ENERGY TRANSITION PATHWAY TOWARDS LARGE SHARE OF RENEWABLE ENERGY IN THE POWER, HEAT AND TRANSPORT SECTORS FOR BANGLADESH

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ABSTRACT

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Bangladesh is one of the fastest developing countries with 166 million people residing in an area of 147,570 km^2 with the population expected to grow to about 237 million by 2045. Consequently, the demand for energy will grow enormously with rising population and increasing purchasing power. On the other hand, it is a country which is extremely vulnerable to the devastating impacts of climate change like the rising sea level and irregular monsoons. Currently, Bangladesh depends on domestic and imported fossil fuels to satisfy its energy needs. However, it has an enormous potential of renewable energy, especially solar energy. More than 95% renewable energy share by

2045, is possible in the energy sector as shown by this research. This is possible by utilizing indigenous renewable energy available in Bangladesh, making it completely independent of energy imports, and having universal access to energy. The LUT Energy System Transition Model is used to simulate a pathway towards large of share of renewable energy in 5-year time steps from 2020 to 2045. By 2045, the share of renewables in the entire energy system reaches about 99%, with the majority of generation from solar PV. The levelised cost of electricity first peaks in 2025 to about 88 €/MWh, then starts decreasing and 2045 it drops to 36 €/MWh. The price on GHG emissions accelerates the energy transition, however cost competitiveness of renewables forces a decline in fossil fuel usage in the energy system. Solar photovoltaics with a share of 99% plays a key role in 2045. As a result, GHG emissions decrease from a peak of 126 $MtCO_{2eq}$ in 2030 to 18 $MtCO_{2eq}$ in 2045. An energy transition to a sustainable and secure energy system for all by 2045 is both technically possible and economically feasible.

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Lappeenranta, 11 October 2021.
Md Masuduzzaman

Abbreviations

FHL	Full Load Hours
GHG	Greenhouse Gases
LCOE	Levelised Cost of Electricity
GOB	Government of Bangladesh
BERC	Bangladesh Energy Regulatory Commission
BREB	Bangladesh Rural Electrification Board
SHS	Solar Home Systems
SMG	Solar Mini Grids
IDCOL	Infrastructure Development Company Limited
LUT	Lappeenranta-Lahti University of technology
LDV	Light Duty vehicles
MDV	Medium Duty Vehicles
HDV	Heavy Duty Vehicles
HVAC	High Voltage Alternating Current
WACC	Weighted Average Cost of Capital
SMG	Solar Mini grids
SIP	Solar Irrigation Pumps
NEM	Net Energy Metering
SREDA	Sustainable and Renewable Energy Development Authority
CAPEXt	Capital Expenditure of a Technology

$OPEXfix_{,t}$	Fixed Operational Expenditures for a Technology
$OPEXvar_{,t}$	Variable Operational Expenditure of a Technology
$instCap_{t,r}$	Installed Capacity of a Technology in a Region
$rampCost_{,t}$	Ramping Cost of a Technology
$Egen_{,t,r}$	Electricity generation of a Technology in a Region
TFEC	Total Final Energy Consumption
WHO	World Health Organisation
MSW	Municipal Solid Waste

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1. Introduction

Bangladesh is a low-lying country in the Ganges Delta that has a tropical climate. About 75% of the nation lies less than ten meters above sea level [1], and the country's boundaries are crisscrossed by more than 700 rivers [2]. As of 2020, around 166 million people reside in an area of 147,570 km^2, making it a country with the highest population density in the world [3]. The population of Bangladesh is equivalent to 2.11% of the total world's population and Bangladesh ranks 8th in the list of the countries by population [4]. The population density is 1265 per km^2 which makes it a highest densely populated country in the world [5]. About, 38.4% of the population lives in the urban area and the rest of the people live in rural areas [6]. The population growth has been declining slowly over the last few years. Currently, the fertility rate is 2.1 which is significantly lower, compared to two decades ago when it had been 4.1 [3]. Bangladesh has a very young population, with 34% of the population aged 15 and younger [3]. Bangladesh is a developing country with per capita gross domestic production (GDP) of 1719 € and a sustained GDP growth rate of 6-8% since 2010 [7]. Consequently, this historical growth in GDP has given rise to energy demand and together are often related to improving living standards and maintaining economic activity. The electricity demand increased at an annual growth rate of 9.7%, according to the Asian Development Bank [8].

Global warming is the main cause of rising sea levels, resulting in melting of glaciers and ice sheets and increasing the water level in the ocean and the volume of seawater is expanding day by day. Geographically, Bangladesh has many rivers that flow through the heart of the country and the climate is subtropical which means heavy rainfall in monsoon season, resulting in typhoon, flood, land degradation that are a common natural phenomena that makes the country more vulnerable to climate change [9]. It is one of the most vulnerable countries when it comes to the prospect of rising sea levels, with extreme consequences on its low-lying coastal districts. According to Islam and Amstel [10], one-fifth of the country will be submerged if the sea level rises by 1m, resulting in significant increase in climate change refugees in the next decades and displacing millions of people from their place of residence. Air pollution is an acute problem in recent years because of unplanned industries, relying heavily on fossil fuels, two-stroke engines and diesel-run vehicles, brick kilns, biomass burning, new construction and the fossil use in the power sector. Furthermore, the quantity of particulate matter has been steadily growing since 2010, and approximately 173,000 people die each year [11]. While Bangladesh emits less than 0.35% of global greenhouse gases, it has recently taken steps to support climate change initiatives. Bangladesh can become a forerunner in climate change strategy and action by adopting a budgetary framework that prioritizes adaption investments. New environmental guidelines encourage green financing, green banking, and dedicated money for the renewables. Bangladesh actively seeks international grant funding, especially through the Green Climate Fund. The Government of Bangladesh also introduced an energy strategy shifting gradually fossil fuel-based energy to renewable energy [12].

1.1 Research Objective

The objective of this thesis is to show that an energy transition pathway towards a large share of renewable energy in the power, heat and transport sector is technically possible and economically feasible. The major goal of this thesis is to show that an energy with 100% renewables is technically possible and economically feasible with a least cost and zero GHG emission at the end of the transition period.

1.2 Renewable Energy Trends

Renewable energy has seen remarkable growth in terms of capacity additions over the last decade, and yearly growth has been outpacing expectations every year. Renewable energy sources accounted for 17.1% of the total final energy consumption (TFEC) energy mix in 2017. Over the past decade, the proportion of renewable energy in total final energy consumption (TFEC) excluding traditional biomass uses, increased by 2.5% [13].

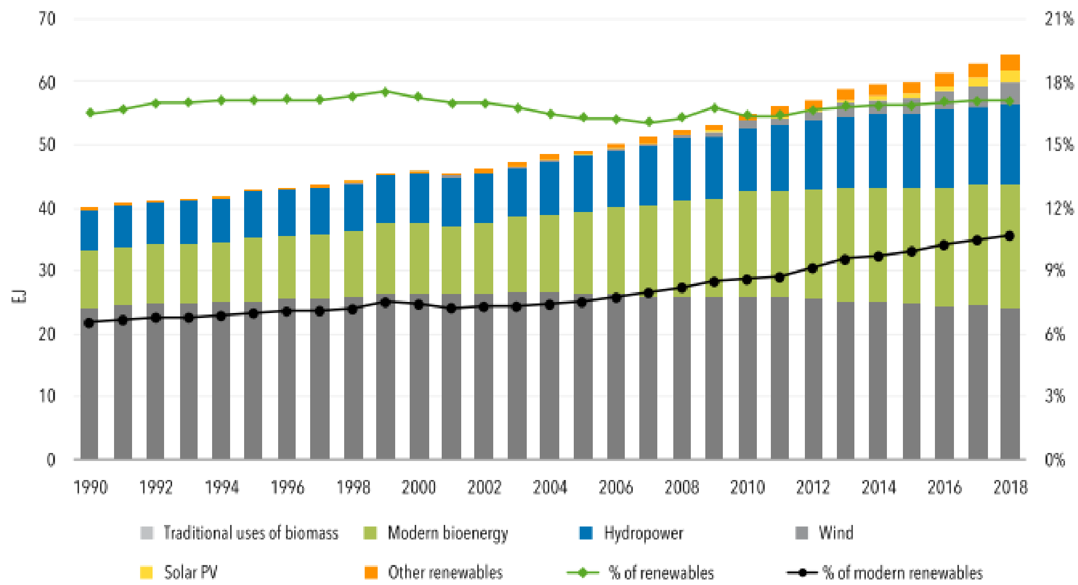

Figure 1: Global renewable energy contribution to overall energy consumption [13].

The expansion of wind and solar PV in the recent decade was the most significant of any technology, increasing the usage of modern renewable energy by over a third. Bioenergy, including traditional uses of biomass, currently accounts for around 70% of global renewable energy consumption, with hydropower, wind, and solar PV the next-largest renewable sources [13].

Renewable energy accounts for the greatest and most dynamic share of final consumption in the electricity generation sector, growing from 24.7% in 2017 to 25.4% in 2018. Nearly half of the world's modern renewable energy consumption is derived from renewable electricity generation, and three-quarters of its year-over-year growth is derived from renewable electricity. In terms of electricity capacity installations, renewables have seen remarkable progress 7.4% in 2018 and 7.9% in 2019. However, traditional fossil fuel electricity generation is much higher compared with renewable resources [13]. Renewable energy sources provide about 22.8% of the energy into the heat sector, the majority of which 13.6 % corresponds to conventional biomass usage [13].

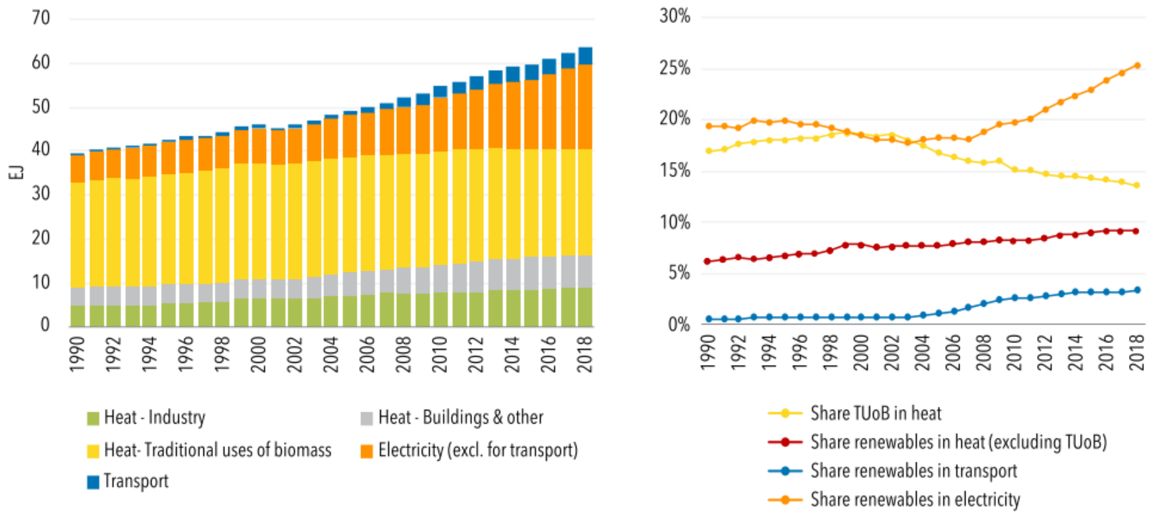

Figure 2: Consumption and proportion of renewable energy by end use sectors, 1990-2018 [14] [15].

As far as transportation is concerned, biofuels account for most of the renewable energy consumption, but in the electrical sector, renewable energy consumption is gradually increasing as electric trains and electric cars gain popularity [14], [15].

From 2010 to 2020, solar and wind energy technologies have had an unprecedented period of cost decrease. Through a combination of targeted policy support and industry push, solar and wind energy have evolved from costly niche technologies to direct competitors with fossil fuels for new capacity installations. Renewables have established themselves as the backbone of the power system, helping to decarbonize electricity generation at a cheaper cost than a business-as-usual future.

A global weighted average levelised cost of electricity (LCOE) for utility-scale solar photovoltaic (PV) installations that commenced operation between 2010 and 2020 declined by 85% from 0.33 €/kWh to 0.049 €/kWh [16]. This occurred because the global cumulative installed capacity of all utility-scale and rooftop solar PV (as of the end of 2010) rose from 42 GW to 714 GW by the end of 2020. Also, residential photovoltaic systems' LCOE decreased significantly over the time period.

The global weighted average cost of electricity for onshore wind projects was expected to fall by 56% over the 2010-2020 time period, from 0.077 €/kWh to 0.034 €/kWh, because of higher capacity factors (from 27% to 36%) and reduced total costs (from 1792 €/kW to 1232 €/kW). From 178 GW to 699 GW of cumulative installed capacity, the overall installed capacity has grown [16], [17].

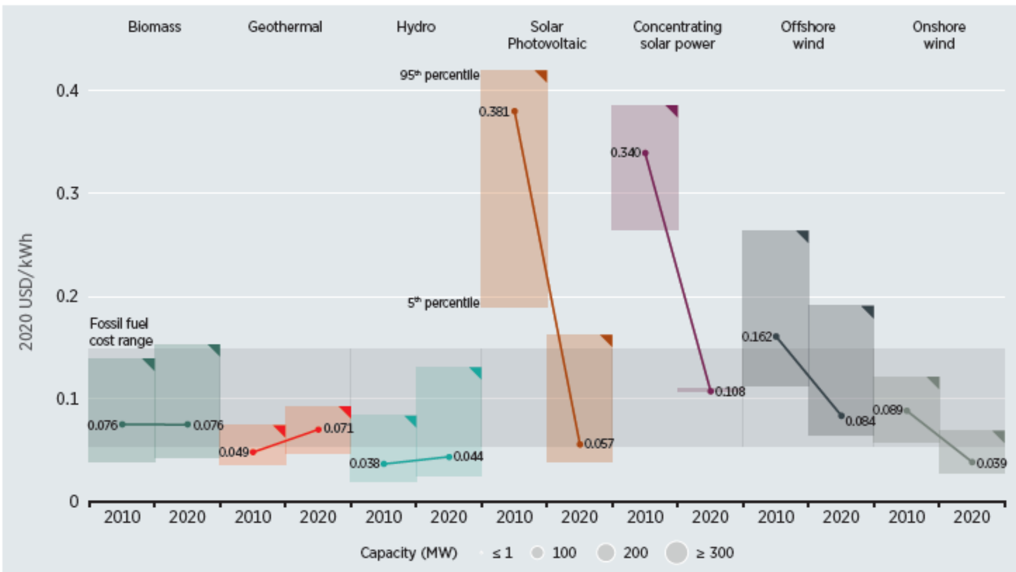

Figure 3: Global LCOEs from newly commissioned utility-scale renewable electricity production technologies [16] [17].

1.3 Barriers to Renewable Energy Investments

Even though renewable energy use is increasing in many countries, significant constraints exist to a rapid increase of renewable energy use. Many barriers have emerged to renewable energy investment, as highlighted by Greenpeace [18]. Some of the barriers are overcome over the time period such as reduce cost of renewable technologies, research and development, lack of information, access of technology etc. However, policy and legal barriers and the access of finance are major obstacle in renewable energy development. In many countries, the government provides subsides on traditional energy sector rather than renewable energy and limited policy reinforcement on renewable sectors [19]. Figure 4 depicts the barriers for renewable energy.

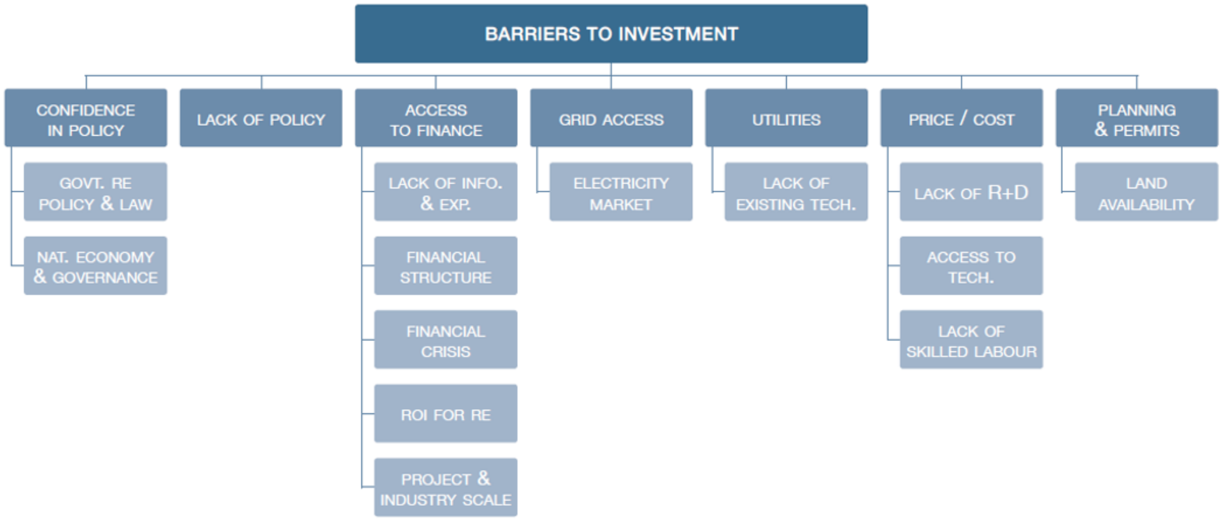

Figure 4: Five major obstacles to renewable investment [18].

Although many countries share broad categories of barriers to renewable energy expansion, the nature of the barriers differs substantially. For new projects, political and regulatory support, grid infrastructure, power markets, and planning restrictions must all be addressed locally. In certain places, policy uncertainty, rather than a lack of policy support measures, is holding back investment. Investors are optimistic that legislation will be kept the same or that renewable energy requirements will be met, let alone increased, in the medium term [18]. It is also difficult for developers in many nations to predict whether or not they will be able to sell all of the electricity generated during the project development phase [20].

1.4 The impact of the COVID-19 on renewable energy development

Beyond acute health implications, the COVID-19 pandemic has impacted economic activity and, thus, energy usage. When it comes to renewable energy development, COVID-19 has a different impact on different end-use sectors. The International Energy Agency predicted that global electricity demand will reduce by 2% in 2020 compared to 2019, but renewable energy will grow by nearly 7% [13] because of long-term contracts, low marginal costs, easy grid access, and constant renewable capacity addition.

This growth more than offset declines in industrial and transportation bioenergy demand. Indeed, reduced economic activity reduced global heat demand by 3%, affecting renewable energy usage (less than 1% decline). Bioenergy and waste utilization in energy-intensive enterprises such as paper and pulp and cement dropped as commercial, industrial, and residential activity fell [13].

Transport biofuel is the most exhausting renewable energy source, with utilization anticipated to reduce by 8% in 2020. Biofuel output has fallen for the first time in two decades due to lower transportation fuel demand and cheaper fossil fuel costs with other additional factors like low energy efficiency, loss of biodiversity and destruction of rain forests in many countries. The ethanol production in the US and Brazil, as well as biodiesel in Europe, has declined significantly [13].

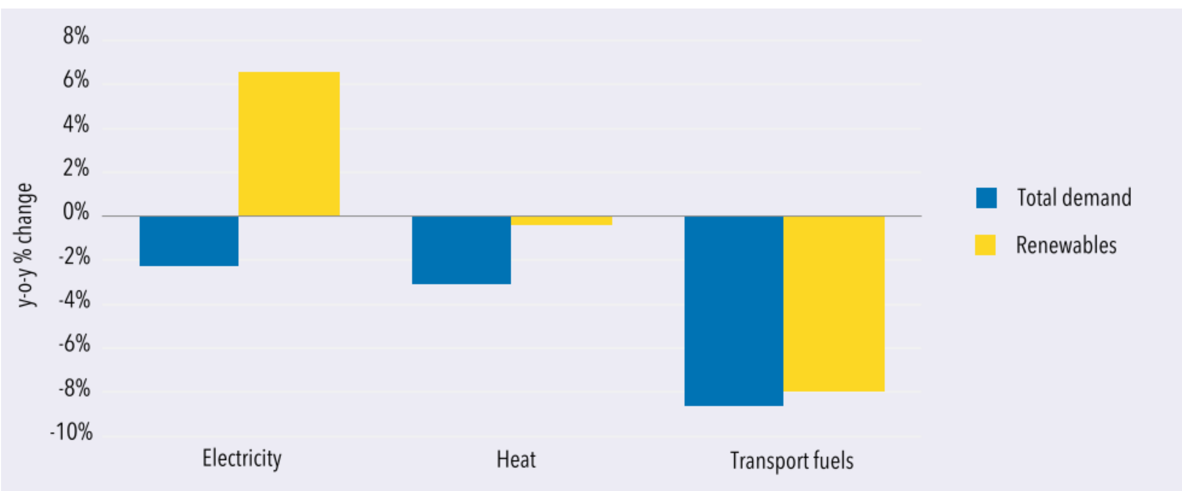

Figure 5: Energy demand and renewable energy production in electricity, heat, and transportation, 2019-2020 [13].

In general, these variables increased renewable energy's share of electricity generation, but not heat or transportation, while overall renewable energy consumption climbed by 1% in 2020 [13].

1.5 Current Energy Situation in Bangladesh

Energy demands are rising as a result of industrialization, economic growth, and technological progress [21]. Furthermore, the current status of fossil fuel-based energy exploration, utilization and discovered energy will be consumed within the next few decades. Energy is said to be a vital component in our existence [20], [23]. Government of Bangladesh has set a goal of becoming a developed country by 2041. For an economy to grow, electricity has to be available to everyone. Recognizing this, the government established a goal of providing uninterrupted and reliable electricity to everyone at a reasonable cost. As a result, the government has launched immediate, short-term, medium-term, and long-term plans and initiatives to improve generation, transmission, and distribution. To promote a favourable business environment for the private sector, changes in policy, legislation and regulatory framework have been undertaken for the renewable energy sector. Around 96% of the population (including electricity generation from off-grid system) has access to electricity, with per capita generation of 510 kWh. In Bangladesh, the need for electricity is steadily increasing, due to increasing population and economic activity.

In Bangladesh, road travel is the most common means of transportation. From 2010 to 2018, The number of registered trucks are 135,081, buses are 44,374, cares are 335,660, tankers are 4939, tractor are 40,867, taxicab are 45,231, delivery vans are 27,936, cargo vans are 8830, covered vans are 27,936, ambulances are 5299, minibuses are 27,962, microbuses are 98,175, auto rickshaws are 249,091, auto tempos are 249,091, human haulers are 17,516, motor cycles are 2,145,659, jeeps are 54,437, pickups are 105,159, special purpose vehicles are 9606, and others are 16,522. So, in total there are 3,419,884 numbers of registered vehicles with a carrying capacity of 3–30 tons are employed to transport all types of commodities [24]. It is no surprise that the transport sector is the largest consumer of liquid fossil fuels with a share of 50.26% [25].

Inland waterways are the second most often used means of travel in Bangladesh. The country operates around 14,000 cargo vessels, which include dry-cargo vessels, barges, tankers, and double-bottom vessels that are mostly used to transport petroleum products. Also, around 261,000 of country boats (small types of traditional boat made by wood) are used as cargo. However, it is quite difficult to quantify the importance of those boats [26].

There is only one rail transit provider in Bangladesh, and that is Bangladesh Railways. Major activities include the transportation of bulk commodities throughout Bangladesh and containers from Chattogram Port to Kamalpur Container Depot in the Dhaka region, where it operates inland container depots [27].

There are three international airports in Bangladesh (in Dhaka, Chattogram, and Jessore). For air cargo, only the Dhaka airport is used. Ready-made clothing, machinery, electronics, frozen food, and pharmaceutical products are the key export-import businesses that use air transportation [27].

Indigenous natural gas, coal, imported oil, liquefied petroleum gas (LPG), imported liquefied natural gas (LNG), imported electricity, and hydro-electricity are all known commercial energy resources in Bangladesh. Oil imported from other countries makes up the lion share of the rest. In 2019, around 8.6 million metric tons of crude and refined petroleum products were imported from other countries [25]. Besides natural gas and crude oil, coal is the primary fuel source for brickfields and thermal power plants.

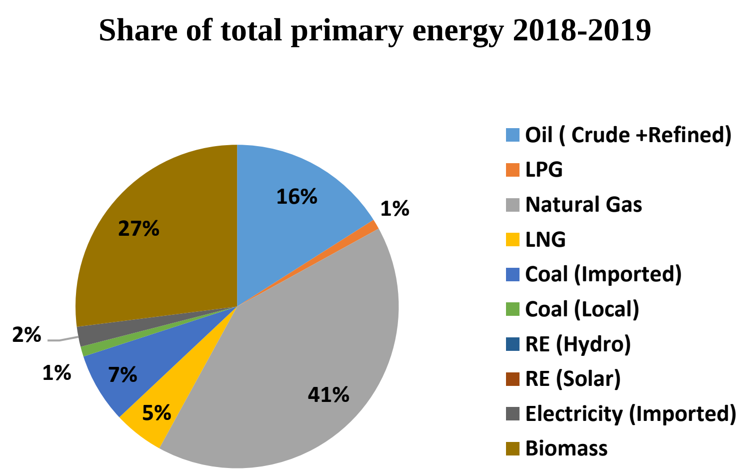

Figure 6: Share various fuels in the overall primary energy supply in 2018-19 [27].

1.6 Bangladesh Power Sector Overview

Grid-based installed capacity, including 9.5 GW in the public sector and 8.3 GW in the private sector and there were 1.7 GW of grid-based electricity trading from India, in total was about 19 GW in FY 2018-19 [28]. In February 2020, 19.6 GW of grid-based installed capacity (i.e. installed capacity plus grid imports) include 9.7 GW in the public sector, 8.7 GW in the private sector, and 1.7 GW coming from India [29]. Considering captive and renewable energy, the total installed capacity of approximately 22.78 GW in Bangladesh [30][31]. The peak hour generation capacity was 12.89 GW until (29 May 2019) [32].

Figure 7 mentioned the share of installed capacity by fuel type and energy generation by fuel wise. During the 2018-19 fiscal year, public and private sector power plants generated a total of 70.5 GWh of net energy, compared to 62.8 GWh in 2017-18 [28]. The maximum generation thus far has been 12.9 GW (29 May 2019). A total of 12,119 circuit kilometres of transmission lines and approximately 560,000 kilometres of distribution lines with essential infrastructure have been built as of February 2020 [30].

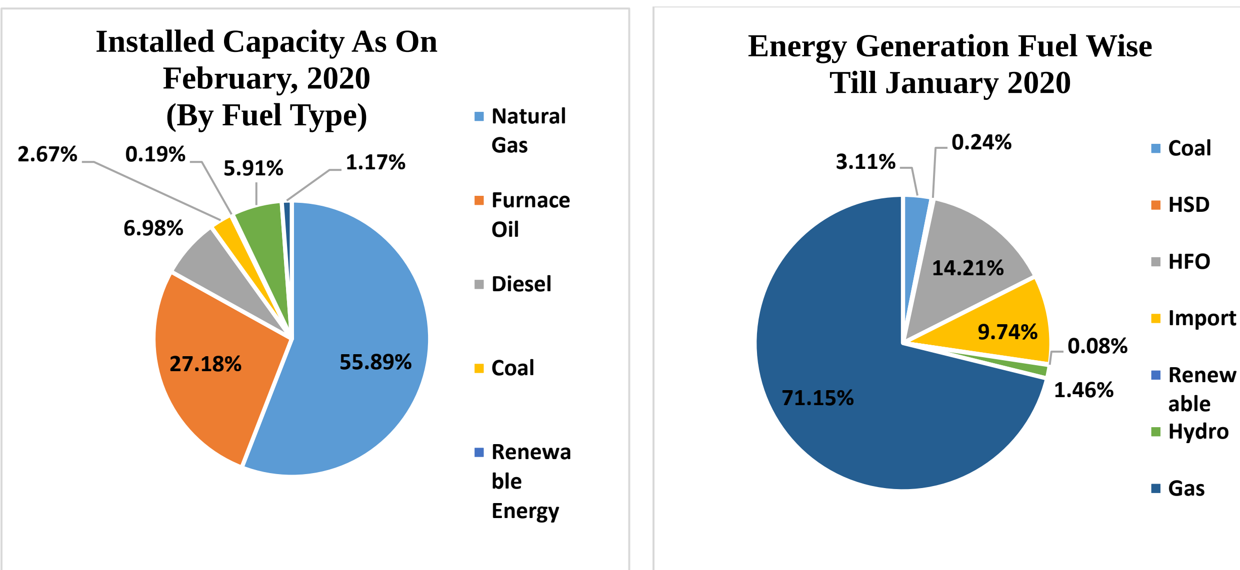

Figure 7: Share of installed capacity (left) and energy generation by fuel type (right) [29].

In order to meet the increased demand for power and to provide electricity for all by 2021, a generation expansion plan has been put in place. Currently, the generation plan is built around the usage of coal, imported electricity from neighboring countries, natural gas and nuclear power plants. Liquefied natural gas (LNG) and furnace oil is supplied to fulfil the peak hour demand. The master plan for the country's electrical grid has been established by the government in 2016.

According to the Master Plan, power generation capacity will be 24,000 MW by 2021, 40,000 MW by 2030, and 60,000 MW by 2041 [33].

Table 1: Power Generation Master Plan [33].

	2020	2021	2030	2041
Power generation capacity (MW)	22,787*	24,000	40,000	60,000
Electricity Demand (MW)	14,800	19,000	33,000	52,000
Transmission line (Ckt. km)	12,119	12,000	27,300	34,850
Grid substation capacity (MVA)	44,340	46,450	1,20,000	2,61,000
Distribution line (km)	5,60,000	5,15,000	5,26,000	5,30,000
Power generation per capacity (kWh)	510	700	815	1475
Access to electricity	96%	100%	100%	100%

*with captive & RE

After the independence in 1971, having an electrical connection did not always guarantee access to power, especially in remote areas. Frequent, brownouts and blackouts occur because of supply constraints, prompting mass protests against Bangladesh rural electrification board (BREB). Bangladesh has expanded its generation capacity, which has resulted in a considerable reduction in load-shedding. By June 2020, the total power generating capacity was 23.548 GW, with 1.16 GW of imports [29]. Due to policymakers' efforts, public sector expenditures, private sector involvement, and foreign development partners' assistance, power generating capacity increased dramatically from 16 GW in 2018. In the next five years, generation capacity is anticipated to quadruple. In 2020, per capita, electricity usage was 510 kWh, up from 375 kWh in 2014. By 2020, 97% of the country had access to electricity [34].

1.7 Energy Policies in Bangladesh

On March 13, 2003, the Government of Bangladesh (GOB) passed a law creating the Bangladesh Energy Regulatory Commission (BERC). Electricity, gas, and petroleum products are all regulated by the BERC. The responsibilities include:

- issuance, cancellation, amendment, and determination of license conditions and exemptions;
- ensuring efficient use, quality services;
- establishing tariffs and enhancing the safety of energy generation and transmission, marketing, supply, storage, and distribution;
- cooperating with and advising the government, when appropriate, on issues relating to electricity generation, transmission, marketing, supply, distribution, and storage;
- drafting essential laws, rules, and regulations for the establishment of a sustainable energy system;
- compiling and updating an inventory of RE resources and related technologies to build short-medium, and long-term development plans to expand the usage of RE with specified objectives, as well as taking the required measures to put those plans into action;
- putting in place the essential arrangements to attract and promote private investment in the RE sector;
- Taking the required efforts to raise public knowledge and motivation for the use of renewable energy in both the public and private sectors;
- Use renewable energy resources to their full potential and spread renewable energy technology in rural, peri-urban, and urban areas;
- Increase renewable energy contributions to both electricity and heat energy

2. Renewable Energy Resources

2.1 Solar Energy

Bangladesh has huge potential for renewable energy, notably solar energy. The map depicts the solar yield distribution in Bangladesh. Bangladesh receives 1095 - 1460 kWh/(m^2a) of solar radiation and according to [35] it has a potential to generate 380 TWh of electricity, which would require around 10% of Bangladesh's entire land area (excluding area under agricultural and forest cover) [36]. This potential is on conservative side as Bangladesh has much more potential of solar PV generation. According to Gulagi et al. [37], Bangladesh can install 1130 GW of solar PV utilizing 6% of the total land area and generate about 1000 TWh of electricity. In addition to this, floating solar PV and rooftop solar PV van be installed, which will add to the electricity generated from solar PV. This potential is much greater than the annual power demand at the moment and could meet projected electricity demand.

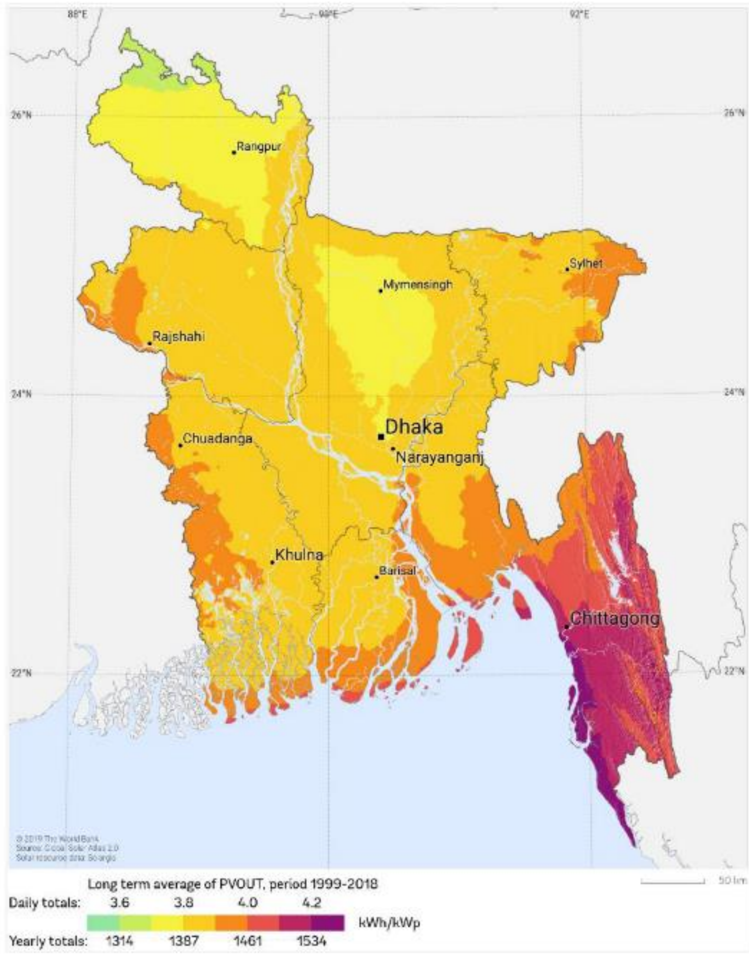

Figure 8: Photovoltaic power potential in Bangladesh [37].

Solar Home Systems (SHSs), Solar Mini-grids (SMGs), Solar Irrigation Pumps (SIPs), Rooftop systems under net energy metering (NEM), Solar drinking water systems, Solar-powered telecom towers, large-scale grid-tied solar PV projects, and other applications including vehicles are a part of solar development initiatives in Bangladesh. In 2017, the first grid-tied solar power project in Bangladesh was put in place in the village of Sharishabari in Jamalpur district. This project was implemented on Independent Power Producer (IPP) basis by Concord Progati Consortium Ltd. and is in operation with 3.28 MW of installed capacity. Through June, 2020, a total capacity of 1.7 GW of 27 large-scale solar IPP projects has been taken up by the Government of Bangladesh (GOB) [38]. In order to fulfil the renewables mandate in 2019, 0.007 GW of solar electricity contributes to the energy mix of utilities. Three large-scale requested grid tied solar IPP projects have also been proposed by the Government of Bangladesh. The independent power producer (IPP) projects will be able to provide power to 0.5 GW, all of which will be placed on land within 200 meters of the 132/33 kV grid sub-station in island areas where the access of electricity is not available such as Boriahat, Rangunia, and Netrokona etc.

The Solar Home System program has begun in 2003 with Infrastructure Development Company Limited’s (IDCOL) involvement. In order to provide power access to the distant and off-grid villages of the country, and to realize the Government of Bangladesh's ambition to achieve universal access to electricity by 2021, the project began with initial grant funding from the World Bank and Global Environment Facility (GEF) with the intention of leveraging those resources. Later, many other development partners including Deutsche Gesellschaft für Internationale, Zusammenarbeit GmbH (GIZ), Japan International Cooperation Agency (JICA), Kreditanstalt für Wiederaufbau (KfW), Asian Development Bank (ADB), Islamic Development Bank (IDB), Global Partnership on Output-Based Aid (GPOBA), United States Agency for International Development (USAID), and several others entered the development alliance. In the eyes of the outside world, this project has proven to be a very effective off-grid electrification program. According to the Bangladeshi, this programme is one of the successful projects in terms of rural area electrification where the extension of national grid line is not possible.

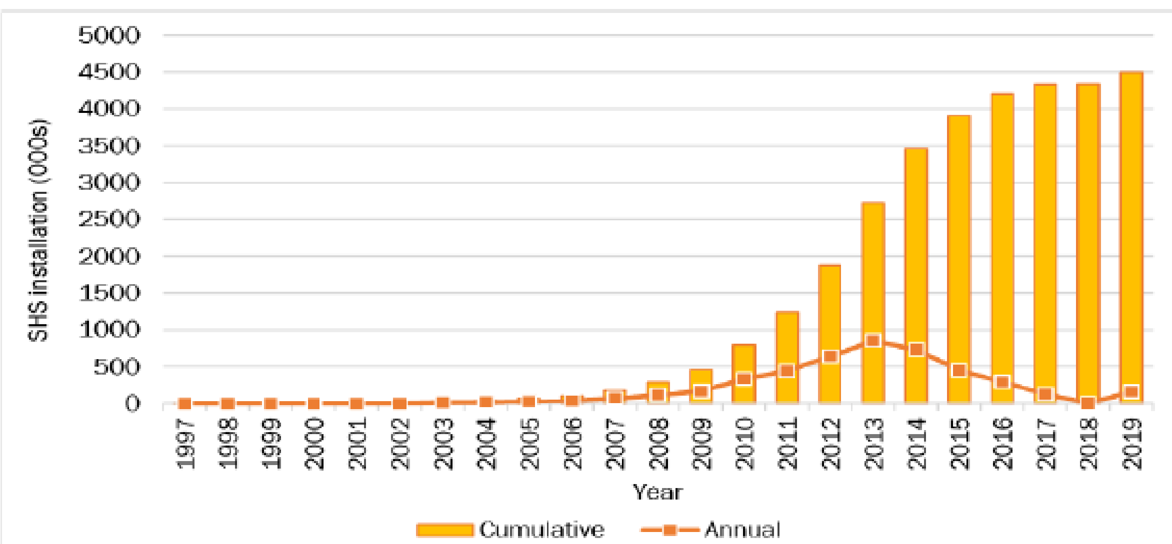

Figure 9: Annual installation of SHSs [39].

Until December 2019, a total of 5,804,225 SHSs had been placed across the country, with over 77% of those deployed through IDCOL's SHSs initiative, which began in 2003. Around 25 million off-grid residents benefitted from the scheme, which has already saved approximately 1.14 million tons of kerosene worth 355 m€ [39].

In order to attract consumers to install solar PV systems on rooftops, integrate with the main grid, and therefore become active prosumers, the Government of Bangladesh (GOB) has issued the Net Metering Guidelines in 2018. Under this policy, public utilities are required to set capacity restrictions for new installations. Recently, private groups and enterprises have shown renewed interest in solar rooftop installations as part of net metering programs. SREDA claims that 16.9 MWp of installed capacity was installed in 1,140 projects that were finished by June 2014 [40].

Table 2: Total renewable energy installed capacity in present-day [39].

Techlology	Off-grid (MWp)	On-grid (MWp)	Total (MWp)
Solar	346.7	185.92	532.62
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.69	0	0.69
Biomass to Electricity	0.4	0	0.4
Total	**349.79**	**416.82**	**766.61**

Floating PV

Only solar PV has achieved recognition in Bangladesh due to its ease of use, affordability and its large potential. However, the drawback of solar PV is that it necessitates a large amount of land for power generation from ground-mounted solar PV, which can range from 0.19 to 0.25 km^2/MW depending on solar irradiation and system performance [41]. However, increasing efficiency of the solar modules has resulted in decreasing area for solar PV installation. Currently, area required is about 0.01 km^2/MW. In a densely populated country like Bangladesh land is premium and space for utility-scale solar power generation is limited due to competing demands of land for agricultural or other purposes. Floating solar PV is a technology advancement that has reduced the load of land requirements [42]. A floating solar photovoltaic system is ideal for installation on still bodies of water such as ponds, lakes, dams, and reservoirs. Floating solar photovoltaic technology has several advantages over its terrestrial counterpart. The most significant benefit is that it takes advantage of unused water surfaces, avoiding direct rivalry with agriculture or other land uses [43], [44]. Second, because of the cooling impact of water beneath the panels, floating solar PV panels have a better power generation efficiency than those mounted on land [43]. The cooler atmosphere also minimizes system stress, increasing its lifespan [43]. Third, floating solar panels can provide shade to the water they float on, reducing evaporation, which is important for water conservation during the dry season [44]. Fourth, floating solar PV is less likely to be shaded and works best in a dust-free environment [43]. Finally, the water required for cleaning is easily available at the source, and the components are less likely to overheat, operating and maintenance expenses are frequently decreased. For the first time in Bangladesh, the Mongla Port Municipality utilized floating solar PV technology to implement a 10 kWp system on the water surface of its water treatment plant reservoir in 2019 [42].

2.2 Wind Energy

With a coastline of almost seven hundred kilometres, several small islands in the Bay of Bengal, and strong south-westerly and north-easterly trade winds during the summer and winter months, the country has one of the world's longest coastlines. Because the wind is generally stronger in coastal areas, offshore islands, along riversides, and other areas with long and powerful wind regimes, the maximum potential of wind energy is 20 GW [45]. To make electricity from wind energy, BPDB installed four 225 kilowatts (kW) grid-connected wind plants, a total of 900 kW, at the Muhuri Dam area of Sonagazi in Feni, and a 1000 kW hybrid wind battery power plant, also referred to as a wind plant was completed in 2008 on Kutubdia Island, which includes 50 wind turbines of 20 kW capacity each [46].

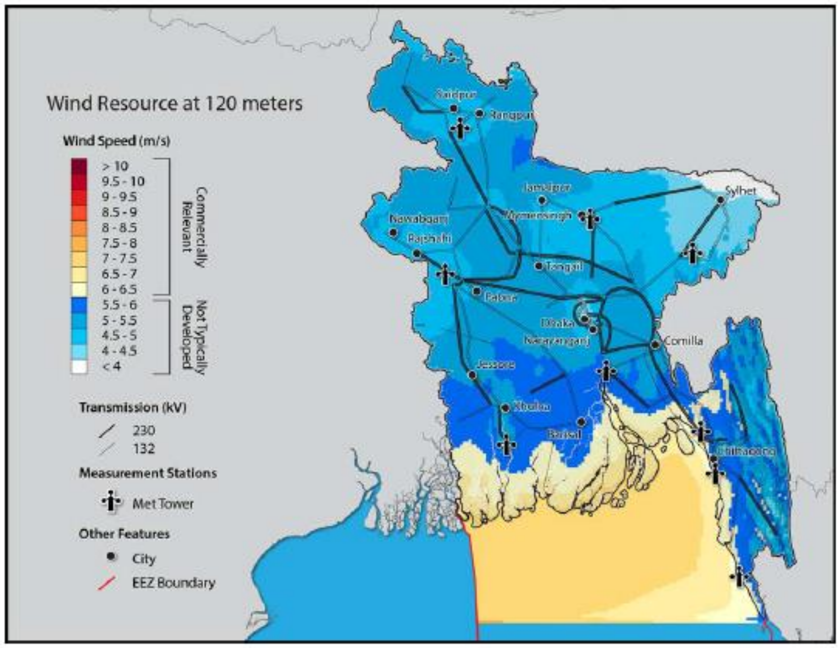

Figure 10: Wind resource map of Bangladesh and measurement locations [45].

2.3 Other renewable energy resources

Due to the flat land surface in Bangladesh, its hydropower resources are minimal. Kaptai Dam, a hydroelectric project on the Karnaphuli River with a capacity of 230 MW, was completed on March 30, 1962. The BPDB operates the plant, which accounts for around 1.46% of the country's total installed capacity for electricity generation in 2020 [5]. Along with generating electricity, the dam was built for irrigation, drainage control, as well as improved forest resource harvesting. The BPDB is proposing expanding Kaptai Dam’s hydropower capacity by 100 MW. The additional energy generation will occur during the rainy season [47]. Hydropower potential actually depends on the monsoon season. During the rainy season, the nine major rivers discharge high flow of water, so the technical potential of hydro energy is about 307 GWh annually. This potential could be vary depending on rainfall and drought [48].

Biomass is a major energy source in many developing countries, particularly in rural areas [49]. Furthermore, biomass is the fourth-largest source of renewable energy in the entire world. Biomass offers a competitive advantage in terms of available resources over other renewable energy sources such as hydropower and wind. Bangladesh is an agrarian economy, with a significant portion of the population involved in land farming, livestock, and poultry-related economic activities. Biomass encompassed all types of organic materials that contain a significant calorific value for cooking, heating, and other necessary activities [50]. On average, Bangladesh produces roughly 35 megaton MT (1 ton = 1000 kg) of paddy each year [51].

Table 3: Total biomass potential in Bangladesh in 2012-2013 [52].

Biomass Sources	Biomass generation (million tons)	Energy content (PJ)	Electricity generation (TWh)	Coal equivalent (million tons)	Gas equivalent (BCM)
Agricultural residues	94.10	582.33	161.80	19.88	14.72
Forest residues	17.44	210.64	58.53	7.19	5.33
Livestock residues	88.89	456.41	126.81	15.58	11.54
MSW	13.38	95.61	26.57	3.26	2.42

Traditionally, biomass has been created in rural regions and utilized for cooking and heating at home. Furthermore, it is used for process heating in both urban areas and select industries. Domestic cooking consumes used more than 80% of all biomass [52]. However, this is mostly used in open cookstoves and is a source of indoor pollution.

Converting biomass into a more energy-efficient fuel is one way to improve rural energy use. Biogas is an excellent fuel for cooking and lighting, as well as for powering a small generator. About 80,000 homes in different villages around the country have biogas plants that are currently operational in Bangladesh. IDCOL has already installed almost 50,000 home biogas systems so there is a real possibility of utilizing basic biogas technology [53].

Municipal solid waste (MSW) is a serious environmental challenge that the country is now experiencing. The country currently has 522 urban centres, which include 311 municipalities and 9 city corporations. Due to increased urbanization and population growth in recent years, a significant amount of solid garbage is generated daily in the country's municipal districts and city corporations. Households, business areas, industries, and hospitals are the primary generators of garbage. The majority of city corporations and municipalities lack a dedicated solid waste management department since solid waste management has been poorly managed up to this point and continues to deteriorate quietly on a daily basis. Landfilling is the most common method of waste disposal in Bangladesh, and it has a detrimental effect on the ecosystem. Currently, various attempts have been done to make use of the huge amount of garbage generated in the country. While reducing negative environmental impacts, the efficient use and generation of energy from this massive volume of MSW will help to fulfil a share of the country's ever-growing electricity demand and reduce methane emissions and pollution due to landfills. The rate of garbage production in urban and rural areas of Bangladesh has been estimated to be 0.41 kg/capita/day in urban areas and 0.15 kg/capita/day in rural areas [5].

2.4 Challenges in Developing Renewable Energy in Bangladesh

- **Scarcity of suitable lands:** Solar parks and mega-grids require large tracts of land. As an agriculture-based economy, GOB protects agricultural areas against solar PV project development. As a result, non-agricultural areas are few, primarily in the north-east, on riverbanks, islands, sand bars, and along the coast. Again, these places are remote from or constrained by the national grid.
- **Land development:** Bangladesh's flat topography makes it prone to floods, and the most ideal area for solar PV projects is around rivers. Most of the land accessible for solar PV installations needs to be backfilled, adding to the project's cost.
- **Weather conditions:** Due to its position, Bangladesh frequently suffers from cyclones in the south. A mounting framework and assembly are required, which adds to the project cost.
- **Dust:** Bangladesh has substantially more dust on solar panels than other countries, resulting in greater O&M costs. As a result, the project O&M budget must be increased, increasing the cost of solar PV electricity.

- **Longer implementation period:** During the monsoon, most of the country's land is submerged, making construction difficult and costly.
- **Insufficient local human resources:** There is a lack of human resources with sufficient technical knowledge of solar PV project development in Bangladesh.
- **Insufficient transmission infrastructure:** The transmission network's capacity constrains the development of large-scale solar photovoltaic installations as well. According to government policy, the majority of eligible land for solar project development is located in Bangladesh's northwestern and southern regions, however transmission line capacity constrains progress on solar project development in those regions. Additionally, for other places, a lack of transmission line capacity is a significant impediment to the development of larger solar photovoltaic (PV) projects.

3. Methodology

The purpose of this study is to examine an all-sector energy transition pathway towards a large share of renewables for the energy system in Bangladesh. The LUT Energy System Transition Model is applied on an hourly temporal resolution at a 5-year interval from 2020 to 2045. On the above-mentioned temporal resolution, an exogenous model for self-generation and consumption of electricity and heat is also simulated. The next sections discuss the model in-depth, including the input data, technical and financial assumptions, and different assumptions and constraints.

3.1 LUT Energy System Transition Model overview

The LUT Energy System Transition Model [54] [55] is a linear optimization tool that simulates a transition of the integrated power, heat, and transportation sectors on an hourly scale for every 5-year time step between 2020 and 2045, under a set of applied constraints. The model specifies an optimal cost structure and operating modes for each of the energy system's technologies to produce the least optimal cost for a particular integrated energy system. The hourly time scale improves the accuracy of the results by accounting for the fact that demand and supply matches for every hour of the year. The optimization goal is to reduce the system's total cost, which is defined as the sum of yearly capital and operational expenses, including ramping costs, for all of the technologies included in the modeling, as shown in Equation 1

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

Abbreviations are for $Egen_{,t,r}$ - electricity generation by a technology *t* and in a region *r*, $rampCost_{,t}$ - ramping cost of each technology, $totRamp_{,t,r}$ - annual total power ramping values for each technology, reg - region, and tech – technology, $CAPEX_t$ - Capital cost of each technology; $crf_{,t}$ - capital recovery factor for each technology, $OPEXfix_{,t}$ - fixed operational cost for each technology, $OPEX_{var,t}$ - variable operational cost each technology, $instCap_{t,r}$ - installed capacity in a region.

Individual residential, commercial, and industrial prosumers can self-generate power and heat by installing rooftop photovoltaic systems and heating technologies. These electricity- or fuel-based heating methods meet the demand for hot water. These prosumers' electrical storage is provided by lithium-ion batteries. These prosumers can acquire electricity during periods of low generation or sell excess electricity to the distribution grid to meet their energy needs. The prosumers' objective is to reduce the cost of electricity and heat utilized. This cost is determined as the annual cost of power, heat, and storage capacity, the cost of fuel required for heating, the cost of energy acquired from the grid, and the profit earned on selling excess electricity to the grid.

The following are some of the key constraints that were utilized in the modeling of the energy system and the prosumers: The first is a prohibition on the construction of new coal, oil, and nuclear power facilities beyond 2020 for sustainability reasons. As a result, power plants that are proposed or under construction after the start period are not included in this analysis. Gas turbines, on the other hand, may be constructed since they can be powered by switching from fossil to synthetic gas or biomethane. Second, no more than 20% of total installed capacity share of renewable power capacities can be increased in any 5-year time step to avoid installing large RE capacity in a single time step, which could cause power system disruption. Third, if lucrative, the proportion of prosumers in the population may rise from 3% in 2020 to 20% in 2045. Figure 11 depicts the basic flow of the LUT model from data preparation through results and assessment, while Bogdanov et al. [54], [55] provide a thorough description of the model.

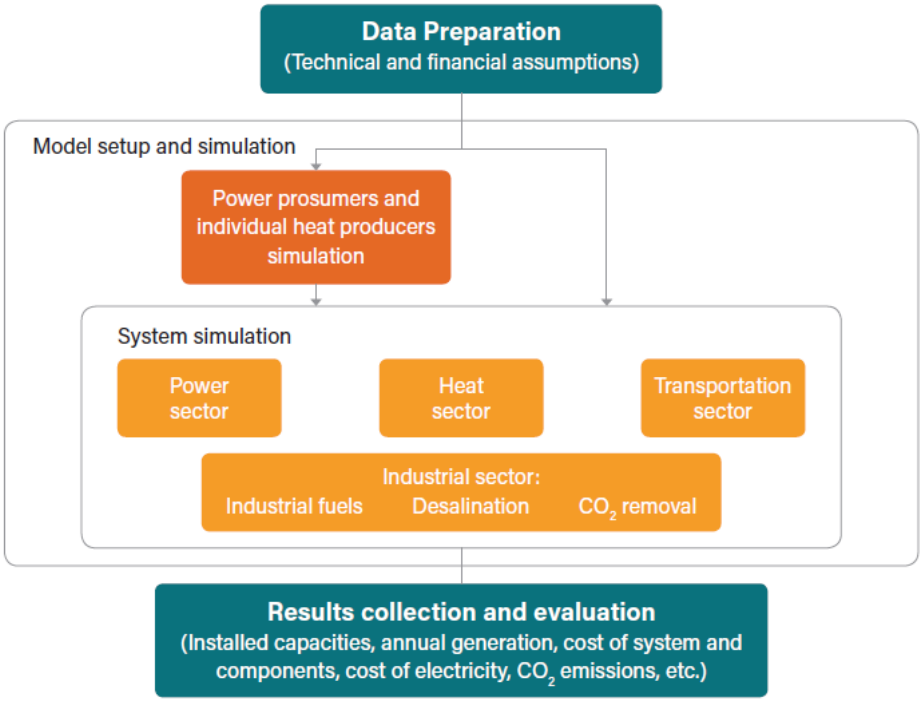

Figure 11: Process flow diagram of the model input data, optimization and results.

3.2 Assumptions used in the modelling

This research makes several assumptions about the supplied data. The study's financial and technological assumptions are detailed in Sections 3.2.1 and 3.2.2 respectively. The last part discusses demand growth across all industries and the technologies that are being used.

3.2.1 Financial Assumption

Table A8 of the Appendix contains information on financial assumptions for the various technologies used in the modelling for Bangladesh. For all RE technologies, the weighted average cost of capital (WACC) is set at 7%, however, for residential PV rooftop prosumers, a WACC of 4% is considered due to reduced risk and hence lower financial return expectations. Due to the lack of country-specific cost estimate data, financial projections for all technologies were based on a worldwide average. The cost of most RE-based technologies is decreasing internationally, implying that capacity installation of RE-based technologies will continue in the future. Technology improvements and industrial enhancements are expected to lead to cheaper raw materials and additional installations in the next decade. The increased capacity, along with lowering battery costs, has triggered a fast increase in capacity installations in several nations [56].

Electricity costs for three categories of users (residential, commercial, and industrial) were estimated using data from Bangladesh's power development board in 2020. The projected electricity price till 2045 was estimated using the method of Breyer and Gerlach [57]. The cost estimates for adopting Bangladesh's energy system technologies are presented in the Appendix Table A8.

3.2.2 Technical Assumption

Tables S8 and S9 of the appendix provide assumptions on the technical lifespan and efficiency of the power plants. Currently, installed capabilities are expected to be used until they reach the end of their useful life and then to be decommissioned. Except for gas power plants, no new fossil or nuclear power facilities are developed due to sustainability reasons and for avoiding stranded assets. As indicated in Section 3.2.5, the upper limitations for solar and wind energy were calculated. Fuels required for biomass and waste-to-energy technologies were believed to be dispersed equally throughout the year.

3.2.3 Resource potential and input profiles

Hourly capacity factor profiles for a whole year of solar PV, wind energy, and hydropower were used as inputs for the modeling. Solar photovoltaic (PV) systems were classified as optimally tilted, single-axis tracking, and in addition Concentrating Solar Power (CSP) is offered to the model. In the case of wind energy alone, only onshore wind is considered. The raw data is for the year 2005 and has a resolution of 0.45° x 0.45°. It was obtained from NASA databases [58], [59] and reprocessed by the German Aerospace Center [60]. Further processing of these data results in the generation of hourly capacity factor profiles, as described in Bogdanov and Breyer [61] and Afanasyeva et al. [62].

Three categories of biomass were identified: solid wastes (municipal garbage and waste wood), solid residues (agricultural and forestry waste), and biogas (biowastes, manure and sludge). The basic data on biomass and waste resources were gathered from the United Nations Food and Agricultural Organization. The potentials were determined using the method described in Mensah et al. [63]. International Energy Agency and Intergovernmental Panel on Climate Change statistics were used to compute costs for each of three biomass types. For municipal solid waste, a gate charge of 50 euros per ton is anticipated in 2020, increasing to 100 euros per ton in 2045 for waste incineration plants, resulting in negative costs for solid waste [64]. Solar PV and wind potentials (upper limits on installed capacity) were estimated using the condition that total land area availability should not exceed 6% and 4%, respectively. Farfan and Breyer [65] and Bangladesh power development board [66] provided the installed capacity for generation technologies in 2020.

3.2.4 Demand Estimation

To depict the regional variability of Bangladesh, it was divided into nine sub-regions, with the capital Dhaka as one of the sub-regions. The electricity demand of Bangladesh was calculated based on the demand per capita and the population in each of the sub-regions. Different growth rates were used to calculate the demand for each of the transition periods. Different growth rates of electricity demand for Bangladesh were applied to estimate the future electricity demand. The growth rate of electricity demand applied were 10.2% from 2020-2025, 7.9% from 2025-2030, and 5.8% from 2030 onwards. The heating demand in Bangladesh is primarily for hot water for domestic purposes and industrial process heat demand. The total heat demand from 2020 to 2050 is taken from Ram et al. [67], Bogdanov et al. [55] and Keiner et al. [68]. The total heat demand was divided according to the share of population in each of the sub-regions.

A portion of the country's total demand was used to compute the hourly load profile for electricity and heat for the region in Bangladesh. Toktarova et al. [69] provided the synthetic power load profiles. The heat profiles for space heating, residential hot water, biomass-fired cooking, and industrial heat are extracted from Ram et al. [67], Bogdanov et al. [55] and Keiner et al. [68]. Since Bangladesh does not have district heating networks, it is assumed that this will remain the same also in the future.

The main transport modes in Bangladesh are road, marine, rail, and aviation. Due to Bangladesh's developing economy, demand for transportation in all forms will increase in the future. For road, rail, marine, and aviation transportation modes, Bangladesh's overall transport demand was separated into sub-regions based on relative population size. Individual forms of transport were subdivided further into passenger (p-km) and freight (t-km) demand. Passenger travel on the road was classified as light-duty vehicles (LDV), buses (BUS), and 2-3 wheelers (2/3W), whilst freight transport was classified as medium-duty vehicles (MDV) and heavy-duty vehicles (HDV) New seaports are likely to be build due to the economic growth, But the uncertainty where these new seaports will be located. So, no change in related shares are assumed. New seaports may be built in comparable regions as of today. According to Khalili et al. [70], the varying fuel demand from these transport modes and several vehicle kinds was assumed.

3.2.5 Technologies in Use

An energy system overview is given, which outlines the various renewable and nonrenewable energy sources and technologies used for electricity, heat, and transportation showed in the Fig. 12. For example, the various technologies can be classified based on the source of electricity generation: electrical power derived from RE and fossil fuels; heat generated from RE and fossil fuels; road, rail, marine and aviation modes of transportation and electricity storage that includes power, heat, fuels and electricity transmission using High Voltage Alternating Current (HVAC) [71].

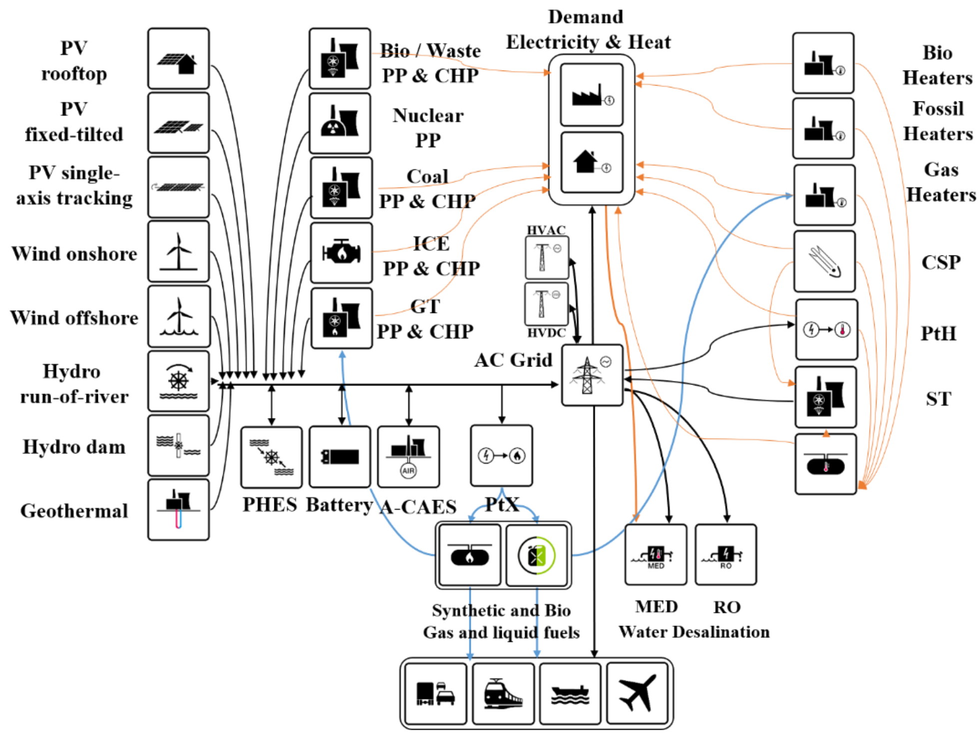

Figure 12: LUT Energy System Transition Model's schematic diagram for power, heat and transportation [68].

3.2.6 Applied Energy Transition Scenario

The major goal of this scenario is to have a renewable energy based power, heat and transport sector with the lowest cost and GHG emissions by the end of 2045. Certain assumptions were made in order to attain this target. First, with the exception of gas turbines, no new fossil fuel capacity was allowed to be added after 2020. Meanwhile, fossil-fuel capacity is being phased out and renewables and storage technologies are being allowed to take its place. As a result, no fossil fuel imports from other countries are necessary. Second, it was assumed that greenhouse gas emissions would be priced. The cost of GHG emissions would begin at 28 € per ton of CO_2 in 2020, gradually increasing to 53 €, 61 €, 68 €, 75 €, 100€, and finally 150 € per ton of CO_2 in the five-year intervals of 2025, 2030, 2035, 2040, 2045. Third, to avoid excessive RE capacity installation in a single time step, the total installed renewable power capacity share cannot rise more than 20% in any 5-year time step.

Among the features of this scenario are the potential role of prosumers (self-consumption of power and heat), rooftop photovoltaic (PV)-based electricity generation, and the possibility of installing batteries during the transition period. Customers in the residential, commercial, and industrial sectors are covered by this policy. Furthermore, after meeting their demand, prosumers can sell any excess electricity back to the grid at a price of 0.02 €/kWh. However, they are only allowed to sell up to 50% of their generation back to the grid.

4. Results

The following sections show the results obtained using the LUT model for Bangladesh.

4.1 Demand for primary energy during the transition

This sector shows the primary energy demand according to the different demand sectors for the scenario defined in this study. The total primary energy demand during the transition period from 2020 to 2045 is shown in Figure 13. The primary energy demand increases dramatically over the time, from 400 TWh in 2020 to more than 1100 TWh in 2045. The increase in population from 166 million in 2020 to 237 million in 2045, as well as the accompanying per capita energy consumption, are the reasons for such rapid growth. The highest share is accounted by the heat sector (54%) then followed by the power sector (29%) and transport (17%) in 2020. In 2045, the power assumes a major role in primary energy demand with a share of 47%. Also, the share of the transport sector in primary energy demand increases through the transition. The primary energy demand for the heat sector is quite stable until 2035, after that it is increasing gradually till 2045.

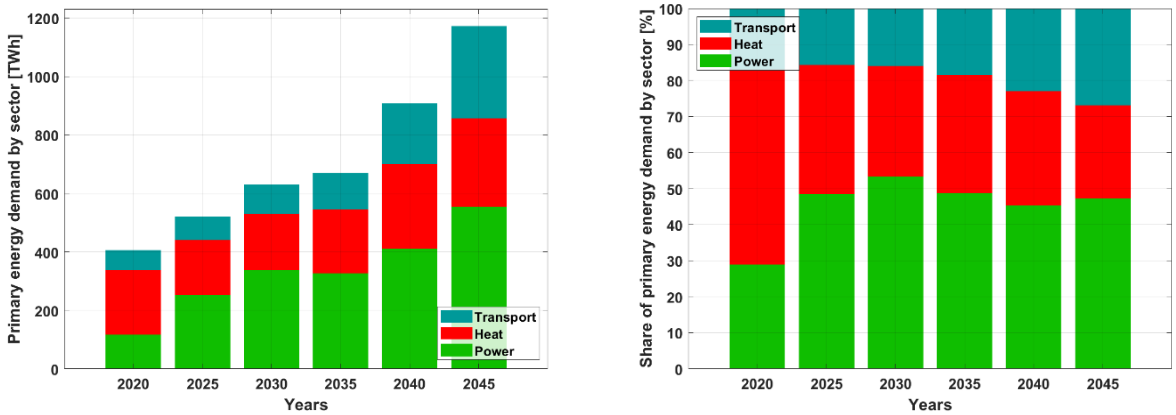

Figure 13: Primary energy demand during the transition for power, heat, and transport sectors.

In Figure 14 the total primary energy demand is shown by the energy source during the entire transition period. The fraction of fossil fuels in primary energy demand falls to zero in 2045 during the transition, as low cost renewables form a majority share. The share of electricity, as a fundamental energy type increases during the transition since it forms the backbone of the entire energy system, as low cost electricity from renewables replaces the expensive electricity from fossil sources. The share of electricity in the primary energy demand from renewable resources increases dramatically from 0.4% in 2020 to 91.6% by 2045.

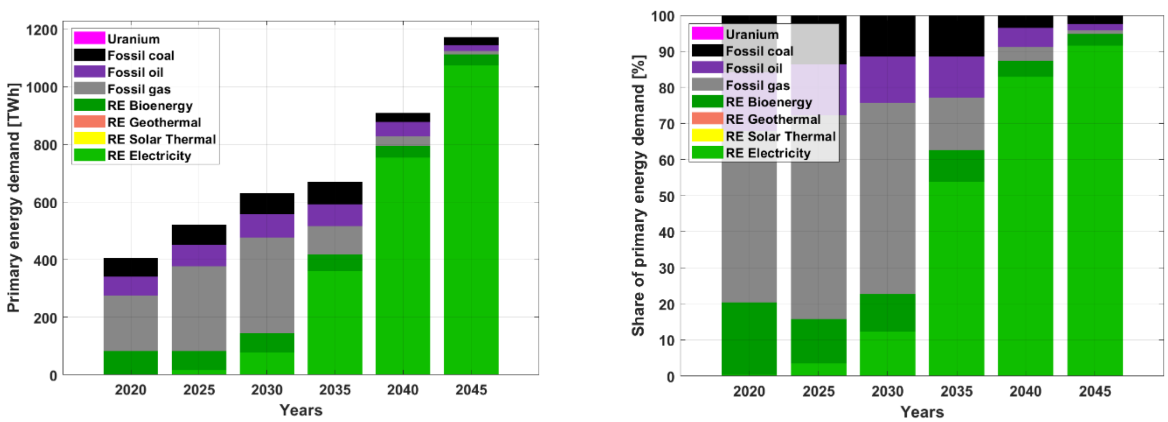

Figure 14: Primary energy demand by energy form during throughout the transition period 2020 to 2045.

Figure 15 shows the vital role of electricity during the transition. Direct and indirect use of electricity contribute significantly to the reduction of total primary energy consumption. If the low use of electricity in the primary energy demand will continue as it is in the current energy system, the total primary energy demand will increase exponentially from 406 TWh in 2020 to 1561 TWh in 2045, representing an increase of approximately 284%. On the other hand, an energy system with high levels of electrification, would limit primary energy consumption to only 1173 TWh by 2045. The increase in total primary energy demand is often related to the county's GDP growth, standard of living and per capita energy use. The energy system will be highly efficient compared to the current fossil fuel-based energy system due to almost 99% renewable resource based energy supply and high direct and indirect electrification in the power, heat and transport sectors.

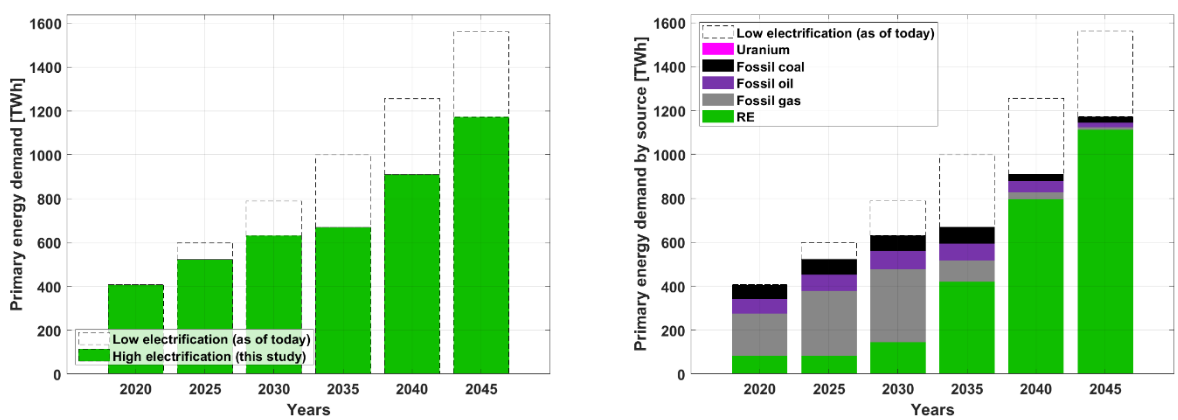

Figure 15: Efficiency gain in primary energy demand with low and high electrification during the transition years.

4.2 Electricity generation and installed capacities

The installed capacity, which is dominated by renewable energy sources, has increased significantly, especially solar PV will play a big part in a fully renewable energy system in 2045 due to its economic viability and abundant resource availability. Renewable gas-based turbines and biomass contribute in periods of low solar radiation.

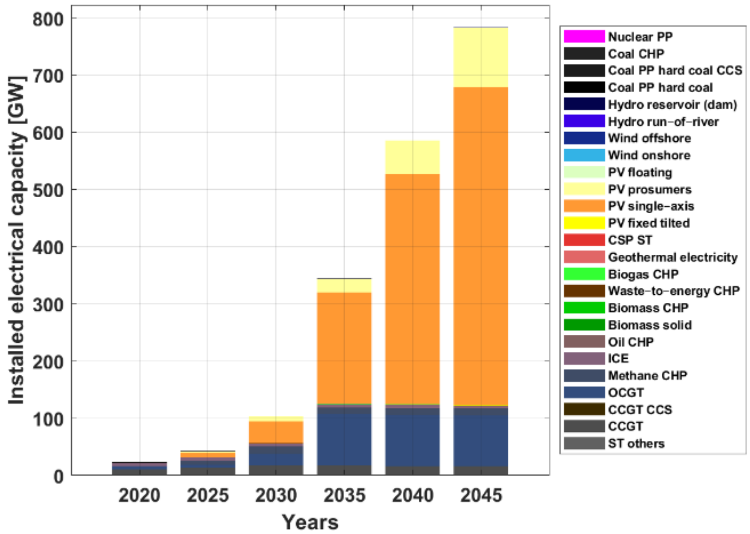

Figure 16: Cumulative installed capacities for all power generation technologies from 2020 to 2045.

To meet the power, heat and transportation demand of Bangladesh in 2045, the total electricity generation is 1091 TWh. Figure 16 depicts the total electricity generated by various technologies. It is apparent that solar PV forms the backbone of the electricity generation, supplemented by biomass and renewable gas-based turbines. There is a transition away from fossil fuel-based supply towards solar PV for the period 2020–2045, with roughly 98% reliance on imported fossil fuels in 2020 and the remaining from imported power expected to be fossil fuel-based. Other renewable energy sources, such as wind and hydropower, have a limited role in 2045 for electricity generation. Fossil fuels have been the dominant source of electricity generation in the previous decades. On the other hand, solar photovoltaic (PV) technology has exceeded fossil fuels in terms of cost, modularity, and installation time. Furthermore, solar PV will account for approximately 99% of total electricity generated in 2045. The remaining energy is generated from wind, biomass, and hydroelectricity.

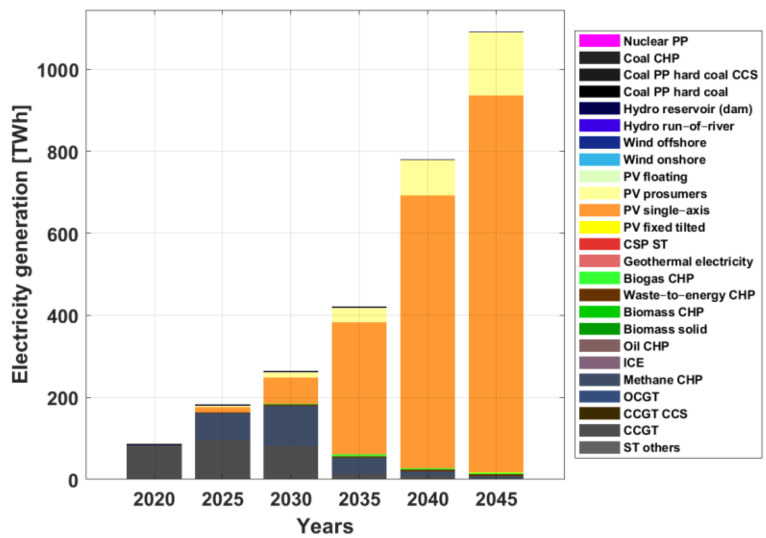

Figure 17: Technology-wise electricity generation during the transition period.

4.3 Generation of heat and installed capacities

Figure 18 shows the overall installed capacity in the heat sector for various heat production technologies during the transition period.

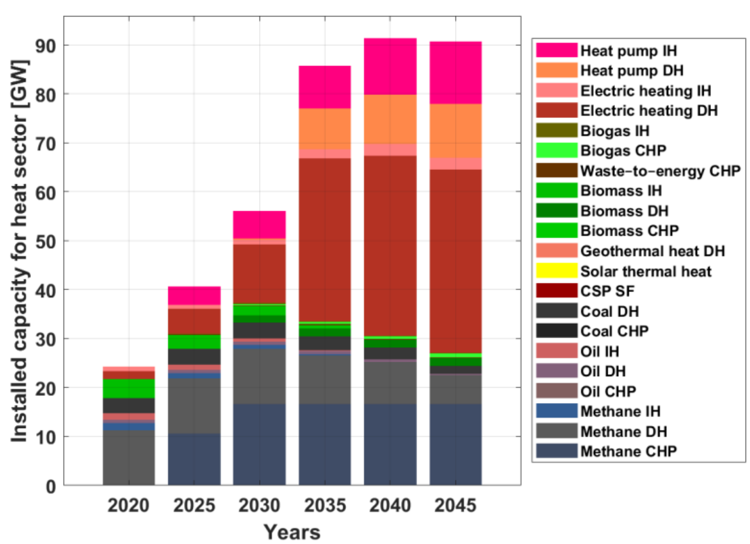

Figure 18: Installed capacity in the heat sector in the transition years 2020 to 2045.

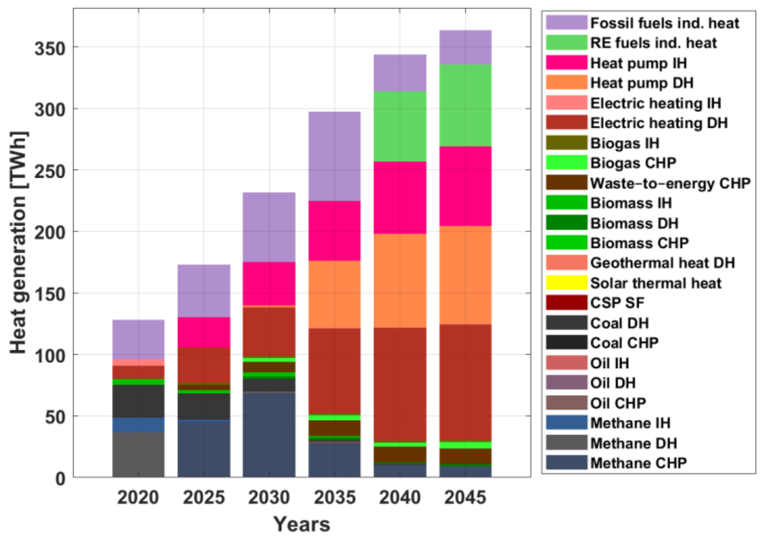

Figure 19: Heat generation in the transition years 2020 to 2045.

During the transition, electric heating systems and heat pumps heat generation dominates the heat sector in the scenarios. In 2020, the bulk of biomass was used as a source of heat for cooking, which is extremely unsustainable and causes indoor air pollution and other health risks. However, biomass use in cooking is replaced by electricity-based cooking throughout the transition period. During the transition period, the usage of agricultural and forest residues and municipal solid waste will increase. Other heat generation technologies based on direct electricity consumption and oil as a transition fuel will be available in 2020. In 2020, majority of the heating is based on natural gas, biomass and coal. During the transition, for fossil fuels based heating a gradual reduction is observed and replaced by more efficient; direct electricity based heating and heat pumps.

4.4 Transport sector

Fig. 20 shows the total energy demand in the transport sector by different transportation modes, as well as by fuel types. Until 2035, the total energy demand for transportation will grow gradually. Following that, the demand will increase to about 146 TWh by 2045. The aviation transportation and marine transportation is experiencing a substantial growth in energy demand as a result of rising of living standards and economic development. For the freight and passenger transportation, energy demand is closely related to the number of passengers and freight.

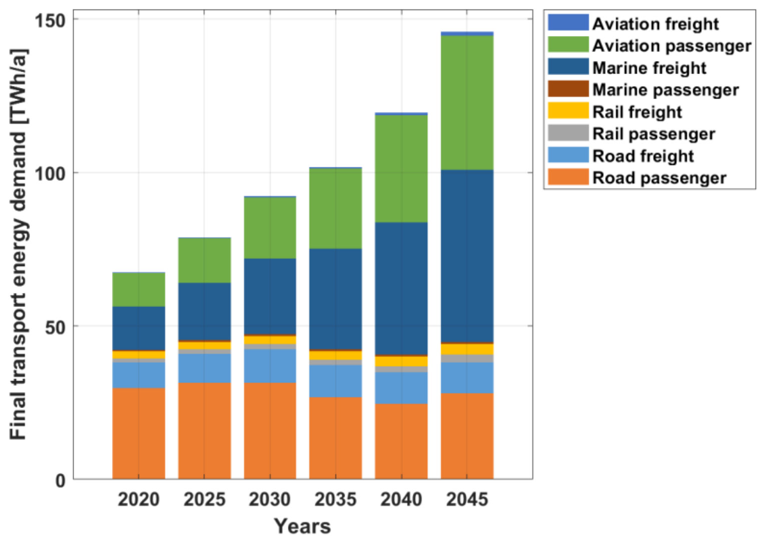

Figure 20: Final energy demand in the transport sector by different transportation modes during the transition period.

As illustrated in Figure 21, direct use of electricity has a significant impact on meeting the total transportation demand by 2045. Electricity, on the other hand, played a minor role in 2020, with the majority of energy coming from less efficient fossil fuel sources. During the transition, however, the share of direct and indirect electrification increases as more cost-effective choices become available in the transport sector.

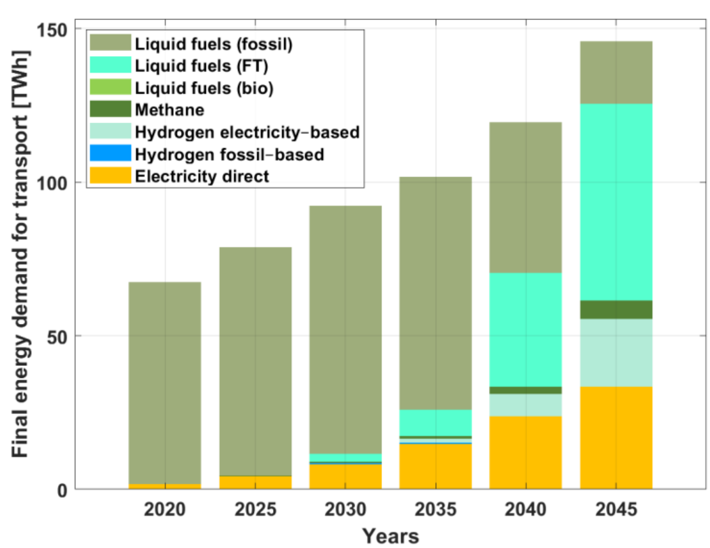

Figure 21: Final energy demand for the transportation sector by fuel for the transition period.

During the transition, the share of direct electricity increases from the early 2030s to 2040s, and the share of Fischer Tropsch (FT) liquids from 2030 onwards and hydrogen from 2035. In a highly sustainable transport sector in 2045, direct electricity has a share of 23%, while hydrogen and synthetic liquid fuels have 63%, while the remaining is from fossil fuels. During the transition, the role of liquid fossil fuels declines to maintain the strict criteria of sustainability; nonetheless, synthetic liquid fuels are employed for air and marine transportation for reducing the GHG emission in 2045.

Use of direct electricity is important in the shift of the transport sector towards sustainability but converting renewable electricity to hydrogen and synthetic fuels can achieve sustainability in the entire transport sector. Figure 24 shows the capacities of technologies required during the transition. Almost 100 GW capacity of fuel conversion technologies are installed, with water electrolysers accounting for the majority, as hydrogen is used as a fuel and to produce synthetic hydrocarbons. Other conversion processes, such as Fischer-Tropsch, liquid hydrogen generation, and methanation, account for a smaller percentage of the total.

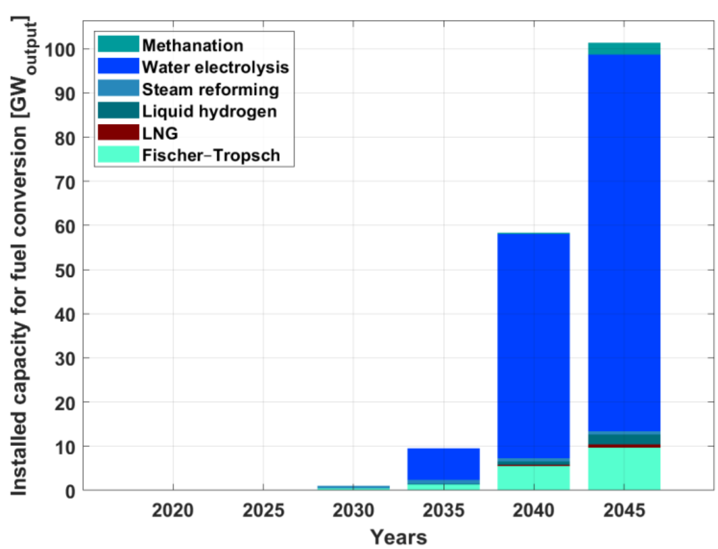

Figure 22: Installed capacity needed for transport fuel conversion during the transition years.

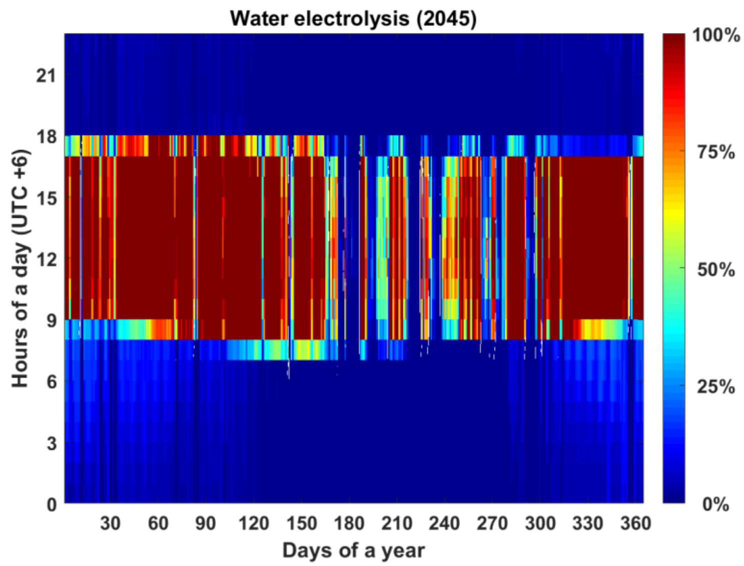

Figure 23: Hourly profile for water electrolysis in 2045.

4.5 The importance of storage technologies

During the shift to large-scale renewable energy use, energy storage systems are crucial for balancing the temporal low predictability of demand and generation. As solar PV dominates the future energy supply and due to its variability and intermittency storage technologies will provide the required supply to balance the demand. After 2030, electricity storage demand increases gradually, as in the initial years with a low share of renewable energy output and availability of fossil fuels do not necessitate the use of storage technologies. As illustrated in Figure 24, the installed capacity of the storage technologies increase to about 800 GWh in 2045.

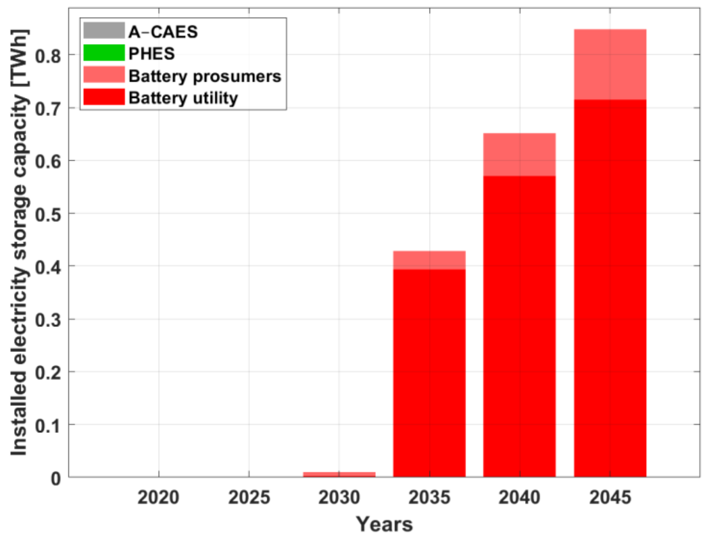

Figure 24: Installed electricity storage capacity in the transition years.

The influence of PV prosumer batteries in storage begins in 2030 due to cheap solar PV rooftop installations. Batteries have the largest share in total storage capacity installed in 2045. As indicated in Figure 25, the combined output of the utility-scale battery and the prosumer battery is about 300 TWh.

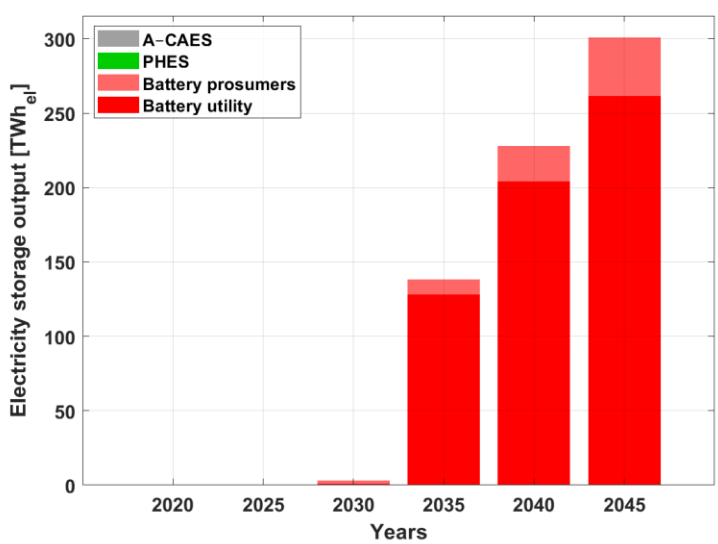

Figure 25: Electricity storage output during the transition years.

To meet the seasonal storage need, a massive quantity of gas storage capacity has been built during the last final years of the transition. The synthetic gas (CH_4) storage accounts for approximately all of the total heat storage capacity. However, gas (CH_4) storage accounts for a relatively small percentage of the total thermal heat output. From 2035, there is a sharp increase in heat storage output, with TES DH and TES HT accounting for 18.7 TWh_{th} and 56.3 TWh_{th} in 2045.

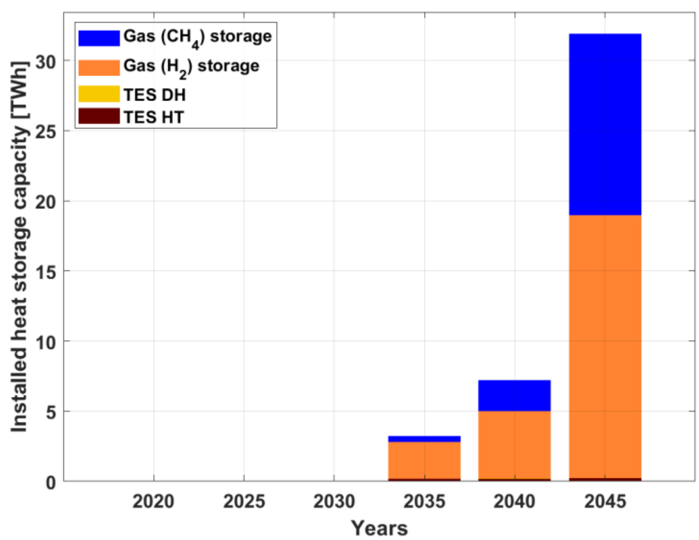

Figure 26: Installed heat storage capacity in the transition years.

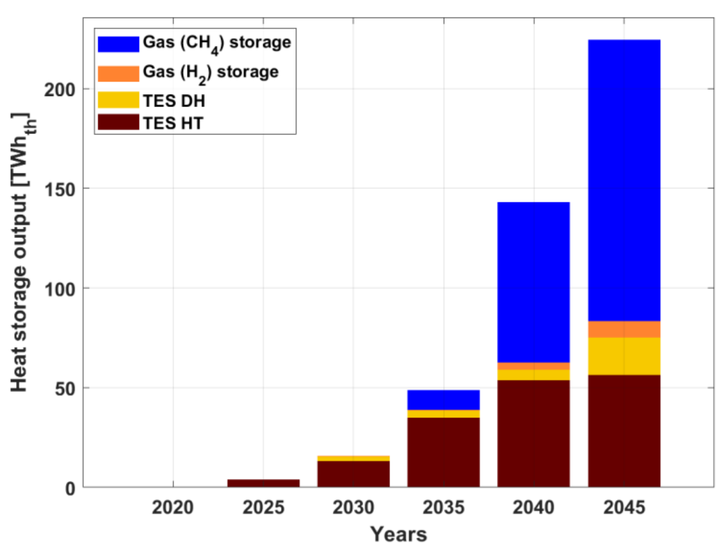

Figure 27: Heat storage output in the transition years.

4.6 Costs of energy during the transition

Figures 28 and 29 depict the overall annual system cost and the levelised cost of energy.

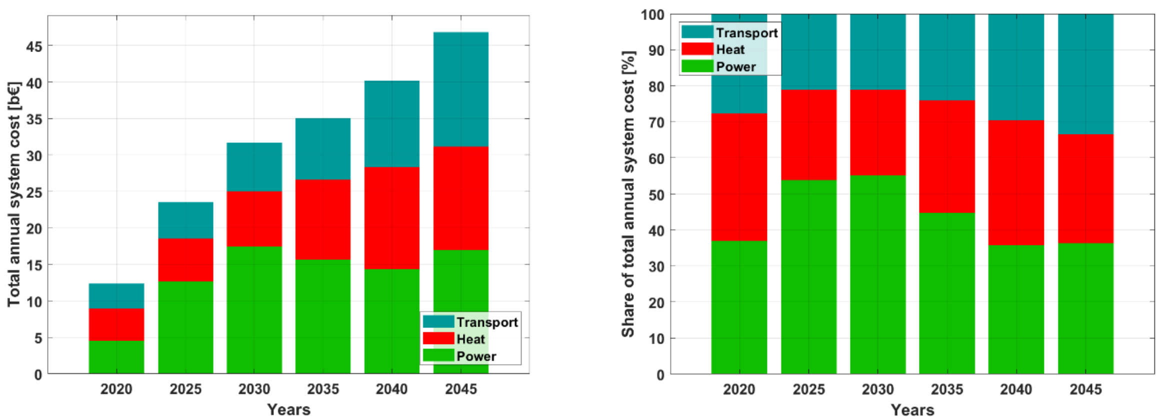

Figure 28: Total annual system cost for the power, heat and transport sectors in the transition years.

The overall yearly system cost during the transition years increases from 12 b€ in 2020 to about 47 b€ in 2045. During the 2020s, the heat sector accounted for about 5 b€ with the remaining 7 b€ coming from the power and transportation sectors. The power and transportation sectors' share in total energy demand rises in the coming years, particularly the power sector, due to rising demand and a complete shift to RE-based resources in power generation, which serves as a foundation for other sectors' energy need. Transportation costs climb progressively over time, peaking in the late 2045s as a result of changes in vehicle stocks and the resulting shift in fuel types.

As illustrated in Figure 29, a 100% RE-based energy system is the most cost-effective solution. The entire energy cost per MWh is expected to fall to 47.5 € in 2045 from 54.5 € in 2020. The large proportion of CAPEX-related costs indicates a surge in the installation of new energy generating and storage technologies. As a result, the cost of imported fuels comes to a halt.

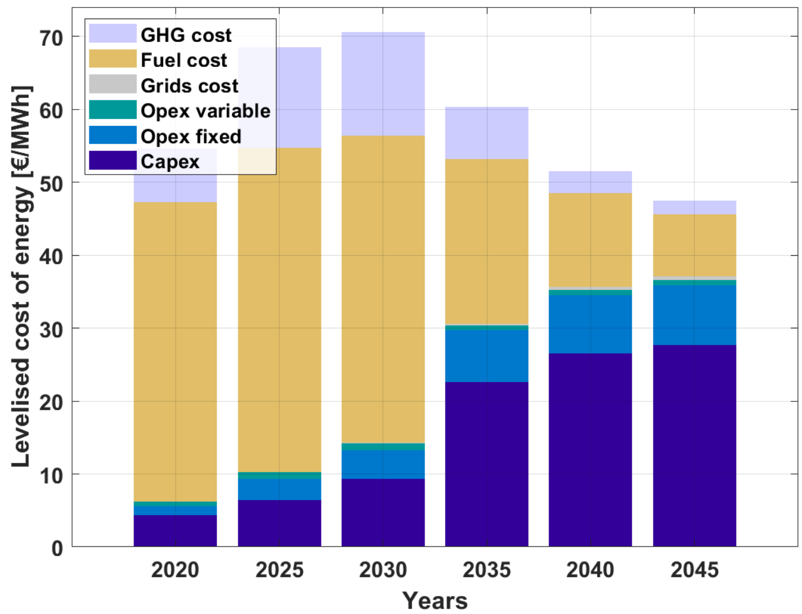

Figure 29: Breakdown of the levelised cost of energy in the transition years.

At the start of the transition, the overall LCOE is 54.5 €/MWh, with fuel costs and GHG emission cost accounting for majority of it. Over the transition the LCOE reduces by 12.8% in 2045. The major drivers are limiting the use of expensive fossil fuel-based energy and the associated GHG emission costs. The photovoltaic technology and battery-based energy storage all play a significant role in the energy sector. As a result, by 2045, a RE-based sustainable energy system will be significantly less expensive than the current energy system.

4.7 Reduction of GHG emissions

Figure 30 shows total GHG emissions from the year 2020 through the transition period.

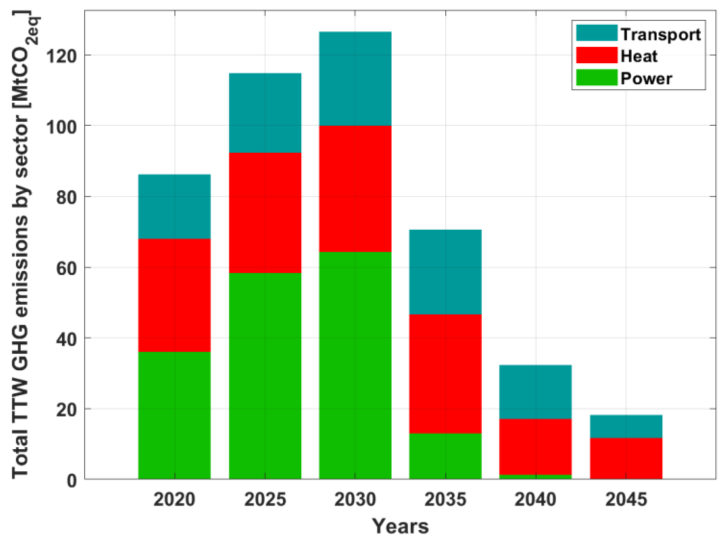

Figure 30: Sector-wise GHG emissions during the transition period.

One of the study's main objectives is to show a most cost-effective pathway to move to an energy system that emits low GHG gases. The energy system in 2045 still has about 19 $MtCO_{2eq}$ of GHG emissions, largely due to the heat and transport sector. In 2020, power sector accounts for the largest share in emissions followed by the heat and the transport sector, respectively. During the transition period, GHG emissions decreases from 86 $MtCO_{2eq}$ in 2020 to 18 $MtCO_{2eq}$ in 2045. The power sector, which is almost GHG emission-free in 2040, is the most substantial and easiest to defossilise. The utilization of direct electricity, hydrogen fuel, and synthetic liquid fuels considerably reduces transportation-related GHG emissions.

5. Discussion

The primary objective of this study was to demonstrate that Bangladesh, in accordance with the Paris Agreement [72] could transition to a low emission energy system by 2045. Freely available indigenous renewable energy resources can be used to accomplish this goal. Additionally, it is necessary to have a strong political will and long-term national policy towards renewables.

The transition towards a large share of renewables in the entire energy sector ensures a low cost source of energy and also reduces import cost and GHG emissions. From generation to storage, this study looks into various aspects of a sustainable energy system. The levelised cost of energy drops from 54.5 €/MWh in 2020 to 47.5 €/MWh in 2045 as a result of a large share of low cost renewables. On the other hand, the levelised cost of electricity decreases more from 67 €/MWh in 2020 to 37 €/MWh in 2045, as low cost solar and battery hybrid becomes the primary source electricity generation in Bangladesh.

For Bangladesh such a research has never been conducted for this scope before, looking at how the country's power, heating, and transport sectors can transition towards a low cost and net zero emission energy system.

In 2045, solar PV will dominate the energy sector, generating roughly 1073 TWh of electricity. This would require about 660 GW of total PV capacity. The total ground mounted solar PV installed capacity in 2045 is 557 GW, which would require about 4% of the land area (25% of area excluded as forest cover in calculation). Bangladesh has huge potential for solar PV installation as in agro-PV and installation in open land area. To reduce the impact on land area floating and offshore PV can also be installed in areas suitable. There is huge ongoing research especially in floating PV technology and it will be very important in the context of Bangladesh, if the country decides to 100% renewable based in the transport and industry sector. Bangladesh has the potential to produce green hydrogen and other synthetic fuels locally and be independent of energy imports. Bangladesh needs to invest in local manufacturing of solar PV panels and batteries to further create jobs. Additionally, more research needs to be done in offshore wind and waste to power plants as Bangladesh has a long coastline and huge population, respectively, which can complement solar PV in the future.

The supply-demand balance is aided by hydropower, biomass and renewable gas based energy supply. Heat demand will be covered by 2045 thanks to a considerable almost 90 GW of installed heat capacity. Because of low cost electricity, heat pumps and direct electricity based heating will be a key source of heat generation. In addition, the total phase-out of fossil fuel-powered cars, the transport sector is undergoing enormous changes. Aviation and marine modes of transportation utilize hydrogen and liquid hydrocarbons in various forms, whilst passenger vehicles are transitioning to direct plug-in electric power.

According to the findings of this study, Bangladesh must make use of locally accessible resources and ensure that everyone, regardless of where they live, has access to electricity. Decentralized energy generation also necessitates an unneeded and costly grid expansion, as well as a reduction in grid losses over time. Despite the challenges of topography and settlement in rural areas, a wise investment in locally available resources like solar PV assures access to electricity for every household. For reducing GHG emissions and eliminates the need to import expensive fossil fuels from other countries. The Government of Bangladesh strategy [33] to provide cheap electricity to all inhabitants is enabled by a mix of renewable energy sources and a mix of centralized and decentralized energy supply. Solar PV-based electricity generation is excellent for the demand-supply balance in Bangladesh due to the short seasonal inconstancy of solar energy.

According to data from the Bangladesh Power Development Board (BPDP) [73], on 28 September 2021, there was 1965 MW of electricity load shedding due to technical difficulties, and another 776 MW of power production was lost due to a shortage of sufficient gas supply to power plants. The essential issue is that real-time energy supply is significantly less secure. Outside of capital region, the situation is quite dire, with load shedding lasting between 6 and 8 hours each day. Due to the large share of renewables in the energy system and supporting battery storage capacity, the pathway is predicted to be much less expensive than the current energy system. There has been a significant reduction in the cost of solar PV and batteries, which are projected to play an important role in power generation and storage. Use of low-cost solar PV technologies should be encouraged in Bangladesh.

To summarize, Bangladesh can build its future energy system with low-cost renewable energy, ensuring that everyone has access to affordable energy and also achieving the goals of the Paris agreement. The governments of the individual countries should enact robust rules and guidelines about the necessity to phase in RE-based solutions. For Bangladesh, recommendations are made to build roadmaps, regulations, procedures, and incentives to attract citizens to invest in region-specific capacity for exploiting accessible renewable energy sources in Bangladesh. Moreover, partnership with neighboring India, which is much ahead of the game when it comes to generating renewable energy and also collaboration with the entire SAARC area.

6. Conclusions

Bangladesh has considerable potential in terms of renewable energy resources. It must follow the road of renewable energy in order to provide affordable, reliable, and sustainable energy to all. By 2045, renewable energy technologies and storage solutions will be able to reliably supply energy to all sectors at all hours of the year. Advanced renewable energy conversion technology is capable of producing electricity, which may then be used to meet demand in the heating and transport sectors. Bangladesh's levelised cost of energy is projected to be 47.5 €/MWh by 2045 and 54.5 €/MWh in 2020, which is almost 13% reduced from the current fully fossil fuel based energy system. The vulnerable transport sector in Bangladesh, which is entirely reliant on imported fossil fuels, will undergo significant changes as a result of the establishment of RE-based direct and indirect electrification. Finally, this analysis indicates that a large share of renewables in the energy system is technically and economically feasible across all sectors by 2045, with a primary focus on renewable electricity and very low GHG emissions.

Bangladesh's national policies must be bold, severe, and intense in order to achieve an energy transition of the current system towards renewable energy system capable of very low GHG emissions by 2045.

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Appendix:

Table A1: Population projection of Bangladesh 2020 to 2045.

	Unit	2020	2025	2030	2035	2040	2045	Sources
Population	[mil]	166	203	214	223	231	237	[4] [3]

Table A2: Projection of power, heat and transport demands from 2020 to 2045.

Energy service demand	Unit	2020	2025	2030	2035	2040	2045
Power demand	**[TWh]**	58	125	184	245	325	432
Total heat demand - heat sector	**[TWh]**	204	227	267	317	361	384
Industrial heat demand	**[TWh]**	105	142	189	242	290	315
Space heating heat demand	**[TWh]**	0	0	0	0	0	0
Domestic water heating heat demand	**[TWh]**	22	30	40	51	60	66
Biomass cooking heat demand	**[TWh]**	76	54	38	23	10	2.5
Centralised heating heat demand	**[TWh]**	105	142	189	242	290	315
Individual heating heat demand	**[TWh]**	98	84	78	75	71	68
Total electricity demand	**[TWh]**	67	143	207	270	350	460
Total electricity demand system	**[TWh]**	67	142	200	250	305	386
Road 2W/3W passenger transport demand	**[mil km]**	33051	39238	47933	60314	77991	103031
Road Bus transport demand	**[mil km]**	3046	3403	3883	4536	5424	6618
Road MDV transport demand	**[mil km]**	1613	1960	2440	3111	4051	5358
Road HDV transport demand	**[mil km]**	1425	1732	2156	2749	3580	4735
Rail pass transport demand	**[mil p-km]**	16054	17837	20328	23858	28886	35981
Rail freight transport demand	**[mil t-km]**	51865	56236	62165	70488	82501	100132
Aviation pass transport demand	**[mil p-km]**	21043	28506	40224	54534	79569	111236
Aviation freight transport demand	**[mil t-km]**	1362	2049	3121	4789	7483	11435
Marine pass transport demand	**[mil p-km]**	807	866	934	1014	1110	1226
Marine freight transport demand	**[mil t-km]**	349442	463245	623547	849994	1166735	1602317

Table A3: Projected specific energy demand by transport mode and vehicle type from 2020 to 2045.

Mode and Vehicle type	Unit	2020	2025	2030	2035	2040	2045
Road LDV ICE	**[kWh,th/km]**	0.7471	0.7338	0.6004	0.5690	0.5696	0.53606
Road LDV BEV	**[kWh,el/km]**	0	0.1476	0.1332	0.1225	0.1169	0.11062
Road LDV FCEV	**[kWh,th/km]**	0	0	0.2171	0.20026	0.1999	0.1756
Road LDV PHEV, primary	**[kWh,el/km]**	0	0.1509	0.1382	0.1276	0.12206	0.11109
Road LDV PHEV, secondary	**[kWh,th/km]**	0	0.1151	0.1039	0.09705	0.09315	0.08769
Road 2,3W ICE	**[kWh,th/km]**	0.14285	0.14285	0.14285	0.14285	0.14285	0.14258
Road 2,3W BEV	**[kWh,el/km]**	0.05	0.05	0.05	0.05	0.05	0.05
Road 2,3W FCEV	**[kWh,th/km]**	0	0	0	0	0	0
Road 2,3W PHEV, primary	**[kWh,el/km]**	0	0	0	0	0	0
Road 2,3W PHEV, secondary	**[kWh,th/km]**	0	0	0	0	0	0
Road Bus ICE	**[kWh,th/km]**	4.0233	4.017	4.0094	3.8710	3.8364	3.8063
Road Bus BEV	**[kWh,el/km]**	0	1.74388	1.6946	1.6276	1.6090	1.5787
Road Bus FCEV	**[kWh,th/km]**	0	2.8533	2.7768	2.6313	2.5825	2.5191
Road Bus PHEV, primary	**[kWh,el/km]**	0	1.918	1.9377	1.9154	1.9053	1.8847
Road Bus PHEV, secondary	**[kWh,th/km]**	0	0.8719	0.8486	0.8143	0.8035	0.7851
Road MDV ICE	**[kWh,th/km]**	2.2696	2.2494	2.212	1.971	1.971	1.873
Road MDV BEV	**[kWh,el/km]**	0	0.747	0.6896	0.6253	0.5994	0.56887
Road MDV FCEV	**[kWh,th/km]**	0	1.286	1.218	1.1499	1.089	1.0446
Road MDV PHEV, primary	**[kWh,el/km]**	0	1.286	1.232	1.156	1.1218	1.07040
Road MDV PHEV, secondary	**[kWh,th/km]**	0	0.2988	0.2755	0.2517	0.2413	0.2275
Road HDV ICE	**[kWh,th/km]**	3.2527	3.2104	3.1345	2.6655	2.5620	2.4946
Road HDV BEV	**[kWh,el/km]**	0	1.494	1.348	1.248	1.1945	1.1162
Road HDV FCEV	**[kWh,th/km]**	0	1.805	1.690	1.559	1.467	1.375
Road HDV PHEV, primary	**[kWh,el/km]**	0	2.106	1.9905	1.830	1.75694	1.6290
Road HDV PHEV, secondary	**[kWh,th/km]**	0	0.448	0.413	0.377	0.362	0.3364

Rail pass fuel	**[kWh,th/(p-km)]**	0.1036	0.1035	0.1035	0.1035	0.1035	0.1035
Rail pass elec.	**[kWh,el/(p-km)]**	0.0654	0.0654	0.0639	0.0624	0.0605	0.0584
Rail freight fuel	**[kWh,th/(t-km)]**	0.0625	0.06233	0.0619	0.06128	0.06128	0.06128
Rail freight elec.	**[kWh,el/(t-km)]**	0.0319	0.0317	0.0314	0.0307	0.02923	0.02727
Marine pass fuel	**[kWh,th/(p-km)]**	0.6569	0.6557	0.6535	0.6520	0.6520	0.6520
Marine pass elec.	**[kWh,el/(p-km)]**	0	0.3226	0.3238	0.3246	0.3249	0.3249
Marine pass LH2	**[kWh,th/(p-km)]**	0	0	0.5653	0.5346	0.4973	0.4811
Marine pass LNG	**[kWh,th/(p-km)]**	0	0.6340	0.6217	0.615	0.607	0.5989
Marine freight fuel	**[kWh,th/(t-km)]**	0.00904	0.0089	0.0088	0.0087	0.0086	0.0086
Marine freight elec.	**[kWh,el/(t-km)]**	0	0.0044	0.0044	0.0044	0.0044	0.0044
Marine freight LH2	**[kWh,th/(t-km)]**	0	0	0.0077	0.0073	0.0068	0.0065
Marine freight LNG	**[kWh,th/(t-km)]**	0	0.0088	0.0088	0.0084	0.0068	0.0082
Aviation pass fuel	**[kWh,th/(p-km)]**	0.4018	0.3964	0.3864	0.3763	0.364	0.359
Aviation pass elec.	**[kWh,el/(p-km)]**	0	0	0	0.1288	0.1234	0.1184
Aviation pass LH2	**[kWh,th/(p-km)]**	0	0	0	0.2471	0.2368	0.2270
Aviation freight fuel	**[kWh,th/(t-km)]**	0.0746	0.0712	0.0688	0.06628	0.06628	0.06411
Aviation freight elec.	**[kWh,el/(t-km)]**	0	0	0	0	0	0
Aviation freight LH2	**[kWh,th/(t-km)]**	0	0	0	0.0459	0.0440	0.0421

Table A4: Projected shares of passenger demand by transport mode and vehicle type from 2020 to 2045.

Passenger mode and vehicle type		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Road LDV ICE - liquid fuel	%	94.00	79.90	50.00	20.00	11.00	7.00
Road LDV BEV - electricity	%	3.00	10.00	39.00	68.00	74.00	73.00
Road LDV FCEV - hydrogen	%	0.00	0.10	1.00	2.00	5.00	10.00
Road LDV PHEV - electricity/liquid fuel	%	3.00	10.00	10.00	10.00	10.00	10.00
Road 2W/3W ICE - liquid fuel	%	65.00	60.00	40.00	25.00	15.00	10.00
Road 2W/3W BEV - electricity	%	35.00	40.00	60.00	75.00	85.00	90.00

Road BUS ICE - liquid fuel	%	78.90	47.90	16.90	5.90	4.90	3.90
Road BUS BEV - electricity	%	20.00	50.00	80.00	90.00	90.00	90.00
Road BUS FCEV - hydrogen	%	0.10	0.10	0.10	0.10	0.10	0.10
Road BUS PHEV - electricity/liquid fuel	%	1.00	2.00	3.00	4.00	5.00	6.00
Rail - electricity	%	14.70	24.10	39.70	54.30	68.80	81.80
Rail - liquid fuel	%	85.30	75.90	60.30	45.70	31.20	18.20
Marine - liquid fuel	%	99.40	98.40	95.90	91.20	79.40	57.20
Marine - electricity	%	0.10	0.60	1.10	2.80	5.60	7.80
Marine - hydrogen	%	0.00	0.00	1.00	3.00	10.00	25.00
Marine – LNG	%	0.50	1.00	2.00	3.00	5.00	10.00
Aviation - liquid fuel	%	100	100	100	96.50	86.00	68.50
Aviation - electricity	%	0.00	0.00	0.00	1.20	4.70	10.50
Aviation - hydrogen	%	0.00	0.00	0.00	2.30	9.30	21.00

Table A5: Projected share of freight demand by transport mode and vehicle type form from 2020 to 2045.

Freight mode and vehicle type		**2020**	**2025**	**2030**	**2035**	**2040**	**2045**
Road MDV ICE - liquid fuel	%	88.90	78.00	47.00	16.00	5.00	4.00
Road MDV BEV - electricity	%	10.00	19.00	48.00	75.00	80.00	80.00
Road MDV FCEV - hydrogen	%	0.10	1.00	2.00	5.00	10.00	10.00
Road MDV PHEV - electricity/liquid fuel	%	1.00	2.00	3.00	4.00	5.00	6.00
Road HDV ICE - liquid fuel	%	97.50	88.00	77.00	46.00	12.00	4.00
Road HDV BEV - electricity	%	1.00	8.00	15.00	30.00	50.00	50.00
Road HDV FCEV - hydrogen	%	0.50	2.00	5.00	20.00	30.00	30.00
Road HDV PHEV - electricity/liquid fuel	%	1.00	2.00	3.00	4.00	8.00	16.00
Rail – electricity	%	14.70	24.10	39.70	54.30	68.80	81.80
Rail- liquid fuel	%	85.30	75.90	60.30	45.70	31.20	18.20
Marine - liquid fuel	%	99.40	98.40	95.90	91.20	79.40	57.80
Marine - electricity	%	0.10	0.60	1.10	2.80	5.60	7.20

Marine - hydrogen	%	0.00	0.00	1.00	3.00	10.00	25.00
Marine – LNG	%	0.50	1.00	2.00	3.00	5.00	10.00
Aviation - liquid fuel	%	100	100	100	97.70	90.70	79.00
Aviation - electricity	%	0.00	0.00	0.00	0.00	0.00	0.00
Aviation - hydrogen	%	0.00	0.00	0.00	2.30	9.30	21.00

Table A6: Projected final energy demand by sector from 2020 to 2045.

Sector	Unit	2020	2025	2030	2035	2040	2045
Power	**[TWh]**	58	125	184	245	325	432
Heat	**[TWh]**	204	227	267	317	361	384
Transport	**[TWh]**	65	74	83	84	86	84

Table A7: Projected final energy demand by energy form from 2020 to 2045.

Energy form	Unit	2020	2025	2030	2035	2040	2045
Power demand	**[TWh]**	67	143	207	270	350	460
Heat demand	**[TWh]**	204	227	267	317	361	384
Fuel demand	**[TWh]**	65	74	83	84	86	84

Table A8: Financial and technical assumptions of energy system technologies used from 2020 to 2050.

Technologies		Unit	2020	2025	2030	2035	2040	2045	Sources
PV rooftop – residential	**Capex**	**€/kW$_{el}$**	1045	842	715	622	551	496	[74]
	Opex fix	**€/(kW$_{el}$ a)**	9.13	7.66	6.66	5.88	5.26	4.75	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	30	35	35	35	40	40	
PV rooftop - commercial	**Capex**	**€/kW$_{el}$**	689	544	456	393	345	308	[74]
	Opex fix	**€/(kW$_{el}$ a)**	9.13	7.66	6.66	5.88	5.26	4.75	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	30	35	35	35	40	40	
PV rooftop - industrial	**Capex**	**€/kW$_{el}$**	512	397	329	281	245	217	[74]
	Opex fix	**€/(kW$_{el}$ a)**	9.13	7.66	6.66	5.88	5.26	4.75	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	30	35	35	35	40	40	
PV optimally tilted	**Capex**	**€/kW$_{el}$**	432	336	278	237	207	184	[74], [75]
	Opex fix	**€/(kW$_{el}$ a)**	7.76	6.51	5.66	5	4.47	4.04	

	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	30	35	35	35	40	40	
PV single-axis tracking	**Capex**	**€/kW$_{el}$**	475	370	306	261	228	202	[76]
	Opex fix	**€/(kW$_{el}$ a)**	8.54	7.16	6.23	5.5	4.92	4.44	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	30	35	35	35	40	40	
PV Floating	**Capex**	**€/kW$_{el}$**	1296	1008	695	474	414	368	
	Opex fix	**€/(kW$_{el}$ a)**	25.92	20.16	13.9	9.48	8.28	7.36	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	25	25	25	30	30	
Wind onshore	**Capex**	**€/kW$_{el}$**	1150	1060	1000	965	940	915	[77]–[79]
	Opex fix	**€/(kW$_{el}$ a)**	23	21	20	19	19	18	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	25	25	
Hydro Reservoir/ Dam	**Capex**	**€/kW$_{el}$**	1650	1650	1650	1650	1650	1650	[78]
	Opex fix	**€/(kW$_{el}$ a)**	49.5	49.5	49.5	49.5	49.5	49.5	
	Opex var	**€/(kWh$_{el}$)**	0.003	0.003	0.003	0.003	0.003	0.003	
	Lifetime	**years**	50	50	50	50	50	50	
Hydro Run-of-River	**Capex**	**€/kW$_{e}$**	2560	2560	2560	2560	2560	2560	[78]
	Opex fix	**€/(kW$_{e}$ a)**	76.8	76.8	76.8	76.8	76.8	76.8	
	Opex var	**€/(kWh$_{e}$)**	0.005	0.005	0.005	0.005	0.005	0.005	
	Lifetime	**years**	50	50	50	50	50	50	
Geothermal power	**Capex**	**€/kW$_{el}$**	4970	4720	4470	4245	4020	3815	[78]
	Opex fix	**€/(kW$_{el}$ a)**	80	80	80	80	80	80	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	40	40	40	40	40	40	
Coal PP	**Capex**	**€/(kW$_{el}$)**	1500	1500	1500	1500	1500	1500	[80]
	Opex fix	**€/(kW$_{el}$ a)**	20	20	20	20	20	20	
	Opex var	**€/(kWh)**	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	40	40	40	40	40	40	
CCGT	**Capex**	**€/(kW$_{el}$)**	775	775	775	775	775	775	[80]
	Opex fix	**€/(kW$_{el}$ a)**	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	**€/(kWh$_{el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	35	35	35	35	35	35	
OCGT	**Capex**	**€/(kW$_{el}$)**	475	475	475	475	475	475	[78]

	Opex fix	**€/(kW$_{el}$ a)**	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	35	35	35	35	35	35	
Steam turbine (CSP)	**Capex**	**€/(kW$_{el}$)**	968	946	923	902	880	860	[81]
	Opex fix	**€/(kW$_{el}$ a)**	19.4	18.9	18.5	18	17.6	17.2	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	30	30	30	
Biomass PP	**Capex**	**€/kW$_{-el}$**	857	1019	1181	1343	1505	1668	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	51.5	48.4	45.3	42.2	39.1	36	
	Opex var	**€/(kWh$_{-el}$)**	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	
	Lifetime	**years**	25	25	25	25	25	25	
CHP NG Heating	**Capex**	**€/kW$_{-el}$**	880	880	880	880	880	880	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	74.8	74.8	74.8	74.8	74.8	74.8	
	Opex var	**€/(kWh$_{-el}$)**	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	**years**	30	30	30	30	30	30	
CHP Oil Heating	**Capex**	**€/kW$_{-el}$**	880	880	880	880	880	880	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	74.8	74.8	74.8	74.8	74.8	74.8	
	Opex var	**€/(kWh$_{-el}$)**	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	**years**	30	30	30	30	30	30	
CHP Coal Heating	**Capex**	**€/kW$_{-el}$**	2030	2030	2030	2030	2030	2030	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	46.7	46.7	46.7	46.7	46.7	46.7	
	Opex var	**€/(kWh$_{-el}$)**	0.005	0.005	0.005	0.005	0.005	0.005	
	Lifetime	**years**	40	40	40	40	40	40	
CHP Biomass Heating	**Capex**	**€/kW$_{-el}$**	3400	3300	3200	3125	3050	2975	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	97.6	94.95	92.3	90.8	89.3	87.8	
	Opex var	**€/(kWh$_{-el}$)**	0.0038	0.00375	0.0037	0.003725	0.00375	0.003775	
	Lifetime	**years**	25	25	25	25	25	25	
CHP Biogas	**Capex**	**€/kW$_{-el}$**	1463	1269	1074	880	685	491	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	65.1	56.2	47.3	38.4	29.5	20.7	
	Opex var	**€/(kWh$_{-el}$)**	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	30	30	30	30	30	30	
Waste incinerator	**Capex**	**€/kW$_{-el}$**	5630	5440	5240	5030	4870	4690	[78]
	Opex fix	**€/(kW$_{-el}$ a)**	253.4	244.8	235.8	226.4	219.1	211.0	
	Opex var	**€/(kWh$_{-el}$)**	0.007	0.007	0.007	0.007	0.007	0.007	
	Lifetime	**years**	30	30	30	30	30	30	
Biogas digester	**Capex**	**€/kW$_{-th}$**	811	784	755	725	702	676	[82]

	Opex fix	**€/(kW.th a)**	32.5	31.4	30.2	29	28.1	27	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	25	25	25	
Biogas upgrade	**Capex**	**€/kW.th**	322	300	278	255	244	233	[82]
	Opex fix	**€/(kW.th a)**	25.8	24	22.2	20.4	19.5	18.7	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
CSP (solar field. parabolic trough)	**Capex**	**€/kW.th**	344.5	303.6	274.7	251.1	230.2	211.9	[81], [83], [84]
	Opex fix	**€/(kW.th a)**	7.9	7	6.3	5.8	5.3	4.9	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	25	25	
Residential Solar Heat Collectors - Space Heating	**Capex**	**€/kW.th**	1214	1179	1143	1071	1000	929	[85]
	Opex fix	**€/(kW.th a)**	14.8	14.8	14.8	14.8	14.8	14.8	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	30	30	30	30	
Residential Solar Heat Collectors - hot water	**Capex**	**€/kW.th**	485	485	485	485	485	485	[85]
	Opex fix	**€/(kW.th a)**	4.85	4.85	4.85	4.85	4.85	4.85	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	
DH Electric Heating	**Capex**	**€/kW.th**	100	100	75	75	75	75	[85]
	Opex fix	**€/(kW.th a)**	1.47	1.47	1.47	1.47	1.47	1.47	
	Opex var	**€/(kWh.th)**	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	35	35	35	35	35	35	
DH Heat Pump	**Capex**	**€/kW.th**	660	618	590	568	554	540	[86]
	Opex fix	**€/(kW.th a)**	2	2	2	2	2	2	
	Opex var	**€/(kWh.th)**	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	**years**	25	25	25	25	25	25	
DH Natural gas Heating	**Capex**	**€/kW.th**	75	75	100	100	100	100	[86]
	Opex fix	**€/(kW.th a)**	2.775	2.775	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh.th)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	
DH Oil Heating	**Capex**	**€/kW.th**	75	75	100	100	100	100	[85]
	Opex fix	**€/(kW.th a)**	2.775	2.775	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh.th)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	
DH Coal Heating	**Capex**	**€/kW.th**	75	75	100	100	100	100	[85]

	Opex fix	**€/(kW.th a)**	2.775	2.775	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh.th)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	
DH Biomass Heating	**Capex**	**€/kW.th**	75	75	100	100	100	100	[85]
	Opex fix	**€/(kW.th a)**	2.8	2.8	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh.th)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	
DH Geothermal Heating	**Capex**	**€/kW.th**	3642	3384	3200	3180	3160	3150	[85]
	Opex fix	**€/(kW.th a)**	133	124	117	116	115	115	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	
Local Electric Heating	**Capex**	**€/kW.th**	100	100	100	100	100	100	[85]
	Opex fix	**€/(kW.th a)**	2	2	2	2	2	2	
	Opex var	**€/(kWh.th)**	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	30	30	30	30	30	30	
Local Heat Pump	**Capex**	**€/kW.th**	780	750	730	706	690	666	[78]
	Opex fix	**€/(kW.th a)**	15.6	15	7.3	7.1	6.9	6.7	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Local Natural gas Heating	**Capex**	**€/kW.th**	800	800	800	800	800	800	[85]
	Opex fix	**€/(kW.th a)**	27	27	27	27	27	27	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	
Local Oil Heating	**Capex**	**€/kW.th**	440	440	440	440	440	440	[85]
	Opex fix	**€/(kW.th a)**	18	18	18	18	18	18	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Local Coal Heating	**Capex**	**€/kW.th**	500	500	500	500	500	500	[85]
	Opex fix	**€/(kW.th a)**	10	10	10	10	10	10	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	
Local Biomass Heating	**Capex**	**€/kW.th**	675	675	750	750	750	750	[85]
	Opex fix	**€/(kW.th a)**	2	2	3	3	3	3	
	Opex var	**€/(kWh.th)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
	Capex	**€/kW.th**	800	800	800	800	800	800	[85]

Local Biogas Heating	**Opex fix**	**€/(kW$_{.th}$ a)**	27	27	27	27	27	27	
	Opex var	**€/(kWh$_{.th}$)**	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	
Water electrolysis	**Capex**	**€/kW$_{.H2}$**	803	586	446	381	347	313	[87]
	Opex fix	**€/(kW$_{.H2}$ a)**	28.1	20.5	15.6	13.3	12.1	11.0	
	Opex var	**€/(kWh$_{.H2}$)**	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	
	Lifetime	**years**	30	30	30	30	30	30	
Methanation	**Capex**	**€/kW$_{.CH4}$**	558	409	309	274	251	227	[87]
	Opex fix	**€/(kW$_{.CH4}$ a)**	25.7	18.8	14.2	12.6	11.5	10.4	
	Opex var	**€/(kWh$_{.CH4}$)**	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	
	Lifetime	**years**	30	30	30	30	30	30	
CO2 direct air capture	**Capex**	**€/t$_{CO2}$ a**	730	481	338	281	237	217	[88]
	Opex fix	**€/t$_{CO2}$ a**	29.2	19.2	13.5	11.2	9.5	8.7	
	Opex var	**€/t$_{CO2}$**	0	0	0	0	0	0	
	Lifetime	**years**	20	25	25	30	30	30	
Fischer-Tropsch Unit	**Capex**	**€/kW.FT$_{Liq}$**	1017	1017	1017	1017	915	915	[89]
	Opex fix	**€/kW.FT$_{Liq}$**	30.5	30.5	30.5	30.5	27.5	27.5	
	Opex var	**€/kWh.FT$_{Liq}$**	0	0	0	0	0	0	
	Lifetime	**years**	30	30	30	30	30	30	
Battery storage	**Capex**	**€/(kWh$_{el}$)**	234	153	110	89	76	68	[90]
	Opex fix	**€/(kWh$_{el}$ a)**	3.28	2.6	2.2	2.05	1.9	1.77	
	Opex var	**€/(kWh$_{.el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery interface	**Capex**	**€/(kW$_{el}$)**	117	76	55	44	37	33	[90]
	Opex fix	**€/(kW$_{el}$ a)**	1.64	1.29	1.1	1.01	0.93	0.86	
	Opex var	**€/(kWh$_{.el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery PV prosumer - residential storage	**Capex**	**€/(kWh$_{el}$)**	462	308	224	182	156	140	[85]
	Opex fix	**€/(kWh$_{el}$ a)**	5.08	4	3.36	3.09	2.81	2.8	
	Opex var	**€/(kWh$_{.el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery PV prosumer - residential interface	**Capex**	**€/(kW$_{el}$)**	231	153	112	90	76	68	[85]
	Opex fix	**€/(kW$_{el}$ a)**	2.54	1.99	1.68	1.53	1.37	1.36	
	Opex var	**€/(kWh$_{.el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
	Capex	**€/(kWh$_{el}$)**	366	240	175	141	121	108	[85]

Battery PV prosumer - commercial storage	**Opex fix**	**€/(kWh$_{el}$ a)**	4.39	3.6	2.98	2.68	2.54	2.38	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery PV prosumer - commercial interface	**Capex**	**€/(kW$_{el}$)**	183	119	88	70	59	53	[85]
	Opex fix	**€/(kW$_{el}$ a)**	2.2	1.79	1.5	1.33	1.24	1.17	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery PV prosumer - industrial storage	**Capex**	**€/(kWh$_{el}$)**	278	181	131	105	90	80	[85]
	Opex fix	**€/(kWh$_{el}$ a)**	3.89	3.08	2.62	2.42	2.25	2.08	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
Battery PV prosumer - industrial interface	**Capex**	**€/(kW$_{el}$)**	139	90	66	52	44	39	[85]
	Opex fix	**€/(kW$_{el}$ a)**	1.95	1.53	1.32	1.2	1.1	1.01	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	
PHES	**Capex**	**€/(kWh$_{el}$)**	7.7	7.7	7.7	7.7	7.7	7.7	[91]
	Opex fix	**€/(kWh$_{el}$ a)**	1.335	1.335	1.335	1.335	1.335	1.335	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	
PHES interface	**Capex**	**€/(kW$_{el}$)**	650	650	650	650	650	650	[91]
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	
A-CAES	**Capex**	**€/(kWh$_{el}$)**	75	65.3	57.9	53.6	50.8	47	[91]
	Opex fix	**€/(kWh$_{el}$ a)**	1.16	0.99	0.87	0.81	0.77	0.71	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	40	40	40	40	40	40	
A-CAES interface	**Capex**	**€/(kW$_{el}$)**	540	540	540	540	540	540	[91]
	Opex fix	**€/(kW$_{el}$ a)**	17.5	17.5	17.5	17.5	17.5	17.5	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	40	40	40	40	40	40	
Gas Storage	**Capex**	**€/(kWh$_{el}$)**	0.05	0.05	0.05	0.05	0.05	0.05	[92]
	Opex fix	**€/(kWh$_{el}$ a)**	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	**€/(kWh$_{-el}$)**	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	
	Capex	**€/(kW$_{th}$)**	100	100	100	100	100	100	[92]

Gas Storage interface	**Opex fix**	**€/(kW$_{th}$ a)**	4	4	4	4	4	4	
	Opex var	**€/(kWh$_{-th}$)**	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	
Hot Heat Storage	**Capex**	**€/(kWh$_{.th}$)**	41.8	32.7	26.8	23.3	21	19.3	[85]
	Opex fix	**€/(kWh$_{.th}$ a)**	0.63	0.49	0.4	0.35	0.32	0.29	
	Opex var	**€/(kWh$_{-th}$)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	30	30	30	
District Heat Storage	**Capex**	**€/(kWh$_{th}$)**	40	30	30	25	20	20	[85]
	Opex fix	**€/(kWh$_{th}$ a)**	0.6	0.5	0.5	0.4	0.3	0.3	
	Opex var	**€/(kWh$_{-th}$)**	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	30	30	30	
Hydrogen Storage	**Capex**	**€/(kWh$_{th}$)**	0.28	0.28	0.28	0.28	0.28	0.28	[92]
	Opex fix	**€/(kWh$_{th}$ a)**	0.01	0.01	0.01	0.01	0.01	0.01	
	Opex var	**€/(kWh$_{-th}$)**	0.00	0.00	0.00	0.00	0.00	0.00	
	Lifetime	**years**	30	30	30	30	30	30	
Hydrogen Storage interface	**Capex**	**€/(kW$_{th}$)**	100	100	100	100	100	100	[92]
	Opex fix	**€/(kW$_{th}$ a)**	4	4	4	4	4	4	
	Opex var	**€/(kWh$_{-th}$)**	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	
CO2 Storage	**Capex**	**€/ton**	142	142	142	142	142	142	[88]
	Opex fix	**€/(ton a)**	9.94	9.94	9.94	9.94	9.94	9.94	
	Opex var	**€/ton**	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	
	Lifetime	**years**	30	30	30	30	30	30	

Table A9: Efficiency and self-discharge rates of storage technologies.

Technology	Efficiency [%]	Self-Discharge [%/h]	Sources
Battery	90	0.0	[93]
PHES	85	0.0	[91]
A-CAES	70	0.1	[91]
TES	90	0.2	[93]
Gas storage	100	0.0	[93]