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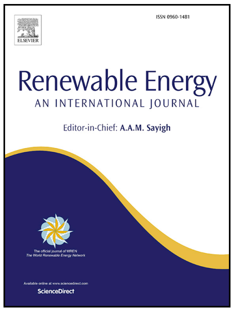

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Current Energy Policies and Possible Transition Scenarios adopting Renewable Energy: A Case study for Bangladesh

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ABSTRACT

This study analyses energy transition pathways for the case of Bangladesh. The LUT Energy System Transition model, a high temporal - spatial resolution linear optimisation tool, is used to model an energy system transition from 2015 to 2050 for the case of Bangladesh. Four scenarios aimed at analysing different energy policies were created in order to replicate the present and alternative renewable energy based policies, with and without greenhouse gas emissions costs. The results show that emissions costs accelerate the transition towards a fully renewable energy system, however, removing emissions costs does not significantly affect the energy system, as renewables would still contribute 94% of the electricity generation by 2050. The Current Policy Scenario increases electricity and greenhouse gas emissions costs significantly starting in 2025. The results indicate that countries like Bangladesh are prone to serious and complicated national risks that lead to several vulnerabilities like high electricity costs, increase in greenhouse gas emissions, energy insecurity and poor political trust, if present energy policies are pursued. However, focusing on indigenous renewable resources could help mitigate this vulnerability and bring about socioeconomic benefits.

Keywords: Bangladesh, Energy Transition, 100% renewable energy, Energy economics, Storage technologies

Nomenclature

A-CAES	Adiabatic compressed air energy storage
AC	Alternating Current
BAU	Business-as-usual
BERC	Bangladesh Energy Regulatory Commission
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CSP	Concentrating solar thermal power
FLH	Full load hours
GoB	Government of Bangladesh
GHG	Greenhouse gases
HVDC	High-voltage direct current
IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
LCOC	Levelised cost of curtailment
LCOE	Levelised cost of electricity
LCOG	Levelised cost of gas

LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
NCBD	National Committee Bangladesh
OCGT	Open cycle gas turbine
OPEX	Operational expenditures
PHES	Pumped hydro energy storage
PSMP	Power System Master Plan
PtG	Power-to-gas
QRPP	Quick Rental Power Plant
RE	Renewable energy
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
WACC	Weighted average cost of capital

1. Introduction

In the past, industrial development, rise in population and an increase in living standards led to significant increase in global primary energy consumption [1]. While, this trend is expected to continue in the future, global energy consumption could double by 2100 [2]. Maintaining fast-paced economic growth at the same level as population increase, particularly in developing countries together with climate change mitigation targets, have put tremendous pressure on governments to supply stable, uninterrupted and sustainable power [3]. High dependence on domestic or imported fossil fuels have environmental consequences of their own, in addition to risks related to long term energy security and cost competitiveness of electricity production. Therefore, governments around the world are revisiting their energy strategies to enable transitions towards increased adoption of renewable energy sources [4], [5]. This has resulted in the addition of around 160 GW of renewables, globally in 2017, which is far more than the installed capacities of fossil fuel and nuclear power. However, most countries are still taking cautious steps towards embracing renewables [5]. Recent studies have shown that these cautious steps carry significant risks for countries that plan to rely on fossil fuels [6]. The level of risk and vulnerability could be more significant for developing countries, who do not revise their policies frequently and those depending on fossil fuel imports. Bangladesh is one of the countries that appear to be prone to such risks.

Bangladesh is one of the rapidly developing countries in South Asia [7]. It is also one of the most densely populated countries with a population density of around 1079 per km^2 [8].The average annual GDP growth rate was 5.7% in the period 1996 to 2016, with a peak of 7.1% observed in 2016 [9]. According to the Government of Bangladesh (GoB), GDP is expected to grow at an average growth rate of 6.1% from 2016 to 2041 [8]. On the other hand, electricity demand grew at an average annual growth rate of 9.7% from 2004 to 2015 [10]. The historical growth in GDP and electricity demand are correlated because rise in electricity demand is often associated with improving standards of living and national economic activity. This was observed in the growth of electricity access from 40.6% in 2004 to 68.2% in 2015 [11]. However, it should be noted that Bangladesh has a per capita electricity consumption of just 387 kWh, which is amongst the lowest in the world [8].

Bangladesh has been dependent on fossil fuels for its electricity generation [12] and a continued reliance will require an increase in fossil fuel imports to satisfy the growing demand for electricity due to limited domestic reserves. A high contingency on imported gas, coal and oil will not only add economic pressure on Bangladesh, but also raise serious questions on its long-term energy security [13]. Moreover, as one of the world's most vulnerable countries to be impacted by the threats of rising sea level on its low-lying areas [14], burning fossil fuels puts Bangladesh in a more precarious position due to eroding trust towards its government's integrity and commitment to address its society's vulnerability. Specifically, studies show that about 1 meter sea level rise will submerge one-fifth of the country's land mass, which might dramatically increase climate change refugees in the coming decades, displacing millions of individuals and communities from their homes [15], [16], [17]. In addition, PM 2.5 concentration is steeply rising in Bangladesh since 2010 and about 100 thousand people die each year due to increasing air pollution [18]. The above facts obligate countries such as Bangladesh to take a leading role in working towards a renewable future.

Currently, renewable energy is gaining momentum in the global energy mix, which is seen as a low risk option in comparison to fossil fuels. This is mainly attributed to the expected cost decline [19], of the main renewable energy technologies, PV [20], [21] wind [22] and batteries [23], [24]. Additionally, the levelised cost of electricity production have become cost competitive with fossil fuels [25]. These factors have triggered a positive outlook towards renewable energy technologies all around the world. Several studies have reported the technical feasibility and economic viability of 100% renewable energy systems for various parts of the world, e.g. Finland [26], Denmark [27], Australia [28], Israel [6], India [29], [30], Pakistan [31], Southeast Asia [32], Nigeria [33], Sub-Saharan Africa [34], etc. According to Brown et al. [35], 100% renewable energy systems are already technically feasible and economically viable with decreasing costs every year. Hansen et al. [36] present an overview on 100% RE studies and comment on the status and perspectives of the respective research. This suggests that achieving 100% RE by 2050 is possible but often hindered by political will. The above discussion clearly puts renewables in the forefront for achieving a lower levelised cost of electricity by 2050 than the present energy policies.

For Bangladesh, renewable energy sources can provide a viable alternative in tackling energy shortage, energy security and long-term energy planning with reduced GHG emissions, whilst complying with climate change targets. For these reasons, Bangladesh presents a good case study for developing countries: First, it is a developing country that is highly dependent on fossil fuels for its electricity generation and its future energy policy is inclined towards the imports of fossil fuels. Second, it lies in a region of high solar potential, hence its future energy supply will have a large share of solar PV. Third, presence of the monsoon season and few electricity generation options other than solar in a fully renewable energy system.

In addition, there is no research on future energy transition scenarios that are fully based on a broader potential of renewable energy (RE) resources for Bangladesh. Table 1 summarises various energy scenarios and their key findings. Unfortunately, none of them have considered broader RE resources and as a result achieved lower RE shares. Moreover, the modelling tools adopted lack a key requirement, such as, the ability to handle an hourly dynamics of storage and the needed hourly balance between demand and generation, in order to simulate high variable RE systems appropriately [37], [38].

This study contributes to the various existing studies on the energy transition pathways for Bangladesh. However, it goes a few steps further by considering the multi-nodal approach with an hourly resolution for an entire transition year [29], [30], [39] in addition, to its broader power generation, storage and flexibility options including grid balancing among the regions. Further, it identifies the risks associated with future energy policies of the Government of Bangladesh, like energy security in this changing geo-political world, increasing greenhouse gas emissions, climate change and high electricity

94 costs and the potential opportunities in embracing renewables. This paper shows how RE could solve the
95 energy security challenges of Bangladesh as well as meet the climate change goal of reducing its GHG
96 emissions.

97 **Table 1**. Various studies on future electricity demand and renewable energy system for Bangladesh.

Study	Scope	Key findings
Mondal M. A. H. et al., 2014 [40]	Bangladesh	Different scenarios analysed from 2010 to 2035 using MARKAL. Different policy scenarios developed for the analyses of the power sector. The analyses show that energy imports are needed to satify the growing energy demand in the future. However, imports can be reduced by having CO_2 reduction targets or fast increase in renewable energy deployment. Additionally, this would also improve energy security and reduce environmental impacts without increase in discounted total energy system cost. The highest installed capacities of solar PV is observed in the Null Coal Import scenario of about 41 GW and electricity generation is 84 TWh. The renewables share in total installed capacity in 2035 is about 41%.
Power System Master Plan (PSMP), 2016 [41]	Bangladesh	In 2041, the total electricity demand would be 335 TWh, which would be supplied by coal (35%), gas (35%), imports/renewable (15%), nuclear (10%), and oil (5%). Approximate generation costs would be in the range of 97-124 €/MWh.
IEEFA, 2016 [10]	Bangladesh	Total electricity demand will be 92.5 TWh by 2024/2025. Renewable energy will have the highest share in electricity production ataround 50%, followed by gas 26% and oil 12%. 62% of the total renewable electricity will be provided by various solar energy technologies.
National Committee Bangladesh (NCBD), 2017 [13]	Bangladesh	By 2041, the approximate electricity demand would be 490 TWh in which renewable energy contributes 55%, natural gas 37%, and others have 8% share. Batteries would be used as storage technologies with a capacity of 78 TWh.
Das A. et al., 2018 [42]	Bangladesh	Four scenarios were explored till 2045: Power System Master Plan scenario, a high power import scenario, a higher use of renewable scenario and a combined scenario with high power imports and high renewable energy use. The results were optimised using a TIMES model and indicated that the combined scenario with high renewable energy and high imports lead to a least cost system. The maximum installed capacity for PV and wind in the high renewable energy scenario is 10 GW and 4.6 GW respectively and total generation from renewables is around 22.7 TWh in 2045. The maximum imports for the combined scenario is around 100 TWh. Due to the modelling strategy, this study also leads to significant fossil fuels consumption even under the best policy scenario.

2. Methodology

This research assesses energy transition scenarios for Bangladesh from 2015 to 2050. The modelling was performed using LUT Energy System Transition model, which is summarised below. More detailed information about the model and its inputs can be found in Bogdanov and Breyer [39], [43].

The LUT Energy System Transition model optimises energy systems under a set of linear constraints and assumptions for future RE power generation and demand for a particular area. The transition is modelled starting from the energy system in 2015 towards a fully RE system in 2050, in 5-year time steps. The model ensures that all technologies, which are built in the transition period, are fully amortised. The model is comprised of a clearly defined objective function, which optimises for every 5-year time step, so that all constraints and assumptions are satisfied, resulting in a least cost energy system. The optimisation is currently carried out using a third party solver, MOSEK ver. 8. The post processing of the optimisation results and model compilation is done using Matlab. The target function for the optimisation is given in Eq. 1.

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t)\cdot instCap_{t,r} + OPEXvar_t \cdot E_{gen,t,r} + rampCost_t \cdot totRamp_{t,r}\right) \tag{1}$$

where the abbreviations stand for Capital cost of each technology, $CAPEX_t$, capital recovery factor for each technology, crf_t, fixed operational cost for each technology, $OPEXfix_t$, variable operational cost each technology, $OPEXvar_t$, installed capacity in a region, $instCap_{t,r}$, electricity generation by each technology, $E_{gen,t,r}$, ramping cost of each technology, $rampCost_t$, annual total power ramping values for each technology, $totRamp_{t,r}$, each and every region, *reg*, and each and every technology, *tech*.

The LUT Energy System Transition model has the following important features among other things:

- Hourly resolution for an entire year depicting an accurate synergy between different system components utilised, guaranteeing an energy system much closer to reality, including energy supply security.
- A transition of an energy system can be modelled until any given year in the future, as long as data is available.
- Utilisation of different storage technologies.
- A multi-nodal approach of the model enables a country or a region to be divided into different sub-regions, each sub-region can act as a different node and the nodes can be interconnected to form a transmission network.

Figure 1 presents a simplified representation of the model input data, optimisation and results.

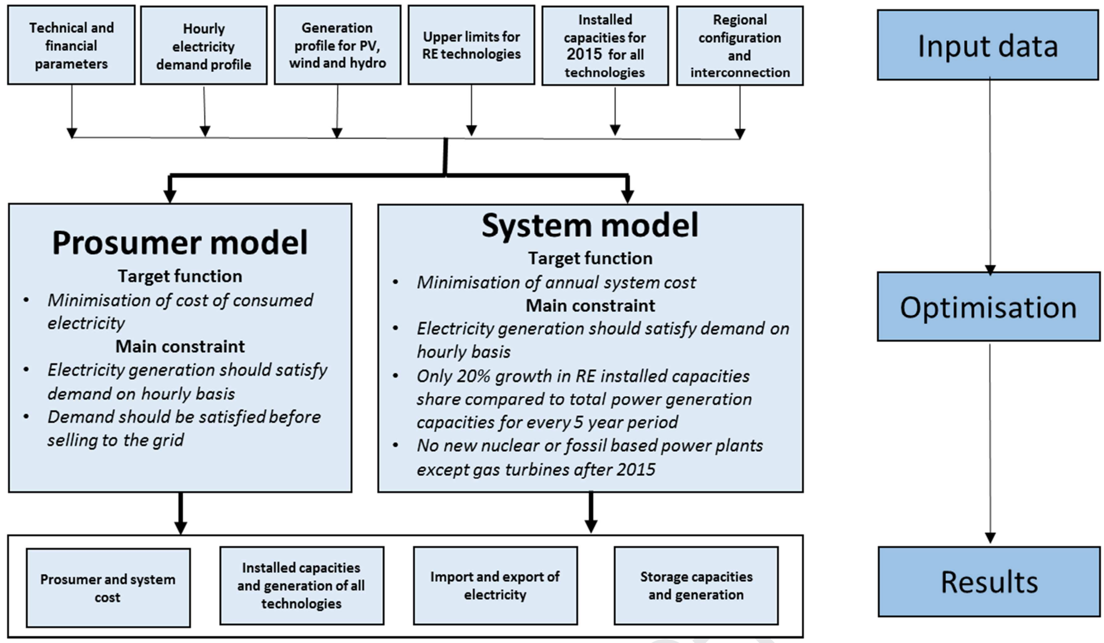


Figure 1: A simplified version of the LUT Energy System Transition model flowchart from input parameters to results.

Electricity is generated using a mix of fossil fuels and renewable generation technologies. Additionally, intermittency of renewables is balanced by deploying appropriate storage technologies and flexibility options. The supply of electricity to the nodes is secured by utilising the assumed network of High Voltage Alternating Current (HVAC) transmission lines. The list of various technologies is given in Table 2 and Figure 2.

Table 2: The list of technologies utilised for the energy system transition.

	Technologies utilised
Generation	**Renewables:** PV rooftop for prosumers, PV fixed-tilted, PV single-axis tracking [44], wind onshore, hydropower, geothermal, biomass and waste-to-energy **Fossil:** coal, gas and oil Nuclear power
Storage	Batteries, pumped hydro energy storage (PHES), adiabatic compressed air energy storage (A-CAES) [45], gas storage and thermal energy storage (TES).
Transmission	High Voltage Alternating Current (HVAC)

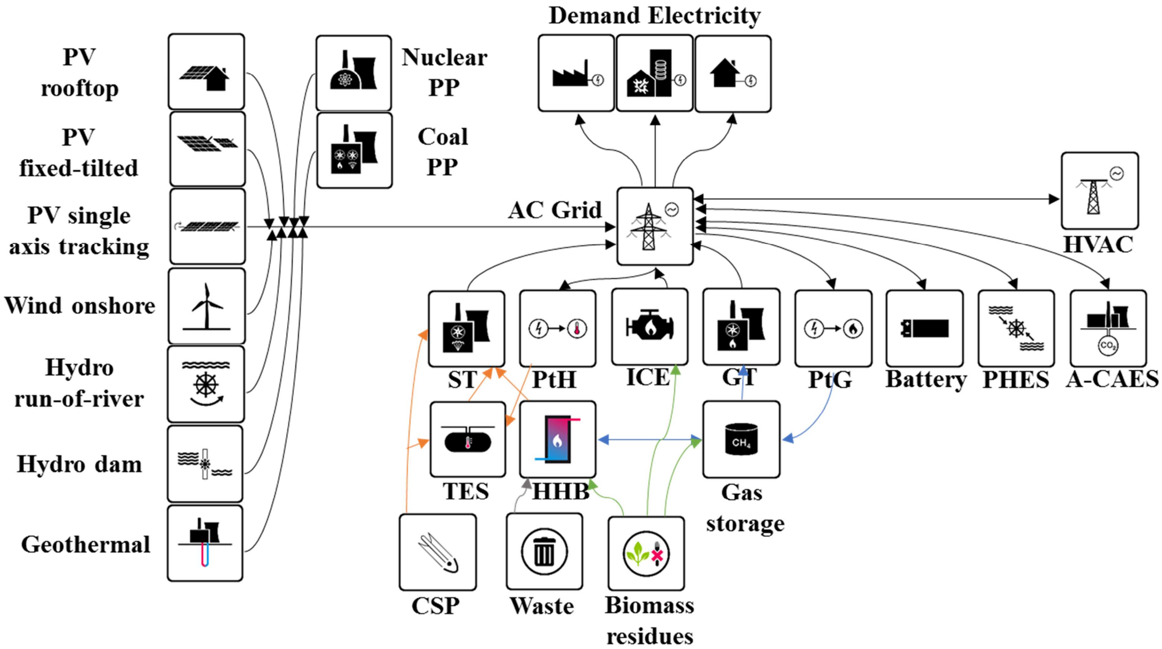


Figure 2: The LUT Energy System Transition model [31].

3. Scenario development for the energy system analysis of Bangladesh

In this section, we briefly explore the energy system of Bangladesh and present the scenarios designed to perform this study and the related baseline assumptions.

3.1 Current and future energy policies in Bangladesh

In 2016, nearly 92% of the total electricity generation in Bangladesh was sourced from fossil fuels, with major contribution from natural gas (60%) and the remaining from expensive furnace oil and diesel (32%) [10], [46]. In future, electricity generation will be dependent on imported natural gas as its domestic natural gas fields are fast depleting. According to Ahmed et al. [47], natural gas fields in the country will be empty within 15 years and running an energy system that will be entirely depend on imported fuels, will undermine the energy security of the country.

The power sector in Bangladesh is entirely managed by the Bangladesh Power Development Board (BPDP), which is responsible for electricity generation, transmission and distribution. The current installed capacity is around 18 GW, which includes 2 GW of renewable energy [46], [48]. Due to the persistent problems of under generation, transmission and distribution losses [49], current installed capacity is not enough to satisfy the ever-growing demand. To overcome the power shortage problem, the government has undertaken Quick Rental Power Plant (QRPP) project based on oil. However, price fluctuations of crude oil in the international market have increased the costs of electricity from these power plants. Even if the government is committed to purchase electricity at the cost of production, the effect failed to provide the aspired least cost of electricity to society [50].

According to the future policy of the Government of Bangladesh, coal and natural gas are expected to be the main fuel sources for power generation until 2041 [41]. However, local reserves of these resources are limited and therefore the nation will rely on increasing fuel imports regardless of further risks associated with GHG emissions increase [50]. It should be noted that the power sector alone contributes to 40% of the GHG emisisons in Bangladesh [51]. The target (untill 2030) for example, aspires to increase the installation capacity of coal power plants: 11.5 GW from domestic coal and 8.4 GW from imported coal [51].

3.2 Renewable energy and GHG emissions abatement strategy in Bangladesh

Bangladesh is amongst the developing countries with a small share of GHG emissions on the global level [52]. However, it is one of the most vulnerable countries in the world to climate change. The Government of Bangladesh has ratified the United Nations framework for climate change mitigation on 22nd April 2016 [53]. The submitted Intended Nationally Determined Contribution (INDC) includes emissions reduction goals in the power, transport and industry sectors with an additional clause of conditional and unconditional contributions. An unconditional contribution is to reduce the total GHG emissions by 5% from the business-as-usual (BAU) levels in 2030. However, with additional international support it plans to reduce its GHG emissions by 15% from the BAU levels by 2030. To support its commitment, Bangladesh has a number of activities and targets to reduce GHG emissions. Some of these activities include reducing the energy intensity (per GDP) by 20% by 2030 compared to 2013 levels, increasing the energy efficiency of new buildings, increasing penetration of renewables to 10% by 2020. The planned renewable energy increase is intended to utilise the abundant solar potential, by increasing the distribution of solar home systems, solar irrigation pumps, solar mini-grids and nano-grids [54], along with building utility-scale solar PV systems [52].

Bangladesh has good renewable energy potential, especially for solar energy. Figure 3 shows the distribution of solar yield in Bangladesh. According to Ahamad and Tanin [55], Bangladesh receives an average solar irradiation of around 1095 - 1460 kWh/($m^2 \cdot a$) and has the potential to generate 380 TWh of electricity, requiring about 10% of the total area of Bangladesh (excluding areas under agricultural and forest cover) [10], [56]. This potential is significantly higher than the present annual electricity demand and could satisfy the projected electricity needs. Bangladesh can follow suite of its neighbouring country India, where the cost of electricity generated from solar PV is currently amongst the lowest in the world, at about 35 €/MWh [57]. To realise the solar PV potential and cost competitiveness against fossil fuel power plants, India has set up targets to install 100 GW by 2022 [58] and 227 GW by 2027 [59].

Similarly, the Government of Bangladesh has initiated a number of programs to take advantage of its renewable energy potentials. The renewable energy policy was adopted in 2008 with an aim to boost renewable power generation [60]. In 2015, Bangladesh joined the International Solar Alliance to collaborate towards increased adoption of solar energy [61]. The installation of solar home systems in off-grid areas had been booming in the last decade [62]. So far, 218 MW of solar home systems have been installed [63]. There were about 5 million solar home system (SHS) installations in 2017, for the benefit of 30 million people and has created 140,000 new jobs [64]. Rooftop solar installations for commercial and residential buildings has been gaining popularity in recent years [65]. For utility-scale solar PV, non-agricultural land owned by the government is being used, mainly to develop solar parks [65]. Wind energy potential is around 340000 MW in Bangladesh with its nearly 740 km long coastline and many small islands, where strong winds are present during the monsoon season (May-October) [66]. Municipal waste has the potential to become a good energy resource for Bangladesh. In 2015, 27 million tons of municipal solid waste was produced in different municipalities [48]. Out of this, organic waste constitutes 78.9% [48], which can produce 10 TWh_{th} of biogas. Bangladesh also has a large potential of biomass due to its agricultural economy. Agricultural and forest residues form a major component in its biomass potential. According to Hossen et al. [67], agricultural, municipal waste, industries, animals and other sources of waste can generate about >950 TWh_{th} of energy considering that all waste is recovered. In addition, 315 MW of small scale and large-scale hydropower plants can be installed in Bangladesh [60].

To ensure long term energy security without burdening the economy or the enviornment, Bangladesh will need to stress on policies that will exploit these RE potentials.

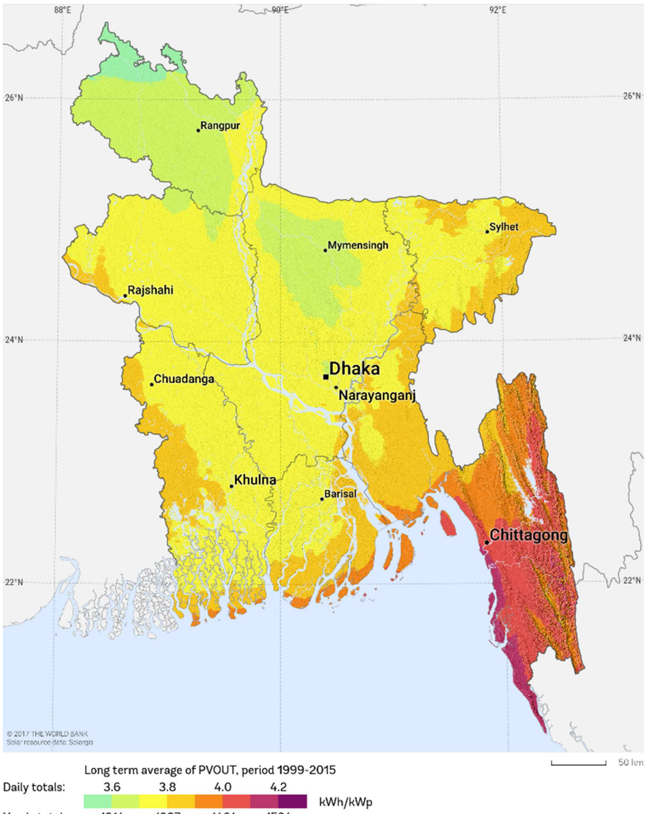


Figure 3: The photovoltaic power generation potential for an optimally fixed tilted 1 kWp system for Bangladesh [68].

3.3 Parameters and assumptions in the modelling

3.3.1 Subdivision and grid structure of Bangladesh

For the purpose of this study, Bangladesh was sub-divided into seven sub-regions based on population distribution, consumption of electricity and the grid structure. The division of Bangladesh into seven regions enables for a high spatial resolution of the power system, as shown in Figure 4. The assumed grid structure is based on the current power grid with Dhaka as the main consumption centre, which is connected with all the sub-regions. The inter-regional connections are via HVAC lines and intra-regional connections are based on existing AC grid structure of the country.

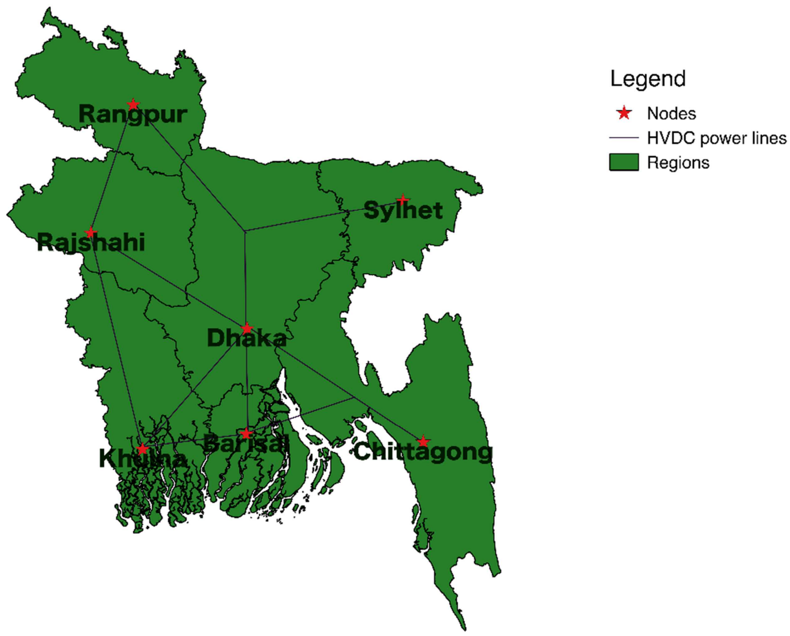


Figure 4: The seven sub-regions in Bangladesh and the grid connections.

3.3.2 Potential and feed-in profiles for generation technologies

The generation profiles for single-axis tracking and optimally tilted PV, solar CSP, wind energy and hydropower were provided as input data to the model. The feed-in profiles were calculated according to Bogdanov and Breyer [39], whereas single-axis tracking PV was modelled according to Afanasyeva et al. [44]. For the base year 2015, installed capacities of solar PV, wind and hydro are taken from Farfan and Breyer [69]. The upper limits of the RE capacities were added after evaluating the potential. The potential of wind and hydro power are limited [65], [70]. On the other hand, Bangladesh has one of the best solar resource availability [10], but a criteria was set so that the total land area availability for solar PV installations does not exceed more than 6% of the total area of a sub-region. It should be noted that solar resource variation over an area such as the sub-regions in Bangladesh, is negligible [71], [72]. Thus, one selected site in each sub-region can give a good representation of the resource availability in that particular sub-region, and the respective algorithm from Bogdanov and Breyer had been applied [39]. The variable solar resource characteristic was according to real weather year 2005. The overall wind energy potential in Bangladesh is limited to the coastal areas and mainly available during the monsoon season [65], [73], [74]. Additionally, due to the spatial resolution of wind data, there could be some spots with good wind speed profiles that may not have been captured, especially in the coastal areas. The impact of such data limitations should be assessed when better data are available.

Additionally, the model utilises the potential of storage technologies in each of the regions. The Energy-to-Power ratios and the efficiencies of the storage technologies are given in [31]. The installed capacity of each storage technology is based on the requirement of energy-to-power ratio and the economic performance.

Biomass was divided into three categories: solid wastes, solid residues and biogas. The potential of biomass for Bangladesh was obtained from [75] and divided into different sub-regions, according to the area and population of each region. The cost calculations for the three biomass categories were done according to the data from International Energy Agency [76] and Intergovernmental Panel on Climate

Change [77]. For solid fuels a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected in the negative costs for solid waste [31].

At present, geothermal energy does not play a critical role in Bangladesh. However, the model input consists future geothermal potential for all the seven sub-regions, which is calculated according to the method described in [30].

The lower and upper limits for renewables are given in the Supplementary Material (Table S3).

3.3.3 Financial and technical assumptions

The weighted average cost of capital (WACC) for Bangladesh is set at 7% in real terms for the investments considering the stability and the potential of renewable energy in the country. For residential rooftop PV installations, WACC of 4% was used due to lower financial return requirements. The increase or decrease in WACC does not alter the costs of electricity considerably [19].

The economic assumptions for capital expenditures (CAPEX) and operating expenditures (OPEX fixed and variable) and the technical assumptions for efficiency and lifetimes of the different technologies utilised in the energy transition of Bangladesh are tabulated in the Appendix Table A.1 and A.2. Due to absence of country specific cost projection data, a global average of the financial cost projections were assumed. The financial assumptions of important renewable technologies are based on the steady cost decline from around the world and the expected fast cost decline with faster capacity additions in the future. This is reported in a number of established studies [23], [78], [79]. It is assumed that with the ongoing improvements in technology and production processes, the costs of materials and installations will fall considerably from their current values until 2050. For example, the cost of power produced from solar PV has gone down to 14.9 €/MWh in 2017 from around 70 - 80 €/MWh in 2014 [80], [81]. It should be noted that 14.9 €/MWh is globally the least cost observed, but a range of 20-25 €/MWh is regularly achieved worldwide. In addition, globally the costs of batteries have decreased by 77% in the last 7 years [23], [82], [83]. The costs of onshore and offshore wind power plants, particularly offshore wind plants are expected to decline sharply in the future [84]. The sharp decline in costs is possible due to the expected learning curves [85].

The price of electricity for 2015 for the three prosumer categories are assumed from Dhaka Electric Supply Company Limited [86] and future prices until 2050 were calculated according to the methodology described in Breyer and Gerlach [87]. The electricity prices for Bangladesh are provided in the Supplementary Material (Table S1).

3.3.4 Electricity demand

The electricity demand is taken from Power System Master Plan report 2010 [88] and 2016 [41] and extrapolated until 2050 with the provided growth rate. The hourly load profile for electricity for each sub-region is calculated as a fraction of the total demand in Bangladesh based on synthetic load data according to Toktarova et al. [89], weighted by the sub-region's population.

3.4 Description of the Scenarios

For this study, four scenarios were developed after reviewing the local energy policies and future energy planning. The scenarios help to focus on the policy options leading to a transition towards 100% RE system taking into account the GHG emissions reduction and the overall system costs. The description of the scenarios and the assumptions are given in Table 3.

Table 3: Detailed description of the four scenarios

Scenario	Detailed description
Best Policy Scenario (BPS)	This scenario focusses on achieving a 100% renewable energy system by 2050. To achieve the stated target, three main assumptions were considered. First, no new fossil fuel capacities are allowed to be installed after 2015, except gas firing power plants, and the phased out capacities can only be replaced by renewables and storage, also imports were restricted from the neighbouring countries after 2015. Second, the model assumes a carbon cost of 9 € in 2015, which increases in 5-year time steps to 28, 53, 61, 68, 75, 100 and 150 € per ton till 2050, respectively. Third, no more than 20% growth in RE installed capacities share compared to total power generation capacities can be achieved for each 5-year time step, to avoid meaningless increase in capacities. The BPS scenario incorporates the potential role of prosumers (rooftop PV, optionally with batteries) during the system transition using an exogenously estimated prosumer capacity. The prosumer potential calculation is performed using an hourly optimisation model, which installs rooftop PV and optionally battery systems for residential, commercial and industrial customers. The target function for prosumers is cost minimisation of the consumed electricity, calculated as a sum of generation, annual costs and costs of electricity consumed from the grid. The prosumers have an option to sell the excess generation to the grid at an assumed price of 0.02 €/kWh, after fulfilling their own demand, but not more than 50% of their own generation. The limit on prosumer installations is 20% of the total electricity demand in 2050.
Best Policy Scenario with no carbon cost (BPS-NCC)	This scenario is similar to the BPS scenario. The only difference is the removal of the assumed GHG emissions costs throughout the transition period. Currently, Bangladesh does not have any GHG emissions costs. There is no evidence that any costs will be applied in the future as well. Thus, a scenario without GHG emissions costs will show the potential role of renewables as derived by their cost competitiveness. In addition, this scenario does not limit fossil fuels by 2050, as in the BPS scenario.
Current Policy Scenario (CPS)	This scenario is based on the national 'Power System Master Plan 2016' [41]. This plan was developed to diversify the power generation sources and transform the country into a high-income country by 2041. As the current domestic natural gas supply is diminishing, the increasing electricity demand is expected to be satisfied by importing fossil fuels. In addition, imports of electricity will play a significant part in satisfying the growing demand. While, local renewables are expected to play a minor role in the overall electricity generation mix of the country. However, for this scenario a GHG emissions costs similar to the BPS scenario is assumed. The levying of carbon tax would bring a huge monetary benefit annually to the Government of Bangladesh. The implementation of a carbon tax was previously discussed on a wide scale [90], however before the elections in 2017, it was scrapped citing various reasons [91]. The main reason being that a carbon tax would increase the price of electricity and raise living costs. The authors have not considered a scenario by the National Committee to Protect Oil, Gas, Mineral Resources Power and Ports (NCBD), a study that appears to show a possibility of more renewable alternative as opposed to the proposed PSMP plan [41]. Because the study analyses the case of 2041 without presenting any detail of what happens in between. Moreover, the high renewable future that was intended to be demonstrated by the NCBD report is investigated in much detail in the BPS and BPS-NCC scenarios. The masterplan by the Government of Bangladesh shows that electricity imports will be an important factor to satisfy the future demand growth, for stable base load supply and supply diversification [41]. In 2015, Bangladesh imported 500 MW of power from India. The 3.8 TWh of imported electricity contributed about 9.5% to the total consumption in that year [46], [92]. In addition to an increasing capacity of imports from India, Bangladesh plans to import power from the neighbouring countries of Bhutan, Myanmar and Nepal. The future share of imports is expected to rise to around 15 to 25% of the total power generation until 2041 [40]. In order to account for electricity imports in the LUT modelling tool, the 'Deflated demand'

	approach was adopted. In this, the imported electricity is subtracted from the total demand and the new residual demand is used as the input for the simulation. This logic follows the prosumer approach, so that finally the domestic residual system demand is optimised. As the Government of Bangladesh wants to use the imported electricity to meet the base load, this methodology may be a better way to represent the role of imported electricity in the power system. As Bangladesh will have power purchase agreements with the respective neighbouring countries for imported electricity, assuming a constant hourly import is a simplified way to capture the hourly distribution.
Current policy scenario with no carbon costs (CPS-NCC)	This scenario is similar to the CPS scenario, except the consideration of GHG emissions costs, similar to the BPS-NCC scenario.

3.5 Model Calibration

The model was calibrated using the 2015 generation and installed capacities for the different power technologies obtained from the Government of Bangladesh [41]. This was done by reproducing the 2015 results for each of the scenarios of Bangladesh using the installed power plant capacities and demand data, the results for the energy generation by each technology is in agreement with the actual generation in 2015. All scenarios use this result as a starting point and continue to 2050 depending on the intended scenario constraints as discussed in Table 3.

4. Results

The optimised results with respect to the cost structure, installed capacities of generation and storage technologies and annual GHG emissions in the transition period will be presented as follows.

4.1 Cost structure of the transition

The results related to the levelised cost of electricity (LCOE) in the transition period for the BPS, BPS-NCC, CPS and CPS-NCC scenarios, respectively are presented in Figure 5.

LCOE is the highest for CPS and CPS-NCC scenarios for all the transition years. These two scenarios are primarily comprised of fossil fuels, particularly natural gas and oil in the initial years of the transition and later on supported by coal power plants. GHG emissions costs have a huge impact on the total LCOE in all the scenarios, particularly the CPS scenario, where the total LCOE in 2050 is higher by 69% in comparison to its LCOE in 2015. The combination of high GHG emissions costs and close to 90% fossil fuels in total electricity generation in 2050 are primary reasons for the high LCOE. Completely abolishing the GHG emissions costs (CPS-NCC scenario) during the transition, decreases the LCOE in comparison to the CPS scenario, however, the LCOE is still higher than the two BPS scenarios and has very high GHG emissions, which is to be explained in the section 4.6.

Fossil fuels are associated with a 'fuel cost' i.e. cost of producing a unit of electricity from a particular fuel. For the year 2015, oil is associated with the highest fuel cost of 52.5 €/MWh (89.3 €/bbl) and natural gas of 21.8 €/MWh (0.23 €/Nm^3). The high fuel costs associated with natural gas and oil, contribute to about 80% of the total generation, and the associated costs of emissions contribute to the LCOE in 2015. The fuel costs for all the fossil fuel technologies and the emissions costs assumed are provided in the Supplementary Material (Figure S6 and Table S6 respectively). After 2015, the LCOE decreases in 2020 for all the scenarios, due to the influx of flexible power generation technologies, however, after 2020 the LCOE increases for the CPS scenarios.

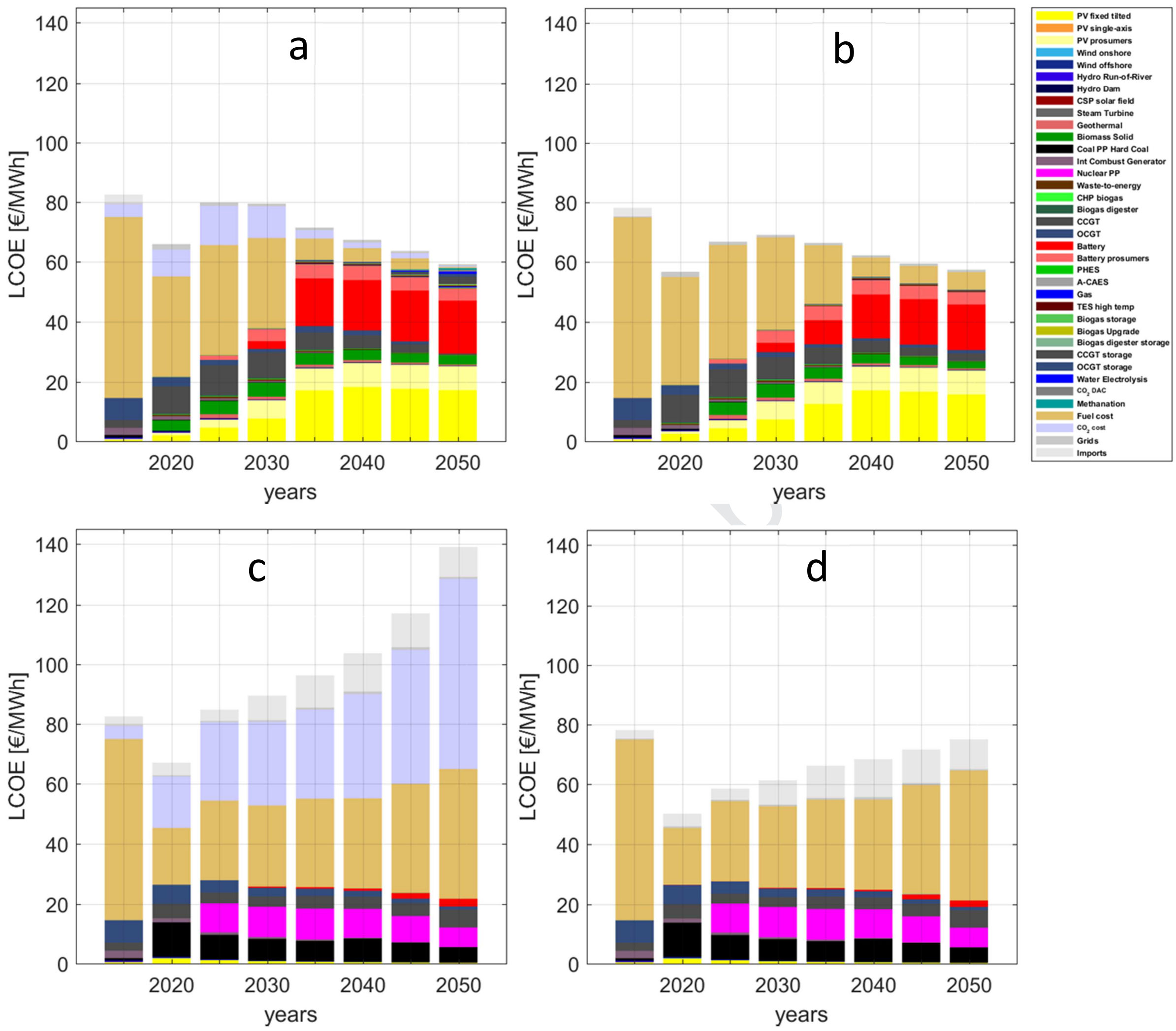


Figure 5: The LCOE distribution according to each technology in the transition years from 2015 to 2050 for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

For the BPS scenarios Figure 5 a and b, LCOE decreases by about 20-28% in 2020 compared to 2015, primary factors being the reduction in utilisation of expensive fossil fuels and the associated GHG emissions costs. The power generation from expensive, inefficient and inflexible oil and diesel based power plants reduced considerably from 15% in 2015 to almost 0% in 2020. This decrease is in agreement with the government's policy of not installing new oil and diesel based power plants in the transition years, though unlike their vision, these scenarios replace the created fossil fuel generation shortfall with an increased electricity production from renewables especially solar, biomass and municipal waste.

Specifically, the large biomass and municipal waste resource discussed in section 3.2, plays a major role in replacing the fossil fuel generation as observed from 2015 to 2020. With the falling cost of solar PV during the transition years, it becomes the main source of electricity generation in both BPS scenarios. Despite the similarity in cost trends between BPS and BPS-NCC scenarios, it can be seen that LCOE remains lower in the BPS-NCC scenarios. This is because of the avoided costs of GHG emissions in this scenario and the reduced costs of achieving a faster transition as observed in the BPS scenario. The impact of fast transition requirements of the BPS scenario has resulted in 100% RE in 2050, as compared to 94% for the BPS-NCC scenario for the same year. While the LCOE for BPS-NCC scenario presented in Figure 5b shows the fossil fuel role, it can be inferred that Bangladesh could remove significant power sector GHG emissions by promoting solar and battery storage technologies (subject to be detailed later). Note that by 2050, emissions in the BPS scenario becomes zero. However, the relatively higher LCOE by 2050 of 4% is due to the increased investments in renewable capacities and the need to install storage technologies to arrive at 100% RE.

For the CPS scenarios with and without GHG emissions costs as given in Figure 5c and d, LCOE decreases slightly in the year 2020 in comparison to 2015, due to the planned investments in relatively cheaper fossil fuel generators than oil-based power plants. In Figure 5c and d, corresponding LCOE increases in the transition years from 2020 onwards. In comparison to BPS scenarios, LCOE for CPS scenarios are higher for all the years. In 2050, LCOE for CPS and CPS-NCC scenarios are 58% and 25% higher than the BPS scenario, respectively. The low price of imported electricity may have reduced total LCOE in transition years, as compared to the expensive electricity generation options in Bangladesh. It can be concluded that a solar-based policy would provide Bangladesh the best transition option, as compared to the present fossil-based policy.

The total annual costs of the system in 2050 for all the scenarios is given in Figure 6. The total costs are calculated as a sum of annual costs from all the power generation capacities, energy generation, generation ramping of the technologies, storage technologies and transmission costs of the generated electricity for each of the transition year. The BPS-NCC scenario shows the lowest costs, which suggests economically to be a favourable scenario, however this scenario does not give a 100% RE system. The CPS scenario has the highest cost due to the combination of high fuel costs and emissions cost followed by CPS-NCC scenario. On the other hand, BPS scenarios with and without GHG emission costs show that a high share of renewables in the energy system does not increase the total costs of the system. The annual costs of the BPS-NCC scenario is lowest and the BPS scenario costs about 4% more than the BPS-NCC scenario.

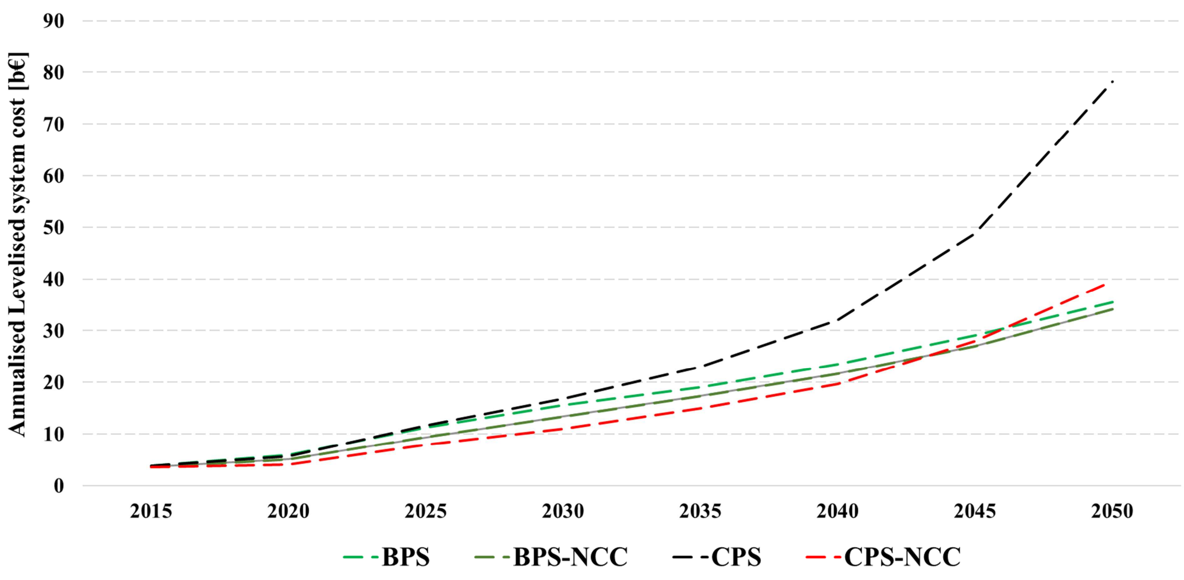


Figure 6: Total annual costs of the system for all the scenarios in the transition years.

4.2 Primary electricity generation during the energy transition period

The previous section shows that Bangladesh obtains a better transition option if it emphasises on a solar-based policy by producing cheaper electricity for its customers. In this section, we will examine detailed electricity generation by each technology type in all the scenarios as presented in Figure 7.

For the BPS scenarios, phasing out of fossil fuels, especially gas, is substituted by an increase in generation from solar PV and biomass for the year 2020. However, it should be noted that the share of biomass remains constant after 2025 because of full exploitation of the maximum resource potential assumed for the scenarios and that of solar PV increases throughout the transition. The application of GHG emissions cost to the BPS scenario enforces a fast decrease of the electricity generation from natural gas from 2035 onwards, which reaches zero in 2050 as compared to the BPS-NCC scenario that expects approximately 6% electricity generation from fossil gas in 2050.

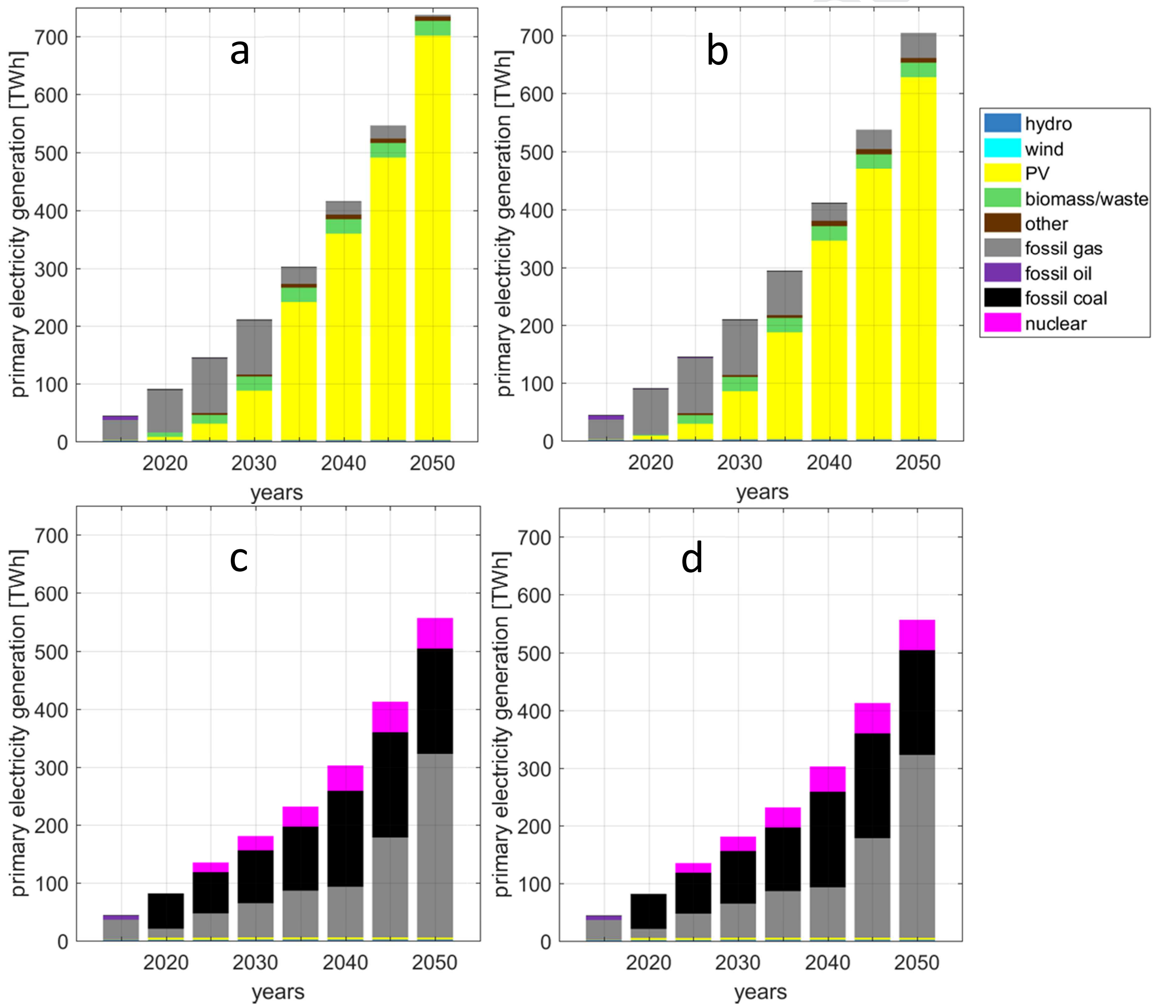


Figure 7: Primary electricity generation in the transition years for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

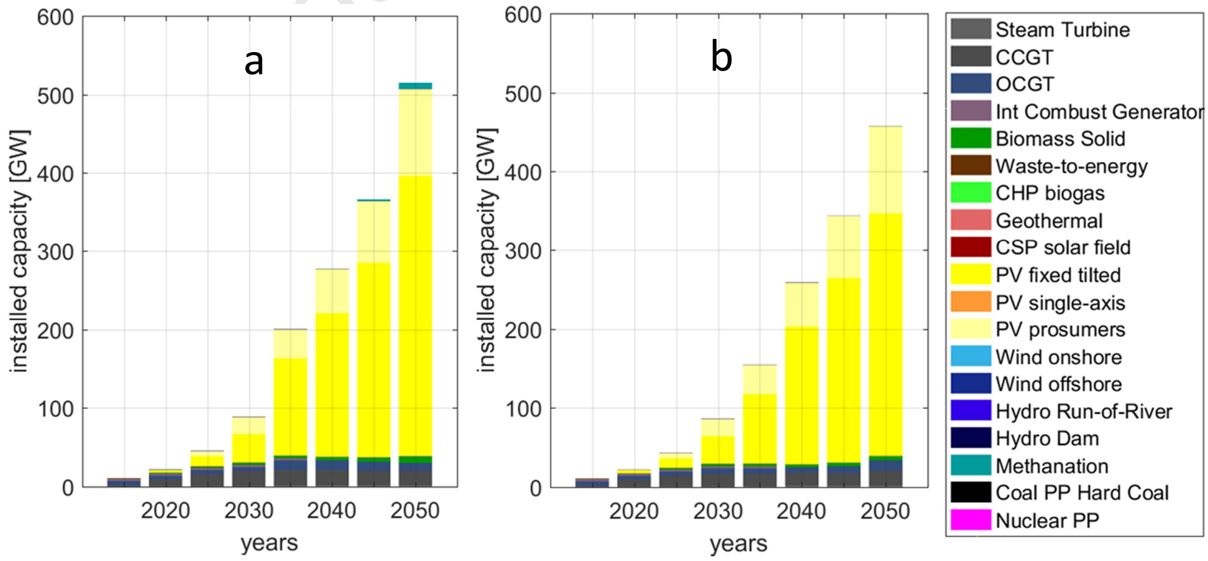
On contrary, CPS scenarios rely on electricity generation from fossil fuels, including nuclear energy, and electricity imports from neighbouring countries. The primary electricity generation in 2015 is dominated by natural gas in the CPS scenarios, due to its vast domestic availability. However, due to forecasted depletion of the local natural gas reserves [42], electricity generation was planned to shift to coal in 2020, which is demonstrated in Figure 7c and d. As a consequence, in 2020, coal and natural gas power plants contribute 75% and 19% of the electricity generation, respectively. After 2020, following the government plans, scenarios show an increased role of natural gas, nuclear and electricity imports. Evidently, the share of renewables in primary electricity generation is almost invisible.

4.3 Installed capacities of the technology mix in the transition

The installed capacities of different technologies in the transition period for the four scenarios is shown in Figure 7 and absolute numbers can be found in the Supplementary Material (Table S2).

In the BPS scenarios, the fossil fuel dominated capacity mix gradually changes to renewables, dominated by solar PV in 2050. For the year 2015, total installed capacity is around 10 GW. For the BPS and BPS-NCC scenario, capacity increases to around 530 GW and 457 GW in the year 2050. The difference in installed capacities is due to the fact that in the BPS scenario, additional capacities are required for converting electricity to RE-based synthetic natural gas (SNG) via methanation plants (Figure 7a), which is further utilised by CCGT and OCGT power plants to produce electricity [93], [94]. This is further emphasised by the installed capacities of gas storage technologies (Figure 8). However, for the BPS-NCC scenario, these extra capacities are not needed due to utilisation of fossil gas.

The BPS scenario places an additional financial constraint on the system to install renewables, particularly, solar PV which can be observed from relatively higher installed capacities in each of the transition years in comparison to the BPS-NCC scenario. To reduce the overall cost of the system, the BPS scenario invests at a faster rate in RE technologies, which aim at reducing GHG emissions. However, the BPS-NCC scenario still leads to very high penetration (94% of the annual generation) of renewables in 2050. The overall trend shows that the cost decline of solar PV with batteries (see section 4.4 for additional information) is the main factor for high penetration in both BPS scenarios. This finding is similar to the results presented in Solomon et al. [6].



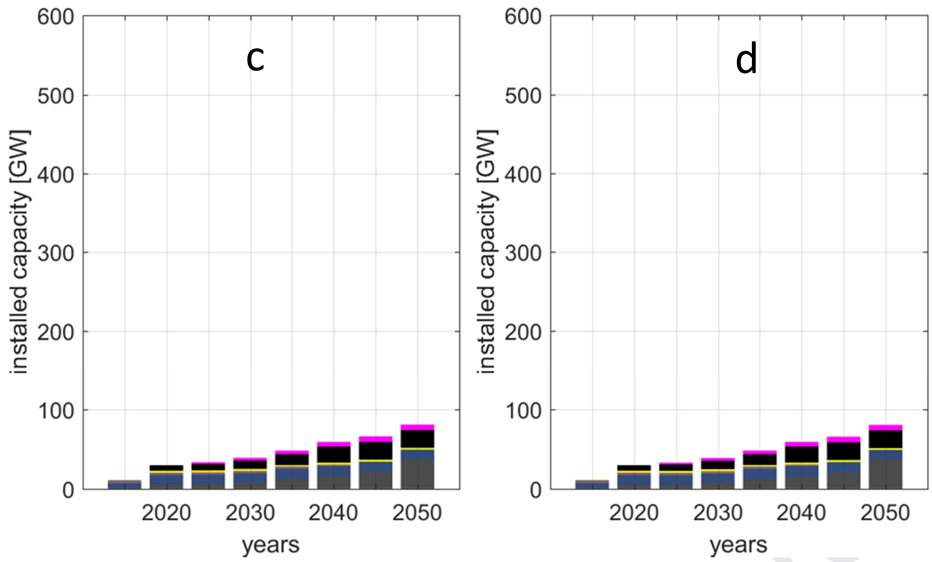


Figure 8: Installed capacity mix in the transition years for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

The technology mix for the CPS scenarios mirrors policy direction of the government to invest in fossil fuels (Figure 8c and d). In comparison to the BPS scenarios, these pathways show an increasing trend in installations of coal, natural gas and nuclear capacities. With negligible renewable capacity addition, the share of solar PV remains constant during the transition, maintaining the current relatively small capacity mix throughout the transition period. Overall, it can be seen that Bangladesh pushes itself into a vulnerable position with respect to energy security by following a path that leads to significant dependence on fossil fuel imports.

For the BPS scenarios, Figure 9a and b, in each region, installed share of solar PV is the highest. The PV share is between 20 – 83%, lowest being in the region of Barisal and highest in the region of Khulna. In the year 2050, it is observed that solar PV and battery provide low-cost electricity to power the increasing demand. The BPS-NCC scenario has a lower aggregated total installed capacity, however, some regions show an increase in their individual total capacities. The regions of Sylhet and Barisal show an increase in total installed capacities primarily due to utilisation of the existing installed gas turbines and further additional installations in 2050, as synthetic gas is not created, which can be later used to generate power, rather the system uses the available natural gas. This scenario does not enforce a transition to a fully renewable energy system in 2050.

For the CPS scenarios, in Figure 9c and d, sub-region’s installed capacities are based on coal, gas and nuclear. The region of Khulna has a share of around 77% and Chittagong accounts for 57% of the total coal capacity installed in Bangladesh. The nuclear power plant at Ruppur in the Rajshahi region is planned to be commissioned from 2023 – 24 and the government plans to install more capacities in the future. This is assumed to be constructed at the same location, therefore the installed capacities are located only in the Rajshahi region. The installed capacity of nuclear power plants is about 7 GW in 2050.

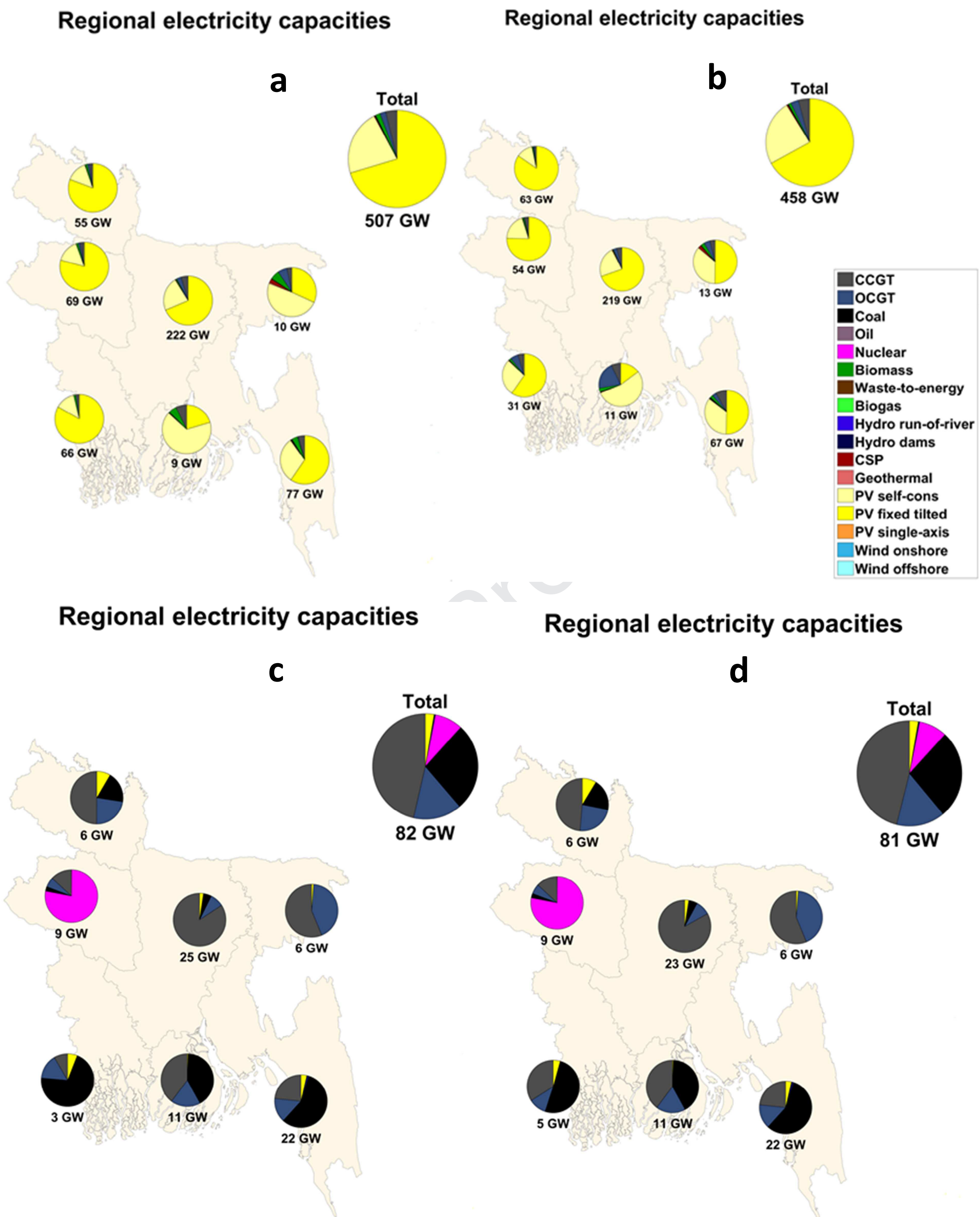
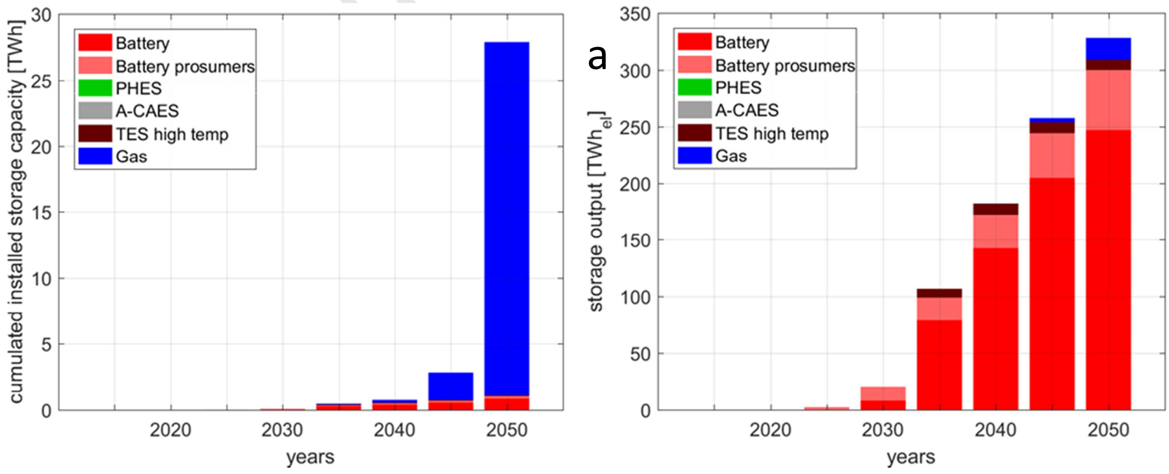


Figure 9: Installed capacities according to the sub-regions of Bangladesh in 2050 for a) BPS; b) BPS-NCC; c) CPS; and d) CPS-NCC scenarios.

4.4 The role of energy storage technologies in the transition

This section shows that the need for storage technologies depend on scenarios as presented in Figure 10. Scenarios emphasising on high shares of RE lead to large scale energy storage as compared to the current policy direction of the country, which plans to rely heavily on fossil fuel generators. In the initial years, due to a lower share of renewables in the system, the model builds the most cost effective storage options, which can provide diurnal energy transfer depending on the scenarios. For the BPS scenarios, prosumer batteries appear first in 2025, due to higher penetration of prosumer PV in the system, which is followed by utility-scale batteries in 2030. The trend is similar for storage capacity installations and storage output for both BPS scenarios, except for gas storage, however, the absolute numbers differ significantly. As discussed before, the BPS scenario emphasises on faster transition through RE penetration in order to comply with the GHG emissions costs constraint. As a result, Figure 10 shows a huge installation of gas storage for the BPS scenario and almost zero for the BPS-NCC scenario. The order of storage technology deployment observed in this study follows the requirement of the penetration-storage-curtailment nexus discussed in [95]. Batteries transfer daytime PV generation to the evening and night hours on a daily basis and disruption of this cycle or peak demand is taken care by CCGT and OCGT power plants, which run on fossil gas for the BPS-NCC scenario. Batteries provide the system with required flexibility and a cost effective option than utilising balancing from fossil fuel power plants for electricity generation. The share of electricity provided by batteries in total electricity demand is 50% and 55% in the year 2050, for the BPS and BPS-NCC scenario, respectively. The increasing share of solar PV (Figure 7a and b) corresponds to the rising share of battery output (Figure 10), as hybrid solar PV-battery systems evolve as a least cost combination to provide electricity until 2050. Gas storage for the BPS scenario is utilised from the year 2045 onwards, when the share of renewables crosses 96%, however huge installed capacities of the gas storage are observed in the year 2050. The electricity output from gas storage is very low in comparison to batteries as seen from Figure 10a. Gas storage provides around 6% of electricity to the total electricity demand in the year 2050. It has to be noted that the capex of gas storage is rather small compared to battery storage per stored energy, which is the reason why the LCOE of the entire energy system further declines (Figure 5a).



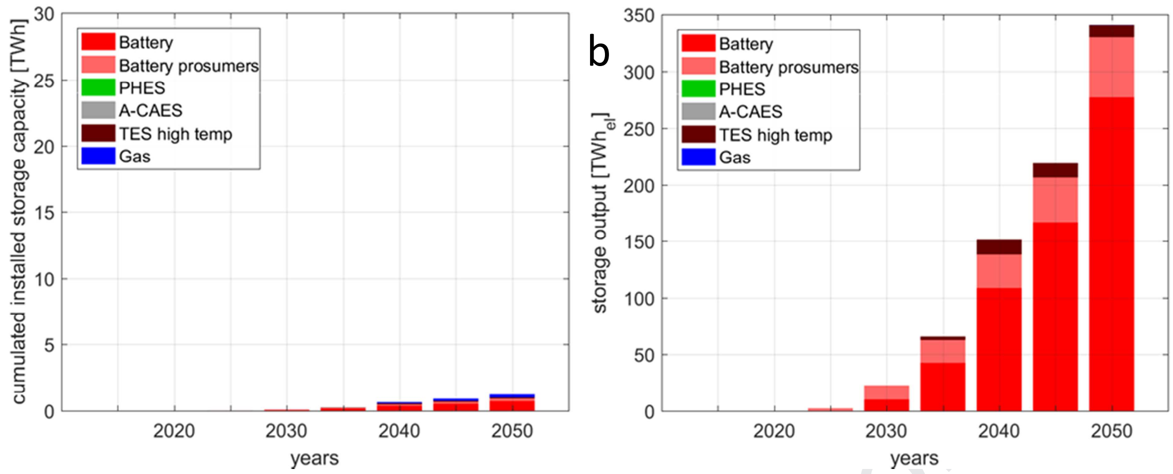


Figure 10: Energy storage installed capacities and output by different storage technologies in the transition years for BPS (a) and BPS-NCC (b) scenarios.

Storage requirement in the CPS scenarios are very different in comparison to the BPS scenarios, as the storage requirements of fossil fuels are different. This is observed from the installed capacities of storage technologies and their outputs in Figure 11a and b.

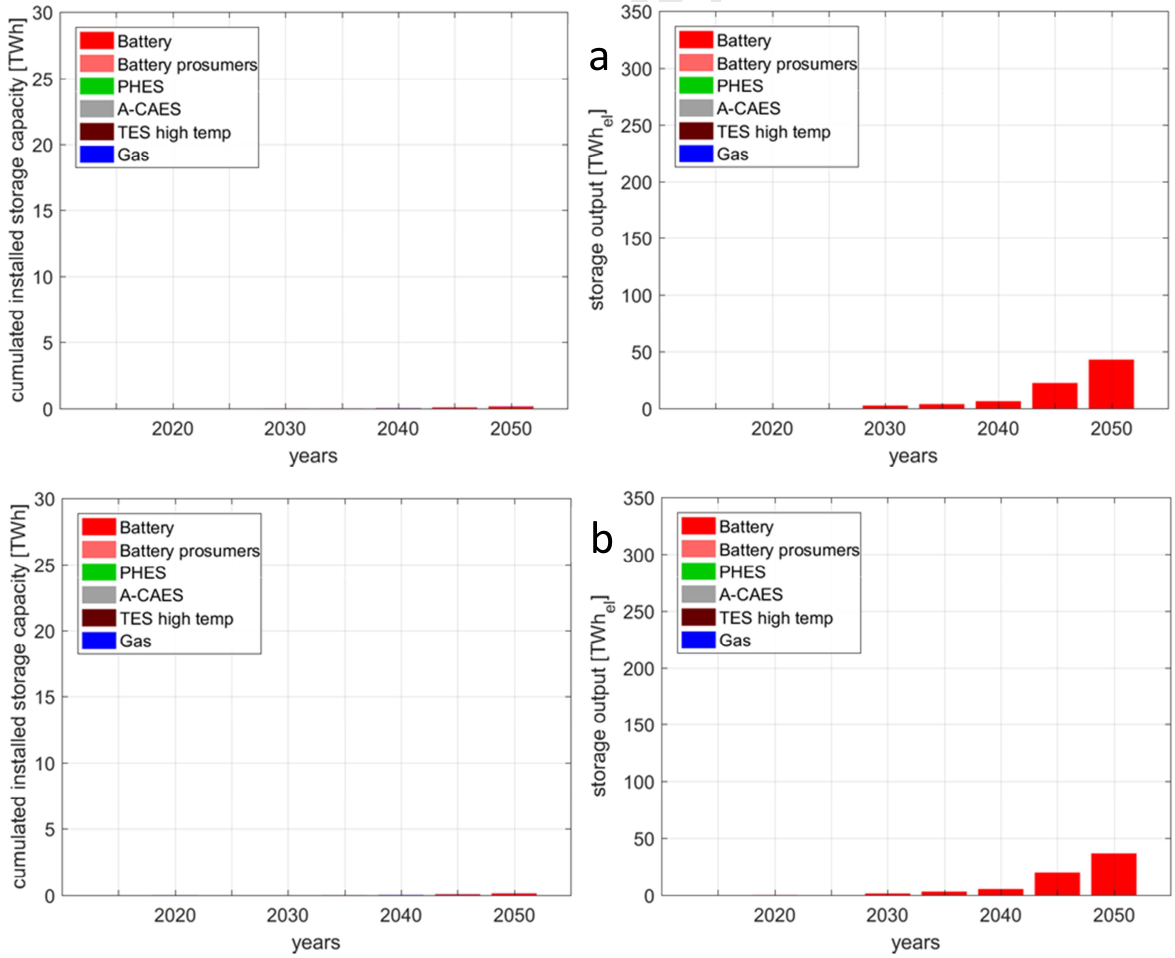


Figure 11: Energy storage installed capacities and outputs by different storage technologies in the transition years for CPS (a) and CPS-NCC (b) scenarios.

4.5 Effects of monsoon on a fully renewable energy system

Solar PV as a resource is well distributed in all the sub-regions of Bangladesh, for most parts of the year except for some months in the monsoon season. Batteries are used on a daily cycle to store solar electricity and satisfy the evening and night time demands in a fully renewable energy system. A slight change in the daily cycle of batteries is observed from days 175-275. This is due to onset of the monsoon season, where batteries are not charged to their full capacity. However, in summer months, excess electricity from the solar PV is converted to synthetic natural gas and stored in gas storage. It is observed from Figure 12, that the gas storage is fully charged till the end of the summer season and slowly discharged around 175th day of the year, to compensate the decrease in solar electricity generation.

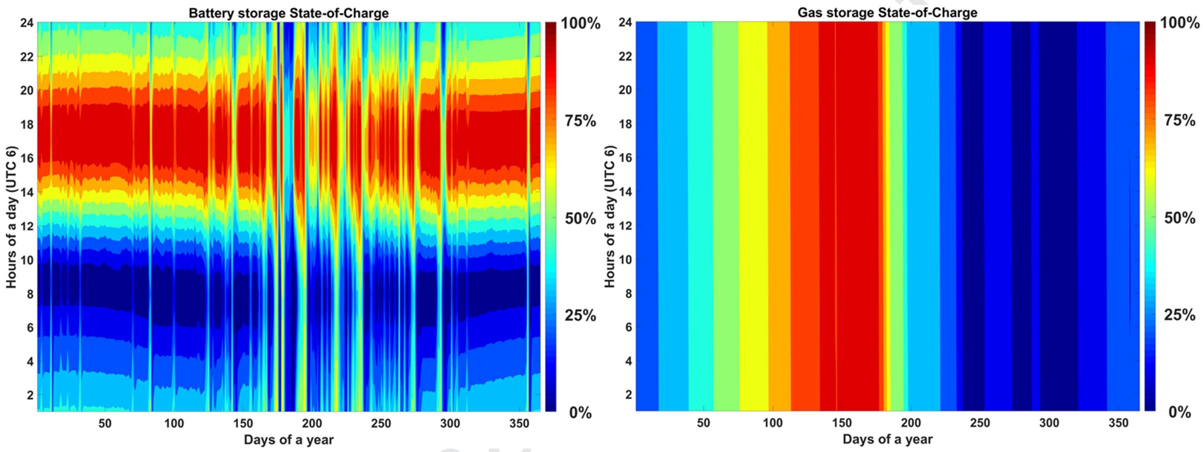


Figure 12: State of charge of battery (left) and gas storage (right) in the BPS scenario in 2050.

The hourly dispatch of electricity in a monsoon week for the capital region of Dhaka for the BPS scenario is shown in Figure 13. Additionally, an hourly dispatch diagram for the non-monsoon week can be found in the Supplementary Material (Figure S5), where it is observed that the solar resource is excellent to satisfy the daytime demand and also store excess electricity in batteries to satisfy the night time demand.

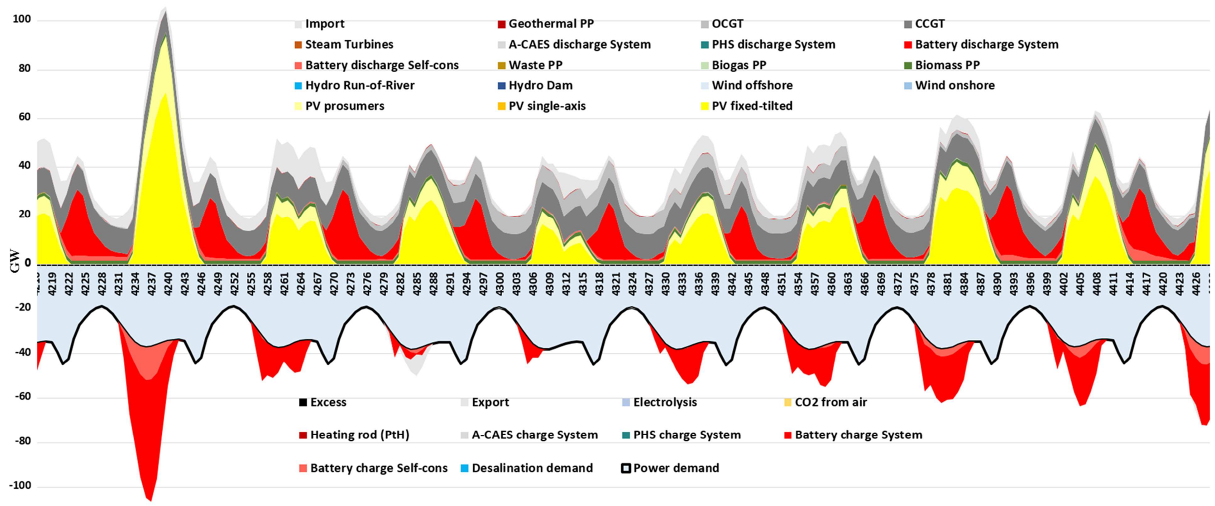


Figure 13: Hourly dispatch of electricity in a monsoon week in the Dhaka region for the BPS scenario in 2050. The x-axis represents a particular hour in a year and the y-axis represents the capacity.

The monsoon affects electricity generation from solar and as a result batteries cannot provide electricity for the night time demand. The additional demand is met by PtG process utilising the combined gas turbines to produce electricity from synthetic natural gas. Additionally, at some hours, electricity is imported from neighbouring connected regions of Rangpur and Rajshahi to satisfy the demand as observed from Supplementary Material Figure S6. In the period of low solar radiation, gas turbines and electricity transfer among sub-regions power the fully renewable energy system in Bangladesh.

4.6 Annual CO_2 emissions in the transition period

The annual net CO_2 emissions of the four scenarios in the transition period is illustrated in Figure 14. The direct CO_2 emissions released to the atmosphere are considered in this study. Particulate matter (PM) and other GHG emissions such as methane, nitrous oxide, ozone, chlorofluorocarbons and hydrofluorocarbons are not considered. It can be inferred that proportional reduction is possible for other greenhouse gases and PM in the transition years for the BPS scenarios.

The two BPS scenarios follow the same path until 2030, but after 2030 the additional constraint of GHG emissions costs causes the BPS scenario to incorporate more RE in order to reduce the GHG emissions to zero in 2050. The remaining GHG emissions in 2050 for the BPS-NCC is due to the utilisation of fossil gas. The BPS scenarios show a slight increase in GHG emissions in 2025 due to the peak consumption of fossil gas in power generation, as the solar PV and battery hybrid are not cost competitive yet. It should be noted that, GHG emissions cost increases during the transition years from 9 €/t_{CO2eq} in 2015 to 150 €/t_{CO2eq} in 2050.

On the contrary, with same starting point in 2015, emissions related to the CPS scenarios follow an upward trend due to negligible RE generation capacity in the transition years. The installation of coal and fossil gas based power plants release more and more GHG emissions into the atmosphere as the share of these technologies rises. The GHG emissions increase to 94.5 Mt_{CO2eq} in 2030 and after that increase linearly to 256 Mt_{CO2eq}, as the generation from fossil fuels increases considerably. The GHG emissions grow to 981% by 2050 in comparison to the emissions in 2015.

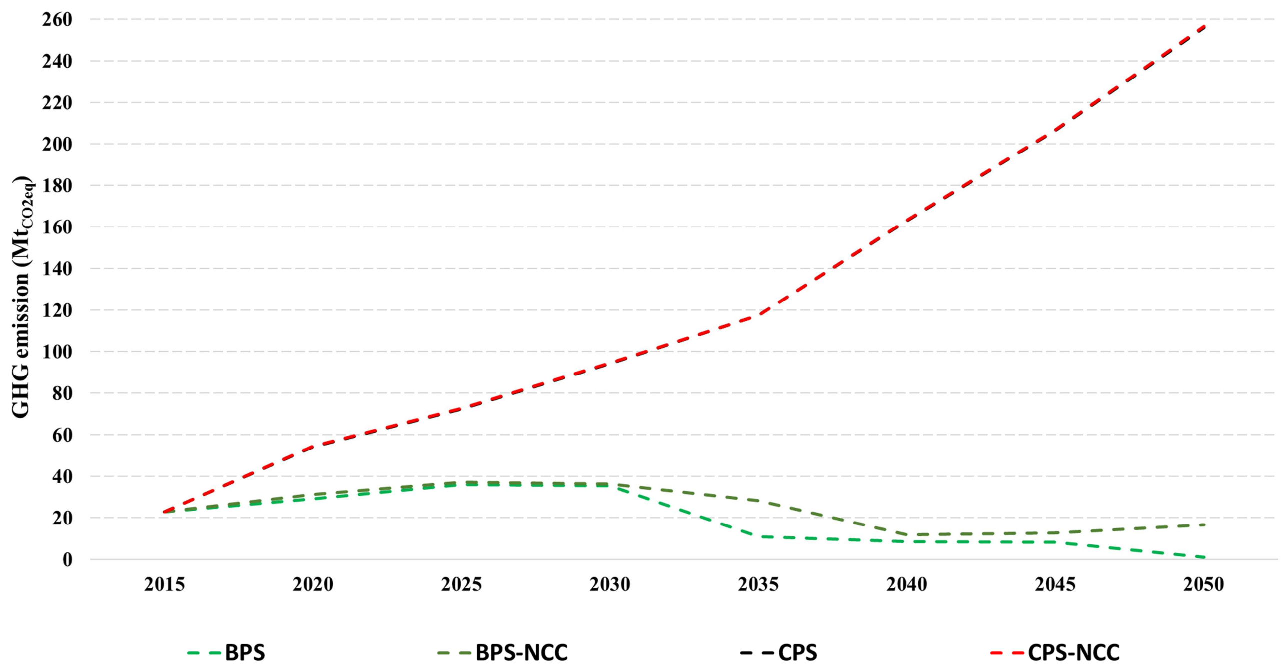


Figure 14: GHG emission in the transition years from 2015 to 2050 for all the scenarios.

5. Discussion

This study presents various energy transition pathways for Bangladesh. The BPS scenarios, which are compatible with the Paris Agreement, lead to a least cost energy system in 2050 and are the best options for expanding the current energy system. Additionally, these scenarios avoid the risk of increase in GHG emissions and the likelihood for stranded investments in fossil fuel based capacities. On the contrary, it was shown that the government's plan emphasises on the most polluting and expensive options. Consequently, its present policies are a serious national risk that exposes it to several vulnerabilities, such as high costs of electricity, energy insecurity, and poor political trust. Similar risks were also reported in Solomon et al. [6]. However, the level of risk for Bangladesh appears to be much higher and more complicated due to its burgeoning population.

The first risk relates to domestically available resources. Domestically available natural gas will be exhausted around 2031, at the current rate of extraction [96]. On the other hand, government plans to install around 7 GW of coal capacities by 2020 and even more in the later years. With the coal capacity being at 0.2 GW in 2015, building new capacities would require huge mobilisation of all resources. Currently, no new coal power plants have been constructed. This is on top of the risks associated with the planned nuclear power plants, which have the associated high costs and other safety and environmental risks [97], [98]. With these policies, Bangladesh not only imports the technology, but faces the need for an increased volume of fossil and nuclear fuels to be imported. The volatility of global fuel prices also makes the dependence on imported fossil fuels a high risk strategy. This compounds into a significant national risk in terms of trade and energy security. On the other hand, investing in locally available abundant renewable energy resources such as solar PV will not only decrease the GHG emissions, but also provide power to households living on remote islands, where grid extension has been an issue. A combination of centralised and decentralised solar PV systems will help achieve the government's aim to provide electricity to each and every individual in a cost effective way, moving away from expensive diesel generators. With low seasonal variability of solar resource, solar-based power generation is ideal for the demand and supply situation in Bangladesh. However, being one of the most densely populated countries, issues have been raised on the availability of land for huge utility-scale PV installations. The total land area of Bangladesh is 147,570 km^2 [56]. Currently, the land area suitable for agricultural purposes plus the portion covered by forests constitutes 81% of the total land area. Installing 357 GW of ground mounted solar PV (as in the BPS year 2050) would require about 10% of the land area from the remaining portion [56], assuming a PV module efficiency of 30% in 2050 [99] and the method of Bogdanov and Breyer [39], leading to 1.9% of required total land area. Rooftop PV systems are not considered since they can use the available roof area. The upper limit in the model is set to 6% of the total land area that would lead to a potential of about 1130 GW. It should be noted that water bodies, which could provide potential area for floating solar PV systems [100]–[103], cover about 12% of the area in Bangladesh. The government is considering the options to utilise Kaptai and other lakes, dams, beels, etc. which could provide electricity to remote locations [102]. Further, new designs of utility-scale power plants allowing crops to grown with them [103] and the various options of agricultural solar PV systems [105]–[107], can be explored to reduce stress on the land area requirements.

The other risk is related to the associated increase in GHG emissions. Bangladesh is one of the most climate vulnerable countries due to its low-lying areas, despite being a low emitter of GHG emissions per capita. Continuing these emissions trend with the underlying fact will make the government appear reluctant in protecting its citizens both locally and globally, leading to poor political trust.

The electricity sector in Bangladesh is grappling with various issues such as insufficient installed capacities, which are not able to satisfy the growing demand. Frequent blackouts and brown outs have become a daily part of the activities and incur huge losses to the GDP. Additionally, poor operational practices, inefficient technologies and inadequate maintenance add to the issues of the energy sector. These scenarios show that Bangladesh has important alternatives to its present strategy. The results of the BPS scenario show that, transition towards a 100% RE and zero emissions system is financially viable compared to the CPS scenario, due to rapidly declining renewable energy costs. The declining costs of renewables, especially, solar PV in the transition years provides better cost competitive options as shown in both BPS scenarios. Additionally, costs of the BPS scenarios would be even lower if the government's benchmark costs for solar PV is considered from neighbouring India [108]. Bangladesh should utilise the recent cost reductions in solar PV and tap into the growing market with local manufacturing and creating new jobs.

The technological mix, transition trends and typical RE future observed in these scenarios are also common to several other studies that investigate the case for other geographic regions [6], [29], [31]. Especially, recent studies on countries in the SAARC region, India [29] and Pakistan [31] grappling with similar issues as Bangladesh, show that a fully renewable energy future is possible with solar PV and batteries forming the backbone of the energy supply with cost competitive electricity generation. With monsoon playing a big part in this region, the electricity system in India manages to overcome the decrease in solar PV with increase in generation from wind and hydropower plants, in addition to utilising the transmission line connections for electricity exchange between different regions in India [29], [109]. However, with limited availability of good wind conditions and hydropower, Bangladesh overcomes the decrease in solar PV output via increase in electricity production from synthetic natural gas storage via CCGT and OCGT turbines. This is a unique case for a country in the Sun Belt region and having a high share of solar PV in the system [20] and this presents a case for regions that will be highly dependent on solar PV, with no other resources to complement the decrease in solar electricity production. Gas storage will be an important technology in a fully renewable energy system. For Bangladesh, already existing infrastructure of gas turbines can be utilised with a fuel switch, i.e utilising synthetic natural gas in place of fossil gas.

The stability and reliability of a fully renewable energy system on an hourly basis is provided by renewable technologies (mainly solar PV), batteries, the Power-to-Gas process and gas turbines utilising synthetic gas. Interaction of the above mentioned technologies can be observed from Figure 12 and 13, showing the shifting of daily electricity by batteries to the night hours and when there is no electricity available from the batteries, the stored synthetic gas is utilised by gas turbines to produce electricity. Additionally, ancillary services are needed to stabilise and secure the electricity system, which are provided by conventional generators today. However, in a 100% RE-based system, synchronous condensers also called synchronous compensators, could provide all the ancillary services of conventional generators like fault current, inertia and voltage support, while active power can be provided by renewable generators and storage technologies [35]. According to Oyewo et al. [110], synthetic inertia provided by renewable technologies and batteries is extremely important for the stability of 100% RE systems. Additional flexibility options such as grid integration between countries would provide flexibility and stability to the power system in Bangladesh [30], [111].

However, to implement the BPS scenario, Bangladesh needs to have appropriate policies, institutions and public awareness. Development of the Sustainable and Renewable Energy Development Authority (SREDA) in 2014 was a step in the right direction, but this organisation has to be developed and strengthened. One way to do this may be to collaborate with neighbouring countries that are leading in renewable energy development. For example, India, which has a similar energy situation as Bangladesh has improved the growth of installed capacities of renewables with the establishment of an exclusive ministry for renewables. This together with its experience in successful implementation of solar home systems (SHS) deployment programme to electrify its rural population [112], Bangladesh could lead to a quick jump in prosumer and utility-scale PV. It is acknowledged that barriers do exist towards embracing renewables and moving away from the current fossil fuel mix. However, these barriers can be overcome by creating innovative policies by the government. Innovative financing mechanisms can be adopted from other countries that have a similar situation and are leading in large-scale RE deployment and adopted to local conditions. The government should encourage local manufacturing of renewable energy systems in order to reduce technology import costs and create new employment opportunities [113].

6. Limitations of this study and future research needs

This study tries to showcase techno-economic optimisation of the Bangladesh energy system through various scenarios, however, future policy decisions will be based on various other factors. So, the conclusion and findings of this study should not be seen as prediction of the future but rather one of the various ways to achieve the common goal of zero GHG emissions. We directly assume the electrification of the currently un-electrified population through being connected with the grid, however the growth in electrification will follow a different pathway. This is the next research focus to integrate rural electrification into the national energy transition modelling.

The assumptions concerning various parameters used in this study shape the results of the various scenarios. Sensitivity analysis of the input parameters will alter the results but not drastically, however this is recommended as future work. Higher spatial resolution of the data will provide more detailed insights and will better describe the regional variability. The results showcase only the power sector transition, however, addition of other sectors such as transport and industry will have a major impact on the results.

7. Conclusion

In this study, two scenarios (namely CPS) selected based on the government's policy direction and (BPS) created to study the possibility of achieving high RE shares in the future were devised to analyse the energy transition pathways for Bangladesh. One of the Current Policy and the Best Policy scenarios involved a scenario with GHG emissions pricing. The key findings of the study are given below:

A 100% RE-based power system is possible for Bangladesh by 2050 with the costs of electricity lower than in 2015 for the BPS scenarios. However, policy approach from the government increases GHG emissions and electricity costs considerably in future years. This implies that Bangladesh needs to exploit indigenous renewable energy resources. It was observed that application of GHG emissions costs on the BPS scenario accelerates the transition towards zero emissions system, however, removing GHG emissions costs, does not drastically alter the capacity mix and generation by 2050. It was observed that the electricity generation was based on 94% renewables and the remaining was fossil gas. If the system was allowed to run until 2060-2070 with additional investments, the system would be fully based on renewables. So, Bangladesh can think about the transition scenario even without enforcing GHG emissions costs, but based on a least cost pathway.

In the BPS scenarios, RE technologies produce enough electricity to cover the total electricity demand by 2050. The share of storage technologies, especially batteries increases simultaneously as the shares of renewables increases in the system, without increasing cost of the system. Solar PV and batteries dominate the installed RE technologies due to their low costs and the excellent solar resource conditions in Bangladesh. The fast declining costs of solar PV and batteries force the system to phase out fossil fuels including nuclear energy. Additionally, there is available land area for PV installations, along with new technologies such as floating PV and efficiency improvements in PV technology, utilising the huge resource potential would be beneficial for Bangladesh.

Overall, this study shows that Bangladesh entails serious national risks that lead to several vulnerabilities such as high costs of electricity, energy insecurity, and poor political trust due to its present policy direction. Similar risks were also observed for other developing countries. However, the level of risk for Bangladesh appears to be much higher and complicated. This study shows that RE solves the trilemma of security, reliability and cost effectiveness of energy services, which are hampering the growth of Bangladesh.

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Supplementary Material

Supplementary data associated with this article can be found at:

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Appendix A

Table A.1: Technical and financial assumptions of all energy system components used in the energy transition from 2015 to 2050 for Bangladesh. Assumptions are taken from Pleßmann et al. [114] and European Commission [115] and further references are individually mentioned.

Name of component			**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Reference**
PV rooftop - residential	Capex	€/kWp	1360	1169	966	826	725	650	589	537	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kWp	1360	907	737	623	542	484	437	397	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kWp	1360	682	548	459	397	353	318	289	[78]
	Opex fix	€/(kWp a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally fixed-tilted	Capex	€/kWp	1000	580	466	390	337	300	270	246	[78]
	Opex fix	€/(kWp a)	15	13,2	11,8	10,6	9,6	8,8	8,0	7,4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kWp	1150	638	513	429	371	330	297	271	[78], [116]
	Opex fix	€/(kWp a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW	1250	1150	1060	1000	965	940	915	900	[117]
	Opex fix	€/(kW a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/m^2	270	240	220	200	180	170	150	140	[118], [119]
	Opex fix	%	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	
	Opex var	-	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW	5250	4970	4720	4470	4245	4020	3815	3610	[115], [120]
	Opex fix	€/(kW a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	

	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW	800	685	500	380	340	310	280	260	[121], [122]
	Opex fix	€/(kW a)	32	27	20	15	14	12	11	10	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW	492	421	310	234	208	190	172	160	[121], [124]
	Opex fix	€/(kW a)	10	8	6	5	4	4	3	3	
	Opex var	€/(kWh)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	
CO_2 direct air capture	Capex	€/kW	749	641	470	356	314	286	258	240	
	Opex fix	€/(kW a)	29.9	25.6	18.8	14.2	12.6	11.4	10.3	9.6	
	Opex var	€/(kWh)	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
	Lifetime	years	30	30	30	30	30	30	30	30	
CCGT	Capex	€/(kW_{el})	775	775	775	775	775	775	775	775	[123]
	Opex fix	€/(kW_{el} a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW_{el})	475	475	475	475	475	475	475	475	[123]
	Opex fix	€/(kW_{el} a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW_{el})	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW_{el} a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30	30	30	30	
Steam turbine (coal-fired PP)	Capex	€/(kW_{el})	1500	1500	1500	1500	1500	1500	1500	1500	[123], [124]
	Opex fix	€/(kW_{el} a)	20	20	20	20	20	20	20	20	
	Opex var		0	0	0	0	0	0	0	0	
	Efficiency	%	45	45	45	45	46	46	47	47	
	Lifetime	years	40	40	40	40	40	40	40	40	
Nuclear PP	Capex	€/(kW_{el})	6210	6003	6003	5658	5658	5244	5244	5175	[115], [125], [126],
	Opex fix	€/(kW a)	162	157	157	137	137	116	116	109	

	Opex var	€/(kWh,el)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	[127]
	Efficiency	%	37	37	37	38	38	38	38	38	
	Lifetime	years	40	40	40	40	40	40	40	40	
Biomass CHP	Capex	€/kW	3400	2900	2700	2500	2300	2200	2100	2000	
	Opex fix	€/(kW a)	238	203	189	175	161	154	147	140	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	36	37	40	43	45	47	47.5	48	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas CHP	Capex	€/kW	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	35	36	39	42	44	46	46	47	
	Lifetime	years	30	30	30	30	30	30	30	30	
Waste incinerator	Capex	€/kW	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/(kWh)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	29.5	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW	340	290	270	250	230	220	210	200	
	Opex fix	€/(kW a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	[128]
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWhel)	600	300	200	150	120	100	85	75	
	Opex fix	€/(kWhel a)	24	12	8	6	4.8	4	3.4	3	
	Opex var	€/(kWhthroughput)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	[129]
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	

Adiabatic compressed air energy storage (A-CAES)	Capex	€/kWh	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	
	Opex var	€/(kWh)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh_{th}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table A.2: Energy to power ratio and self-discharge rates for storage technologies

Technology	Energy /Power Ratio (hrs)	Self-Discharge [%]	References
Battery	6	0	[114]
PHES	8	0	[114], [115]
A-CAES	100	0.1	[115]
TES	8	0.2	[114]
Gas storage	80·24	0	[114]

Highlights

- Current energy policy of Bangladesh leads to higher power cost and GHG emissions
- Best policy scenarios are the least cost by 2050 for Bangladesh
- GHG emissions cost expedite transition towards 100% renewable energy system by 2050
- Without GHG emissions cost the energy generation is still 94% renewable in 2050
- Solar energy and batteries form the backbone of a fully renewable energy system

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: