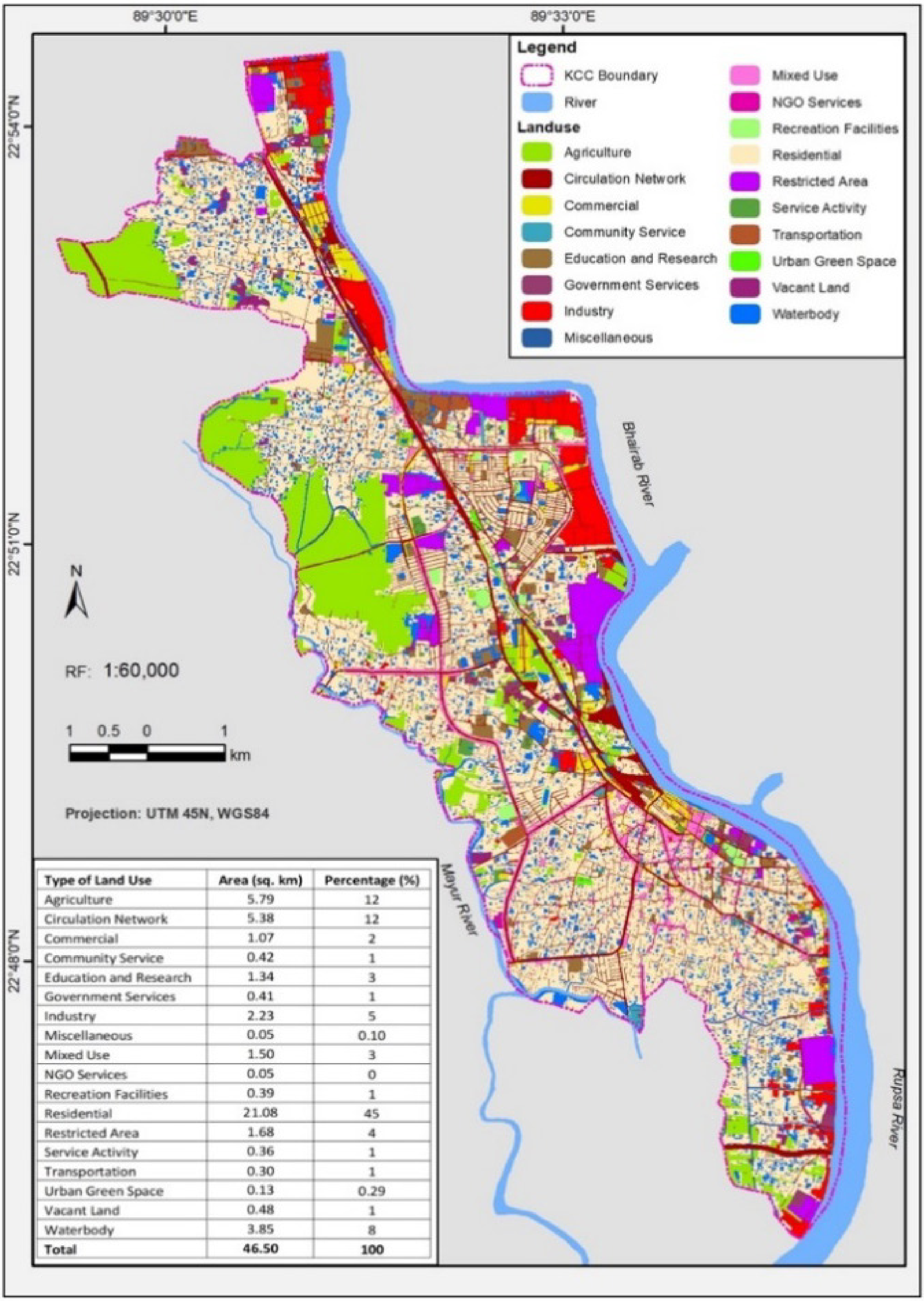
5.2 Land Use Characteristics and Land Use-Land Cover Change

Land use is the major determinants of functions for any city. In broader sense, pattern and distribution of land uses over city has a profound impact on the city's functioning. Fig. **10** shows the existing major land uses for the KCC where 45% area is allocated for residential purpose. But in the master plan component [13], the highest amount of land (48.45%) have been allocated for residential use which usually forms the principal part of the urban built up area. Agricultural land accounts for 12% and it is decreasing with times. 5% Waterbodies without rivers is playing major role in determining the climatic condition of the city. Agricultural land uses bear great importance as it includes majority portion as shrimp cultivation. Field observation and land use – land cover analysis shows that most agricultural land retains water all through the year. So, these areas act as retention pond during the monsoon. Khulna is an industry-based city, which encompasses 5% area. Recreational facilities and urban green spaces cover only 1.5% area which is really a major concern for the city planners thinking of the open space availability standard for ensuring the healthy and sound environment.

History of Development plan for Khulna city dates back in 1960s. But due to land use declaration criteria, pattern of survey and survey techniques, difficulties of comparing land uses of different time horizons for change detection is quite difficult. Furthermore, it is proven that land use change in the past especially before 1990s was slower than the present. For 14 years, from 1998 to 2012, 41% agricultural and 36% industrial and manufacturing land were reduced and transformed into other uses. On the other hand, there was an increase of 56% commercial and 25 residential land in the same period of time [17], [36].

It is evident that once the city was functioning based on industrial and manicuring activity and now it is decreasing. This indicates that the city is facing de-industrialization. Commercial activities are increasing, which indicates positive economic growth in the city and surroundings during the period under consideration. Detection of Land use and land cover changes calls for the need of assessing the environmental condition especially micro climatic at local levels, climate change for keeping the sustainability of the biodiversity at greater sense. As there is no survey data after 2012, land use-land cover changes resulted based on satellite images for 2005, 2010, 2015, 2019.

It is evident from Figure 11 that a substantial amount of vegetation together with open agricultural field is dominant in four different time horizons though it is decreased from 69% in 2005 to 52% in 2019. Furthermore, it is also observed that amount of water body is increased from 7% to 14% within the 14 years. In 2010, waterbody increased to 12% and 14% in 2015 and remained the same till 2019. Transformation of agricultural land into waterbodies for shrimp culture, retention of water during the rainy seasons, inundation during the tides, etc. are the major reasons for increasing the waterbodies. Built-up areas cover 24% of the city in 2005 and increased to 32% in 2010 and remained the same till 2015. In 2019, 34% built-up area is detected and a total of 10% expansion of built-up area was found where the yearly rate of conversion is less than 1%. In a nutshell, an increase of waterbody, and a slower rate of increase of built-up areas indicates the positive aspects for ensuring the overall environmental condition.



Type of Land Use	Area (sq. km)	Percentage (%)
Agriculture	5.79	12
Circulation Network	5.38	12
Commercial	1.07	2
Community Service	0.42	1
Education and Research	1.34	3
Government Services	0.41	1
Industry	2.23	5
Miscellaneous	0.05	0.10
Mixed Use	1.50	3
NGO Services	0.05	0
Recreation Facilities	0.39	1
Residential	21.08	45
Restricted Area	1.68	4
Service Activity	0.36	1
Transportation	0.30	1
Urban Green Space	0.13	0.29
Vacant Land	0.48	1
Waterbody	3.85	8
Total	46.50	100

Fig. 10. Land use for KCC area.
Data Source: Authors, 2020 based on [17]

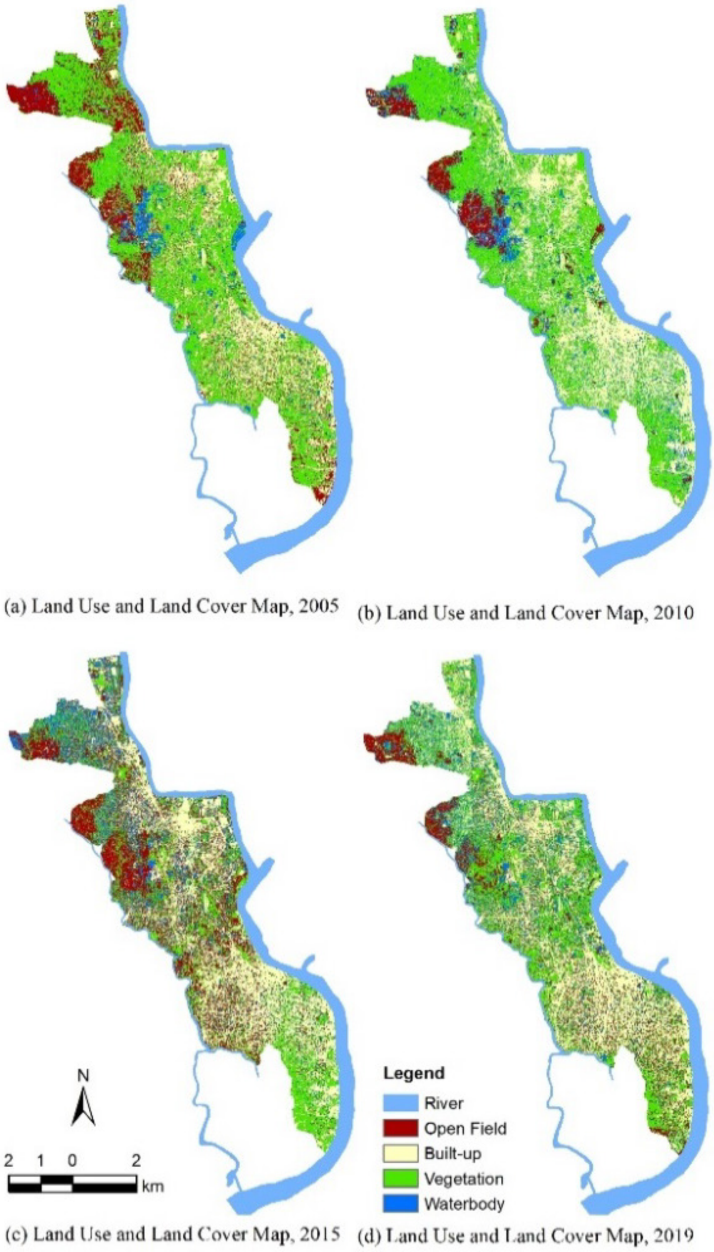


Fig. 11. Land use – Land cover changes for 2005, 2010, 2015, and 2019.
Source: Quickbird Satellite Image (2005), Google Earth Image (2010, 2015 and 2019)

5.3 Risk and Vulnerability under Climatic Change and Sea Level Rise

Bangladesh with a vast dynamic coastal zone is under the threat of sea level rise due to climate change. Climate change impact is not faraway now in Bangladesh and rather it has the far-reaching impacts on various aspects. Frequency and severity of natural hazards like flood, cyclones, storm surges, landslides, etc. are increasing with times. A recent evidence showed that a third of the flood-prone country is underwater after heaviest rains in a decade and at least 1.5 million people were affected, with village homes and roads flooded [19]. Due to her inherent nature especially vast low-lying areas, situated in the mouth of the funnel like Bay of Bengal, Bangladesh is regarded as one of the most climate vulnerable countries in the world. The coastal zone of Bangladesh is perceived as the zone of multiple disasters covering 19 districts (32% of the country) out of 64 representing around 30% of the population [20]. The coastal zone of Bangladesh has the highest concentration of natural hazards in the world which are cyclone and storm surge, land erosion, flood, drainage congestion, salinity intrusion, draught, earthquake, shortage of drinking water and arsenic contamination, ecosystem degradation, pollution and climate change [21]. Among them, drainage congestion, urban flooding, climate change, salinity intrusion is very common at the coastal cities.

Khulna City has been identified as one of the 15 most vulnerable cities under climate change impact and it has been considered as one of the most vulnerable coastal cities [22]. The city has a great tidal influence from the Bay of Bengal and has the increasing trend of salinity intrusion into the city waters. Water supply in the city is seriously hampered by excessive presence of salinity in the groundwater (GW) as well as surface water (SW) sources. Frequency of climate change induced hazards like cyclone, storm surges and their severity are increasing and adversely affects the salinity intrusion. A 10% intensification of the current 1-in-100-year storm surge combined with a 1m Sea Level Rise (SLR) could affect around 23% of Bangladesh's total coastal land area. Increases in salinity intrusion as a result of SLR pose a serious issue for Bangladesh [37]. Asean Developmetn Bank (2010) study report anticipated sea level rise for the city which has a major impact on the blue, green and grey features along with the drainage infrastructure. The different parts of the city face frequent waterlogging during the rainy season. The report also shows that the possible increase in precipitation due to climate change coupled with sea level rise will make the situation even worse. In that study, Khulna Urban Drainage (KUD) model was developed for the first time for Khulna City considering A2 regional growth scenario with 10 years return period to show the waterlogging condition. A2 storyline and scenario family describes a very heterogeneous world especially consider the impacts of climate change and translate those impacts on the water sector. Fig. **12** shows separately the waterlogging condition with climate change and sea level rise and with improvement interventions and adaptation. It shows that waterlogging condition is varied in 2030 and 2050 for different conditions and also with improvements and adaptation. Waterlogging covers 54% area of the city if no adaptation or improvement measures are taken. On the other hand, 29% waterlogging condition is reduced if improvements for the drainage system are implemented.

It is interesting that KCC is not subject to direct flooding from her surrounding rivers in the core parts of the city, but the low-lying areas situated on the western and southern part of the city floods due to the rain and tidal effects during monsoon season. Improper operation and maintenance of natural canals and man-made drains, blockage in the existing drains, absence of integrated network comprising secondary and side drains, haphazard expansion of the settlements which obstructs the natural drainage system, uncontrolled and haphazard disposal of solid waste into the drainage system and siltation in drainage channels with consequent reduction of discharge capacity are the main reasons for waterlogging in the city [7]. Waterlogging situation is directly observed in different parts of the city from the fields and validated with the waterlogging situation for 2020 (Fig. **12**) during the month of July and August 2020 which are shown in Figure 13. In some areas, the inundation of the waterlogging is worse than the modelled situation. Overall, where the drainage density is low having low capacity the inundation level of the waterlogging is severe in ward-27, ward-28, and ward-30 of Khulna City. The reverse scenario for inundation level is observed where the drainage density is high with higher capacity [9]. It is obvious from the analysis that where amount of waterbody (in area) is larger, less waterlogging is observed (Fig. **8**b). It is surprising that in the core part of the city, a severe waterlogging is observed despite having high drainage density. In a catchment with having large amount of waterbodies, severe water logging is observed (Fig. **8**a and Figure 13). These waterbodies are not directly connected to the rainwater surface runoff and the capacity of the waterbodies are low.

Climate experts predict that by 2050, rising sea levels will submerge some 17 percent of the nation's land and displace about 20 million people [23]. It is now proven that climate change impact is observing in Bangladesh and will be exacerbated in the future if there is taken enough mitigation and adaptation measures. Fig. (a) shows the inundation based on conceptual sea level rise at different heights. If 0.25m sea level is risen, 5% area of the city will be inundated which accounts for 4% agricultural land and residential 0.47 (Table 1). Agricultural lands here are mostly ditches and water retention areas. When 0.50m sea level is considered 9% area will be inundated that account for 6% agriculture and residential will be increased to 1%. If 0.75m is considered as sea level rise, 13% land will be inundated which encompasses 8% agriculture and residential 2.5%. When 1m sea level rise is taken, 18% land will be inundated that will account for 10% agriculture and 5% residential. With the increase of sea level rise, significant percentage of residential building is started to inundate Fig. (b). When the lower sea level rise is considered, there will have less impacts on the built environment.

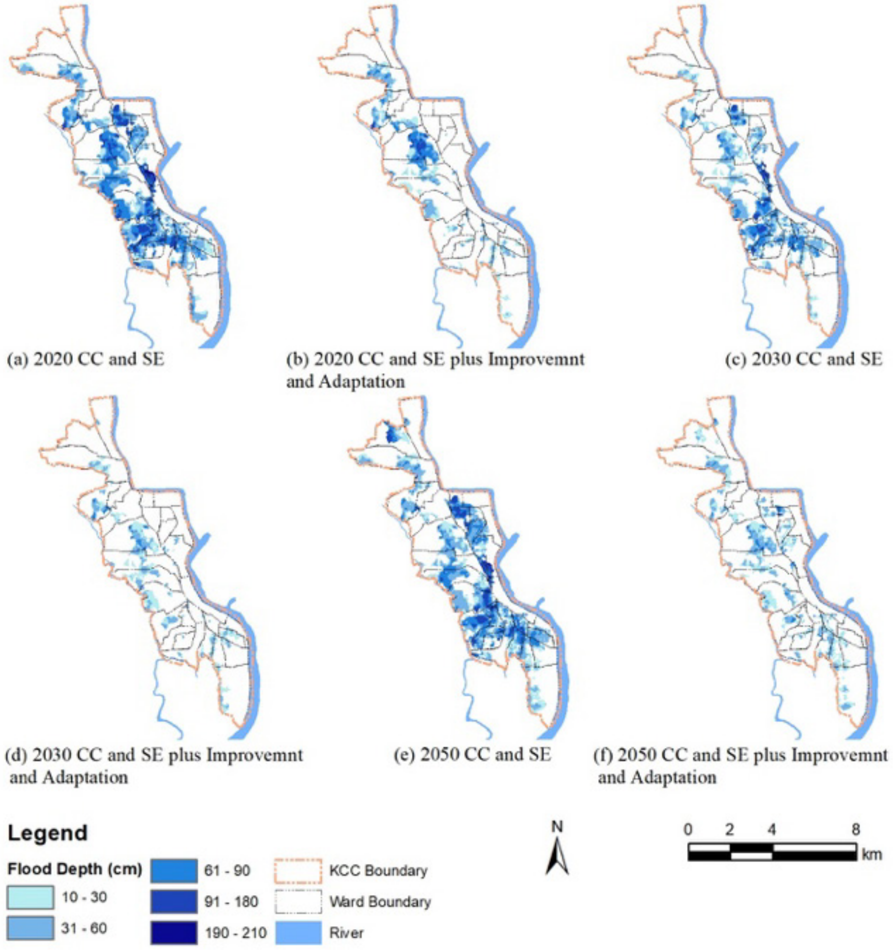


Fig. 12. (a) Waterlogging scenario for 2020 under climate change and sea level rise
(b) Waterlogging scenario for 2020 under climate change and sea level rise with improvement and adaptation
(c) Waterlogging scenario for 2030 under climate change and sea level rise
(d) Waterlogging scenario for 2030 under climate change and sea level rise with improvement and adaptation
(e) Waterlogging scenario for 2050 under climate change and sea level rise
(f) Waterlogging scenario for 2050 under climate change and sea level rise with improvement and adaptation.
Data Source: Authors, 2020 based on [8]

Table 1. Type of land use to be impacted at sea level.

Type of Land Use	Percentage of Land Uses under different sea level rise (MSL)						
	Up to 0.25m	0.50m	0.75m	1m	1.5m	> 1.5m	Total
Agriculture	3.74	2.4	2.15	1.43	1.14	1.59	12.45
Residential	0.47	0.7	1.37	2.6	8.42	31.77	45.33
Waterbody	0.57	0.28	0.42	0.63	1.4	4.97	8.27
Education and Research	0.02	0.02	0.02	0.05	0.19	2.6	2.89
Mixed Use	0.01	0.01	0.05	0.08	0.31	2.77	3.23
Transportation	0.1	0.11	0.17	0.3	1.17	10.35	12.21
Commercial	0	0.01	0.02	0.02	0.07	2.19	2.31
Others	0	0.04	0.14	0.35	1.33	11.43	13.31
Total	4.92	3.57	4.33	5.46	14.04	67.67	100

Data source: Analysis based on [8], [17]

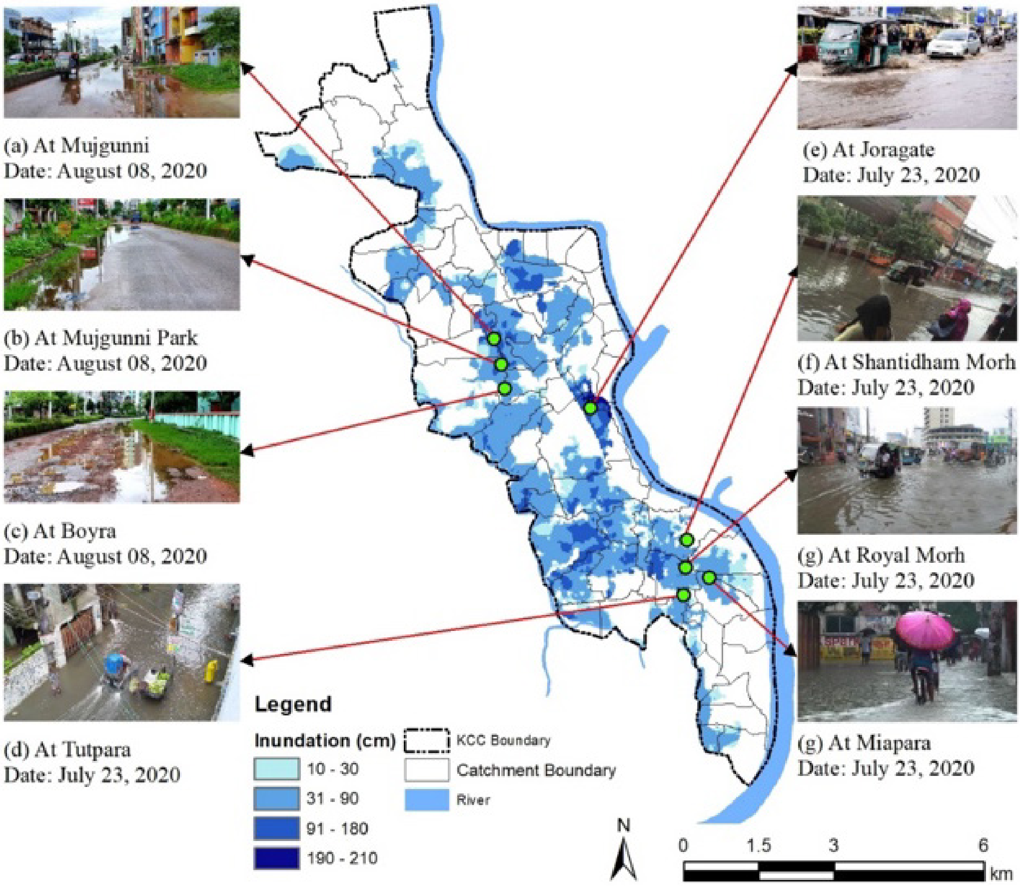


Fig. 13. Waterlogging situation during the months of July and August 2020.
Source: Field Survey, 2020

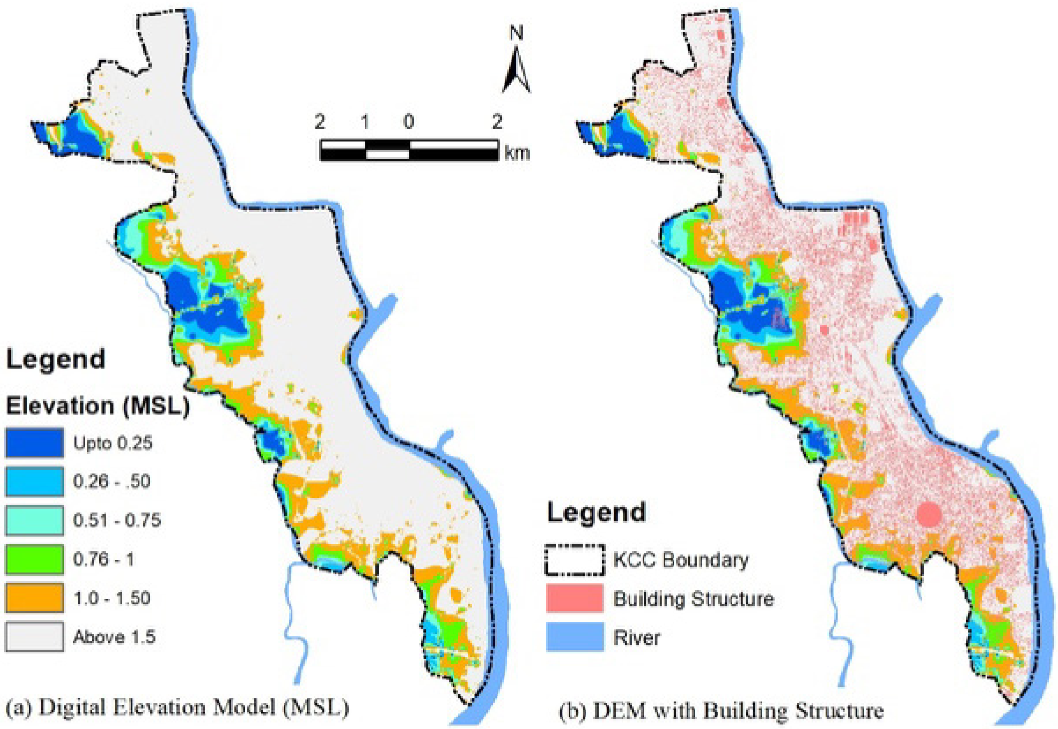


Fig. 14. (a) Conceptual inundation under sea level rise (b) Conceptual inundation under sea level rise with building structure.
Data Source: Authors, 2020

5.4 Opportunities in Building the Climate Resilient City Focusing on Nature Based Solutions (NBS)

Nature Based Solution are often terms as ecosystem-based adaptation (EbA), urban green infrastructure (UGI) and ecosystem services (ESS). All these related concepts are has become a prominent issue now-a-days and researchers are trying to create evidence by applying the concept. From the results stated above together with water management both ground and surface water, adaptation with the changing climates, etc. Khulna has a huge scope of applying NBS against the climate induced hazards and its impacts on the city level. There are many status quo gaps and challenges to be overcome for building the climate resilient city which include the social, economic, physical, environmental and technological aspects. In this research, physical and environmental aspects are explored and examined to find out the weakness against the strengths of the city. Nature based climate proofing aspects are explored through analysis and how these could be implemented to build a climate resilient city is discussed below.

(a) Green spaces help to uptake and permeate water through Soil, decreasing runoff rates which subsequently reduces the pressure on the existing drainage system. The high retention capacity of vegetation makes it important for mitigating floods and managing urban storm water. Khulna once renowned for its green resources but in recent times the city is losing its greeneries very rapidly. Urban green space is very important because of its ability to make the land permeable. And rapid destruction of green planting is giving a negative impact on soil. The amount of existing urban green space is 377.11 acre. Recently, KDA proposed to develop about 872.26 acre urban open space [13]. From the land use and land cover analysis, it is shown that about 52% of the city covers open field (agricultural land) and greeneries in 2019. Agricultural land is treated as the sources of retention for surface runoff. Moreover, the city corporation authority and KDA can enact a mandatory 'urban Greening policy' for the conservation and enhancement of urban greening and urban forestry in Khulna City.

(b) Urban Blue Space both is the most important physical, aesthetic landscape, indispensable elements and possesses importance in urban quality of life. They are environmental — and sometimes historic-ecological — assets of great importance for any city. But unfortunately, there is no clear plan for preserving the existing water bodies in the city development plan. But the positive aspect is that the city is surrounded by rivers and crisscrossed by many canals. Inside the city there are 5% area covers waterbody. Numbers of waterbody (more than 1000) represents significant but do not function significantly due to reducing the capacity of the waterbodies which calls for the need of digging out. On the other hand, existing waterbodies preservation techniques (viz. ecosystem services) or policy must be enacted by the development authority. It is found from the land use and land cover analysis over the 14 years since 2005 that amount of waterbody increased to 14% from 7%. Though it is happening due to shrimp culture, socio-economic factors, etc., still it is beneficial for the city thinking of the environmental aspects.

(c) The roof garden is a good way to enhance buildings in urban areas through landscape design, which can transform the obsolete areas into a valuable area that provides ecological and economic services. For instance, the most suitable structures of rooftop gardens are structures with a flat roof (concreate building). Total number of concreate structure of the Khulna city under residential use is around 27000 which covers the total area of 635 acres. Roof gardening is started everywhere in Bangladesh and Khulna is well ahead in this regard. If we consider 25% residential building under rooftop garden, 160 acres greeneries will be added to the existing 377acres greeneries, which is expected to create positive impacts on the environment. If we consider more residential buildings under rooftop gardening, there will have more positive impacts.

(d) Rainwater harvesting can be considered as a probable solution of the drinking water crisis in this salinity prone areas. The main limitation of this option is no availability of rainwater around the year. A study shows that Khulna, during the entire year, the rain falls for 95 days, which is one-fourth of the year and collects up to 1809.4mm of precipitation. So, it can be widely used as a supplementary source of rainwater is properly stored in the rainy season. It is already an established culture to harvest rainwater in this region. But in the urban areas, it is long way to go. But rainwater harvesting has begun and increasing with time as the advocacy from different levels at different stakeholders is going on. Many NGOs have already working at the community level to harness the rainwater during monsoon. More advocacy for the adoption of rainwater would certainly lead to a reduction of problems related to water shortage in a monsoon-prone country like Bangladesh and reducing waterlogging during rainy season.

(e) Groundwater is the major source to satisfy the water demand of Khulna City. Despite the easy availability of groundwater, Khulna is facing acute water shortages as a result of improper water management, highly dependent on the groundwater rather than surface water and groundwater pollution. These events are making the Khulna city more vulnerable to climate change and urban flooding. Soil permeability is one of the main components of groundwater recharge. The present condition of the permeable soil is moderate, but it is decreasing with each passing year. The amount of permeable soil area in a city or a region influences the infiltration rate and the groundwater recharge of the area. The more permeable area the more possibility of water infiltration to the ground which will help to enrich the aquifer of the city below as well as help Khulna city become more water resilient. Analysing permeable and non-permeable data it is found that the total area of permeable and non-permeable land is 33 sq.km and 13 sq.km of the city respectively. Building setbacks should be mandatorily kept permeable to increase the percentage of permeable soil that will also increase the greeneries.

(f) Modern cities like Khulna usually have mostly impervious surface and very minimal percentage area is permeable ground cover. In Khulna City, about 34% of all surfaces in the city areas are impervious, which is shown in Figure 11. This impervious soil is supposed to be the main cause of excessive storm water runoff, which leads to low water quality as well. Urban agriculture could be a way to deal with this problem by preserving the high value agricultural land. Urban agriculture (UA) presents an alternative use for modern cities that has not been given adequate consideration as a method of addressing storm water mitigation and other urban environmental concerns. Existing 12% agricultural land, which are mostly hinterland should be preserved for rendering services from many aspects.

(g) As watersheds become developed, rainwater quickly runs off paved surfaces such as roofs, parking lots and driveways increasing flooding while picking up and carrying pollutants into storm drains and surface waters. By reducing storm water runoff, rain gardens effectively change these trends. While an individual rain garden may seem like a small contribution, collectively they produce substantial environmental benefits. If we see the land-use dynamics of Khulna city, the potential spots that's are most suitable for rain garden based on their suitable location for rain garden. Because the rain garden should be in a public area that can be seen by members of your community. Most likely this area will be located on a commercial, industrial or institutional property, so storm water management regulations will have to be taken into consideration and professionals and researchers will be needed to assess the site.

6. CONCLUSION

Khulna City is the most important economic hub in the southern part of Bangladesh connected through rivers, road and railway networks and it is gaining its importance with times. At the same time, climate change leads to extreme calamities and sea level rise together is making the city vulnerable and the infrastructure at risk. Among them, flood and waterlogging are worsening the city. Waterlogging is happening due to drainage congestion, decreasing of waterbodies and their capacities, lack of drainage connectivity and capacity, etc., which is severe compared to impact of sea level rise. Sea level rise impacts on the hinterland (agriculture) which are normally retains waterbody all through the year. The city has 52% open field and greeneries and 14% waterbodies. Many studies show that SLR is expected to have serious impacts on the city. It is seen from the analysis that 0.50m SLR will start to cause 1% inundation of the residential inundation. It proves that city has capacity to absorb the impacts without significant impacts on the built-up areas due to its topographical, hydrological, and physiographical factors. If improvement and adaptation measures are taken, there will have less impacts in terms of the extent and magnitude of waterlogging. It is proven from the study that waterlogging covers 54% area of the city if no adaptation or improvement measures are taken. On the other hand, 29% waterlogging condition is reduced if improvements for the drainage system are implemented. These gaps and challenges need to be addressed proper way to build climate resilient city through exploring, creating and implementing the opportunities to keep the pace with future growth. It is proven in many cities that nature-based solution can contribute much in tackling the problems. In this regard, Khulna has a lot of opportunities to adopt nature based solutions. Furthermore, adaptation with improvement will play important role in minimizing the impacts of the future events.

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Development of Climate Change Perceptions and Programmes (1980-2020) in Bangladesh: Lessons Learned and Way Forward

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Abstract – *Climate change related knowledge and activities have been evolved, and Bangladesh tried to figure out appropriate pathways to address climate change challenges sustainably. This paper critically examined the chronological progression of climate change action programs performed in Bangladesh, aiming to identify the factors that created varied forms of confusion in tackling climate change threats. This review based work identified that the concept of climate change has conveyed into the contexts through disaster management discourse in Bangladesh. Climate change understanding and action programs could be divided into three groups (early-stage (1980-2000), mid-stage (2001-2010), and third stage (2011-2020). While early-stage works related to the basic understanding of ozone layer depletion, greenhouse effect, global warming, and their impacts on natural resources and physical functions, mid-stage reports contain impact narratives on different sectors and outlined action plans. The third stage reports have firm commitments to reduce climate change vulnerabilities of people, processes, and systems. In this stage, climate-resilient development is proposed through mainstreaming climate change investments/expenditures into regular development programs of the government. The roles of actors (both individual and institutional) from the government to non-government entities, varied and conflicting interests (e.g., personal, thematic, and need-based), struggle among the institutions over control over actions/processes. Moreover, local works have little influence on institutional and policy-making processes related to climate change compared to the impact made by global level reports mainly produced by international agencies.*

Keywords – *Bangladesh, climate change, climate change adaptation, climate change policies, climate change research.*

1. INTRODUCTION

Bangladesh has always been seen and presented as uniquely exposed to environmental risk, which has been and is being amplified by climate change. Moreover, different types of hydro-meteorological are primarily originated from the process and dynamics of climatic elements such as temperature, rainfall, humidity, air pressure, wind direction, sunshine. The genesis of these hazards is started being explained by international scientists as results of ozone layer depletion coupled with global warming in the nineteen hundred eighties. Later, scientists refined their proclamations by stating that climate change is responsible for causing the hazards with magnified magnitude (*e.g.,* the First Assessment Report of IPCC, 1990). This inference about climate change made by IPCC (Intergovernmental Panel on Climate Change) scientists and related guidelines provided by UNFCCC (International Climate Change Framework Convention on Climate Change) influenced state policies in making climate-sensitive institutional framework and designing adaptation and mitigation programs.

It has been observed that four decades of assessment and trails of climate change activities in Bangladesh did not bring effective outcomes. Based on which the country could figure out appropriate pathways (*e.g.,* developing policy and institutional frameworks) to address climate change challenges that are economically efficient, socially acceptable, physically viable, and ecologically sustainable. In this backdrop, this paper critically examined the chronological progression of climate change action programs performed in Bangladesh, aiming to identify the factors that created different types of confusion in tackling climate change threats. Reviewing literature was the principal method to conduct the assessment.

2. CHRONOLOGY OF CLIMATE CHANGE WORKS IN BANGLADESH

Disaster events have been the common challenges for Bangladesh, where people adapt themselves to the situations. However, the institutional makeup, priorities, and actions of the state agencies were strongly influenced by the execution of vulnerability reduction efforts for the people, processes, and systems. Bangladesh disaster history has some significant events such as the Bengal Famine of 1943; consecutive severe floods happened in the years 1953, 1954, 1955; the severe cyclone in 1970; famine in 1974 due to

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Brahmaputra flooding and crop failure; widespread and prolonged floods in 1987, 1988; the cyclone in 1991; cyclone Sidr in 2007 and Aila 2009. These events were generally treated as extremes of hydro-meteorological functions. However, during the late 1980s, with the emergence of the concept 'ozone layer depletion' 'global warming' arguments made by the international scientists that the origin of these disasters are linked with these processes. Climate change related research in Bangladesh was started in 1978 when Ganges, Brahmaputra, and Meghna river systems were studied as a part of the global carbon transport program [1]. From 1994 to 2017, more than five hundred articles have been published in peer-reviewed journals on climate change issues of Bangladesh [2]. Apart from these, dozens of local studies and reports in Bangladesh have been appeared focusing on climate change concepts, sectoral impacts, advocacy strategies, critical appraisals, making commitments to global communities, especially to UNFCCC. Table 1 gives a chronology of local works that shows how climate change understanding and action programs have evolved in Bangladesh during the last forty years. The works could be divided into three groups, as outlined below.

(i) The early-stage (1980-2000) works aimed to make understanding clear which focused on knowing the facts of ozone layer depletion, greenhouse effect, and global warming and their impacts on natural resources and physical functions and processes of Bangladesh.

(ii) The mid-stage (2001-2010) reports contain impact narratives on different sectors and outlined action plans. During this stage, discussions/arguments made a sharp departure from global warming concepts and replaced them with the term climate change.

At the early stage, a group of scientists and researchers writing their reports echoing in a similar way the global institutions did. They commissioned research works (*e.g.* [3]) aiming to establish the linkage between local natural disasters with global temperature rise (or climate change). Reports developed during these times on Bangladesh conducted by international research institutions such as the Centre for Environmental and Resource. Studies (CEARS, New Zealand), Climate Research Unit (CRU, UK), and these have appeared immediately after the publication of the first assessment report of IPCC [4]. At the same time, [5], [6], [7] examined the climate change induced vulnerabilities in Bangladesh, focusing on different dimensions. The first formal response from Bangladesh Government took place in 2002 with the submission of Initial National Communication (INC) to UNFCCC [8].

Table 1. Chronology of significant works on climate change in Bangladesh undertaken by different agencies.

No.	The significant works/titles on climate change	Year	Agencies who carried out the work	Impacts/contributions of the work
1.	The greenhouse effect and coastal area of Bangladesh; Part 1 report and Part II report	1989 [9]	Coastal Area Research Development and Management Association (CARDMA)	Develop board understanding on climate change impacts
2.	Guidelines on disaster management in Bangladesh Volume 1 – Pre-disaster phase activities Volume 2 – An action plan to combat disaster impacts Volume 3 – Disaster response in the first three weeks of disaster occurrence Volume 4 – Communication strategies, information management, and conclusion	1993	Md Saidur Rahman BDPC (Bangladesh Disaster Preparedness Center) with support from PACT Bangladesh	Field level guidelines to manage disaster impacts
3.	The Greenhouse Gas emissions and climate change – Briefing document 1 Sea level changes in the Bay of Bengal – Briefing document 2 Effects of climate change and sea-level rise on natural resources of Bangladesh – Briefing document 3 Socio-economic implications of	1994 [3]	BUP (Bangladesh) CEARS (New Zealand) UEA Norwich (UK)	The initial stage to work to develop a comprehensive understanding of Greenhouse Gas (GHG) emissions, impacts of global warming, and climate change

	climate change for Bangladesh – Briefing document 4 Legal implications of global climate change for Bangladesh – Briefing document 5 Climate change and sea-level rise: the case of the coast – Briefing document 6 The implications of climate change for Bangladesh: A synthesis – Briefing document 7			
4.	Vulnerability and adaptation to climate change for Bangladesh	1999 [6]	S. Huq; Z. Karim; M. Asaduzzaman, F. Mahtab	Climate change vulnerability and adaptation provisions
5.	Living with floods	1999 [5]	Imtiaz Ahmed (Ed.)	Local experts understanding on floods
6.	Bangladesh: Climate change and sustainable development	2001 [7]	World Bank	Efforts to harmonize climate change with development targets
7.	Initial National Communication (INC) report submitted to UNFCCC	2002 [3]	Ministry of Environment and Forest (MoEF), GoB	National report to UNFCCC
8.	Comprehensive Disaster Management Programme, Phase I (2003 – 2008)	2003	Several studies were conducted; the Development of Community Risk Assessment (CRA) instrument is one of the key works.	A five-year program that contributed to developing many knowledge products on climate change
9.	Climate Change impacts and vulnerability: A synthesis	2006 [10]	Ahsan Uddin Ahmed, Climate Change Cell, MoEF	Climate change vulnerability
10.	National Capacity Self-Assessment (NCSA) developed for Global Environmental Management	2007 [11]	UNDP; GEF; IUCN	National study as part of (UNFCCC) global study to examine environmental conditions
12.	Climate change in Bangladesh: A closer look into temperature and rainfall data	2010 [12]	Sheikh Tawhidul Islam; Ananta Neelim; published by UPL	Assessment on climate change focusing on local temperature and rainfall data
13.	National REDD (Reducing Emissions from Degradation and Deforestation) proposal submitted, and Bangladesh become an UN-REDD partner country	2010	MoEF, GoB	GHG emission reduction program along with activities to reduce climate-induced vulnerability
14.	Climate change: Issues and perspectives for Bangladesh	2011 [13]	Rafique Ahmed; S. Dara Shamsuddin, published by Shahitya Prokash	A critical assessment of climate change based on local understandings
	The Political Economy of Climate Resilient Development Planning in Bangladesh	2011 [14]	Khurshid Alam, Md Shamsuddoha, Thomas Tanner, *et al.*; Published in IDS Bulletin, Volume 42, Number 3.	The paper suggests that climate change programs taken in Bangladesh must be understood in terms of the interplay of actors, their ideas, and power relations.

15.	Climate Public expenditure and Institutional review (CPEIR)	2012 [15]	Planning Commission, GoB	Strategy paper to identify the scope of mainstream climate change interventions into development programs
16.	Second National Communication (SNC) report submitted to UNFCCC	2012 [16]	Ministry of Environment and Forest (MoEF), GoB	National report to UNFCCC
17.	Climate change sea-level rise and development in Bangladesh	2014 [17]	H. Brammer; published by UPL	Critical examination about climate change impacts in different sectors
18.	Climate Fiscal Framework (CFF) strategy paper aiming to make a pathway to mainstream climate change expenditures into regular development programs	2014 (updated in 2018) [19], [20]		Strategy to devise instruments to allocate budget codes in the IBAS ++ system of Ministry of Finance by which the CAG (Comptroller and Auditor General) and CGA (Controller General Accounts) office could play roles in the allocation of climate change funds and foresee the expenditures
19.	Climate variability: Issues and perspectives for Bangladesh	2015 [21]	S. Dara Shamsuddin, Rafique Ahmed; published by Shahitya Prokash	A critical assessment of climate change based on local understandings
20.	Climate Change Education for Sustainable Development (CCESD)	2015 [22]	BANBEIS, Ministry of Education, GOB	Census level database development (in 12 hot spots) on climate change and disaster impacts on students, teachers, and education learning outcomes
21.	Impacts of climate change on human lives	2015 [23]	Bangladesh Bureau of Statistics (BBS), GoB	Sample survey (on 1800 households) to develop a database on disaster impacts on human lives and properties
22.	Intended Nationally Determined Contributions (INDC)	2015 [24]	Ministry of Environment and Forests (MoEF)	GHG emission reduction (5% from business as usual and 15% conditional by 2030) commitments by taking up different mitigation efforts in power, transport, and industry sectors
22.	Country Investment Plan (CIP) for the environment, forests, and climate change	2017[25]	MoEF, GOB; supported by FAO, USAID	A comprehensive plan developed by MoEF synchronize activities in sectors such as environment, forests, and climate change
23.	The Third National Communication (TNC) to be submitted to UNFCCC	2018 [26]	Ministry of Environment and Forest (MoEF), GoB	National report to UNFCCC

COLOUR LEGENDS:

(green)	Studies carried out to develop a better understanding
(blue)	Program implementation strategy and action plan
(yellow)	National report submitted to UNFCCC
(peach)	Critical appraisals that provide different opinions about climate change and related impacts
(pink)	Policy and institutional preparedness to mainstream climate change interventions into regular development programs

The significant advancement happened from 2000 to 2010 with the implementation of the program titled CDMP (Comprehensive Disaster Management Program, Phase I), where several knowledge products were produced, and field-level interventions took place. The CDMP contributed to merging climate change adaptation (CCA) activities with disaster risk reduction (DRR) approaches. CDMP contributed by the development of the CRA (Community Risk Assessment) tool and increased the capacity of twelve government Ministry officials to align the DPP (Development Project Proposal) instrument of Planning Commission in mainstreaming climate change activities into regular development programs. The Second National Communication (SNC) was prepared by MoEF (Ministry of Environment and Forests) in 2012 for UNFCCC. The National Capacity Self-Assessment (NCSA) report was published in 2007 by MoEF, which expressed climate change challenges through the environmental crisis point of view. Islam and Neelim (2010) [12] critically examined local climate variables (*i.e.,* temperature and rainfall). They argued that local understanding of climate change is a prerequisite to designing climate change interventions to make people, processes, and systems resilient to climate change.

The third stage (2011 onwards) works were more severe and profound in terms of raising questions on the credibility of concepts, generation of data on the climate change impacts, works during this time contributed to formulating policies to mainstream climate change activities into regular development programs. The works such as [13], [17], [21] strongly questioned the way scientists perceive climate change issues. They argued that the hazards and disasters that occurred in Bangladesh are the regular hydro-meteorological phenomenon (*i.e.,* the variabilities and extremes), and change in the climatic parameters does not have any significant influence/relation with that. Even the Department of Environment of Bangladesh assessed Sea Level Rise (SLR) problems in the contexts of sediment deposition, land subsidence, and the compaction of deposited sediments. They were not able to arrive at any conclusive results about the impacts of SLR in coastal resources and the community [27]. Environmental hazards and risk are also increased as a result of climate change [28]. Alam *et al.* (2011) [14] examined the BCCSAP (Bangladesh Climate Change Strategy and Action Plan) formulation process including the contexts of creating BCCTF (Bangladesh Climate Change Trust Fund, managed by MoEF) and BCCRF (Bangladesh Climate Change Resilient Fund, managed by donor consortium). They [14] remarked that formulating climate change policies, program design, investment management, activity priority setting - all are subject to the interplay and interests of powerful actors working on the broader climate change working spheres. BANBEIS (Bangladesh Bureau of Education Information and Statistics) and BBS (Bangladesh Bureau of Statistics) produced reports titled CCESD (Climate Change Education for Sustainable Development) [22] and ICCHL (Impacts of Climate Change on Human Lives) [23] respectively. These two reports generated data on the impacts of climate change on people's lives and education sectors, such as on students and their learning processes, teachers, and school infrastructure.

Bangladesh Government agencies (*e.g.*, Ministry of Environment, Forests and Climate Changes (MoEFCC), Ministry of Disaster Management and Relief (MoDMR), Ministry of Planning (MoP), Ministry of Finance (MoF)) have been playing significant roles in aligning existing instruments efficient for addressing climate change threats. Several government documents created investment pathways on climate change projects. They are CPEIR (Climate Public Expenditure and Institutional Review) conducted by the Ministry of Planning in 2012, Climate Fiscal Framework (CFF, Volume I and II) conducted in 2014 and 2018 by the Ministry of Finance, INDC (Intended Nationally Determined Contributions) in 2015, Country Investment Plan (CIP) in 2017 for the environment, forests and climate change and Third National Communication (TNC) produced by the MoEFCC in 2018. The INDC report identified a significant climate change impact in Bangladesh and proposed where the adaptation program should focus on (Table 2).

3. THE CONTEXT/ROOTS OF CONFUSIONS

The discussions in previous section on chronological developments on climate change aspects in Bangladesh indicate that decisions, actions, and interventions in regard to climate change have gone through turbulence in the conceptualization of the crisis to impact reduction project formulation, finance management, and implementation processes. The roles of actors (both individual and institutional) from the government to non-government entities, varied and conflicting interests (*e.g.*, personal, thematic and need-based), tussle among the institutions over control and over actions/processes, disagreements among the local scientists and researchers on the attribution of hydro-meteorological hazards with a change in the climatic variables, design of adaptation projects with limited understanding all in a collective fashion contributed in creating confusions how the climate change issues and action programs should be taken forward. The concept of climate change has been conveyed into the contexts through disaster management discourse in Bangladesh. The early-stage narratives (the arguments remain the same up till now) argued that the magnitude, intensities and frequencies of disasters like floods, cyclones, droughts (which are common in this lower deltaic and riparian country) have magnified manifold because of change in the climatic pattern. However, after the spending of about 1.5 billion USD per year [15] on climate-sensitive sectors in Bangladesh, the policymakers or the project implementers were not able to provide an effective instrument to discern climate change impacts from other natural disaster impacts. Even it is not adequately clear whether the 'community vulnerability' that are labeled as 'climate change vulnerability' is climate change-induced or these are rooted in the degradation in the environmental resources, inequality and varied forms of development gaps. The government agencies such as the Ministry of Environment, Forest and Climate Change (MoEFCC) considers themselves as the lead agency to tackle climate change problems since they submit the national communication reports on behalf of the government. The works of other agencies such as the Ministry of Planning (carried out CPEIR study in 2012) or the Ministry of Finance (carried out CFF in 2014 and reviewed in 2018) on climate change issues have created tensions over the leadership aspects. Thus, disagreements become noticeable among the institutions working in the climate change sector.

Table 2. Major climate change impact areas and adaptation priorities in Bangladesh (Source: INDC, 2015).

Key areas to address the adverse impacts of climate change	Adaptation priorities for Bangladesh
1. Food security, livelihood, and health protection (including water security)	i. Improved Early warning system for a tropical cyclone, flood, flash flood, and drought
2. Comprehensive disaster management	ii. Disaster preparedness and construction of flood and cyclone shelters
3. Coastal zone management including salinity intrusion control	iii. Tropical cyclones and storm surge protection
4. Flood control and erosion protection	iv. Inland monsoon flood-proofing and protection
5. Building climate resilient infrastructure	v. Climate-resilient infrastructure and communication
6. Increased rural electrification	vi. Climate-resilient housing
7. Enhanced urban resilience	vii. Improvement of urban resilience through the improvement of the drainage system to address urban flooding
8. Ecosystem-based adaptation (including forestry co-management)	viii. River training and dredging (including excavation of water bodies, canals, and drains)
9. Community based conservation of wetlands and coastal areas	ix. Stress tolerant (salinity, drought, and flood) variety improvement and cultivation (including livestock and fisheries)
10. Policy and institutional capacity building	x. Research and knowledge management
	xi. Adaptation of local-level perspectives
	xii. Adaptation to climate change impacts on health
	xiii. Biodiversity and ecosystem conservation
	xiv. Capacity building at individual and institutional level to plan and implement adaptation programs and projects in the country

Also, continuous pressure from global institutions like UNFCCC to develop and submit periodic national reports (especially the national communication reports) put stakeholders (*e.g.*, individuals and agencies; government and non-government) in a baffling situation. Individuals/representatives contribute and respond within this state of confusion and limited understanding. Thus the local knowledge and understanding remained left behind. The arguments given in the national reports are instead pulled over by referring to global assessment exercises. For instance, the Third Assessment Report (TAR) of IPCC [29] mentioned (see [12] for more) that about one-third of Bangladesh will be submerged due to a rise in the mean sea level, and the country national reports quoted this argument. This misinterpretation makes an enormous stir among the local experts and members of civil society. After that, several scientific exercises were commissioned by the Government, and reports appeared in the national daily newspapers opposing the submergence-argument (Figure 1). The media reports even argued that Bangladesh, in the opposite, gained vast amounts of land in the mouth of the Meghna River. These newspaper reports and other related research work as the 'People's Plan of Action' carried out by CEGIS, IWM, and Uttaran in 2013 [30] gave a huge relief to the coastal people who were in psychological trauma developed from the inundation threats.

It is imperative to mention that the British Geographer Hugh Brammer who has been working on Bangladesh issues for about 50 years, expressed strong disagreements with the way climate change challenges are being reported in national documents (https://www.hughbrammer.me/). Based on scientific examinations, he indicated that the floods, cyclones, and drought conditions are a regular natural phenomenon of Bangladesh, and climate change did not influence their magnitude, intensity or frequency of occurrence [17]. In his opinion, Bangladesh's exposure to the growing hazard of sea-level rise in the 21st century needs to be seen in the perspective of its exposure to current environmental hazards and its growing development needs [18]. He also mentioned that priority attention needs to be paid to addressing current development and environmental problems: *i.e.*, intensifying agricultural production; expanding economic activities outside agriculture; reducing exposure to existing levels of drought, floods and cyclones; supplementing dry-season flow in south-western rivers, and minimizing impacts of arsenic-contaminated groundwater used for drinking and irrigation in large parts of the country [18].

Fig. 1. Lead news in the leading national newspapers (in Bengali) that Bangladesh is not going underwater because of sea-level rise.

Bangladesh's exposure to the increasing hazard of sea-level rise in the 21st century needs to be seen in the perspective of its exposure to current environmental hazards and its growing development needs priority attention needs to be paid to addressing current development and environmental problems: *i.e.*, intensifying agricultural production; expanding economic activities outside agriculture; reducing exposure to existing levels of drought, floods and cyclones; supplementing dry-season flow in south-western rivers; and minimising impacts of arsenic-contaminated groundwater used for drinking and irrigation in large parts of the country.

4. CLIMATE PLANNING IN BANGLADESH

The agencies working in climate change sectors in Bangladesh have received a degree of learning from the challenges, as indicated before, and in recent times climate change problems are considered within broader problem domains, not as a standalone crisis.

This outlook and standpoint created opportunities to make the whole state machinery ready and useful to tackle hydro-meteorological disasters (this may come from climate variabilities or extremes or climate change whatever these are being labeled) through regular development intervention processes. Climate Fiscal Framework (CFF 2014 and 2018) undertaken by the Ministry of Finance hence identified twelve different steps (Figure 2) through which conceptualization of climate change impacts happens, and related budgeting processes receive necessary approvals of the government.

It is important to note that this accounting and tracking system helps the government in reporting climate change activities/progress in different national reporting instruments of the government. BESF reports (Bangladesh Environmental Statistics Framework 2016-2030), SEEA report (System of Environmental-Economic Accounting) to facilitate the integration of environmental and economic statistics, DRSF (Disaster Related Statistical Framework, proposed by UNESCAP), PEI (Poverty-Environment Initiative) integrates poverty and environment). The adoption of these processes allows professionals and different oversight bodies to assess the justification of project planning, budgeting, and fund flow functions (Figure 3).

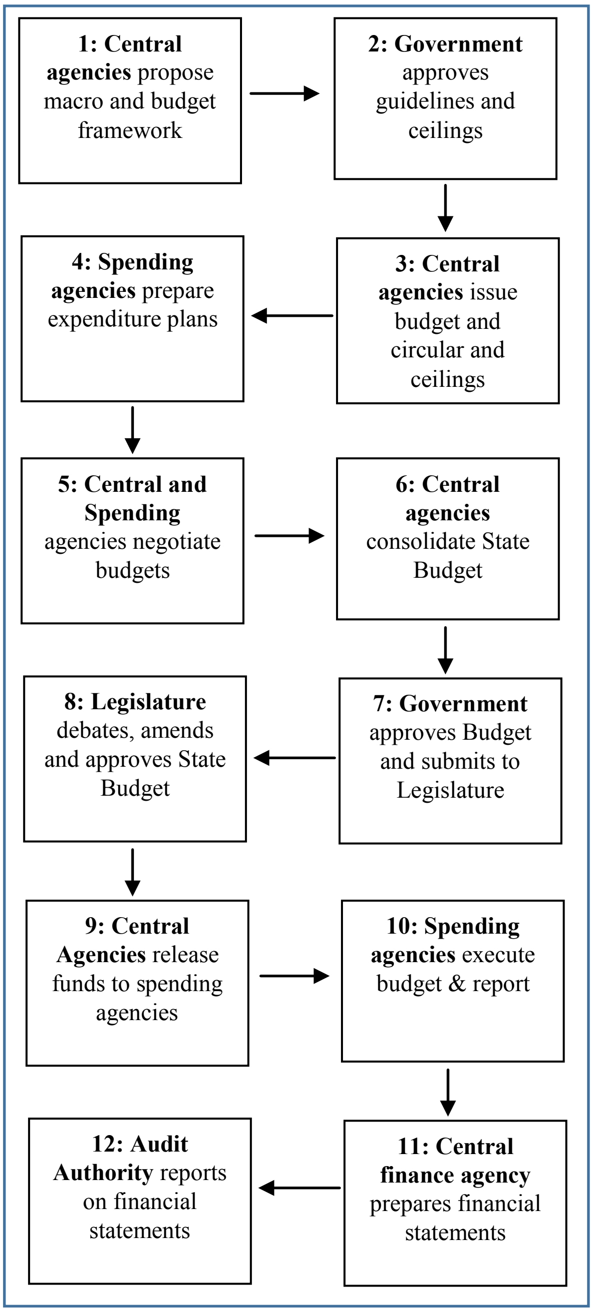

Fig. 2. Twelve steps identified by the Climate Fiscal Framework (CFF, 2018) to allocate financial resources for climate change projects through standard rules of business of the government.

Agencies in Bangladesh responsible for managing disasters before the emergence of climate change concepts (*i.e.*, before the 1980s) used to execute risk reduction projects through normal institutional processes and functions. The current proposition of mainstreaming climate change activities through regular development projects after about four decades of turbulent processes and functions could be considered as a return into the point of origin (*i.e.*, adopting the before-1980s approach) in managing disaster events. However, this approach is efficient and accountable than the execution of standalone projects. It will also give institutional ownership to the project activities with scope to provide post project support (for ensuring the sustainability of the project results) through other different project interventions.

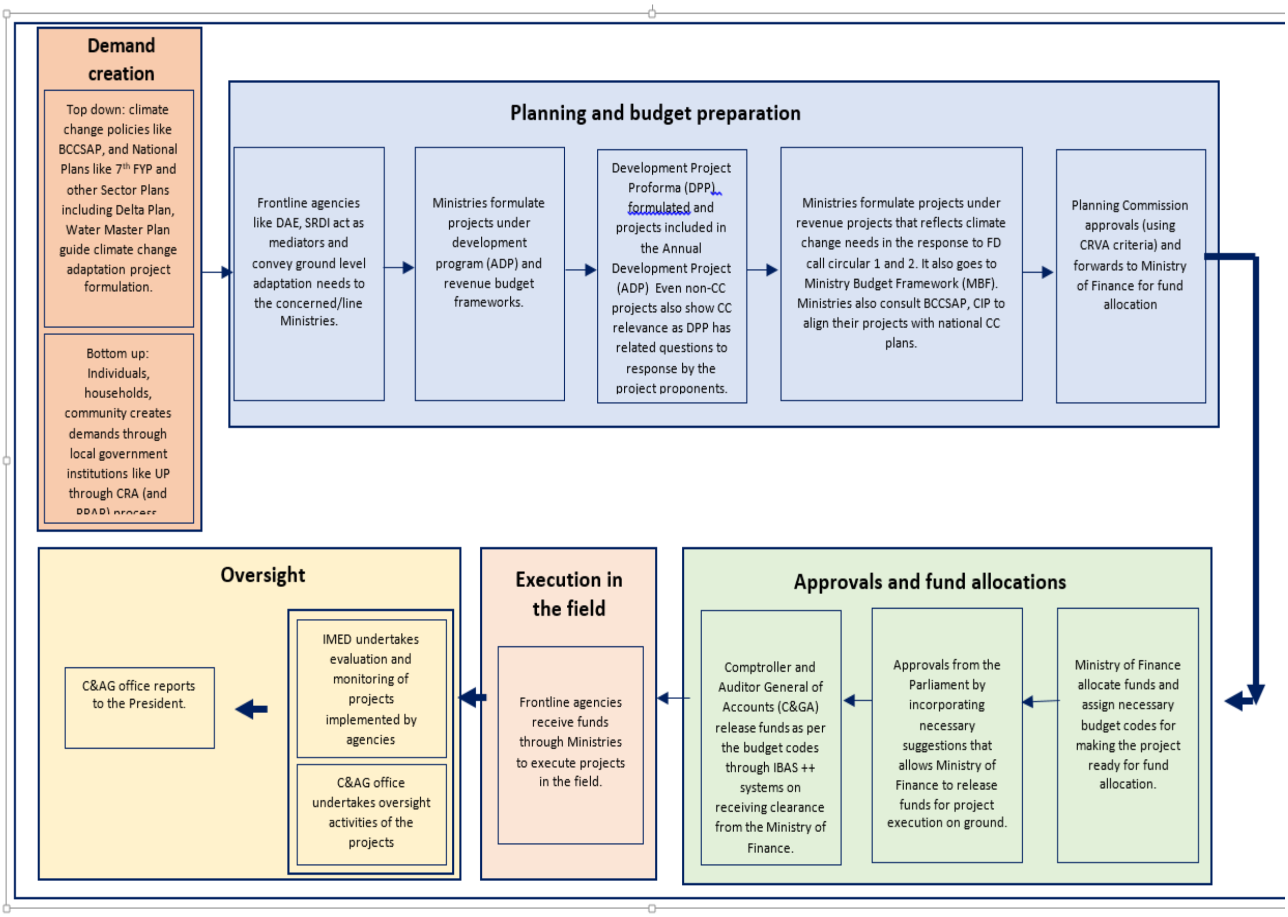

Fig. 3. Funding flow mechanisms of climate change through institutional processes in Bangladesh. (Source: [21]).

5. GAPS IN CLIMATE ACTION STRATEGIES IN BANGLADESH

The examination of the climate change activities in Bangladesh during the last four decades (1980-2020) provides opportunities to construct a few concrete observations. Firstly, it is observed that the decisions of different CoPs (Conference of the Parties) of UNFCCC and the IPCC produced estimates, results, and model predictions overwhelm the discussions and action plans held in Bangladesh regarding climate change. Shifts in the IPCC's assessments on global temperature records over time, substantial departures in decisions/results from one report to the other (*e.g.*, Third Assessment Report to Fifth Assessment Report of IPCC) also influenced and baffled the national-level decision-making processes [29], [31]. The government agencies, non-government organizations, members of civil societies, therefore never been settled on apprehending the degree of change in the climate variables. The confusion descended into the lower tiers of decision-making processes and left the whole sector in a puzzling state. Bangladesh still lacks comprehensive scientific knowledge on climate change issues at the sub-national level. The local works such as: [12], [13], [17], [21], [32], [33], [34] and mentioned in [2] provide useful assessments on climate change related aspects and all the works are critical towards the global and local claims and results. The local works have little influence on institutional and policy-making processes related to climate change compared to the influence made by global level reports mainly produced by international agencies like IPCC. Besides, only temperature and rainfall variables are generally taken into consideration to ascertain climate change. However, other climatic variables like water vapor (or humidity), air pressure, wind speed, and direction, sunshine are not taken into focus in ascertaining the change in the climatic pattern. Rigorous initiatives are rarely taken on how the change in the climatic variables are connected to the enhanced magnitude of disasters like floods, cyclones and droughts in Bangladesh. Besides, no instruments are developed up to now to differentiate commonly held natural disaster impacts from climate change induced phenomenon. This gap in scientific understanding puts the agencies in a dubious position in taking appropriate pathways, whether it should be 'climate finance or development finance', 'climate adaptation or mitigation pathway', 'Disaster risk reduction or climate change adaption'. Resolving these issues is essential while designing and implementing climate change programs as it will ensure more effective use of financial resources, efforts and time of agencies working in both government and non-government domains.

6. CONCLUSION

Activities related to climate change have been in practice in Bangladesh for about the last four decades (1980 to 2020). During this time, evolution happened in several ways, firstly in conceptualizing the science, secondly in policy formulation for tackling the threats, and lastly, in designing field-level programs to develop climate-resilient society and systems. The majority of the cases, international scientific exercises, impact narratives developed by agencies working at global levels played vital roles in local-level decision-making processes, *i.e.*, in policy formulation relating to climate change. In the early stages, climate change threats were being addressed through standalone projects. In recent times climate change programs are proposed to the mainstream through regular development interventions so that fiscal spending could be tracked and made accountable.

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White Paper on Energy, Disaster, Climate Change: Sustainability and Just Transitions in Bangladesh

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This year is 'Mujib Year'- a year-long celebratory year of Bangabandhu's birth centenary. Father of the nation of Bangladesh put people first and for whose sake he dreamt of building a Golden Bengal *"Sonar Bangla*", a concept resembles very closely the long-term Sustainable Development pathway for humanity as a whole.

This white paper is prepared to serve as guide for the decision makers in the context of Bangladesh, who look for quick understanding and solution around energy sector and the link of it with new technologies, sustainable development, disasters and climate change, need and areas of targeted capital investment and overall sensitive policy intervention points. This article is meant for presenting some quick take home messages for policy makers, project developers and funding agencies. This has been prepared from the findings of the deep dive scientific research studies presented in fourteen scientific peer reviewed articles written by the subject experts and compiled in this volume 1 of the Bangabandhu Chair Special Issue of the International Energy Journal. We limit the take home massages to top twenty action items:

1. It is important for a 21st century fast growing economy like Bangladesh to put Sustainable Human Wellbeing at the heart of the Energy System Planning to make it resilient to Resource depletion, Disaster and Climate change at the same time meeting the increasing energy demand.
2. For operationalising the conceptual framework of sustainable development and SDGs there is a need for directing investment focus on five kinds of capital at national and subnational level: human capital, knowledge capital, manmade physical capital like energy infrastructure, social capital like community resilience, natural capital like coastal nature-based erosion protection.
3. Instead of the generic prescription of source diversification of the energy sector in Bangladesh it is better to focus policy and investment priorities on some sensitive intervention points in the energy supply sector that can trigger leapfrog in sustainable energy development for Bangladesh with social justice for economic growth. Focusing on Geothermal energy sources and Hydrogen, Bangladesh can make full use of the national gas infrastructure with trained manpower in the sector through global cooperation within 17 interlinked Sustainable Developmental Goals of 2015. Geothermal sources in Bangladesh can be used for meeting energy demand for providing space cooling services directly.
4. In all new buildings- commercial or residential, -operational cooling energy demand can be drastically reduced by almost 25% through the installation of state-of-the-art window designs. These can be made mandatory for all new buildings being constructed through scientifically defined new standard specification for windows tilt position and appropriate reflective coatings. This can generate local employment as well.
5. Bangladesh can make use of all roof top spaces in a fast urbanizing economy to capture full potential of solar energy and distributing it through either micro grid systems or through grid integration. Emerging photovoltaic technologies with the plasmonic metal nanoparticles can be used to enhance solar cell efficiency. This can create new jobs, engage national experts, laboratories and make solutions cheaper.
6. With increased penetration of variable energy sources, need for energy storage will also increase. Energy storage technology has advanced much going beyond currently practiced technology choice in Bangladesh. So, there is need for engaging experts to constantly set standards for identification and recommendation of technology choice for faster adoption and production domestically.
7. Need for cross sectoral activity coordination through artificial intelligence-based network systems will increase with variable energy source penetration and storage technology integration. Like many other countries with electrification of vehicles increased penetration of intermittent renewable sources in the grid through smart metering system needs to be planned from now to reap medium term and long-term benefit as early adopter. In transport sector, focusing on expansion of public transport by making it comfortable, user friendly, efficient and electricity dependent can reduce import demand of fossil fuel, reduce air pollution, provide storage technology support and mitigate climate change.

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8. To manage power distribution through grid integration reliably through electric vehicles and solar rooftop systems, the power system can be managed better by introduction of Artificial intelligence, combining load shifting and Time of Use (ToU) based electricity pricing. ToU based electricity pricing will encourage the consumer to be aware of using electricity properly benefiting not only themselves but also the utility.
9. With all possible and likely changes in power system, conventional generators cannot support this high and sudden ramp up of power. Consequently, larger grid investment is needed to meet this high peak demand. Again, over current flow during peak-hours can adversely affect the transmission lines and reactive power controlling devices which needs prior planning and technically trained human capacity.
10. Introduction of micro grid in remote and rural areas of the country can reduce the feeling of alienation and neglect of the people living in such remote areas of Bangladesh. This can prevent or discourage such estranged communities from indulging in terrorism and other illegal measures to express any form of dissent. Implementation of solar energy can give rise to a cultural movement and massive paradigm shift of the minds of the common people.
11. Scope for introduction of new biodiesel technology in Bangladesh need not be ignored within the portfolio of domestic energy sources and production will help in creating decent jobs and enhancing self-reliance in energy.
12. Among the different forms of renewable energy sources available, solar energy has the highest potential and feasibility for energy production in Bangladesh and can potentially replace fossil fuels in the future combined with other forms of dispatchable energy to meet the country's growth in energy service demands. However, there has been a growing market for PV cells in the form of microgrids. All these can aid in significant infrastructure development, economic growth, clean environment and better health of the people thus fulfilling the promise of a "golden" Bangladesh. However, there is an immediate need for focusing on educational programmes to create targeted capacity in new energy sectors.
13. It is essential to map multiple risks to energy infrastructures in Bangladesh including seismic risk. There is need for implementation of comprehensive seismic zoning to get site-specific probabilistic seismic hazard map for all major engineering constructions. Disaster risk reduction monitoring measures must be included as mandatory codes in construction and subsequent operation and maintenance to ensure resilient critical infrastructures for Bangladesh.
14. Systematic comprehensive assessment of coastal hazards, changing pattern and their impacts on various communities should be based on scientific tools, long-term knowledge, understanding, and familiarity of the coastal communities to the interconnected human-nature interface in the coastal areas to minimize vulnerabilities. State of the art education programmes for people can create societal and human capital for risk management proactively and significantly reduce post disaster damages and subsequent losses.
15. There is a clear need for continuous knowledge and human capital building through regular updates and participation in educational curriculum, student training; researchers, scientists, technology developers, relief workers, recovery managers, policy makers, financial institutions, to get introduced and ready for a new 21st Century job market for climate service, energy transition studies, disaster risk study, risk reduction and risk mitigating services by expanding joint-,regional-, cross institutional collaborations.
16. A sustainable energy sector needs to adopt a systemic approach through retraining, professional knowledge upgradation now. It needs to focus not only conventional knowledge of generation, transmission and distribution but also storage which provides scope for new job creation, enterprise development, supply chain and business model.
17. The transformative change which is essentially going to be climate resilient and economy wide and fast for Bangladesh need to be led by social actors like educational leaders, investors, entrepreneurs, role models, citizens, consumers , households enabled and supplemented by national policies/ creating new business opportunities, innovative product design and science driven choice making.
18. Policy makers in Bangladesh are overwhelmed with the estimates, results, and model predictions produced by multiple international agencies. There are many highly qualified local experts in national institutions who can be involved to create a larger pool of national scientific consultative group to overcome biases and decipher flow of knowledge from external agencies to develop concrete actions plans for national priorities when it is aiming for developed country status in next two decades.
19. Energy, Disaster, Climate Change, Digital technology, Application of artificial intelligence are the core areas of 21st century new knowledge, research and learning. Each higher educational institute in Bangladesh need to start teaching these fields of study and can collaborate with regional lead institutions to catch up. This can enlarge quickly the locally available adequately skilled manpower who will be the new entrants in the job market to create a new cultural revolution for making sustainable development context dependent.
20. Communication material for building awareness of changing scientific understanding of developmental processes relevant for local context for various stakeholder groups including citizens is an urgent need to enhance social acceptability for effective and inclusive governance of accelerated transitions in multiple directions within a short period of time.

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