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ENERGY TRANSITION PATHWAYS FOR THE HIMALAYAN COUNTRIES NEPAL AND BHUTAN TOWARDS A SUSTAINABLE AND SECURE ENERGY SYSTEM FOR ALL BY 2050

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	Professor Lassi Linnanen
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ABSTRACT

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The Himalayan countries Nepal and Bhutan have been confronting similar climate change and energy emergency for quite a long time. Its influence can be felt as a barrier in financial, social, infrastructural, and political development. Despite having an enormous amount of renewable energy sources, these nations are unable to fulfil their current energy demand by local resources. Thus, depending on energy and fossil fuel imports from India. This study guides to a path of energy independency, energy for all and an energy transition towards a 100% renewable energy system. The modelling of the energy sector is done using the LUT Energy System Transition model for a period from 2015 to 2050 in a 5-year time step. This study covers the main energy sectors: power, heat, and transport. Two scenarios are visualized, one considering greenhouse gases (GHG) emissions and the associated mitigation cost and another without these costs, though both scenarios aim at achieving a high share of renewable energy by 2050. A substantial drop in levelized cost of energy is observed for a scenario without GHG emission cost, however, taxing GHG emissions will accelerate the energy transition with a LCOE on a similar level. It is well possible to transition from

90 €/MWh in 2015 to 49 €/MWh by 2050 for the entire energy system by utilizing indigenous low-cost renewable energy. The role of solar photovoltaics and hydropower is imminent in 2050, having a share of 67% and 31% respectively. Consequently, this leads to zero GHG emissions. An energy transition towards a sustainable and secure energy system for all by 2050 is well possible in Nepal and Bhutan only through 100% renewable sources and it is both technically and economically feasible despite having substantial limitations in infrastructure and economic development currently.

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Helsinki, 4 December 2020

Sanjeev Pathak

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Abbreviations

MAED	Model for Analysis of Energy Demand
LEAP	Long-range energy alternatives planning system
MARKAL	MARKet and ALlocation
A-CAES	Adiabatic compressed air energy storage
BPS	Best Policy Scenario
CCGT	Combined cycle gas turbine
FLH	Full load hours
GHG	Greenhouse gases
LCOE	Levelised cost of electricity
LCOC	Levelised cost of curtailment
LCOS	Levelised cost of storage
LCOT	Levelised cost of transmission
WACC	Weighted average cost of capital
CAPEX	Capital expenditure
OPEX	Operational expenditure
CHP	Combined heat and power
LUT	Lappeenranta-Lahti University of Technology (LUT)
TES	Thermal energy storage
PHES	Pumped hydro energy storage

1 INTRODUCTION

The sixth assessment report from the Intergovernmental Panel on Climate Change (IPCC) on impacts of global warming finds that warming in the South Asian region is expected to be higher than the global average (IPCC-Intergovernmental Panel on Climate Change, 2014). Consequently, resulting in changing monsoon patterns, rising sea levels, and melting glaciers drastically impacting the South Asian society. Nepal and Bhutan, two small countries situated on the Himalayan slopes, will be severely impacted by flooding due to glacier melt and irregular rainfalls; threatening the livelihood, food security, energy security, health and wellbeing across these nations (Climate and Development Knowledge Network, 2014). The impact of Nepal and Bhutan on global greenhouse gases (GHG) emissions is negligible, however, these countries are most vulnerable to climate change.

Nepal (93rd largest) and Bhutan (133rd largest) by size, are the south Asian Himalayan land-locked countries with an enclosed area of 147,181 km^2 and 38,392 km^2 respectively. The population density in Nepal is 196 inhabitants per square kilometre whereas only 20 inhabitants per square kilometre in Bhutan (World Bank, 2020a, 2020b). The general topography of these nations is rough mountainous and hilly terrain structure with a sparsely distributed population mainly residing in the rural areas. The People’s Republic of China borders the countries to the north and India on the east, south and west (Asian Development Bank, 2017). They have tiny economies compared to the emerging supergiant markets of India and China (Peter, 2018). The national population and housing census, which happens in every 10 years, conducted in Nepal in the year 2011 counted the total inhabitants and households in the nation as 26.5 million and 5.4 million respectively (Central Bureau of Statistics, 2012). According to the National Statistics Bureau of Bhutan (National Statistics Bureau, 2019), 735,553 inhabitants resides in Bhutan in which 37.8% lives in the urban areas (Dorji et al., 2019).

Nepal’s main primary energy source is from biomass which is around 80% followed by hydropower, coal and oil in 2014. Because of not having deposits of any petroleum products in the country except some lignite, all petroleum products are imported from India. Biomass mainly in the form of forest firewood, agricultural debris, and animal dung are used for cooking, lighting and heating purposes due to the lack of other alternative energy sources particularly in the rural areas and also because these are locally available sources. More than 84% of energy is consumed in residential sectors, followed by a 7% share in transport and 6% in the industry. The remaining share is consumed in commercial and public places and in the agriculture sector (Asian Development Bank, 2017). Similarly, in Bhutan, biomass in the form of fuelwood, biogas and briquettes dominates the primary energy source in 2015. The other important source, hydropower, mostly run-off-rivers fulfil most of the electricity demand in the country. The import of coal, diesel and other petroleum products from India fulfils the remaining primary energy demand (International Renewable Energy Agency (IRENA), 2019). The primary energy source mix in Nepal and Bhutan in presented in Figure 1.

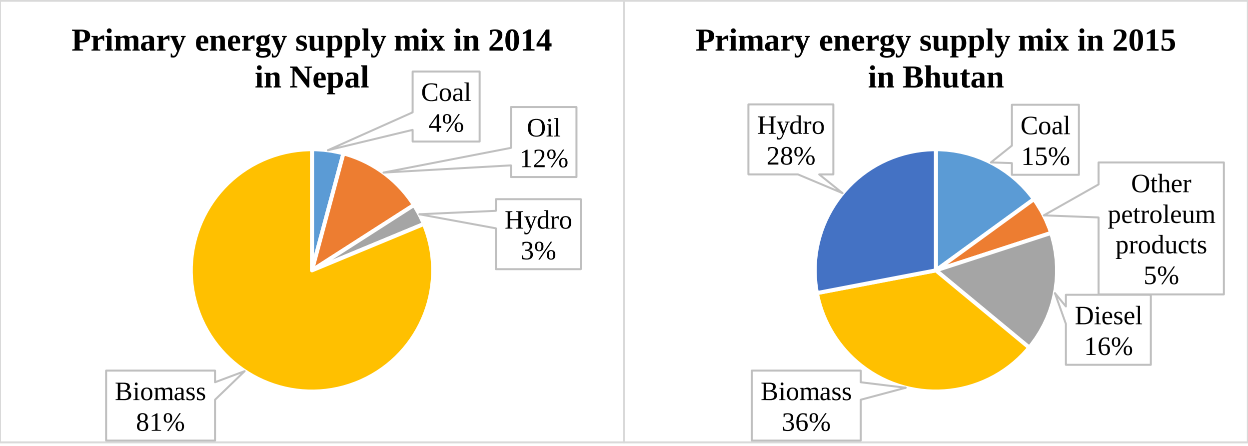

Figure 1: Primary energy supply mix in Nepal and Bhutan in 2014 and 2015 respectively (Asian Development Bank, 2017; International Renewable Energy Agency (IRENA), 2019).

Bhutan has a comparatively large share of the population, around 98% (Asian Development Bank, 2020), that has access to electricity, either by the national grid or from local generation. According to the Asian Development Bank (Asian Development Bank, 2017), in Nepal, the proportion of the population with access to electricity is around 85% in 2017, while it was only around 68% during the 2011 national census (Central Bureau of Statistics, 2012). The total hydropower installed capacity in Nepal by 2019 is 1,127 MW whereas 2,326 MW in Bhutan (International Hydropower Association, 2020). Bhutan’s main source of power is through run-off-rivers hydropower plants, and power generation is highly dependent on the seasons. Bhutan produced around 1500 MW power during its peak season and falls to as low as 300 MW during the winter due to a low run-off in the rivers in 2013 (Druk Green Power Corporation Limited, 2015; Jamtsho, 2015). And winter is the time when they need more power for heating purposes as well. To meet the ongoing demand for power, Bhutan imports electricity from neighbouring India whilst it exports surplus electricity to India during the high run-off in the rivers when electricity production is excess. Bhutan exports its green energy and imports electricity produced from coal and other fossil fuels (Jamtsho, 2015). Consequently, this has a negative influence on the overall energy trade balance and energy security. Bhutan's increasing GDP per capita, which is around three times higher than that of Nepal (Ogino, Nakayama and Sasaki, 2019), and expeditious urbanisation has altered the lifestyles of Bhutanese people. This has led to more motor vehicles in the country and accounts for 18.6% of total energy consumption in 2014 (Kamei et al., 2020), which is 1.2 TWh. Bhutan has acknowledged the transport sector importance and increasing energy demand in the future. Thus, Bhutan introduced the 'Transport Vision 2040' which constitutes nine transport strategies which are road network, civil aviation, intercity passenger transport, freight transport, regional connectivity, urban transport, road safety, road transport regulation and transport sector management (Asian Development Bank, 2013). Moreover, future plans include the ways for transport-based GHG emission reduction and vehicles switching to renewable fuels and electric vehicles (National Environment Commission, 2012). Similarly in Nepal, to address the aggressive increase of transport sector in the future, Nepal Government set up 'Environment-Friendly Vehicle and Transport Policy Issue' in 2014 which targets to have at least 20% of total vehicle fleet be environment friendly vehicles, including electric vehicle. Also, a national sustainable transport strategy (2015-2040) is initiated to lower down the GHG emissions by vehicles. Hydrogen as a potential fuel is also being studied in the country (Zhou, Zhou and Manandhar, 2020). Currently, due to a lack of fossil fuel reserves in the country, Nepal and Bhutan heavily rely on expensive petroleum product imports from India (Alam et al., 2019). Specifically, Nepal has been importing oil products, coal and electricity from India since the last 40 years. State-owned Indian Oil Corporation supplies petroleum products at Indian market rate. Nepal's petroleum storage facility can hold stock upto 20 days of national demand, which is comparably limited compared to 270 days in Israel or 240 days in the Republic of Korea (Asian Development Bank, 2017). This shows Nepal's extreme vulnerability in the transport industry.

Environmentally-friendly renewable energy (RE) sources can be of significant importance in modern economies, which are confronted with issues of supplying sustainably enough energy along with accessibility for all (Chica-Olmo, Salaheddine and Moya-Fernández, 2020). Chien and Hu (Chien and Hu, 2007) concluded for 45 countries that the development of renewable energy may help in elevating country's economy and alternatively, economy may decrease with the usage of conventional fossil fuels. Nepal and Bhutan are blessed with bountiful water sources as the snowmelt from the mountains flow from north to south. The high to low topography from north towards south and continuously flowing snowmelt rivers are the means for electricity generation. Hydropower dominates electricity generation, though other means of RE-based energy generation is also available and possible. There is a commercially exploitable potential of 26,760 MW and 42,000 MW of clean hydropower extraction in Bhutan and Nepal respectively, but only 1,614 MW and 856 MW hydropower is extracted in 2016 (Asian Development Bank, 2017; International Renewable Energy Agency (IRENA), 2019). Besides hydro resources, both these Himalayan countries are rich in other renewable resources. Solar photovoltaic (PV) is also very promising in Nepal as there are on average 300 sunshine days per year with solar irradiation ranging between 1080 - 1860 kWh/(m2·a) (Adhikari, Bhattarai and Gurung, 2013). Satellite maps show the solar radiation varies in Bhutan from 1600 – 2700 kWh/(m2.a) (IRENA, 2019). This makes solar PV a promising and lasting source of energy for Nepal and Bhutan (Nepal, 2012; Poudyal et al., 2019). Unfortunately, these two countries have not been able to harness green energy with respect to its resource availability. Development of more RE technologies is the utmost way for Nepal and Bhutan to be energy independent. Thus, this paper acts as an imperative tool to expedite new pathways towards fully sustainable 100% RE-based self-sufficient energy system for Nepal and Bhutan.

According to the International Energy Agency (IEA) (International Energy Agency (IEA), 2016a), energy, air pollution and health issues are interconnected to each other. Avoiding conventional fuels, and utilising indigenous RE sources towards a sustainable transition could help lower air pollution and eventually lower air pollution borne health hazards (Poudyal et al., 2019; Galimova, Ram and Breyer, 2021). However, usage of biomass as cooking means is being practiced by around 3 billion people around the world and are subject to indoor air pollution which emits harmful gases (Putti et al., 2015; Clements et al., 2020) and also they pollute climate once they mix up in the atmosphere (Shindell et al., 2012; Rupakheti et al., 2019). The majority of people in rural areas of Nepal and Bhutan, mostly women and children are no exception to it. Just only in 2013, there were 15,000 premature deaths in Nepal because of the air pollution from cooking with solid fuels (Forouzanfar et al., 2015; Rupakheti et al., 2019). Table 1 shows the general power sector statistics of Nepal and Bhutan (Ogino, Dash and Nakayama; Bhutan Power Corporation Limited, 2016; Nepal Electricity Authority, 2016; Bhutan Electricity Authority, 2017).

Table 1: Power sector and country data for Bhutan and Nepal.

	Bhutan	**Nepal**
Estimated hydropower potential (MW)	50,000	84,000
Economically feasible hydropower potential (MW)	26,760	43,000
Installed generation capacity (MW) (2016)	1614	856
Peak power demand (MW) (2016)	336	1385
Electrification ratio (%) excluding off-grid supply (2015)	97	53
Average electricity retail tariff (USD cent/kWh) (2015)	3.7	8.4

The bitter truth prevails for Nepal and Bhutan as they lack proper sustainable energy system. Despite having an abundance of RE resource, such as hydro, solar, and biomass (Ahamad and Tanin, 2013; Shahi, Rijal and Shukuya, 2020), due to multiple reasons, it has not been successful in harnessing those energy sources. Particularly in Nepal, issues of energy poverty and energy injustice are critical and persistent problems. Lack of proper management in every sector and inefficient energy distribution triggers more energy problems. The ongoing or upcoming energy projects are delayed by months and years due to the improper handling and lack of technical expertise. Nepalese people suffered on average 90 hours of power blackout weekly during 2011-2016 because of insufficient power generation (Kumar Ramesh, 2018). Also, a major 7.8 Richter scale magnitude earthquake in 2015 disrupted the entire energy system causing landslides and floods which destroyed poorly built hydropower plants. On top of that, intergovernmental political hurdles between Nepal and India in 2015-2016 created an unofficial blockade by India, which led to a cease in the supply of petroleum products in Nepal (Underwood, Hill and Lamichhane, 2020). This created chaos in Nepal's transport sector. These examples show how vulnerable Nepal's energy sector is. The general causes of energy problems in developing countries is shown in Figure 2 alla.

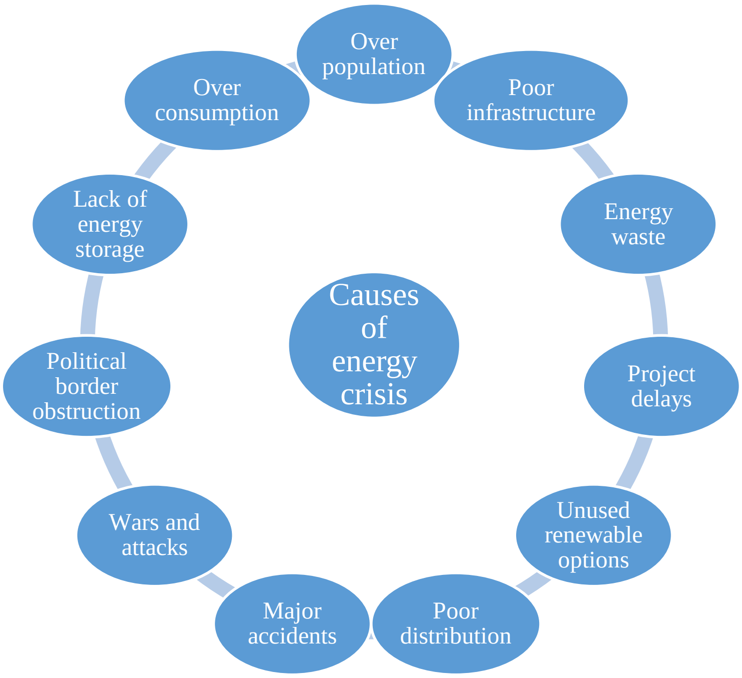

Figure 2: The general causes of energy problems in developing countries (Poudyal et al., 2019).

For Nepal and Bhutan, there have been very limited studies conducted previously regarding the full energy transition possibilities during the past years. Table 2 alla outlines the selected few studies and their key findings. However, none of these studies is in relevance to this study approach, as this study is based on an hourly resolved model for the whole year, which guarantees a sense of reality and accuracy. Also, this study is further assessed in sub-regions to analyse the grid transmission cost structure, which is an essential perspective to breakdown the need for energy storage and its costs. This study deals with the energy transition of power, heat and transport sectors.

Table 2: List of studies conducted on several future energy demands and RE systems for Nepal and Bhutan.

Study	Scope	Key findings
Water and Energy Commission Secretariat, Government of Nepal (Water and Energy Commission Secretariat, 2017)	Nepal	Electricity demand projection throughout 2015-2040 based on MAED considering 3 different scenarios, i.e. (1) Business as usual, current 4.5% GDP growth rate (2) Reference, 7.2% GDP growth rate and (3) High growth, 9.2% GDP growth rate. Total final electricity demand projection reaches to 43.0 TWh, 66.1 TWh and 94.9 TWh respectively by the year

		2040. The share in energy consumption during 2014/15 is through fuelwood, renewables sources, electricity, petroleum, coal, cow dung and agriculture residue which shares to 70%, 3%, 3%, 13%, 4%, 4% and 3% respectively.
Shakya (Shakya, 2016)	Kathmandu, Nepal	A study on GHG mitigation specifically for Kathmandu city using the LEAP framework over a period of 19 years (2012-2030). Six different scenarios are considered in the study. The study concludes that, relative to the base case scenario in 2030, the impact of adopting different low carbon development strategy options will eliminate 35.2% of overall GHG emissions from energy usage. On top of GHG emissions reduction, results also focus on energy security and the economic cost of GHG mitigation. During the year 2030, the final energy consumption is mostly through electricity, diesel, biomass which accounts for 16%, 15% and 14% respectively. The remaining shares is fulfilled by petroleum products, coal and solar.
Yangka & Diesendorf. (Yangka and Diesendorf, 2016)	Bhutan	A MARKAL model framework study on the benefits of electric cooking over traditional kerosene and firewood cooking from the year 2005 to 2040. The fuel share in total primary energy supply in 2005 is mostly from biomass (58%), followed by hydropower (16%), diesel and petrol (14%), coal (7%), kerosene & LPG (4%) and other (1%). The study highlights the socio-economic impacts on the livelihood and emissions reductions of CO_2, SO_2 and NO_x by 17%, 12% and 8% respectively by the year 2040.

2 METHODOLOGY

The objective of this research is to analyse all sector energy transition pathways towards a 100% RE-based system for the Himalayan countries Nepal and Bhutan. The LUT Energy System Transition model is applied on an hourly temporal resolution from 2015 to 2050 at an interval of every 5 years. An exogenous model for self-generation and consumption of power and heat for residential, commercial, and industrial consumers is also simulated on the above-mentioned temporal resolution. A detailed description of the model, input data, technical and financial assumptions and various constraints is described in the following.

2.1 LUT Energy System Transition model overview

The LUT Energy System Transition Model (Bogdanov et al., 2019, 2020)is a linear optimisation tool, which models a transition of the integrated power, heat and transport sectors on an hourly time scale for every 5-year time step from 2015 to 2050, under given specific constraints. For a given integrated energy system, the model defines an optimal cost structure and operation modes for each of the energy system's elements to give a least optimal cost. The hourly time scale increases the reliability of the results, as it takes into consideration that for every hour of a year, demand and supply matches. However, this increases the computation time for every time step. The target function of the optimisation is minimisation of the total cost of the system calculated as the sum of the annual capital and operational expenditures, including ramping costs, for all the considered technologies in the modelling as given in Equation 1. The reference year for this study was chosen as 2015, due to unavailability of all the input data for the year 2020.

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

Abbreviations are for CAPEXt - Capital cost of each technology; crft - capital recovery factor for each technology, OPEXfix,t - fixed operational cost for each technology, OPEXvar,t - variable operational cost each technology, instCapt,r - installed capacity in a region, Egent,r - electricity generation by each technology, rampCostt - ramping cost of each technology, totRampt,r - annual total power ramping values for each technology, reg - region, and tech – technology.

The individual residential, commercial and industrial prosumers can install their own rooftop PV systems and heating technologies as part of self-generation of electricity and heat. These heating technologies based on electricity or fuels satisfy the demand for hot water and space heating. The electricity storage for these prosumers is based on lithium-ion batteries. These prosumers can purchase in times of low generation or sell surplus electricity to the distribution grid in order to fulfil their power demand. Minimisation of the cost of consumed electricity and heat is the target function of the prosumers. This cost is calculated as a sum of power, heat and storage capacities' annual cost, cost of consumed fuels for heating, cost of purchased electricity from the grid minus profit earned on selling excess electricity to the grid.

Some of the important constraints used in the modelling of the energy system and prosumers: First, a restriction on the installation of new coal, oil and nuclear-based power plants after the starting period. Therefore, power plants which are planned or in the construction phase after the starting period are not considered in this study. However, gas turbines can be installed as they can be operated by fuel switching from fossil gas to synthetic gas. Second, no more than 20% of the total installed capacity share can be changed in any 5-year time step to avoid excessive RE capacities installation in a single time step which would lead to disruption of the power system. Third, if profitable, share of prosumers can progressively increase from 3% in 2015 to 20% in 2050.

The general flow of the LUT model from data preparation to the results and evaluation is shown in Figure 3, while a detailed description of the model can be found in Bogdanov et al. (Bogdanov et al., 2019, 2020).

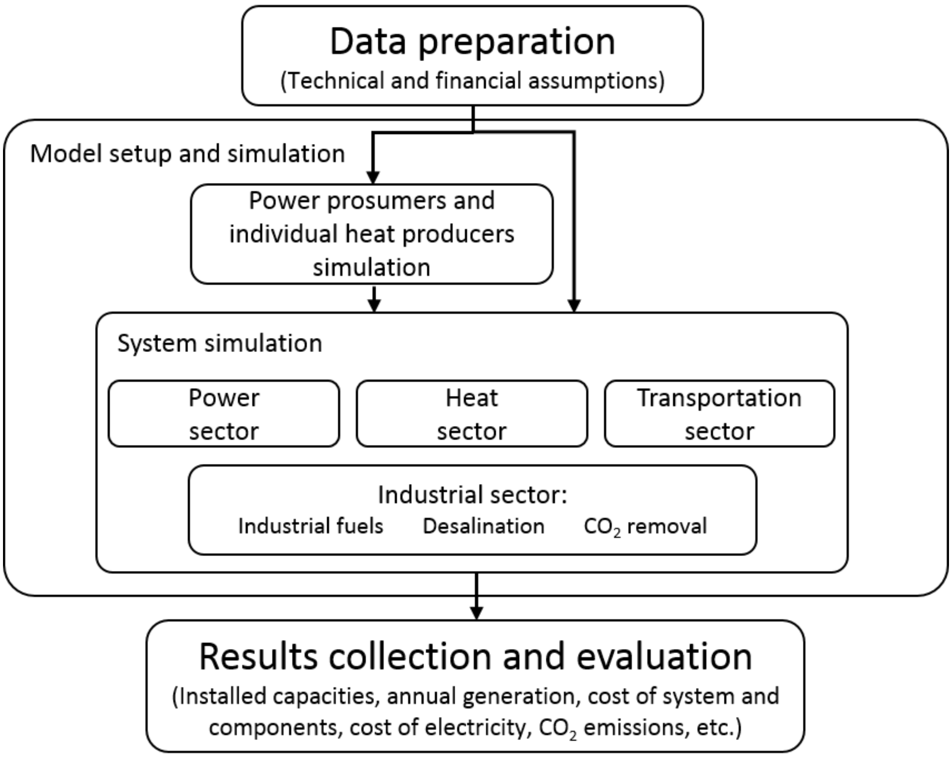

Figure 3: Process flow diagram of the model input data, optimisation, and results.

2.2 Assumptions used in the modelling

The parameters and baseline assumptions for the core analysis of the energy system are briefly explored in this section. The financial and technical assumptions used in the study are given in section **Error! Reference source not found.** and section **Error! Reference source not found.**, respectively. The final section provides the demand growth in all sectors and the applied technologies.

2.2.1 Sub-regions and grid transmission

The sub-division of Nepal is done based on the provincial states, which are 7 regions. The districts which lie under each province are mentioned in Table 3. Bhutan is taken as an individual region, due to its comparatively smaller area. The sub-division to the level of provinces enables high spatial resolution of the individual state’s RE generation potential, consumption pattern and transmission. On top of that, it also facilitates in analysing the energy storage needs for future use. The grid transmission network is assumed to be connected to each of the provincial headquarter, with

Kathmandu as the main consumption center in Nepal as shown in Figure 4. In Bhutan, Thimphu is the main consumption center. The connections between the provinces is assumed to be HVAC and within the provinces, it is assumed that the existing and future grid expansions will supply electricity to all end-users.

Population in Nepal and Bhutan in 2015 and projected population at every 5-year interval till 2050 is tabulated in the Appendix table S1.

Table 3: Distribution of districts by provincial states in Nepal.

States	Districts
Province 1	Taplejung, Panchthar, Illam, Jhapa, Morang, Sunsari, Dhankuta, Tehrathum, Sankhuwasabha, Bhojpur, Solukhumbu, Okhaldhunga, Khotang, Udaypur.
Province 2	Saptari, Siraha, Dhanusha, Mahottari, Sarlahi, Rautahat, Bara, Parsa.
Province 3	Sindhuli, Ramechhap, Dolakha, Sindhupalchowk, Kavrepalanchowk, Lalitpur, Bhaktapur, Kathmandu, Nuwakot, Rasuwa, Dhading, Makawanpur, Chitwan.
Province 4	Gorkha, Lamjung, Tanahun, Syangja, Kaski, Manang, Mustang, Myagdi, Parbat, Baglung, Nawalparasi (East of Bardghat)
Province 5	Nawalparasi (West of Bardghar), Rupandehi, Kapilbastu, Palpa, Argakhanchi, Gulmi, Pyuthan, Rolpa, Dang, Banke, Bardiya, Rukum (East).
Province 6	Rukum (West), Salyan, Surkhet, Dailekh, Jajarkot, Dolpa, Jumla, Kalikot, Mugu, Humla.
Province 7	Bajura, Bajhang, Aachham, Doti, Kailali, Kanchanpur, Dadeldhura, Baitadi, Darchula

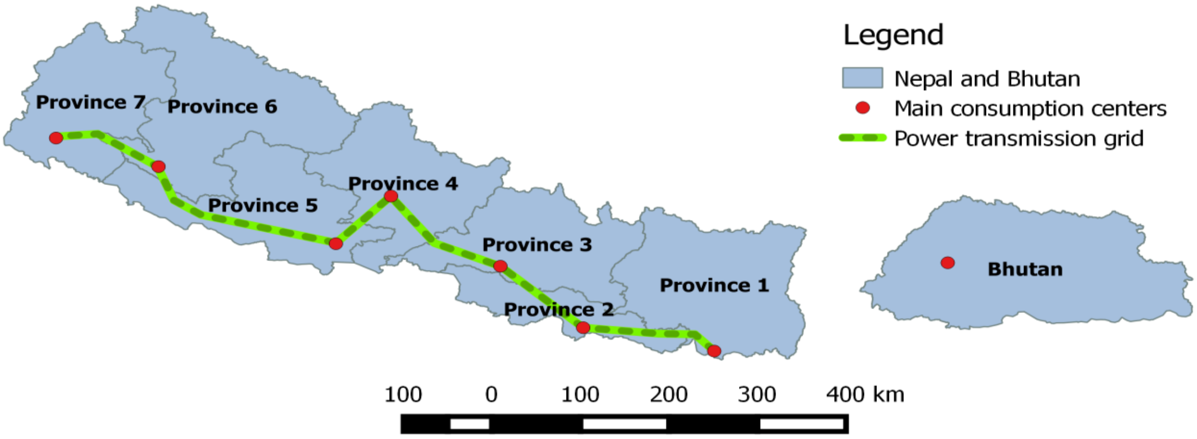

Figure 4: 7 Provincial states of Nepal and Bhutan, linearly inter-connected grid structure.

2.2.2 Financial assumptions

The various financial assumptions related to capital expenditures (CAPEX) and operating expenditures (OPEX fixed and variable) for all technologies, applied during the energy transition for Nepal and Bhutan are shown in the Appendix Table S8. The weighted average cost of the capital (WACC) is set to 7% for all RE technologies whereas a WACC of 4% is considered for the residential PV rooftop prosumers due to associated lower risk and hence lower financial return expectations. Due to the unavailability of country-specific cost projection data, financial projections were assumed based on a global average for all technologies. The cost reduction in most RE-based technologies is following a downward curve globally and it results in a continued RE-based technologies capacity installation in the future (Fasihi, Bogdanov and Breyer, 2016; Schmidt et al., 2017). The price of raw materials and new installations are anticipated to lower down until 2050 due to technology developments and production upgrades. In addition to the electricity generation technologies, the capacity boom and decreasing cost of battery storage has set off a quick ascent in capacity installations in many nations (Nykvist and Nilsson, 2015; Schmidt et al., 2017).

The price of electricity for three prosumer categories i.e. residential, commercial, and industrial, in the year 2015 were assumed from (Nepal Electricity Authority, 2016; Bhutan Electricity Authority, 2017; Ogino, Nakayama and Sasaki, 2019). Based on the methods developed by Breyer and Gerlach (2013), the future electricity price until 2050 was projected. The cost assumptions of the applied energy system technologies for Nepal and Bhutan are tabulated in the Appendix table S8.

2.2.3 Technical assumptions

The technical lifetime and efficiencies of all applied technologies can be found in Appendix Table S8 and S9. The installed capacities till end of 2014 for hydropower and fossil fuels are taken from [51]. and assumed that they will be utilised till their technical lifetime and then decommissioned. The calculation of upper limits for solar and wind is described in the next sub-section, while the economically exploitable hydropower potential is assumed from [34–37].

2.2.4 Resource potential and input profiles

For the modelling, as an input, hourly capacity factor profiles for an entire year of solar PV, wind energy and hydropower were used. Solar PV was divided into optimally tilted PV, single-axis tracking PV and solar CSP. As for wind energy only, wind onshore is considered. The raw data is for the year 2005 from NASA databases (Stackhouse and Whitlock, 2008, 2009) by German Aerospace Center (Stetter, 2014) and having a resolution of 0.45° x 0.45°. These data are further processed to calculate hourly capacity factor profiles as described in Bogdanov and Breyer (Bogdanov and Breyer, 2016) and Afanasyeva et al. (Afanasyeva, Bogdanov and Breyer, 2018). A monthly resolved river flow data for 2005 is used to prepare hydropower capacity factor profiles as a normalised sum of the river flow throughout the country.

The biomass potential was divided into three categories: solid wastes (municipal waste and waste wood), solid residues (waste from agriculture and forestry), and biogas (biowastes, manure and sludge). The raw data on the biomass and waste resources were obtained from Food and Agricultural Organisation of the United Nations. The potentials were calculated according to the methods described in Mensah et al. (Mensah, Oyewo and Breyer, 2020). The cost calculations for the three biomass categories were done according to the data from International Energy Agency (IEA-International Energy Agency, 2012) and Intergovernmental Panel on Climate Change (IPCC-Intergovernmental Panel on Climate Change, 2011). For solid fuels, a 50 €/ton gate fee is assumed for 2015, increasing to 100 €/ton for the year 2050 for waste incineration plants and this is reflected as negative costs for solid waste (Sadiqa, Gulagi and Breyer, 2018). The geothermal energy potential in Nepal and Bhutan is calculated according to the method described in Aghahosseini et al. (Aghahosseini, Bogdanov and Breyer, 2017).

The installed capacities for generation technologies in 2015 were taken from Farfan and Breyer (Farfan and Breyer, 2017) and Department of Electricity Development (Government of Nepal, 2020). The potential (upper limits on installed capacities) for solar PV and wind were calculated based on a criterion that the total land area availability should not exceed 6% and 4%, respectively.

2.2.5 Demand Projection

The 2015 electricity demand for the 7 provinces in Nepal and Bhutan was calculated based on the electricity demand per capita and population (Lhendup et al., 2015; National Statistics Bureau, 2015; UNFPA Nepal, 2017; Water and Energy Commission Secretariat, 2017). The demand for each of the future time steps was calculated based on different growth rates during the transition period. The electricity demand for Nepal was extrapolated using growth rates of 15.1%, 12.2%, 10.2%, 9.6% and 9.5% till 2050, while for Bhutan a growth rate of 11.9% was assumed till 2030 and after that, a growth rate similar to Nepal was assumed (Department of Renewable Energy, 2016). The heat demand from 2015 to 2050 was taken from Ram et al. (Ram et al., 2019). The final electricity and heat demand during the transition for Nepal and Bhutan are given in Appendix Table S2. The final power sector excludes direct electricity used in heat and transport sectors.

The hourly load profile for electricity and heat for the provinces in Nepal was calculated as a fraction of the total demand in the country, while for Bhutan country profiles were used. The synthetic load profiles are taken from Toktarova et al. (Toktarova et al., 2019), while for the space heating, domestic hot water, biomass for cooking, and industrial heat profiles are taken from Ram et al. (Ram et al., 2019). Currently, there are no district heating networks in Nepal and Bhutan and it is assumed that this status will not change until the end of the transition period.

The main transport modes in Nepal and Bhutan are road and aviation. There is one railway line in Nepal, which was assumed in this study and further projected that the demand for rail will increase in the future, due to growth in population and demand for a faster mode of transport. The total transport demand for Nepal was divided on a sub-region level based on relative population for road, rail and aviation transport modes. These individual transport modes were further sub-divided into passenger (p-km) and freight (t-km) demands. The road passenger transport segregated into light-duty vehicles (LDV), buses (BUS) and 2-3 wheelers (2/3W), while freight transport was divided into medium-duty vehicles (MDV) and heavy-duty vehicles (HDV). The different fuel demand from these transport modes and several vehicle types were assumed according to Khalili et al. (Khalili et al., 2019) and is shown in Appendix Table S25 and S26.

2.2.6 Applied technologies

An overview of the energy system presenting the relevant technologies for the power, heat and transport is provided in Figure 5. The technologies can be classified according to the electricity generation from RE and fossil fuels; heat generation from RE and fossil fuels; road, rail, marine and aviation transport modes; energy storage for electricity, heat and fuels and electricity transmission using High Voltage Alternating Current (HVAC).

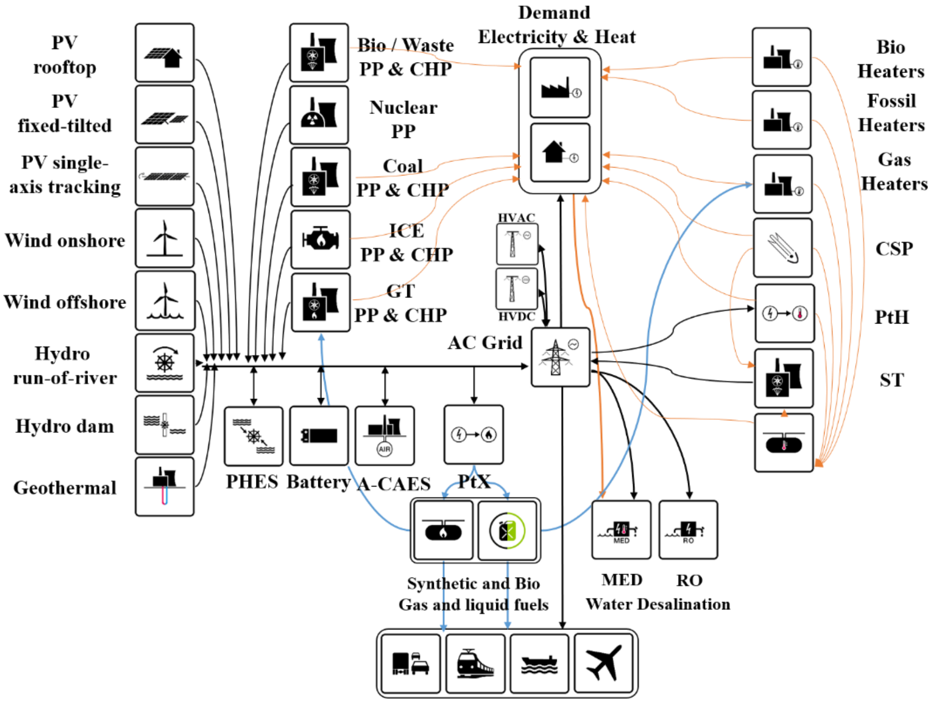

Figure 5: Lappeenranta-Lahti University of Technology (LUT) Energy System Transition model's schematic diagram for power, heat and transportation. (Bogdanov et al., 2021).

2.2.7 Applied scenarios for the energy transition

For this study, transition pathways towards high shares of RE for integrated power, heat and transport sectors is showcased for two scenarios. A Best Policy Scenario (BPS-1) with GHG emission cost and a Best Policy Scenario (BPS-2) without GHG emission cost (BPS-2). Based on the overall system cost and GHG emissions reduction, these scenarios focus on two policy options, leading to an energy transition in Nepal and Bhutan. Table 4 provides a detailed description of the scenarios and specific assumptions made in each of the scenarios.

Table 4: Detailed description of two applied scenarios.

Scenario	**Description**
Best Policy Scenario (BPS-1)	Achieving a 100% RE system with a least cost and zero GHG emissions by the end of the transition period is the primary target. To reach the target, certain assumptions were made. First, no new fossil fuel capacities were allowed to be installed after the year 2015, with the exception of gas turbines. Meanwhile, phased-out fossil capacities are allowed to be replaced by renewables and storage technologies. This results in no fossil fuel imports from other countries. Second, an assumption was made that there will be pricing for GHG emissions. The GHG emissions cost would be 9€ per ton of CO_2 in the starting year 2015 which would gradually increase to 28€, 53€, 61€, 68€,75€ 100€ and finally 150€ per ton of CO_2 in the five-year interval of 2020, 2025, 2030, 2035, 2040, 2045 and 2050, respectively. Third, the total installed capacity share cannot grow more than 20% in any 5-year time step to avoid excessive RE capacities installation in a single time step. This scenario includes the potential role of prosumers (electricity and heat self-consumption), with rooftop PV-based electricity generation and the possibility to install batteries during the transition period. This is applied for residential, commercial, and industrial customers. Furthermore, prosumers can sell the excess electricity to the grid, after fulfilling their

	own demand, at a price of 0.02 €/kWh, however, no more than 50% of their own generation.
Best Policy Scenario (BPS-2) without GHG emission cost	This scenario is assumed to be identical to the BPS-1 with an exception that the cost of the GHG emissions is not taken into consideration for the entire transition period. Currently, Nepal and Bhutan do not have any GHG emissions costs and there is no evidence from the government that any costs will be applied soon. The main idea behind this scenario development is to see the cost competitiveness of RE-based solutions compared to fossil fuel options. Moreover, this scenario does not limit fossil fuel usage.

3 RESULTS

The results obtained by applying the LUT model are presented in the following.

3.1 Primary energy demand during the transition

This section deals in detail with each type of electricity generation technology in BPS-1 and BPS-2. Figure 6 shows the total primary energy demand by sector for the transition years from 2015 to 2050. The share of the primary energy demand varies largely during the years from as low as 100 TWh to as high as 480 TWh in 2015 and 2050, respectively. The highest share is from the heat sector which is almost 61% in 2015 which shrinks to around 20% by the year 2050. The transport share remains quite stable during the period. The main changes happen with the power sector which is just under 20% in 2015 and rises to around 65% in the year 2050. The increase in population from 28.70 million in 2015 to 46.45 million in 2050 and corresponding per capita energy use is the reason behind such massive growth.

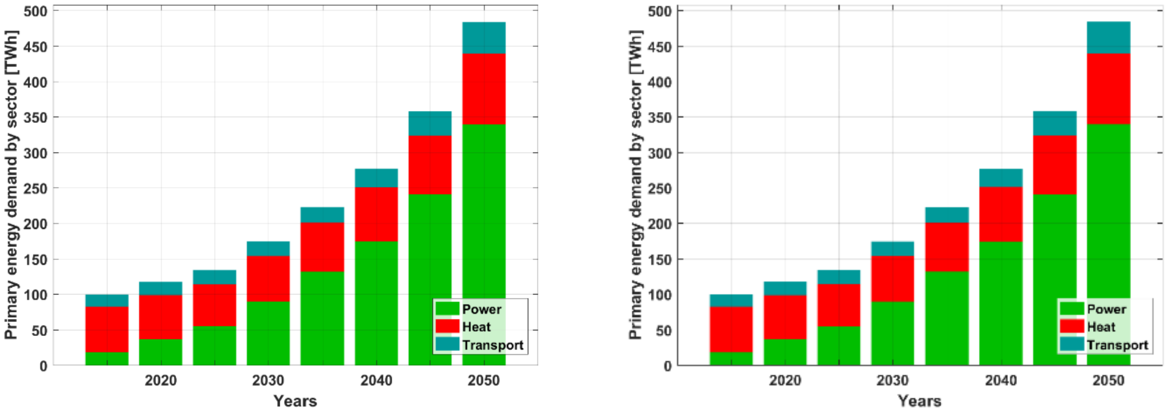

Figure 6: Primary energy demand for power, heat and transport sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

Figure 7 shows the total primary energy demand by the primary energy source during the transition period in both scenarios. During the transition, the share of fossil fuels in the primary energy demand decreases to zero in 2050 in the BPS-1. Even though with no GHG emissions cost in the BPS-2, a downward trend in fossil fuel use is observed, however, it is not completely eliminated in 2050. The decrease in fossil and bioenergy share is compensated by electricity as a primary energy form which increases during the transition as it forms the backbone of the entire energy system. In the BPS-1, the share of electricity grows exponentially from 11% in 2015 to 77% by 2050. Consequently, the share of other sources, especially, bioenergy and fossil fuel shrink from around 89% in 2015 to around 19% in 2050.

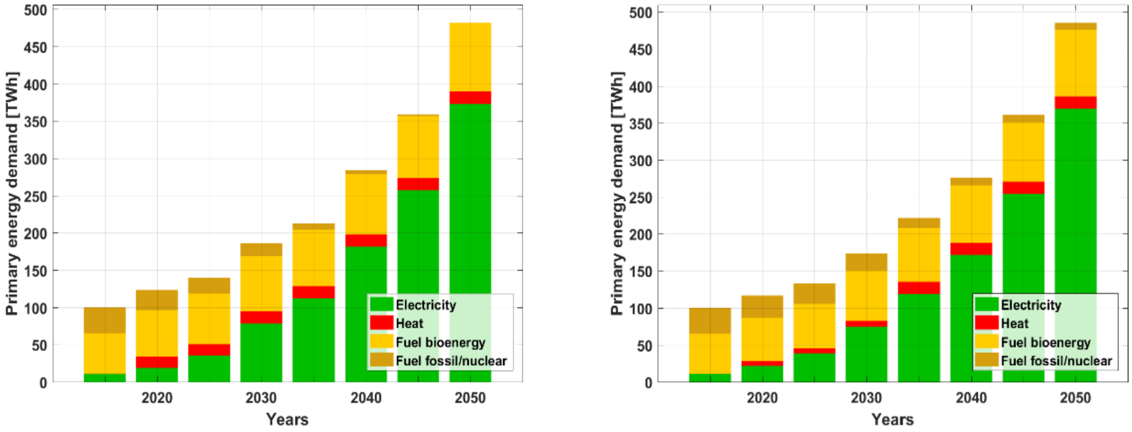

Figure 7: Primary energy demand by energy form for the BPS-1 (left) and BPS-2 (right) throughout the transition period 2015 to 2050.

Figure 8 shows the vital role of direct and indirect electrification, in reducing the total primary energy demand in the two scenarios. In the BPS-1 and BPS-2, proceeding with the current energy system having low electrification, the total primary energy demand would increase exponentially to reach 916 TWh and 858 TWh in 2050 respectively, from 100 TWh in 2015, which is around 815% increase in the BPS-1 and 760% increase in the BPS-2. However, an energy system with high levels of electrification would limit the primary energy demand to only 484 TWh by the year 2050 for both BPS-1 and BPS-2, which is only around 380% increase. This increase in total primary demand is in accordance with the corresponding population, GDP and standard of living growth in Nepal and Bhutan. An aggregate of around 61.7% population increment in 2050 is estimated in comparison to the population in 2015. A 100% renewable resource-based energy supply and high direct and indirect electrification in the power, heat and transport sectors ensure the energy system to be highly efficient compared to the current fossil fuel-based energy system by the end of the transition period in 2050.

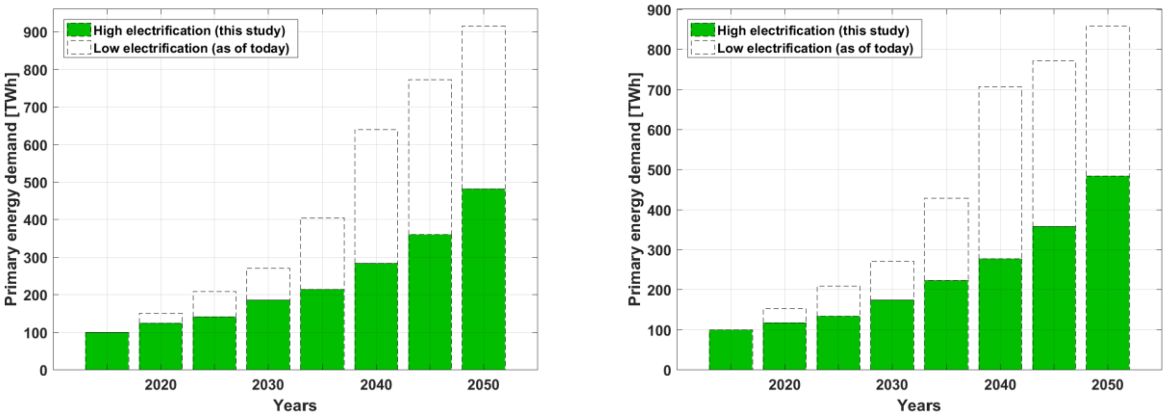

Figure 8: Efficiency gain in primary energy demand with low and high electrification in the BPS-1 (left) and BPS-2 (right) during the transition years.

3.2 Installed capacities and electricity generation

Figure 9 shows a steep increase in the installed capacities dominated by RE-based resources in the BPS-1 and BPS-2. The share of PV is prominent in a fully RE system in 2050 due to its cost competitiveness and excellent resource availability. Mostly, solar PV dominates the entire energy system starting from the year 2030 to fulfil the future energy demand. Hydropower followed by biogas related electricity compliments the energy deficit during periods of low solar irradiation in both scenarios.

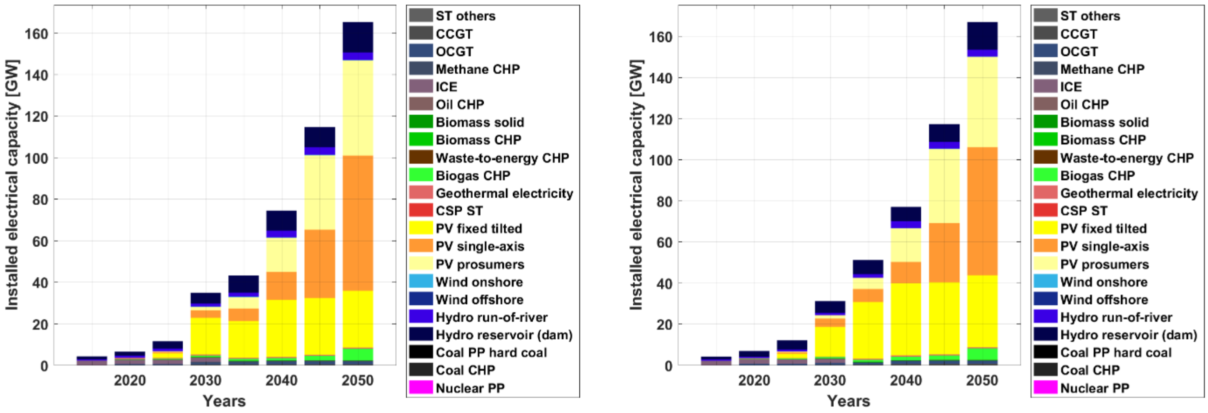

Figure 9: Cumulative installed capacities for all power generation technologies from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

The total electricity generation in the Himalayan countries to cover the demand for power, heat and transport is 382 TWh in the BPS-1 and 379 TWh in the BPS-2. Figure 10 shows the total electricity generation in the BPS-1 and BPS-2 based on different technologies. However, it can be clearly seen that solar PV forms the backbone of electricity supply, complemented by hydropower. With more than 80% dependency on hydropower in 2015, with the remaining contributed by imported electricity assumed to be from fossil fuels, there is a transition away from the present hydropower-based supply towards embracing solar PV during the period 2025 to 2050. The shares of other RE sources like wind and geothermal energy play a minor role in the final electricity generation in 2050. Due to the unavailability of fossil fuel and coal reserves, the share of it is negligible in the electricity generation in 2015. Despite having abundant hydropower as a major electricity generation source since decades, hydropower is overturned by solar PV because of its extremely low cost, high modularity and fast installation time in comparison to hydropower. Thus, solar PV accounts to around 67% share in 2050, followed by around 31% hydropower in the BPS-1. The remaining share is contributed by wind energy, geothermal energy, bioenergy.

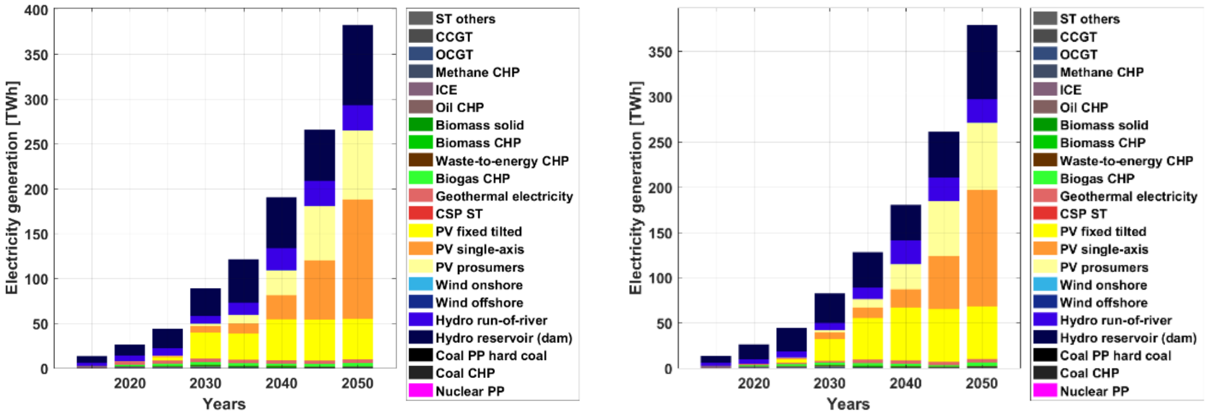

Figure 10: Technology-wise electricity generation in the BPS-1 (left) and BPS-2 (right) during the transition period.

As mentioned earlier in Section **Error! Reference source not found.**, the modelling of the energy system for Nepal was done by further sub-dividing the country into provinces to analyse their detailed energy structure. Figure 11 and Figure 12 shows detailed installed capacities and electricity generation according to the provinces for the two scenarios.

In the BPS-1, the largest total solar PV installed capacity of 46 GW is observed in Province 6, due to excellent solar resource availability and large solar PV potential. This region exports low-cost solar PV electricity to other regions. Province 3 has the second-largest installed capacity of solar PV, while additional capacities of hydropower are needed due to high energy demand in the capital region. Bhutan has installed capacities of 45 GW and 10 GW of solar PV and hydropower, respectively. A similar distribution of solar PV and hydropower shares is observed in the BPS-2.

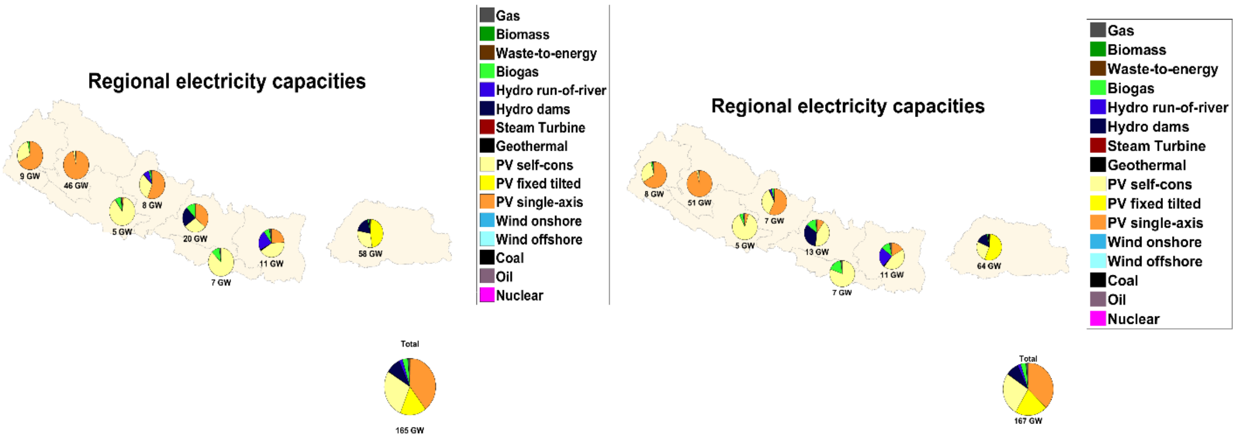

Figure 11: Installed RE capacities in the provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

Solar PV plays an imminent role in the total generation of electricity in both scenarios in 2050. However, electricity generated from hydropower plays an important role in Provinces 1, 3 and Bhutan in both scenarios due to the hydropower potential availability in these regions.

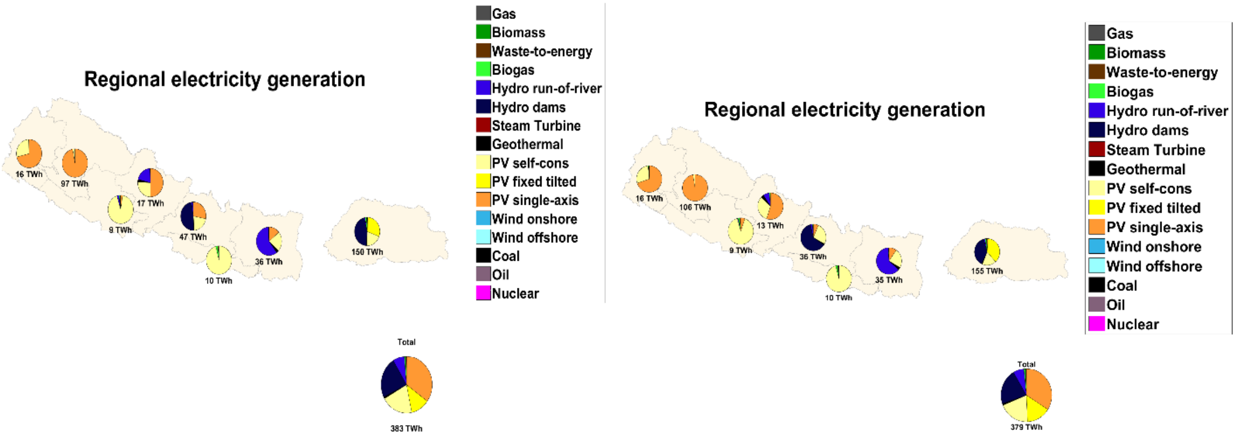

Figure 12: Installed electricity generation in provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

The electricity in far western provinces of Nepal is solely generated via solar PV using single-axis tracking and fixed tilted ground-mounted power plant solutions. The highest power generation is in Province 6 which is 97 TWh and 106 TWh in the BPS-1 and BPS-2 respectively as shown in Figure 12. The eastern and central parts of Nepal have big rivers which flow through the snowmelt mountains from north to south and have a steep topography that accounts for an excellent hydro run-off power generation. The lower southern part is a flat surface geography and is more cost extensive due to the need of construction of large dams for hydropower generation. Therefore, cost-effective solar PV electricity generation is most suited there.

3.3 Heat generation and installed capacities

Figure 13 shows the total installed capacities in the heat sector by different heat generation technologies during the transition period in the BPS-1 and BPS-2.

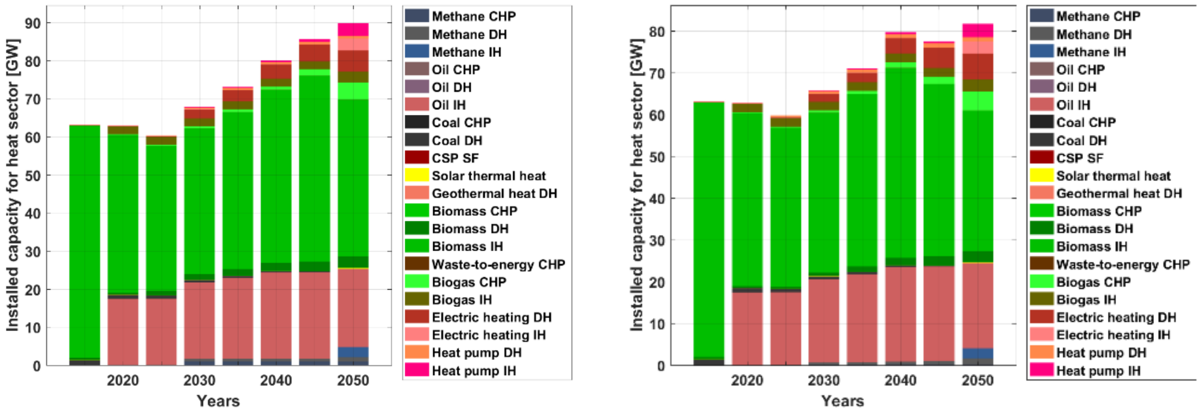

Figure 13: Installed capacity in the heat sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

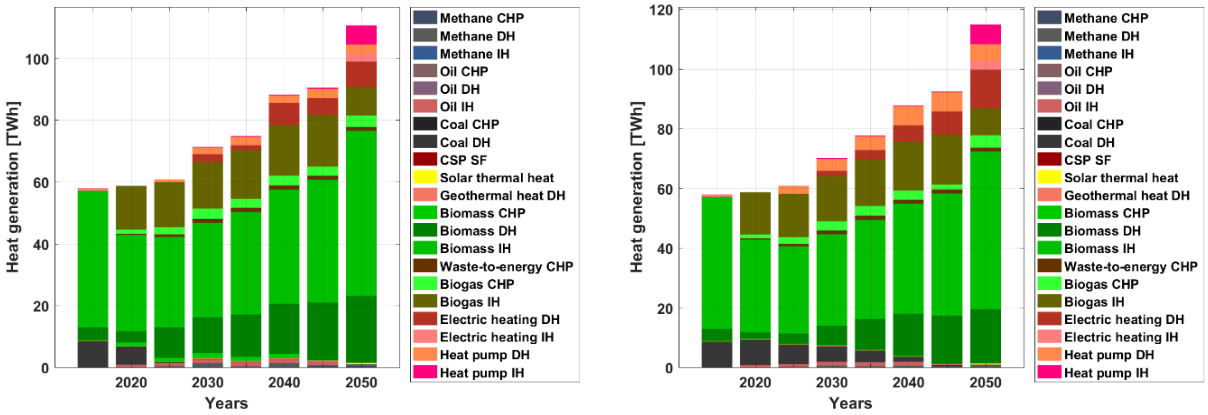

Figure 14: Heat generation in the BPS-1 (left) and BPS-2 (right) in the transition years.

The share of biomass-based heat generation is dominant in the heat sector in both scenarios during the transition. In 2015, the majority of biomass was used as a heat source for cooking, which is highly unsustainable and leads to various issues such as indoor air pollution and related health hazards. However, during the transition, biomass use in cooking decreases and is replaced by electricity-based cooking. The use of agricultural and forest residues and municipal solid waste increases during the transition. In 2020, other means of heat generation technology which are based on direct electricity use and oil as a transition fuel. Oil-based individual heat boilers account for 1.4% of heat generation share in 2020 whilst, biomass accounts for 88% in the BPS-1. While for the BPS-2, there is a small share of heat generation from oil-based boilers mainly in residential and commercial heating, while the majority of share is from biomass which has a share of around 75%. A gradual decrease in fossil-based heating is observed during the transition for both scenarios, replacing with mainly direct electricity-based heating and heat pumps. However, in the BPS-2, a small share from oil-based boilers can be seen in 2050, as there is GHG emission cost.

3.4 Transport sector

The final energy demand for transport according to different modes for the two scenarios is shown in

Figure **15** and by fuel types for the BPS-1 and BPS-2 in Figure 16. The final energy demand for transport increases at a slower rate until 2035. After that, the demand accelerates till 2050 to 37 TWh. An increase of 20 TWh is observed within the start of the transition period until 2050. Due to an increase in standards of living, a rapid increase in energy demand is observed for the aviation sector. The increase in energy demand is directly associated with the increase in transportation for freight and passengers.

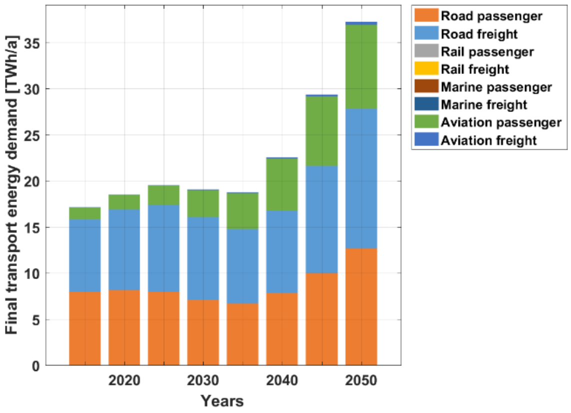

Figure 15: Final energy demand for transportation by transportation modes in the BPS-1 and BPS-2 for the transition period.

The direct use of electricity has a major impact to meet the final demand by 2050, as shown in Figure 16. On the other hand, electricity plays a minor role in 2015, as less efficient fossil fuels form a major share. However, during the transition, shares of direct and indirect electrification increase as a result of more cost-efficient solutions.

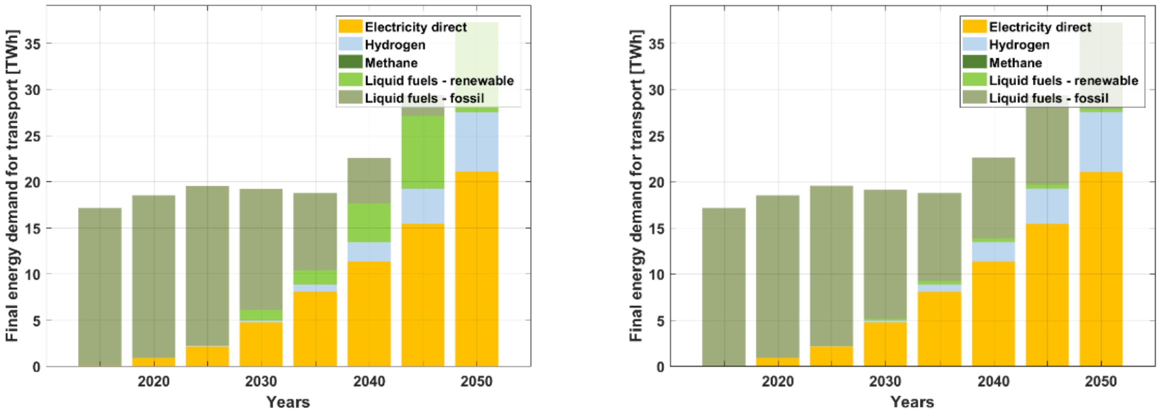

Figure 16: Final energy demand for the transportation sector by fuel in the BPS-1 (left) and BPS-2 (right) for the transition period.

In the BPS-1 and BPS-2, the share of direct electricity from the early 2020s and of hydrogen and synthetic liquid fuel from 2030 onwards increases during the transition period. In the BPS-1, direct electricity has a share of 57%, while hydrogen and synthetic liquid fuels have a share of 17% and 26% respectively, in a fully sustainable transport sector in 2050. On the other hand, the BPS-2 has a fossil fuel share of 25% in 2050, due to no GHG emission pricing, as fossil fuels are cheaper to use. The role of liquid fossil fuels in the BPS-1 decreases during the transition period and does not play any role to meet the transport demand, however, synthetic liquid fuels are utilised for aviation transportation, to achieve full sustainability. GHG emissions cost is factored in the BPS-1, also leading to a full phase-out of polluting fossil fuels. To replace those, technically and commercially viable synthetic liquid fuels are injected to the energy system.

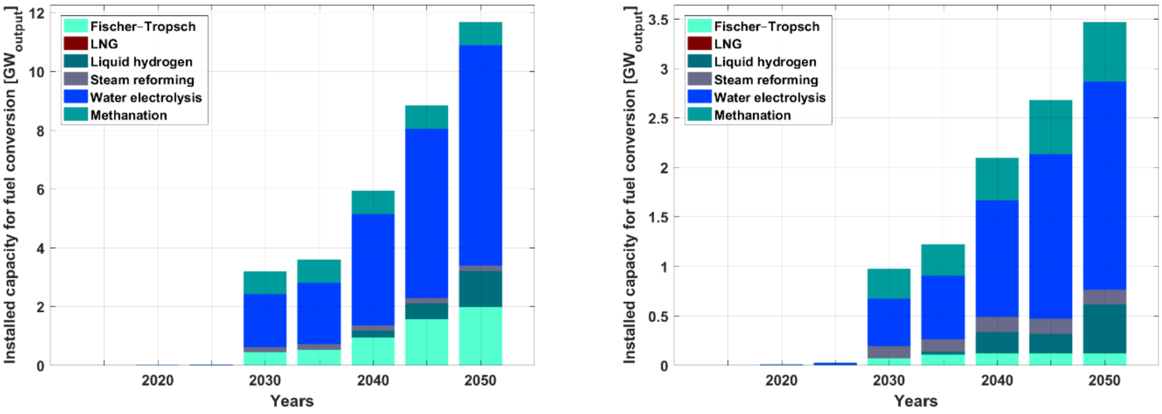

Figure 17: Installed capacity needed for transport fuel conversion in the BPS-1 (left) and BPS-2 (right) during the transition years.

The role of direct electricity is important to a certain share during the transition, however, large scale sustainability in the transport sector is achieved by converting renewable electricity to hydrogen and synthetic fuels. This is clearly observed from the BPS-1 and BPS-2 results. The fuel conversion capacity needed is nearly 3.5 times higher in the BPS-1 compared to the BPS 2 in 2050 as shown in Figure 17. Around 11 GW of fuel conversion technologies are installed in the BPS-1, in which water electrolysis has the largest share, as hydrogen is used as a fuel itself and is used to produce synthetic hydrocarbons. Other conversion processes like Fischer-Tropsch, liquid hydrogen production and methanation have a comparative lower share.

3.5 Role of storage technologies

Energy storage technologies play a crucial role during the transition towards large scale renewables utilisation to balance the temporal variability of demand and generation. As the future energy system is solar PV dominated, the need for batteries is imminent. The demand for electricity storage kicks in after 2030, as in the initial years a low electricity generation share from renewables and the availability of dispatchable fossil fuel share, a need for storage technologies do not arise. The installed electricity storage capacity increases to nearly 320 GWh in 2050 in the BPS-1 as shown in Figure 18.

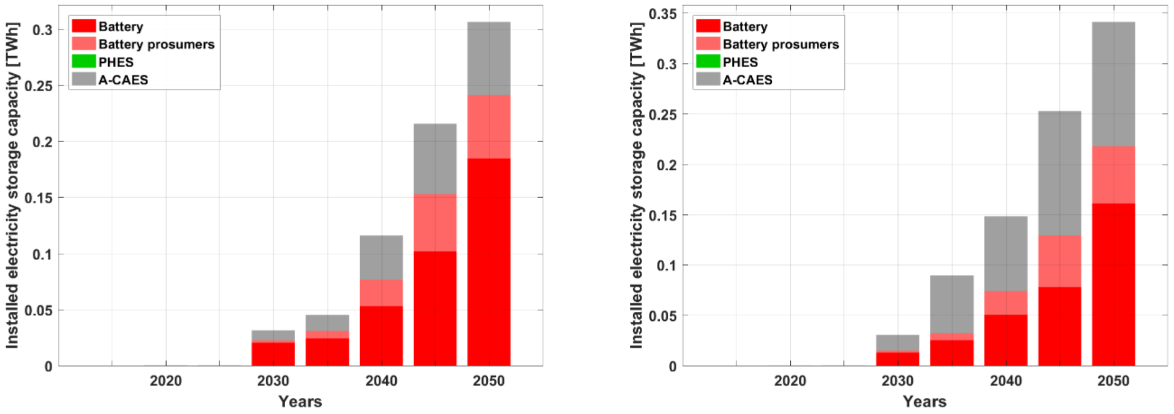

Figure 18: Installed electricity storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

The impact of PV prosumers battery in storage starts in 2035 due to low cost of solar PV rooftop installations in both scenarios. By 2050, the battery capacity share rises for total electricity storage.

Utility-scale battery and prosumer battery together account for nearly 108 TWh electricity output in the BPS-1 as shown in Figure 19. The adiabatic compressed air energy storage (A-CAES) starts appearing already in 2030 with a small share and increased afterwards. Electricity storage output through all electricity storage systems is projected to reach 120 TWh_{el} and 122 TWh_{el} in the BPS-1 and BPS-2 respectively.

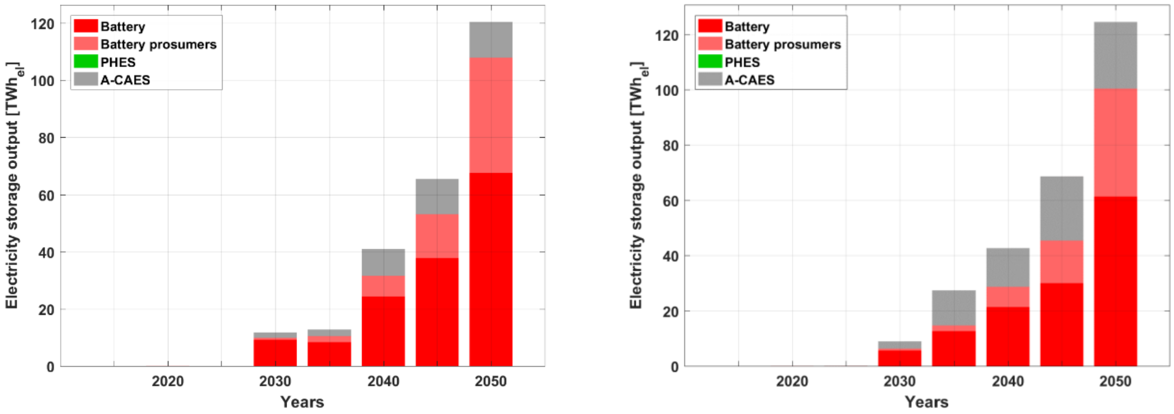

Figure 19: Electricity storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

The need for thermal energy storage (TES) is crucial for the heat sector transition. Figure 20 illustrates the increase of installed heat storage capacity starting from the year 2030, which would scale to 2.7 TWh and 4.4 TWh in the BPS-1 and BPS-2 respectively by 2050. An enormous amount of gas storage capacity is added in the last 10 years of transition in BPS-1 and BPS-2 to provide the seasonal storage need. Gas (CH_4) storage accounts for nearly 99% for the total heat storage capacity in the BPS-1 and BPS-2. However, the share of gas (CH_4) storage in thermal heat output is very limited. A steep rise in heat storage output is noticed in the early 2030s in which TES DH and TES HT together accounts to 50 TWh_{th} and 37 TWh_{th} in the BPS-1 and BPS-2 respectively. A maximum of 82 TWh_{th} in the BPS-1 and 50 TWh_{th} in the BPS-2 is seen during the years 2040 and 2035 respectively.

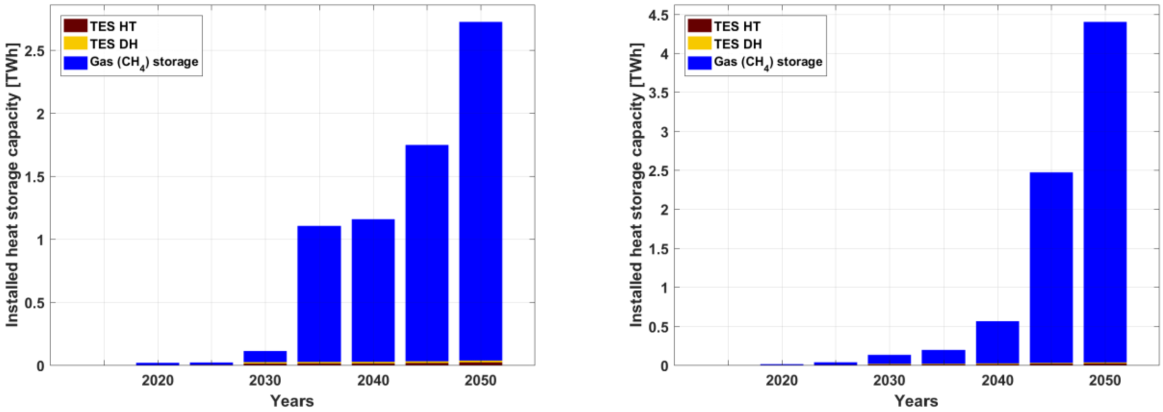

Figure 20: Installed heat storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

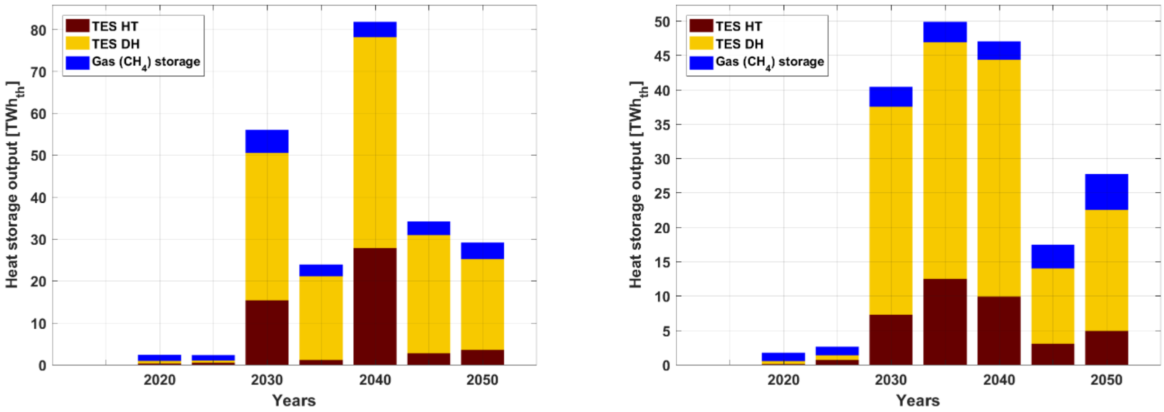

Figure 21: Heat storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

3.6 Energy cost during the transition

The total annual system cost and levelised cost of energy are shown in Figure 22 and Figure 23.

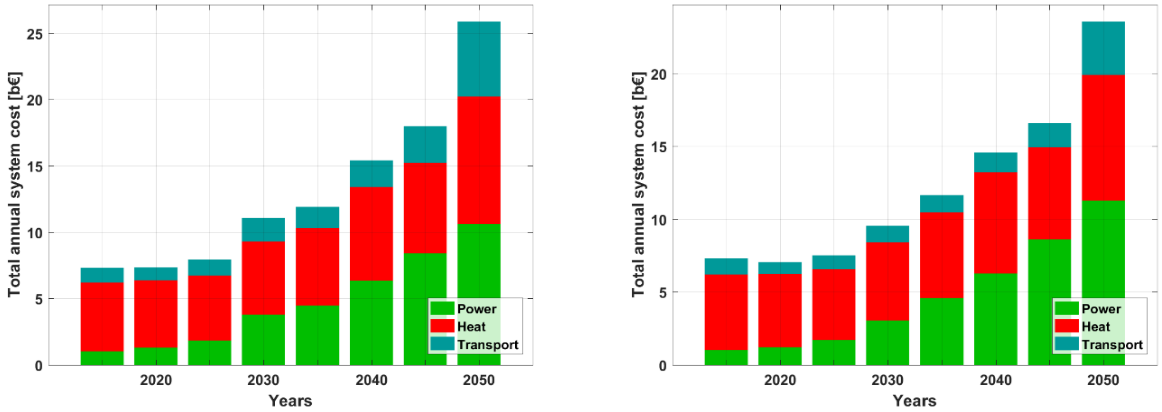

Figure 22: Total annual system cost for power, heat and transport sectors in the BPS-1 (left) and BPS-2 (right) in the transition years.

The total annual system cost during the transition years lies within a range of 7 to 27 b€ and 7 to 18 b€ in the BPS-1 and BPS-2 respectively. The annual system cost in the BPS-2 is comparatively lower than in the BPS-1 as it does not take into consideration the GHG emissions cost, which is not a sustainable solution. Heat sector accounts to around 5 b€ and remaining 2 b€ comes from the power and transport sectors in the total annual system cost during the initial years of transition in the BPS-1 and BPS-2. The share of power and transport sectors increases in the following years, specifically the power sector, due to increasing demand and complete shifting to RE-based resources in power generation which is a base for other sectors' energy demand. The cost of the transport sector slightly increases over the years but sees a high ascend during the late 2040s due to the change in vehicle stocks and the associated shift in corresponding fuel types.

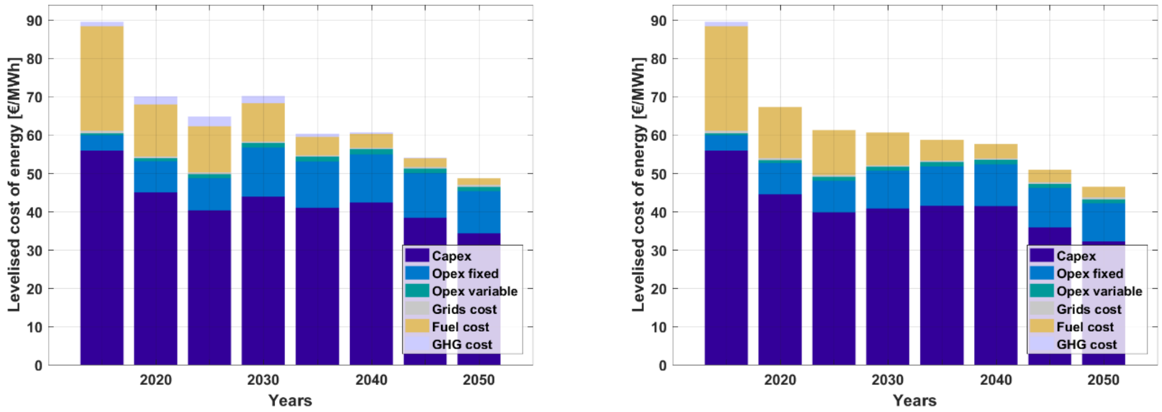

Figure 23: Breakdown of the levelised cost of energy in the BPS-1 (left) and BPS-

2 (right) in the transition years.

A fully RE-based energy system refers to the most cost-effective solution in the energy sector as shown in Figure 23. The overall energy cost per MWh is projected to decline to 49 € in 2050 compared to 90 € in 2015 in the BPS-1. Similarly, it is projected to cost 48 € in the BPS-2 in 2050 but it does not cover GHG emissions costs. This leads to a lower LCOE in the BPS-2 than BPS-1. The high share of CAPEX related cost implies the boom in the installation of new energy generation technologies and energy storage solutions. This leads to a cease in the cost of imported fuels. Operational expenditures are around a quarter of the total cost in 2050. The GHG emission cost is near to zero during early 2035 and remains zero-till 2050 in the BPS-1.

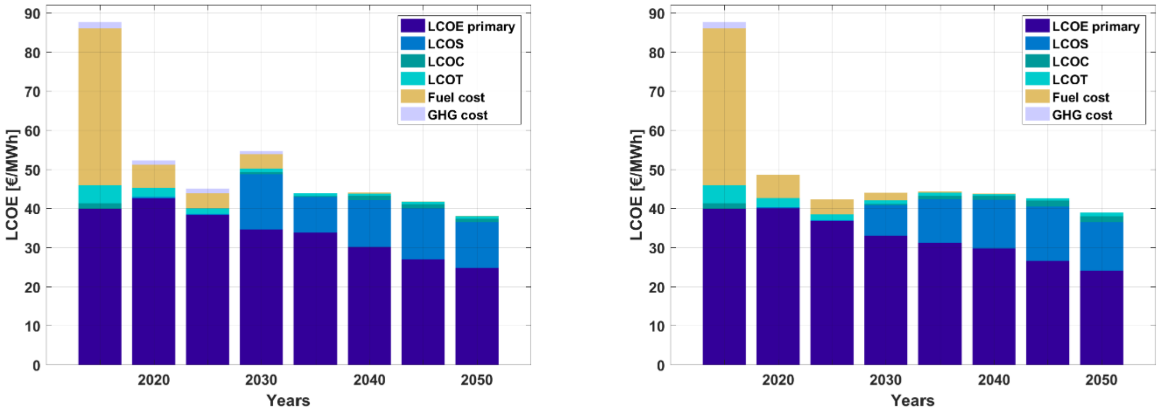

Figure 24: LCOE total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

LCOE is slightly higher in the BPS-1 compared to the BPS-2 in all transition years. In both scenarios during the start of the transition, the total LCOE is 90 €/MWh in which the cost of fuel and LCOE primary has a major share. Mostly fossil fuel costs for the transport sector plays a vital role in having a high 47% share in LCOE costs during 2015. In the BPS-1 scenario in Figure 24 (left), LCOE gets reduced to 52.2 €/MWh from 90 €/MWh, right in the early 2020s of the energy transition. This accounts for around 40% reduction. Limiting the usage of expensive fossil fuels-based energy and the incorporated GHG emission costs are the key drivers. The trend continues to a lower LCOE to 45 €/MWh until 2025. But in the year 2030, the LCOE rises by about 20% and hits 54.3 €/MWh. The rise of the LCOE is in accordance with the installation of new power generation and storage capacities and the associated CAPEX in the energy system. PV technology type, efficient hydropower generation, battery-based storage technology, plays an important role in the energy system which further lowers the LCOE down to 49 €/MWh, realising 54% reduction in total by the end of the transition period in 2050. The BPS-2 excludes GHG emission cost, which is not sustainable, though the LCOE is quite low. Thus, a 100% RE-based sustainable energy system is substantially lower in cost by 2050 than the currently existing energy system.

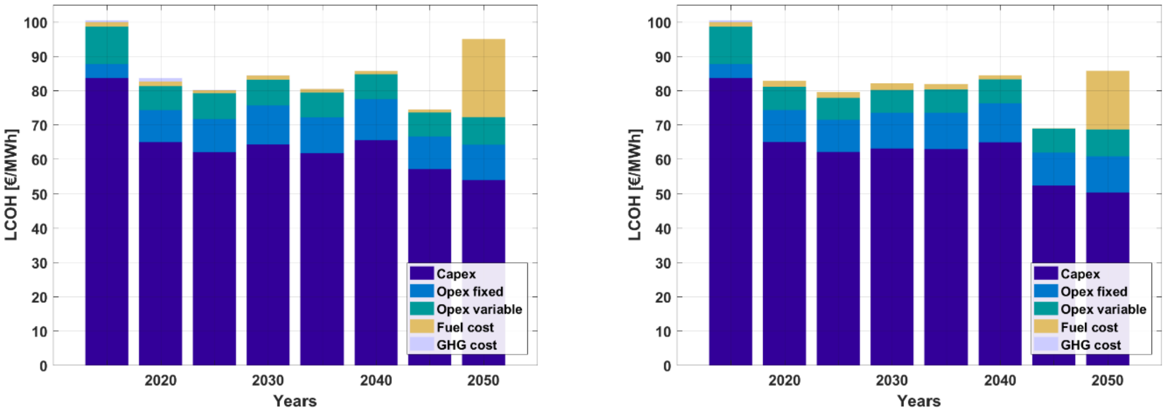

Figure 25: LCOH total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

The LCOH of the heat sector drops down in the early 2020s to around 83 €/MWh from around 100 €/MWh in 2015 in the BPS-1 and BPS-2 as shown in Figure 25. The LCOH remains at 80-85 €/MWh range till 2040. A sudden fall in 2045 and a rapid rise in 2050 is seen in both scenarios with a LCOH of 98 €/MWh and 86 €/MWh in BPS-1 and BPS-2 respectively. CAPEX is the predominant contributor in all years during the transition.

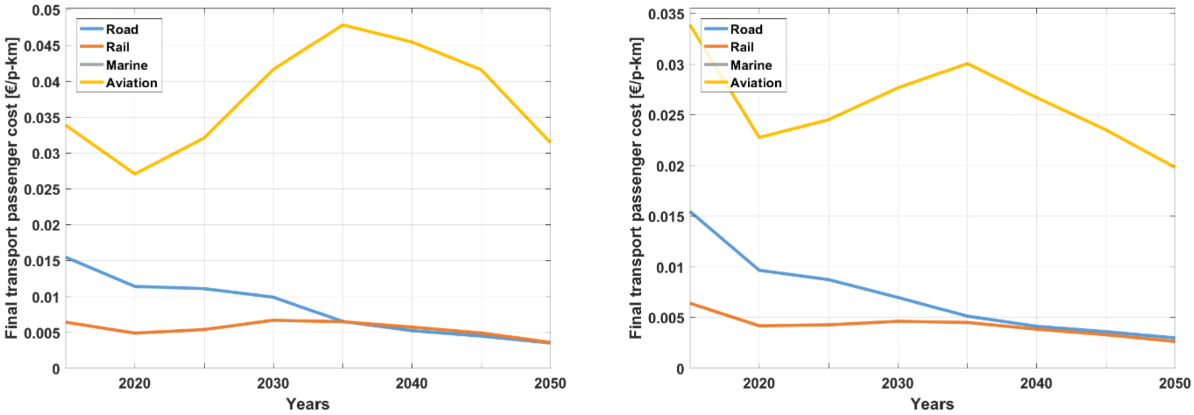

Figure 26: Final transport passenger cost per person-kilometer in the BPS-1 (left) and BPS-2 (right).

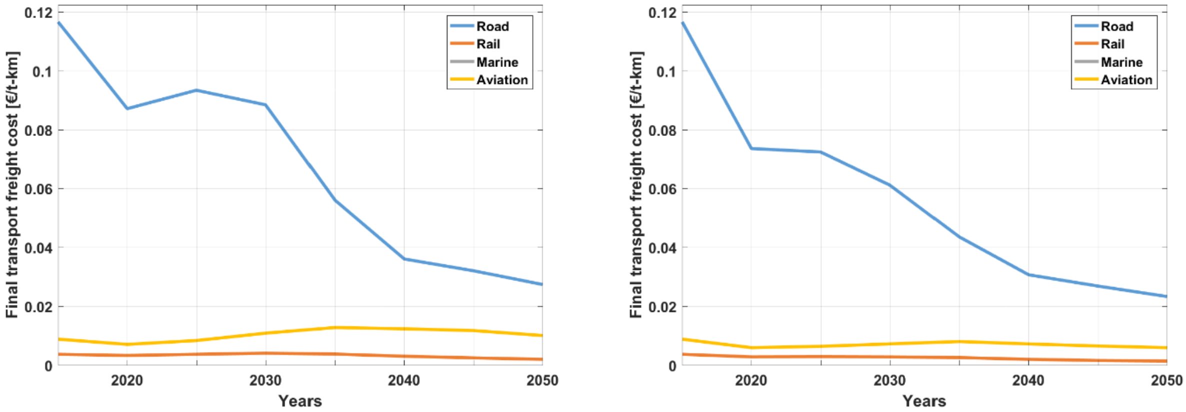

Figure 27: Final transport freight cost per ton-kilometer in the BPS-1 (left) and BPS-2 (right) in the transition years.

Figure 26 and Figure 27 shows the final transport passenger costs and final transport freight costs in the BPS-1 and BPS-2 respectively during the transition years. The final transport passenger cost declines heavily for road whereas aviation and rail transport follow a marginal decrease in the BPS-1 during the transition. In BPS-2, the final transport passenger cost in aviation decreases from 0.034 €/p-km in 2015 to 0.019 €/p-km in 2050. Similarly, final transport freight cost in the BPS-1 and BPS-2 fall off substantially from 0.12 €/t-km in 2015 to around 0.03 €/t-km in 2050. In 2050, transport passenger cost in aviation and transport freight cost in the road have major contribution in the final transportation sector cost.

3.7 GHG emission reduction

The total GHG emissions starting from the year 2015 to the end of transition period 2050 in the BPS-1 and BPS-2 are presented in Figure 28.

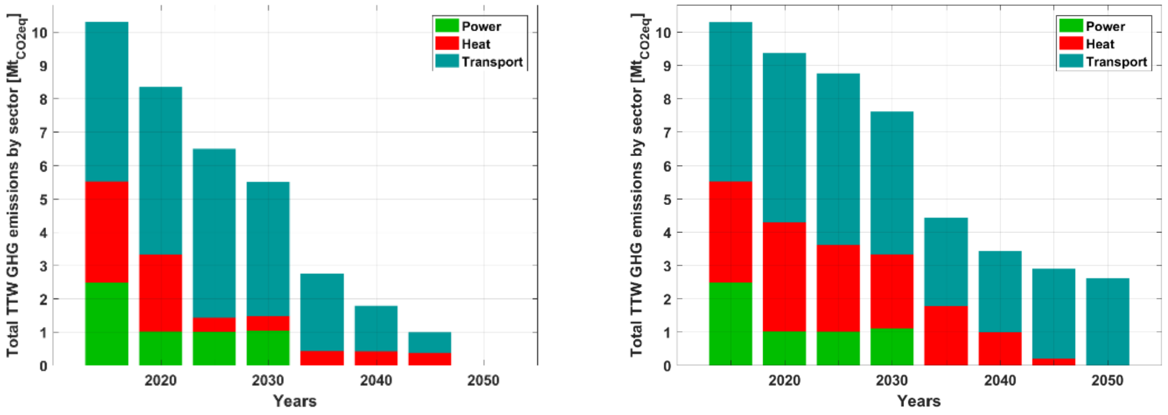

Figure 28: Sector-wise GHG emissions during the transition period in the BPS-1 (left) and BPS-2 (right).

Finding a least-cost transition pathway for an energy system with zero GHG emissions is one of the main targets of this study. The BPS-1 has achieved the GHG emissions-free target by the end of the transition period, whereas in BPS-2 the GHG emissions is still around 2.8 $\mathrm{Mt_{CO2eq}}$ in 2050, which solely comes from the transport sector. Generally, a high share of GHG emissions comes from the transport sector, followed by heat and power sectors in the BPS-1 and BPS-2. Both scenarios having GHG emissions of 10.2 $\mathrm{MtCO_{2eq}}$ in 2015 achieve a steep reduction throughout the transition period. The rate of GHG reduction is already on a good pace starting 2020 in the BPS-1, whereas the reduction rate is slightly slower in the BPS-2 because of no limitation on fossil fuel usage. The heat sector sees a major transition already in the late 2020s in the BPS-1, and its impact on GHG emissions is limited. The most important and less challenging sector to defossilise is the power sector, which is GHG emission-free after 2030 in both scenarios. GHG emissions from the transport sector also get considerably reduced due to usage of direct electricity, hydrogen fuel and synthetic liquid fuels.

4 DISCUSSION

The primary objective of this research was to demonstrate a least-cost energy system transition by 2050 for Nepal and Bhutan, which is aligned to the Paris Agreement (United Nations Framework Convention on Climate Change (UNFCCC), 2015). This can be achieved by the usage of freely available renewable resources in the country. A strong political will and long-term national policies towards renewables is needed. This study illustrates two energy transition pathways. BPS-1 guides a path towards a self-sufficient, least-cost renewable-based GHG emission free energy system, which eventually fades away the danger of climate change, whilst BPS-2 do not consider the GHG emissions and its mitigation cost.

A 100% RE-based system for Nepal and Bhutan ensures the continuous energy supply in power, heat and transport sectors for all. This study engulfs all parameters of a sustainable energy system along with energy storage arrangements. The levelised cost of energy decreases considerably to 49 €/MWh in 2050 compared to 90 €/MWh in 2015 due to the indulge of high shares of renewables into the system. This type of study considering a strong integration of power, heat and transport sectors is the very first of its kind for Nepal and Bhutan.

Solar PV dominates the entire energy system accounting to over 288 TWh of electricity generation in 2050. Electricity generation from hydropower and biomass compliments the balance in supply and demand. In 2050, a substantial 90 GW of heat capacity installed and heat storage systems ensure the heat demand is met. Largely available biomass will be a major source for heat generation. The transport sector faces a major transition due to the complete phase-out of fossil fuel-powered vehicles. The fuel needed for vehicles is required in different forms of energy. Passenger mobility vehicles are shifted to direct plug-in electricity, whereas aviation and rail transport modes utilise hydrogen and liquid hydrocarbons in various form.

A study conducted on the role of renewable energy in Nepal (Nepal, 2012) emphasises the need of locally available renewables be utilised and provide electricity access in all areas and non-dependence on foreign fuel imports. Also, decentralised energy production implies a needless costly grid expansion and eventually grid loss savings. Thus, a good investment in locally prevailing resources such as hydropower and solar PV ensures the power to every household despite difficult terrain and sparse household settlement in the rural areas. This prevents GHG emissions and costly fossil fuel purchase from India. A mix of different RE sources and a blend of centralised and distributed energy supply guarantees a Nepalese government plan (Ministry of Population and Environment, 2016) to provide affordable energy access to every citizen. Due to short seasonal inconstancy of solar energy in Nepal and Bhutan, solar PV based power generation is optimal for the demand and supply balance.

The Alternative Energy Promotion Centre (AEPC), a Nepalese governmental body, set up to mainstream RE supply in Nepal, reports in the year 2016 that there has been around 30 MW of electricity generated from mini and micro hydropower plants, and 15 MW power from solar PV systems on a local level (Ministry of Population and Environment, 2016). The Nepalese government has set up a long-term goal to achieve clean, reliable and affordable RE solutions by 2030. The new policy on Renewable Energy Technologies (RETs) development prioritises on providing long-term loans to investors to meet the UN’s objectives of ‘Sustainable Development Goals’ and ‘Sustainable Energy for All’ (Ministry of Population and Environment, 2016).

Nepal faced on average around 88 hours of load-shedding weekly from the year 2011 till 2016 (Kumar Ramesh, 2018)due to lack of installed power generation capacity. Major cities were hardly hit by frequent, daily blackouts which caused immense losses in economic welfare. On top of that, poor operational performances, and incompetent maintenance summed up the issue. The gap in demand-supply arises the need for more power generation. Thus, the need for sustainable energy transition is necessary which regulates the continuous demand-supply balance. The BPS-1 fully comprehend on this national energy emergency. High shares of renewables in the energy system and supportive battery storage capacities in the BPS-1 are projected to be substantially lower in cost than the current energy system. Specifically, the drastic decline of solar PV cost and batteries, which are projected to play a major role in power generation and storage, lower the energy system cost. Nepal and Bhutan should take the advantage of low-cost solar PV.

Summing up, the BPS-1 which includes the GHG emissions cost is a mere path for Nepal and Bhutan to strengthen the future energy system, which ensures affordable energy supply for all. The respective nations' government should enforce strong policies and guidelines about the need to phase in RE-based solutions. It is recommended to Nepal's RE development governing body, AEPC, and the Royal Government of Bhutan to come up with roadmaps, measures and policies to lure citizens in installing region-specific capacities for utilising available RE source by providing long-term loans and incentives. In addition, the collaboration with the neighbouring country India, which is far ahead in renewable electricity generation, and with a whole SAARC region creates mutual benefits.

4.1 Limitations of the study

Bhutan is taken as a single node based in Thimphu. No further division into regional zones or main energy consumption hubs is done like as in Nepal as the area of Bhutan is about a quarter of Nepal. This implies that the energy demand, installed capacity and energy supply in all sectors were not considered in a higher geo-spatial resolution and it assumes the presence of grid transmission. The grid transmission line in Nepal is assumed to follow a certain path through a currently existing route. In future practice, grid connection paths may follow alternative routes due to economic reasons and land use policies. In further enhanced energy system modelling approach, rural electrification may be incorporated into the national energy transition modelling.

The findings obtained are based on proven technologies and thus, should not be a major challenge to execute it technically in practice. Social acceptance and improper energy policies might be barriers. Hence, it is recommended analysing those perspectives in a more detailed manner to enable a 100%RE system by 2050, or even before.

5 CONCLUSION

The Himalayan countries Nepal and Bhutan are wealthy in renewable resources. They need to follow the path of renewables to provide reliable and sustainable energy for all at a minimum possible cost. The renewable energy technologies and storage solutions can adequately supply energy consistently at every hour in all sectors throughout the year by 2050. Advanced RE resources conversion technology can generate electricity to be used as the base of the transition to also meet the demand in the heat and transport sectors. The levelised cost of energy for Nepal and Bhutan is projected to 49 €/MWh by 2050, which is almost half than the current unsustainable energy system at the beginning of the transition. Despite having huge snowmelt high current rivers and sloping terrain, which is excellent for hydropower generation, the decreasing cost of solar PV and utility-scale batteries are expected to reach even lower cost levels. Abundant amount of biomass-based sources, which accounts for more than 80% of energy demand in 2015, meets the heat demand through different conversion technologies in 2050. The most vulnerable transport sector which is fully dependent on India, for importing fossil fuels will face a major change by establishing RE-based direct and indirect electrification. Conclusively, this study concludes that a 100% RE system is technically feasible and economically viable across all energy sectors, primarily based on renewable electricity by 2050 with zero GHG emissions.

Achieving a complete energy transition to a 100% renewables-based energy system enabling zero GHG emissions by 2050 demands bold, strict, and intense ambitious national policies by the two nations, Nepal and Bhutan. It is recommended that more upcoming studies ought to consider with more detailed scopes to find the best pathways to make it happen for Nepal and Bhutan to be self-sufficient and reach a sustainable 100% renewables-based energy system for all by 2050.

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APPENDIX

Table S5: Combined population projection of Nepal and Bhutan from 2015 to 2050 for the BPS-1 and BPS-2.

	Unit	2015	2020	2025	2030	2035	2040	2045	2050	Source
Population	**[mil]**	28.74	30.78	32.0	35.3	37.81	40.5	43.38	46.47	(UNFPA Nepal, 2017; National Statistics Bureau, 2019)

Table S6: Projection of power, heat and transport demands from 2015 to 2050 for the BPS-1 and BPS-2.

Energy service demand	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Power demand	**[TWh]**	11.86	25.11	41.02	69.23	102.52	142.48	200.78	288.71
Total heat demand - heat sector	**[TWh]**	52.60	60.63	61.14	65.73	72.89	82.49	91.89	101.55
Industrial heat demand	**[TWh]**	9.99	11.78	14.42	17.38	21.93	27.54	33.91	41.81
Space heating heat demand	**[TWh]**	30.31	36.41	34.31	36.01	38.51	42.01	44.21	45.01
Domestic water heating heat demand	**[TWh]**	9.11	9.75	10.45	11.19	11.98	12.84	13.75	14.73
Biomass cooking heat demand	**[TWh]**	3.19	2.68	1.96	1.14	0.46	0.11	0.01	0.00
Centralised heating heat demand	**[TWh]**	9.99	11.78	14.42	17.38	21.93	27.54	33.91	41.81
Individual heating heat demand	**[TWh]**	42.61	48.84	46.72	48.34	50.95	54.95	57.97	59.74

Total electricity demand - all sectors – BPS-1	**[TWh]**	13.10	26.04	43.51	81.09	117.75	175.21	246.27	353.92
Total electricity demand - all sectors – BPS-2	**[TWh]**	13.10	26.03	44.06	77.87	116.97	164.89	231.76	337.92
Road 2W/3W passenger transport demand	**[mil km]**	7242.21	8411.74	9970.53	12525.93	16649.62	23149.1	33019.8	47266.56
Road Bus transport demand	**[mil km]**	1017.9	1107.4	1236.25	1429.4	1778.39	2258.56	3004.32	4010.30
Road MDV transport demand	**[mil km]**	2852.09	3438.94	4171.72	5340.1	7191.85	10068.11	14378.54	20506.84
Road HDV transport demand	**[mil km]**	307.82	371.15	450.25	576.34	776.2	1086.61	1551.83	2213.23
Rail pass transport demand	**[mil p-km]**	56.43	62.14	68.95	79.53	96.47	123.64	166.19	229.13
Rail freight transport demand	**[mil t-km]**	0.07	0.09	0.1	0.1	0.11	0.13	0.17	0.26
Aviation pass transport demand	**[mil p-km]**	2357.03	2972.89	4020.26	5834.04	8355.22	13105.67	19782.57	28126.95
Aviation freight transport demand	**[mil t-km]**	133.51	192.42	288.97	452.67	733.79	1232.64	2033.67	3204.92

Marine pass transport demand	**[mil p-km]**	0	0	0	0	0	0	0	0
Marine freight transport demand	**[mil t-km]**	0	0	0	0	0	0	0	0

Table S7: Projected specific energy demand by transport mode and vehicle type from 2015 to 2050 for the BPS-1 and BPS-2.

Mode and Vehicle type	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Road LDV ICE	**[kWh,th/ km]**	0.78	0.77	0.73	0.69	0.63	0.58	0.51	0.45
Road LDV BEV	**[kWh,el/ km]**	0.00	0.17	0.15	0.13	0.13	0.12	0.11	0.10
Road LDV FCEV	**[kWh,th/ km]**	0.00	0.00	0.23	0.22	0.20	0.20	0.18	0.16
Road LDV PHEV, primary	**[kWh,el/ km]**	0.00	0.19	0.16	0.15	0.13	0.12	0.11	0.09
Road LDV PHEV, secondary	**[kWh,th/ km]**	0.00	0.12	0.12	0.11	0.10	0.09	0.09	0.08
Road 2,3W ICE	**[kWh,th/ km]**	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Road 2,3W BEV	**[kWh,el/ km]**	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Road 2,3W FCEV	**[kWh,th/ km]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road 2,3W PHEV, primary	**[kWh,el/ km]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Road 2,3W PHEV, secondary	**[kWh,th/km]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road Bus ICE	**[kWh,th/km]**	4.09	4.07	4.02	3.99	3.93	3.84	3.76	3.70
Road Bus BEV	**[kWh,el/km]**	0.00	1.81	1.76	1.72	1.66	1.61	1.56	1.50
Road Bus FCEV	**[kWh,th/km]**	0.00	2.99	2.92	2.86	2.70	2.57	2.47	2.35
Road Bus PHEV, primary	**[kWh,el/km]**	0.00	2.01	1.95	1.95	1.92	1.90	1.87	1.84
Road Bus PHEV, secondary	**[kWh,th/km]**	0.00	0.90	0.88	0.86	0.83	0.80	0.78	0.75
Road MDV ICE	**[kWh,th/km]**	2.39	2.34	2.25	2.16	2.06	1.96	1.83	1.68
Road MDV BEV	**[kWh,el/km]**	0.00	0.84	0.78	0.70	0.64	0.60	0.56	0.52
Road MDV FCEV	**[kWh,th/km]**	0.00	1.36	1.29	1.24	1.17	1.10	1.05	0.99
Road MDV PHEV, primary	**[kWh,el/km]**	0.00	1.36	1.31	1.26	1.18	1.12	1.06	0.99
Road MDV PHEV, secondary	**[kWh,th/km]**	0.00	0.33	0.31	0.29	0.26	0.24	0.22	0.21
Road HDV ICE	**[kWh,th/km]**	3.51	3.40	3.21	3.01	2.79	2.63	2.49	2.24
Road HDV BEV	**[kWh,el/km]**	0.00	1.67	1.51	1.40	1.28	1.19	1.12	1.04

Road HDV FCEV	**[kWh,th/ km]**	0.00	1.95	1.83	1.72	1.57	1.47	1.39	1.29
Road HDV PHEV, primary	**[kWh,el/ km]**	0.00	2.28	2.16	2.04	1.89	1.73	1.59	1.48
Road HDV PHEV, secondary	**[kWh,th/ km]**	0.00	0.50	0.46	0.43	0.39	0.36	0.33	0.31
Rail pass fuel	**[kWh,th/ (p-km)]**	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Rail pass elec.	**[kWh,el/(p-km)]**	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Rail freight fuel	**[kWh,th/ (t*km)]**	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Rail freight elec.	**[kWh,el/(t-km)]**	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
Marine pass fuel	**[kWh,th/ (p-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass elec.	**[kWh,el/(p-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LH2	**[kWh,th/ (p-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LNG	**[kWh,th/ (p-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight fuel	**[kWh,th/ (t-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight elec.	**[kWh,el/(t-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight LH2	**[kWh,th/ (t-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Marine freight LNG	**[kWh,th/(t-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation pass fuel	**[kWh,th/(p-km)]**	0.54	0.54	0.52	0.50	0.47	0.46	0.44	0.44
Aviation pass elec.	**[kWh,el/(p-km)]**	0.00	0.00	0.00	0.00	0.17	0.16	0.15	0.15
Aviation pass LH2	**[kWh,th/(p-km)]**	0.00	0.00	0.00	0.00	0.32	0.30	0.29	0.28
Aviation freight fuel	**[kWh,th/(t-km)]**	0.14	0.14	0.14	0.13	0.12	0.12	0.11	0.11
Aviation freight elec.	**[kWh,el/(t-km)]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation freight LH2	**[kWh,th/(t-km)]**	0.00	0.00	0.00	0.00	0.08	0.08	0.08	0.07

Table S8: Projected shares of passenger demand by transport mode and vehicle type from 2015 to 2050 for BPS-1 and BPS-2.

Passenger mode and vehicle type		**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Road LDV ICE - liquid fuel	%	99.60	94.00	79.90	50.00	20.00	11.00	7.00	4.00
Road LDV BEV - electricity	%	0.20	3.00	10.00	39.00	68.00	74.00	73.00	76.00
Road LDV FCEV - hydrogen	%	0.00	0.00	0.10	1.00	2.00	5.00	10.00	10.00
Road LDV PHEV -	%	0.20	3.00	10.00	10.00	10.00	10.00	10.00	10.00

electricity/liquid fuel									
Road 2W/3W ICE - liquid fuel	%	70.00	65.00	60.00	40.00	25.00	15.00	10.00	5.00
Road 2W/3W BEV - electricity	%	30.00	35.00	40.00	60.00	75.00	85.00	90.00	95.00
Road BUS ICE - liquid fuel	%	89.40	78.90	47.90	16.90	5.90	4.90	3.90	2.90
Road BUS BEV - electricity	%	10.00	20.00	50.00	80.00	90.00	90.00	90.00	90.00
Road BUS FCEV - hydrogen	%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Road BUS PHEV - electricity/liquid fuel	%	0.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Rail - electricity	%	14.40	14.70	24.10	39.70	54.30	68.80	81.80	94.70
Rail - liquid fuel	%	85.6	85.30	75.90	60.30	45.70	31.20	18.20	5.30
Marine - liquid fuel	%	100	99.40	98.40	95.90	91.20	79.40	57.20	26.10
Marine - electricity	%	0.00	0.10	0.60	1.10	2.80	5.60	7.80	8.90
Marine - hydrogen	%	0.00	0.00	0.00	1.00	3.00	10.00	25.00	45.00

Marine – LNG	%	0.00	0.50	1.00	2.00	3.00	5.00	10.00	20.00
Aviation - liquid fuel	%	100	100	100	100	96.50	86.00	68.50	43.90
Aviation - electricity	%	0.00	0.00	0.00	0.00	1.20	4.70	10.50	18.70
Aviation - hydrogen	%	0.00	0.00	0.00	0.00	2.30	9.30	21.00	37.40

Table S9: Projected share of freight demand by transport mode and vehicle type form from 2015 to 2050.

Freight mode and vehicle type		**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Road MDV ICE - liquid fuel	%	99.60	88.90	78.00	47.00	16.00	5.00	4.00	3.00
Road MDV BEV - electricity	%	0.2	10.00	19.00	48.00	75.00	80.00	80.00	80.00
Road MDV FCEV - hydrogen	%	0.00	0.10	1.00	2.00	5.00	10.00	10.00	10.00
Road MDV PHEV - electricity/liquid fuel	%	0.2	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Road HDV ICE - liquid fuel	%	100	97.50	88.00	77.00	46.00	12.00	4.00	3.00
Road HDV BEV - electricity	%	0.00	1.00	8.00	15.00	30.00	50.00	50.00	50.00
Road HDV FCEV - hydrogen	%	0.00	0.50	2.00	5.00	20.00	30.00	30.00	30.00
Road HDV PHEV -	%	0.00	1.00	2.00	3.00	4.00	8.00	16.00	17.00

electricity/liquid fuel									
Rail – electricity	%	14.40	14.70	24.10	39.70	54.30	68.80	81.80	94.70
Rail - liquid fuel	%	85.60	85.30	75.90	60.30	45.70	31.20	18.20	5.30
Marine - liquid fuel	%	100	99.40	98.40	95.90	91.20	79.40	57.80	26.70
Marine - electricity	%	0.00	0.10	0.60	1.10	2.80	5.60	7.20	8.30
Marine - hydrogen	%	0.00	0.00	0.00	1.00	3.00	10.00	25.00	45.00
Marine – LNG	%	0.00	0.50	1.00	2.00	3.00	5.00	10.00	20.00
Aviation - liquid fuel	%	100	100	100	100	97.70	90.70	79.00	62.60
Aviation - electricity	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation - hydrogen	%	0.00	0.00	0.00	0.00	2.30	9.30	21.00	37.40

Table S10: Projected final energy demand by sector from 2015 to 2050.

Sector	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power	**[TWh]**	9.05	19.67	33.20	57.89	89.46	129.17	188.46	277.19
Heat	**[TWh]**	52.60	60.63	61.14	65.72	72.88	82.49	91.88	101.55
Transport	**[TWh]**	17.13	18.50	19.52	19.05	18.74	22.54	29.36	37.23

Table S11: Projected final energy demand by energy form from 2015 to 2050.

Energy form	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power demand	**[TWh]**	9.09	20.56	35.31	62.63	97.52	140.49	203.88	298.24

Heat demand	**[TWh]**	52.60	60.63	61.14	65.72	72.88	82.49	91.88	101.55
Fuel demand	**[TWh]**	17.09	17.62	17.41	14.31	10.68	11.22	13.94	16.18

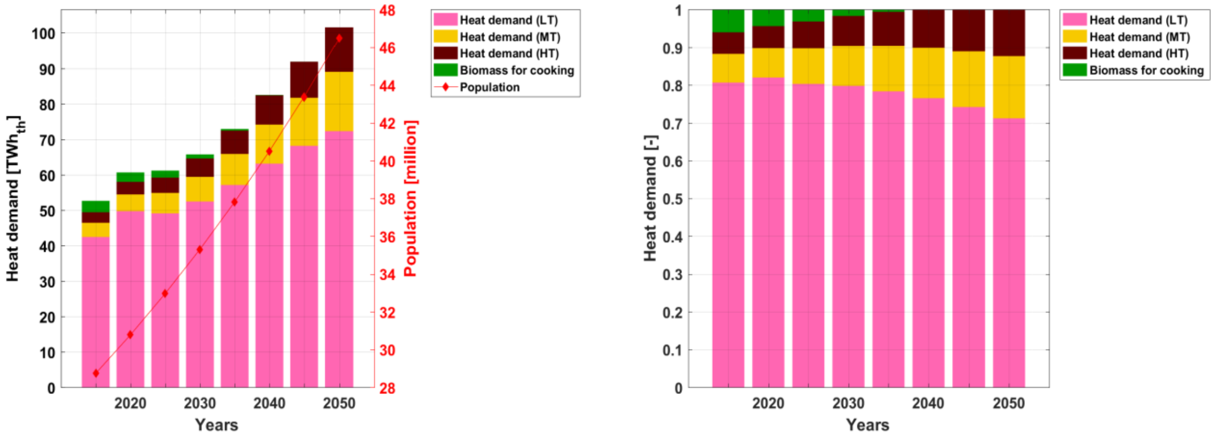

Figure S29: Heat demand by application and temperature levels in absolute (left) and in relative (right) shares.

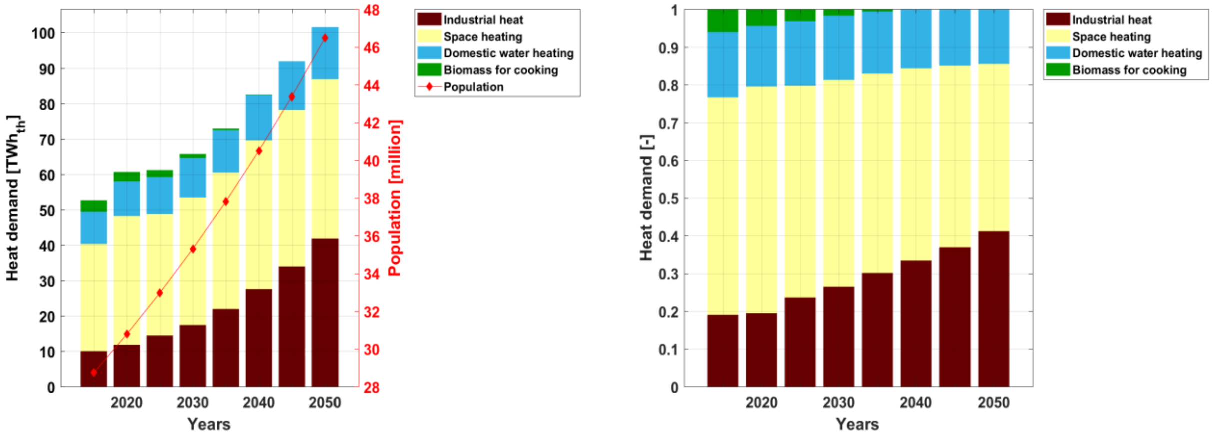

Figure S30: Heat demand by categories in absolute (left) and in relative (right) shares.

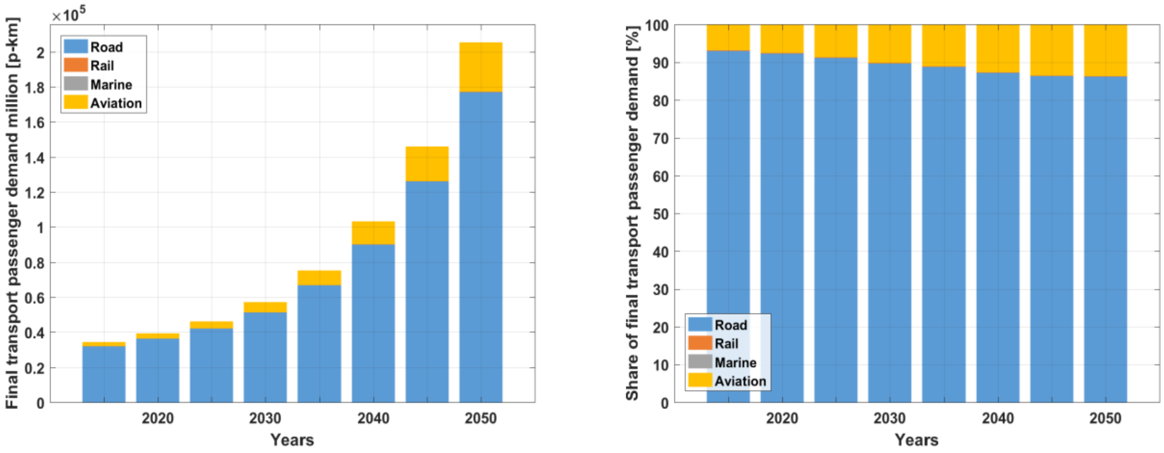

Figure S31: Final transport passenger demand in absolute (left) and in relative (right) shares.

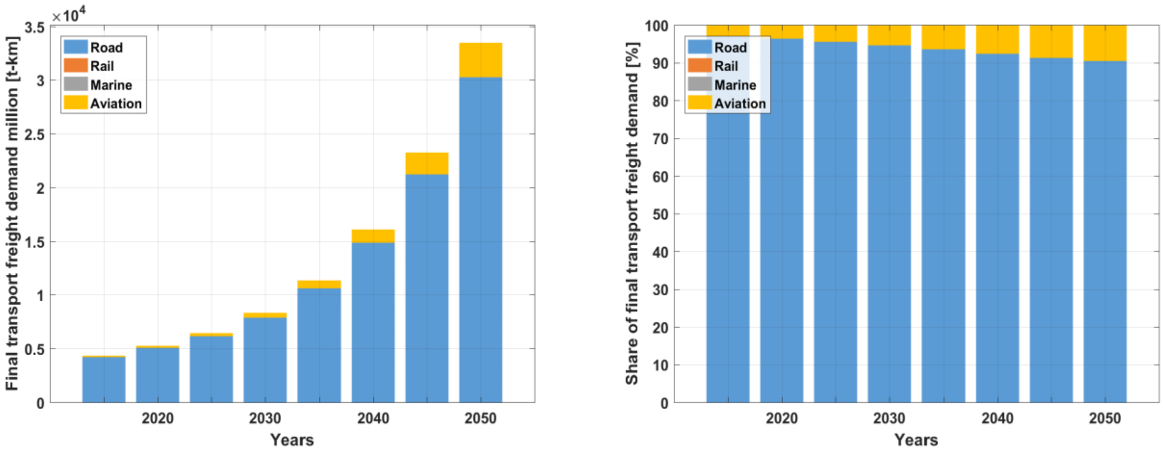

Figure S32: Final transport freight demand in absolute (left) and in relative (right) shares.

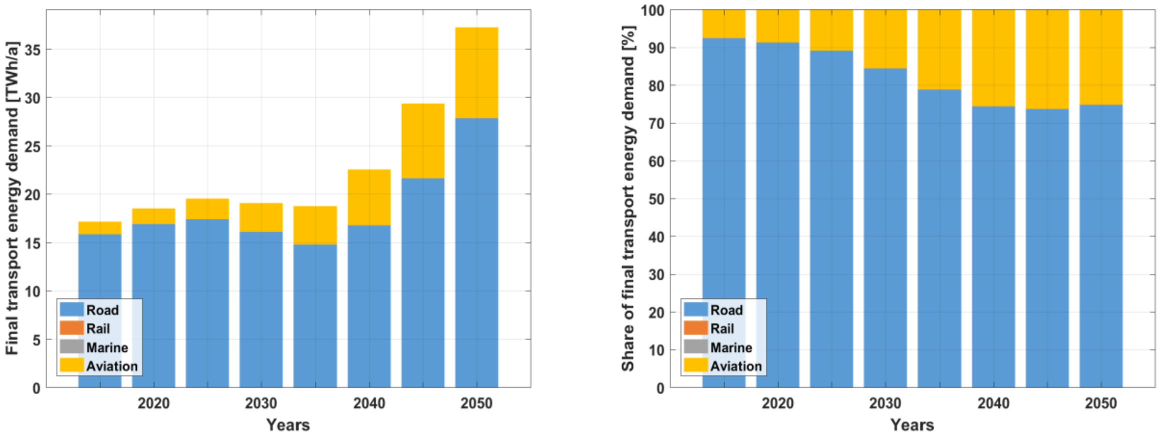

Figure S33: Final transport energy demand by sector in absolute (left) and in relative (right) shares**.**

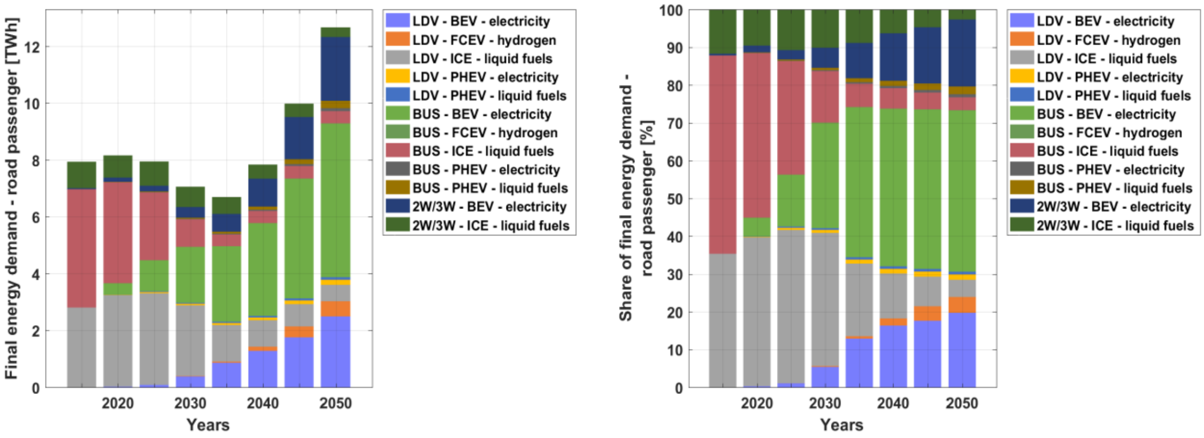

Figure S34: Final energy demand-road passenger by type of vehicle in absolute (left) and relative (right) shares.

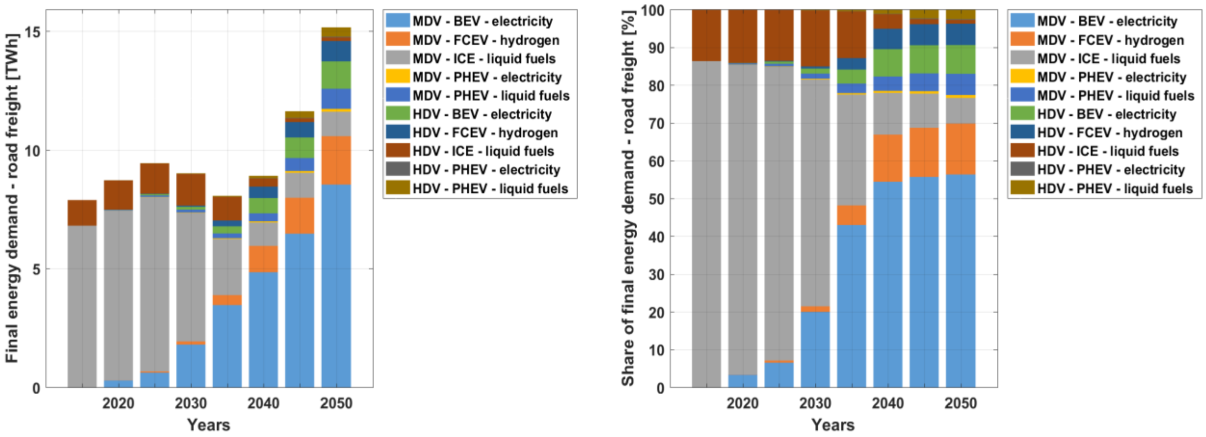

Figure S35: Final energy demand-road freight by type of vehicle in absolute (left) and in relative (right) shares.

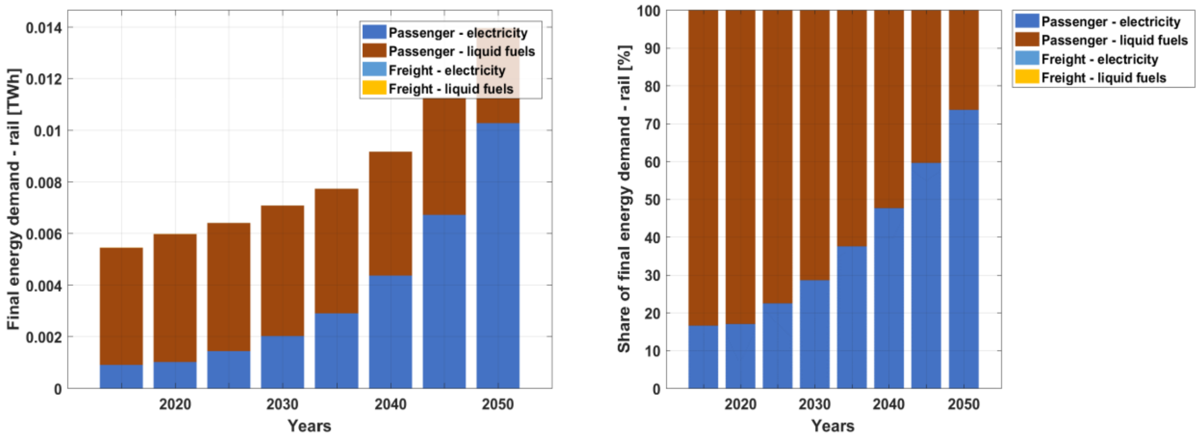

Figure S36: Final energy demand-rail in absolute (left) and in relative (right) shares.

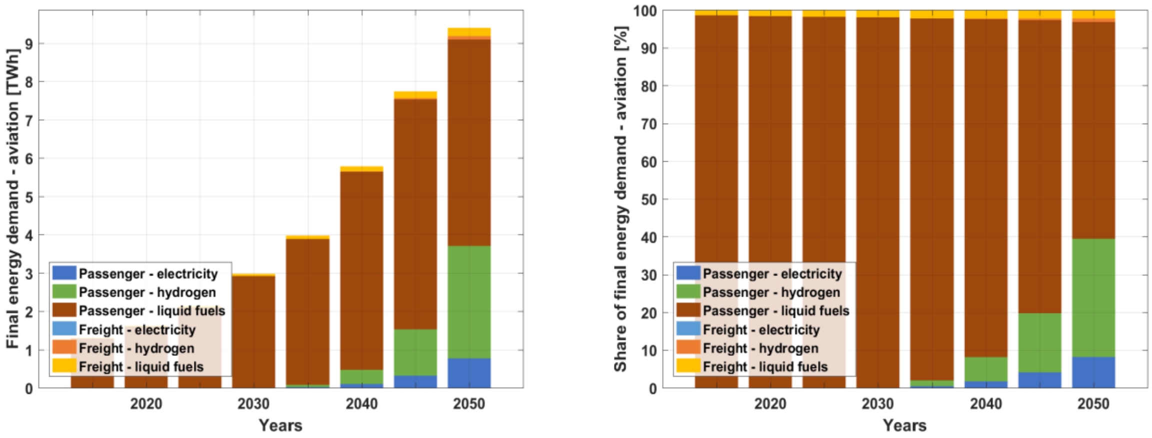

Figure S37: Final energy demand- aviation in absolute (left) and in relative (right) shares.

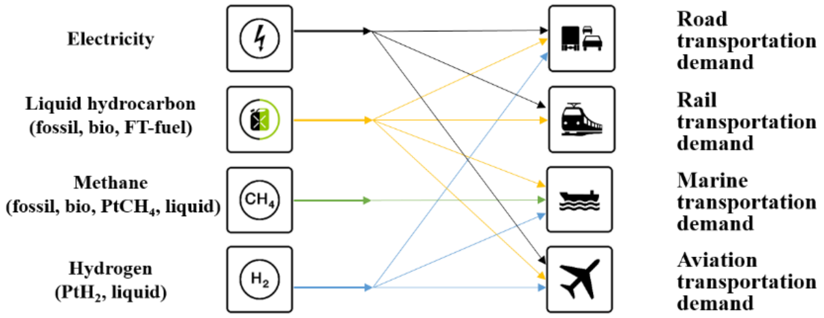

Figure S38: Schematic diagram of the transport modes and corresponding fuels utilised (Bogdanov *et al.*, 2019; Ram *et al.*, 2019).

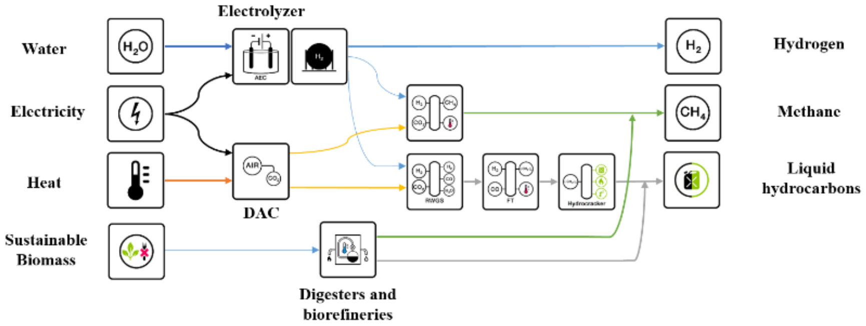

Figure S39: Schematic diagram of the value chain elements in the production of sustainable fuels (Bogdanov et al., 2019; Ram et al., 2019).

Table S12: Financial and technical assumptions of energy system technologies used from 2015 to 2050.

Technologies		Unit	2015	2020	2025	2030	2035	2040	2045	2050	Sources
PV rooftop – residential	**Capex**	**€/kW$_{,el}$**	1360	1169	966	826	725	650	589	537	(M. Bolinger and J. Seel, 2016; Vartiainen, Gaetan and Breyer, 2017)
	Opex fix	**€/(kW$_{,el}$ a)**	20.4	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	35	35	35	40	40	40	
PV rooftop - commercial	**Capex**	**€/kW$_{,el}$**	1360	907	737	623	542	484	437	397	(M. Bolinger and J. Seel, 2016; Vartiainen, Gaetan and Breyer,
	Opex fix	**€/(kW$_{,el}$ a)**	20.4	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	35	35	35	40	40	40	

										2017)
PV rooftop - industrial	**Capex**	**€/kW,$_{el}$**	1360	682	548	459	397	353	318	289	(M. Bolinger and J. Seel, 2016; Vartiainen, Gaetan and Breyer, 2017)
	Opex fix	**€/(kW,$_{el}$ a)**	20.4	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	35	35	35	40	40	40	
PV optimally tilted	**Capex**	**€/kW,$_{el}$**	1000	580	466	390	337	300	270	246	(M. Bolinger and J. Seel, 2016; Vartiainen, Gaetan and Breyer, 2017)
	Opex fix	**€/(kW,$_{el}$ a)**	15.0	13.2	11.8	10.6	9.6	8.8	8.0	7.4	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	35	35	35	40	40	40	
PV single-axis tracking	**Capex**	**€/kW,$_{el}$**	1150	638	513	429	371	330	297	271	(M. Bolinger and J. Seel, 2016; Vartiainen, Gaetan and Breyer, 2017)
	Opex fix	**€/(kW,$_{el}$ a)**	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	35	35	35	40	40	40	
Wind onshore	**Capex**	**€/kW,$_{el}$**	1250	1150	1060	1000	965	940	915	900	(Neij, 2008; European Commission (EC), 2014; Lazard, 2016; Wiser *et al.*, 2020)
	Opex fix	**€/(kW,$_{el}$ a)**	25	23	21	20	19	19	18	18	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	25	25	25	25	
	Opex fix	**€/(kW,$_{el}$ a)**	113	92	84	77	71	67	58	52	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	25	25	25	25	25	25	25	
Hydro Reservoir/ Dam	**Capex**	**€/kW,$_{el}$**	1650	1650	1650	1650	1650	1650	1650	1650	(European Commission (EC), 2014)
	Opex fix	**€/(kW,$_{el}$ a)**	49.5	49.5	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	0.003	0.003	

	Lifetime	**years**	50	50	50	50	50	50	50	50	
Hydro Run-of-River	**Capex**	**€/kW$_{,e}$**	2560	2560	2560	2560	2560	2560	2560	2560	(European Commission (EC), 2014)
	Opex fix	**€/(kW$_{,e}$ a)**	76.8	76.8	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	0.005	0.005	
	Lifetime	**years**	50	50	50	50	50	50	50	50	
Geothermal power	**Capex**	**€/kW$_{,el}$**	5250	4970	4720	4470	4245	4020	3815	3610	(European Commission (EC), 2014; Sigfússon and Uihlein, 2015)
	Opex fix	**€/(kW$_{,el}$ a)**	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	40	40	40	40	40	40	40	40	
Coal PP	**Capex**	**€/(kW$_{,el}$)**	1500	1500	1500	1500	1500	1500	1500	1500	(McDonald and Schrattenholzer, 2001; IEA-International Energy Agency, 2015)
	Opex fix	**€/(kW$_{el}$ a)**	20	20	20	20	20	20	20	20	
	Opex var	**€/(kWh)**	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	40	40	40	40	40	40	40	40	
	Opex fix	**€/(kW$_{el}$ a)**	162	157	157	137	137	116	116	109	
	Opex var	**€/(kWh$_{,el}$)**	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	
	Lifetime	**years**	40	40	40	40	40	40	40	40	
CCGT	**Capex**	**€/(kW$_{el}$)**	775	775	775	775	775	775	775	775	(International Energy Agency (IEA), 2016b)
	Opex fix	**€/(kW$_{el}$ a)**	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
OCGT	**Capex**	**€/(kW$_{el}$)**	475	475	475	475	475	475	475	475	(European Commission (EC), 2014)
	Opex fix	**€/(kW$_{el}$ a)**	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	**Capex**	**€/(kW$_{el}$)**	1000	968	946	923	902	880	860	840	(Breyer *et al.*, 2017)
	Opex fix	**€/(kW$_{el}$ a)**	20	19.4	18.9	18.5	18	17.6	17.2	16.8	

	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	30	30	30	30	
Biomass PP	**Capex**	**€/kW$_{,el}$**	2755	2620	2475	2330	2195	2060	1945	1830	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	55.4	47.2	44.6	41.9	39.5	37.1	35	32.9	
	Opex var	**€/(kWh$_{,el}$)**	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
	Lifetime	**years**	25	25	25	25	25	25	25	25	
CHP NG Heating	**Capex**	**€/kW$_{,el}$**	880	880	880	880	880	880	880	880	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	74.8	74.8	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	0.002	0.002	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
CHP Oil Heating	**Capex**	**€/kW$_{,el}$**	880	880	880	880	880	880	880	880	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	74.8	74.8	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	0.002	0.002	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
CHP Coal Heating	**Capex**	**€/kW$_{,el}$**	2030	2030	2030	2030	2030	2030	2030	2030	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	46.7	46.7	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	0.005	0.005	
	Lifetime	**years**	40	40	40	40	40	40	40	40	
CHP Biomass Heating	**Capex**	**€/kW$_{,el}$**	3560	3300	3145	2990	2870	2750	2645	2540	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	81.9	75.9	72.3	68.8	66	63.3	60.8	58.4	
	Opex var	**€/(kWh$_{,el}$)**	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Lifetime	**years**	25	25	25	25	25	25	25	25	
CHP Biogas	**Capex**	**€/kW$_{,el}$**	503	429	400	370	340	326	311	296	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{,el}$ a)**	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	**€/(kWh$_{,el}$)**	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
	Capex	**€/kW$_{,el}$**	5940	5630	5440	5240	5030	4870	4690	4540	(JRC-

Waste incinerator	**Opex fix**	**€/(kW$_{,el}$ a)**	267.3	253.4	244.8	235.8	226.4	219.1	211.0	204.3	Joint Research Centre, 2014)
	Opex var	**€/(kWh$_{,el}$)**	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
Biogas digester	**Capex**	**€/kW$_{,th}$**	771	731	706	680	653	632	609	589	(W. Urban, H. Lohmann, and G. Girod, 2009)
	Opex fix	**€/(kW$_{,th}$ a)**	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	25	25	25	25	
Biogas upgrade	**Capex**	**€/kW$_{,th}$**	340	290	270	250	230	220	210	200	(W. Urban, H. Lohmann, and G. Girod, 2009)
	Opex fix	**€/(kW$_{,th}$ a)**	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	25	25	25	25	
CSP (solar field, parabolic trough)	**Capex**	**€/kW$_{,th}$**	438.3	344.5	303.6	274.7	251.1	230.2	211.9	196	(Agora Energiewende, 2014; Haysom *et al.*, 2015; Breyer *et al.*, 2017)
	Opex fix	**€/(kW$_{,th}$ a)**	10.1	7.9	7	6.3	5.8	5.3	4.9	4.5	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	25	25	25	25	
Residential Solar Heat Collectors - Space Heating	**Capex**	**€/kW$_{,th}$**	1286	1214	1179	1143	1071	1000	929	857	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	25	25	30	30	30	30	30	
Residential Solar Heat Collectors - hot water	**Capex**	**€/kW$_{,th}$**	485	485	485	485	485	485	485	485	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	15	15	
DH Electric Heating	**Capex**	**€/kW$_{,th}$**	100	100	100	75	75	75	75	75	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	1.47	1.47	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	0.001	0.001	

	Lifetime	**years**	35	35	35	35	35	35	35	35	
DH Heat Pump	**Capex**	**€/kW$_{,th}$**	700	660	618	590	568	554	540	530	(Danish Energy Agency and Energinet, 2016)
	Opex fix	**€/(kW$_{,th}$ a)**	2	2	2	2	2	2	2	2	
	Opex var	**€/(kWh$_{,th}$)**	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	**years**	25	25	25	25	25	25	25	25	
DH Natural gas Heating	**Capex**	**€/kW$_{,th}$**	75	75	75	100	100	100	100	100	(Danish Energy Agency and Energinet, 2016)
	Opex fix	**€/(kW$_{,th}$ a)**	2.775	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh$_{,th}$)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
DH Oil Heating	**Capex**	**€/kW$_{,th}$**	75	75	75	100	100	100	100	100	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	2.775	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh$_{,th}$)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
DH Coal Heating	**Capex**	**€/kW$_{,th}$**	75	75	75	100	100	100	100	100	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	2.775	2.775	2.775	3.7	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh$_{,th}$)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
DH Biomass Heating	**Capex**	**€/kW$_{,th}$**	75	75	75	100	100	100	100	100	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	2.8	2.8	2.8	3.7	3.7	3.7	3.7	3.7	
	Opex var	**€/(kWh$_{,th}$)**	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	**years**	35	35	35	35	35	35	35	35	
DH Geothermal Heating	**Capex**	**€/kW$_{,th}$**	3936	3642	3384	3200	3180	3160	3150	3146	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	144	133	124	117	116	115	115	115	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	22	22	
Local Electric Heating	**Capex**	**€/kW$_{,th}$**	800	800	800	800	800	800	800	800	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	10	10	10	10	10	10	10	10	

	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
Local Heat Pump	**Capex**	**€/kW$_{,th}$**	800	780	750	730	706	690	666	650	(European Commission (EC), 2014)
	Opex fix	**€/(kW$_{,th}$ a)**	16	15.6	15	7.3	7.1	6.9	6.7	6.5	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	20	20	
Local Natural gas Heating	**Capex**	**€/kW$_{,th}$**	800	800	800	800	800	800	800	800	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	27	27	27	27	27	27	27	27	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	22	22	
Local Oil Heating	**Capex**	**€/kW$_{,th}$**	440	440	440	440	440	440	440	440	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	18	18	18	18	18	18	18	18	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	20	20	
Local Coal Heating	**Capex**	**€/kW$_{,th}$**	500	500	500	500	500	500	500	500	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	10	10	10	10	10	10	10	10	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	15	15	
Local Biomass Heating	**Capex**	**€/kW$_{,th}$**	675	675	675	750	750	750	750	675	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	2	2	2	3	3	3	3	3	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	20	20	20	20	20	20	
Local Biogas Heating	**Capex**	**€/kW$_{,th}$**	800	800	800	800	800	800	800	800	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{,th}$ a)**	27	27	27	27	27	27	27	27	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	22	22	22	22	22	22	22	22	
	Capex	**€/kW$_{,H2}$**	800	685	500	363	325	296	267	248	(Breyer *et*

Water electrolysis	**Opex fix**	**€/(kW,$_{H2}$ a)**	32	27	20	12.7	11.4	10.4	9.4	8.7	*al.*, 2015)
	Opex var	**€/(kWh,$_{H2}$)**	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
Methanation	**Capex**	**€/kW,$_{CH4}$**	547	502	368	278	247	226	204	190	(Breyer *et al.*, 2015)
	Opex fix	**€/(kW,$_{CH4}$ a)**	25.16	23.09	16.93	12.79	11.36	10.4	9.38	8.74	
	Opex var	**€/(kWh,$_{CH4}$)**	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
CO2 direct air capture	**Capex**	**€/t$_{CO2}$ a**	1000	730	493	335	274.4	234	210.6	195	(Svensson *et al.*, 2004)
	Opex fix	**€/t$_{CO2}$ a**	40	29.2	19.7	13.4	11	9.4	8.4	7.8	
	Opex var	**€/t$_{CO2}$**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	20	20	30	30	30	30	30	30	
Fischer-Tropsch Unit	**Capex**	**€/kW,FT$_{Liq}$**	947	947	947	947	947	852.3	852.3	852.3	(Fasihi, Bogdanov and Breyer, 2017)
	Opex fix	**€/kW,FT$_{Liq}$**	28.41	28.41	28.41	28.41	28.41	25.57	25.57	25.57	
	Opex var	**€/kWh,FT$_{Liq}$**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	30	30	30	30	30	30	
Battery storage	**Capex**	**€/(kWh$_{el}$)**	400	270	182	134	108	92	78	70	(Pleßmann *et al.*, 2014)
	Opex fix	**€/(kWh$_{el}$ a)**	24	9	5	3.75	3	2.5	2.125	1.875	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery interface	**Capex**	**€/(kW$_{el}$)**	200	135	91	67	54	46	39	35	(Pleßmann *et al.*, 2014)
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer -	**Capex**	**€/(kWh$_{el}$)**	603	407	280	209	170	146	124	111	(Ram *et al.*, 2019)
	Opex fix	**€/(kWh$_{el}$ a)**	36.2	13.6	7.7	5.8	4.7	4	3.4	3	
	Opex var	**€/(kWh,$_{el}$)**	0	0	0	0	0	0	0	0	

residential storage	**Lifetime**	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer - residential interface	**Capex**	**€/(kW$_{el}$)**	302	204	140	104	85	73	62	56	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer - commercial storage	**Capex**	**€/(kWh$_{el}$)**	513	346	235	174	141	120	102	91	(Ram *et al.*, 2019)
	Opex fix	**€/(kWh$_{el}$ a)**	30.8	11.5	6.5	4.9	3.9	3.3	2.8	2.5	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer - commercial interface	**Capex**	**€/(kW$_{el}$)**	256	173	117	87	70	60	51	46	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer - industrial storage	**Capex**	**€/(kWh$_{el}$)**	435	294	198	146	118	100	85	76	(Ram *et al.*, 2019)
	Opex fix	**€/(kWh$_{el}$ a)**	26.1	9.8	5.4	4.1	3.3	2.7	2.3	2	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
Battery PV prosumer - industrial interface	**Capex**	**€/(kW$_{el}$)**	218	147	99	73	59	50	42	38	(Ram *et al.*, 2019)
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	20	20	20	20	20	20	20	
PHES	**Capex**	**€/(kWh$_{el}$)**	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kWh$_{el}$ a)**	1.335	1.335	1.335	1.335	1.335	1.335	1.335	1.335	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	50	50	
	Capex	**€/(kW$_{el}$)**	650	650	650	650	650	650	650	650	(JRC-

PHES interface	**Opex fix**	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	Joint Research Centre, 2014)
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	50	50	
A-CAES	**Capex**	**€/(kWh$_{el}$)**	35	35	32.6	31.1	30.3	29.8	27.7	26.3	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kWh$_{el}$ a)**	0.53	0.53	0.50	0.47	0.46	0.45	0.42	0.40	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	40	55	55	55	55	55	55	55	
A-CAES interface	**Capex**	**€/(kW$_{el}$)**	600	600	558	530	518	510	474	450	(JRC-Joint Research Centre, 2014)
	Opex fix	**€/(kW$_{el}$ a)**	0	0	0	0	0	0	0	0	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	40	55	55	55	55	55	55	55	
Gas Storage	**Capex**	**€/(kWh$_{el}$)**	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	(Michalski *et al.*, 2017)
	Opex fix	**€/(kWh$_{el}$ a)**	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	**€/(kWh$_{,el}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	50	50	50	50	50	50	50	50	
Gas Storage interface	**Capex**	**€/(kW$_{th}$)**	25.8	25.8	25.8	25.8	25.8	25.8	25.8	25.8	(Michalski *et al.*, 2017)
	Opex fix	**€/(kW$_{th}$ a)**	31	31	31	31	31	31	31	31	
	Opex var	**€/(kWh$_{,th}$)**	36.2	36.2	36.2	36.2	36.2	36.2	36.2	36.2	
	Lifetime	**years**	41.4	41.4	41.4	41.4	41.4	41.4	41.4	41.4	
Hot Heat Storage	**Capex**	**€/(kWh$_{,th}$)**	50.8	41.8	32.7	26.8	23.3	21	19.3	17.5	(Ram *et al.*, 2019)
	Opex fix	**€/(kWh$_{,th}$ a)**	0.76	0.63	0.49	0.4	0.35	0.32	0.29	0.26	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	30	30	30	30	
District Heat Storage	**Capex**	**€/(kWh$_{th}$)**	50	40	30	30	25	20	20	20	(Ram *et al.*, 2019)
	Opex fix	**€/(kWh$_{th}$ a)**	0.8	0.6	0.5	0.5	0.4	0.3	0.3	0.3	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	25	25	25	25	30	30	30	30	

Hydrogen Storage	**Capex**	**€/(kWh$_{th}$)**	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	(Michalski *et al.*, 2017)
	Opex fix	**€/(kWh$_{th}$ a)**	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	15	15	
Hydrogen Storage interface	**Capex**	**€/(kW$_{th}$)**	255.9	255.9	255.9	255.9	255.9	255.9	255.9	255.9	(Michalski *et al.*, 2017)
	Opex fix	**€/(kW$_{th}$ a)**	10.23	10.23	10.23	10.23	10.23	10.23	10.23	10.23	
	Opex var	**€/(kWh$_{,th}$)**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	15	15	15	15	15	15	15	15	
CO2 Storage	**Capex**	**€/ton**	142	142	142	142	142	142	142	142	(Svensson *et al.*, 2004)
	Opex fix	**€/(ton a)**	9.94	9.94	9.94	9.94	9.94	9.94	9.94	9.94	
	Opex var	**€/ton**	0	0	0	0	0	0	0	0	
	Lifetime	**years**	30	30	30	30	30	30	30	30	

Table S13: Efficiency and self-discharge rates of storage technologies.

Technology	**Efficiency [%]**	**Self-Discharge [%/h]**	**Sources**
Battery	90	0.0	(Bloomberg New Energy Finance, 2015)
PHES	85	0.0	(JRC-Joint Research Centre, 2014)
A-CAES	70	0.1	(JRC-Joint Research Centre, 2014)
TES	90	0.2	(Bloomberg New Energy Finance, 2015)
Gas storage	100	0.0	(Bloomberg New Energy Finance, 2015)

Table S14: Energy to power ratio of storage technologies for the BPS-1.

Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**

Battery	1.1	1.00	1.00	4.20	4.56	5.17	6.05	6.05
A-CAES	3.62	17.66	17.66	5.32	7.35	7.09	7.89	8.20
TES	1.1	1.04	1.00	1.01	1.00	1.00	1.00	1.00
Gas storage	2.39	81.57	79.36	9.87	119.01	124.75	162.09	253.71

Table S15: Energy to power ratio of storage technologies for the BPS-2.

Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	1.1	1.00	1.22	4.00	4.35	5.09	5.7	5.99
A-CAES	3.62	10.70	7.17	6.03	7.07	8.09	9.32	8.80
TES	1.1	1.00	1.00	1.01	1.00	1.00	1.00	1.00
Gas storage	2.39	62.49	171.77	170.80	156.59	270.71	519.35	898.22

Table S16: Financial assumptions for the fossil fuel prices and GHG emission cost.

Component	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Sources**
Coal	**€/MWh$_{th}$**	7.7	7.7	8.4	9.2	10.2	11.1	11.1	11.1	(Bloomberg New Energy Finance, 2015)
Fuel oil	**€/MWh$_{th}$**	52.5	35.2	39.8	44.4	43.9	43.5	43.5	43.5	(IEA-International Energy Agency, 2015)
Fossil gas	**€/MWh$_{th}$**	21.8	22.2	30.0	32.7	36.1	40.2	40.2	40.2	(Bloomberg New Energy Finance, 2015)
GHG emissions	**€/tCO$_{2eq}$**	9	28	52	61	68	75	100	150	(Bloomberg New Energy Finance, 2015)
GHG emissions by fuel type										

Coal	tCO_{2eq}/MWh_{th}	0.34	(EPA-Environmental Protection agency, 2016)
Oil	tCO_{2eq}/MWh_{th}	0.25	(EPA-Environmental Protection agency, 2016)
Fossil gas	tCO_{2eq}/MWh_{th}	0.21	(Dii GmBH-Renewable Energy Bridging companies, 2015)

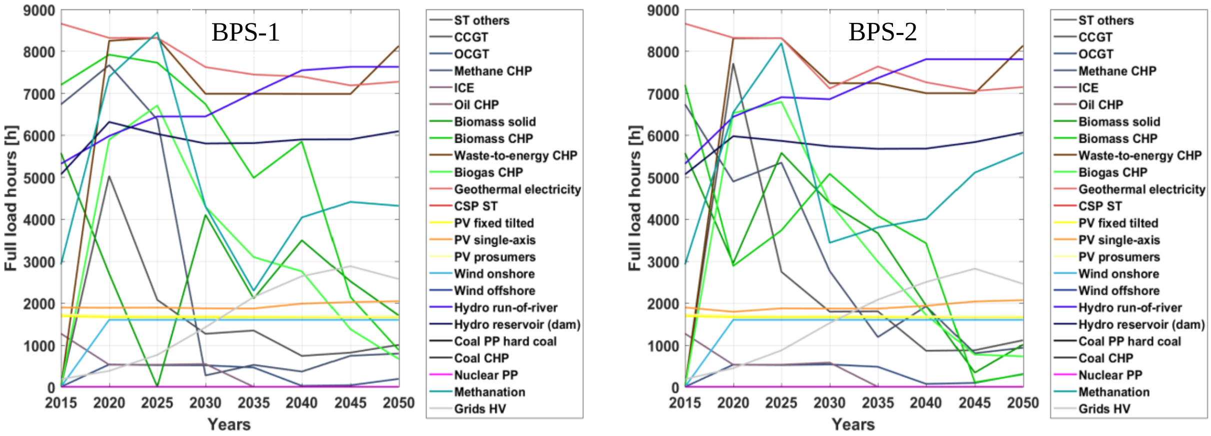

Figure S40: Full load hours- power, heat and transport sectors in the BPS 1 (left) and BPS 2 (right).

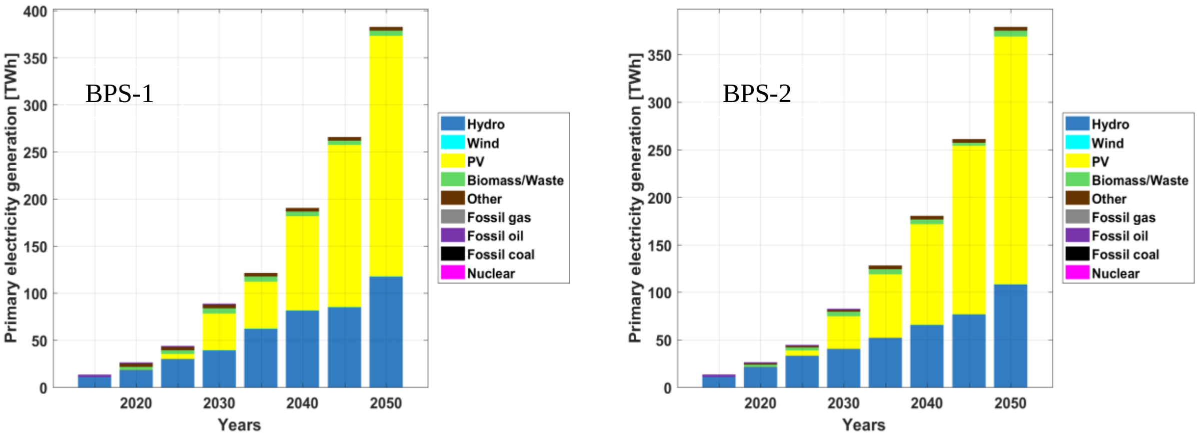

Figure S41: Primary electricity generation in the BPS 1 and BPS 2.

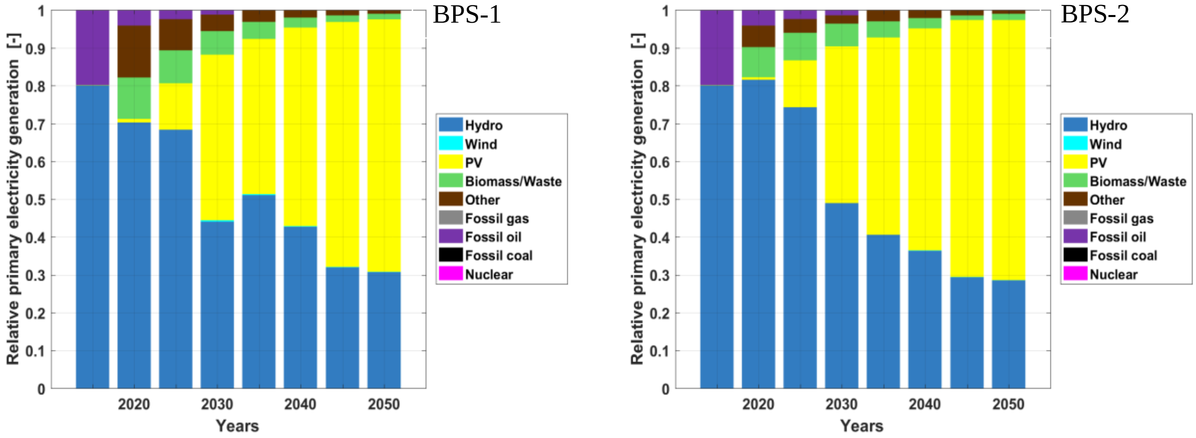

Figure S42: Relative primary electricity generation shares in the BPS 1 and BPS 2.

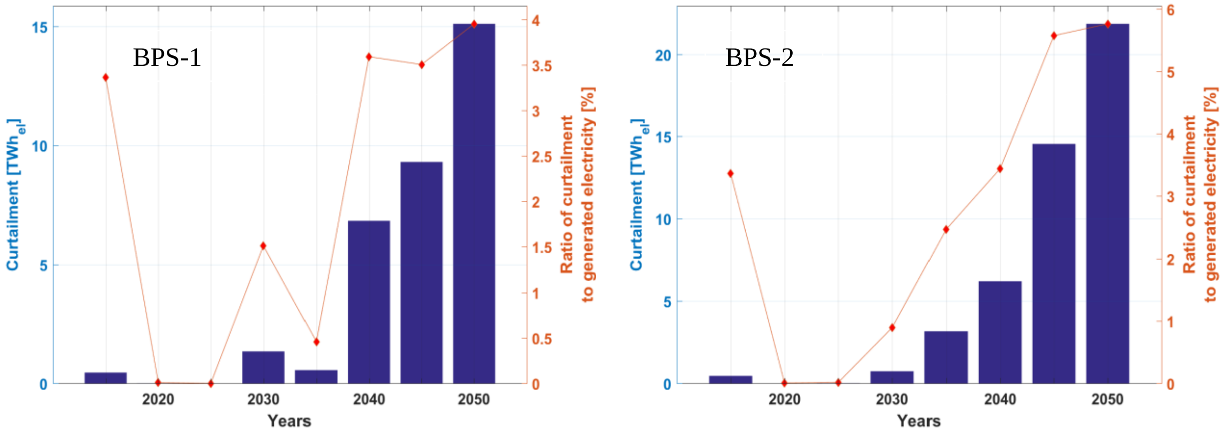

Figure S43: Curtailment-power, heat and transportation sectors in the BPS-1 and BPS-2.

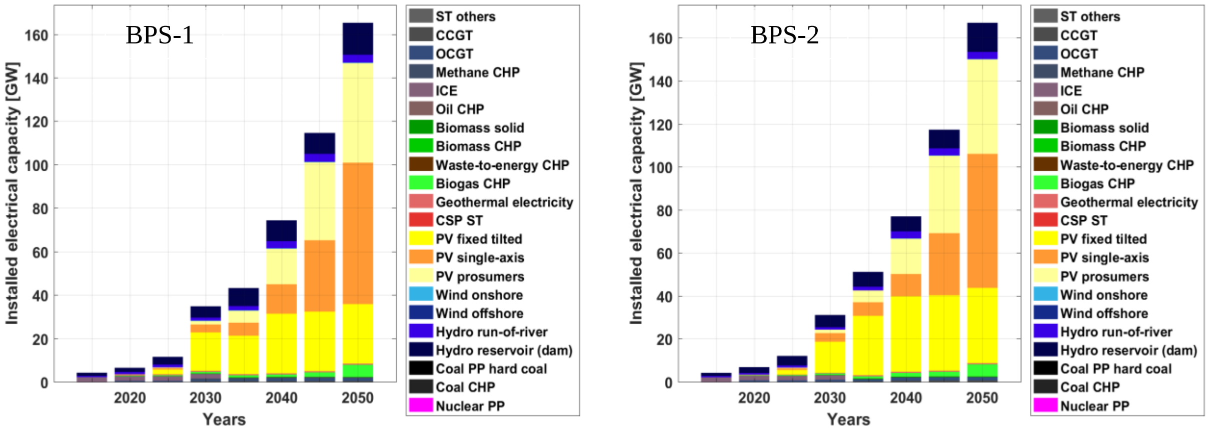

Figure S44: Newly installed electrical capacity on a technology-wise basis in the BPS-1 and BPS-2.

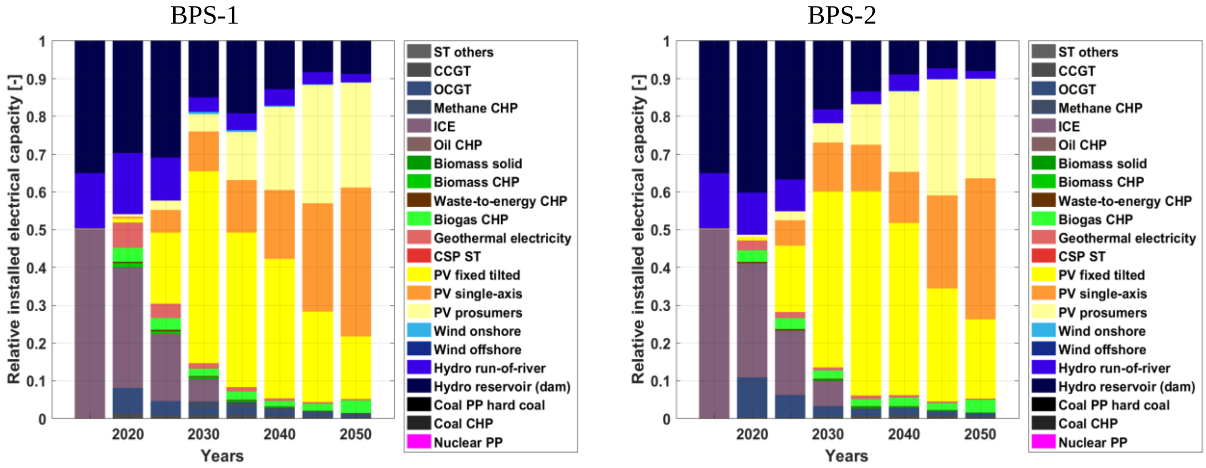

Figure S45: Relative shares in newly installed electrical capacity on a technology-wise basis for the BPS-1 and BPS-2.

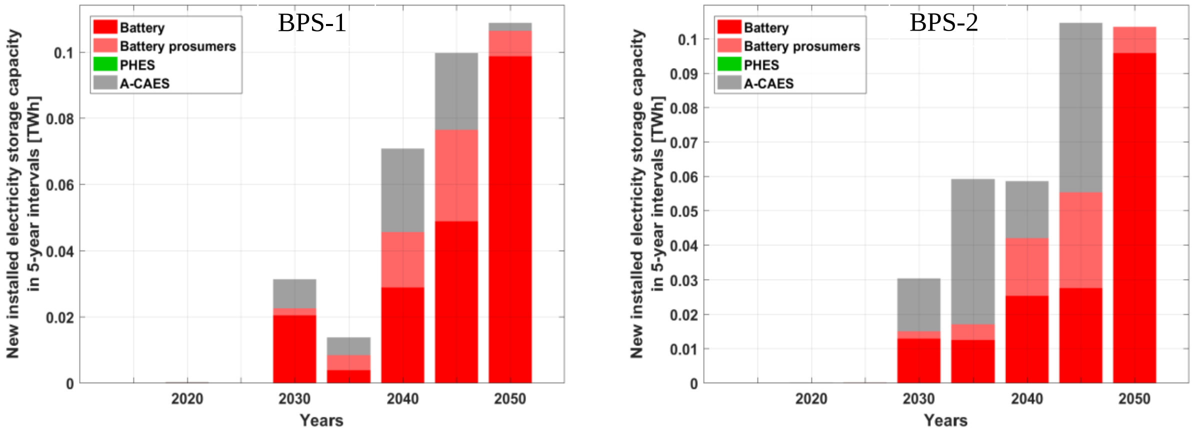

Figure S46: Technology-wise installed electricity storage capacity in 5-year intervals in the BPS-1 and BPS-2.

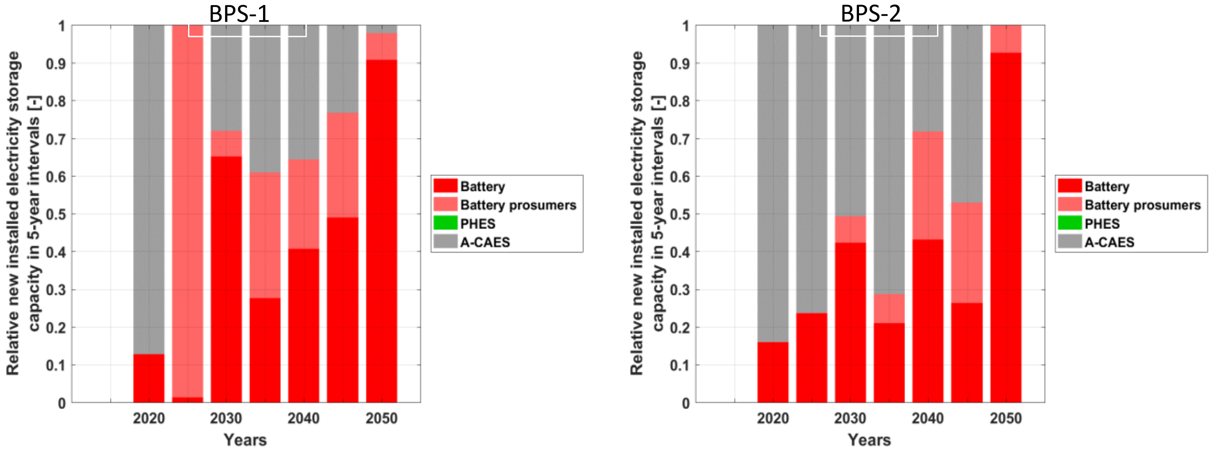

Figure S47: Relative shares in technology-wise installed electricity storage capacity in 5-year intervals in the BPS-1 and BPS-2.

Table S17: Installed capacity: power, heat and transportation sectors in the BPS-1.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV prosumers RES	**[GW]**	0.00	0.03	0.22	1.03	3.62	10.44	23.56	27.12
PV prosumers COM	**[GW]**	0.00	0.01	0.03	0.24	0.81	2.72	6.24	8.01
PV prosumers IND	**[GW]**	0.00	0.01	0.04	0.33	1.06	3.21	6.07	10.66
PV prosumers total	**[GW]**	0.00	0.04	0.28	1.59	5.49	16.37	35.87	45.79
PV fixed-tilted	**[GW]**	0.01	0.07	2.17	17.67	17.67	27.44	27.43	27.37
PV single-axis	**[GW]**	0.00	0.03	0.69	3.67	6.01	13.56	32.84	65.12
CSP ST	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind onshore	**[GW]**	0.00	0.00	0.00	0.21	0.21	0.21	0.21	0.21
Hydro run-of-river	**[GW]**	0.62	1.05	1.31	1.35	1.93	3.26	3.65	3.65
Hydro reservoir (dams)	**[GW]**	1.48	1.93	3.57	5.24	8.33	9.60	9.65	14.69
Geothermal electricity	**[GW]**	0.00	0.43	0.43	0.51	0.52	0.52	0.54	0.54
CCGT	**[GW]**	0.00	0.08	0.08	0.32	0.42	0.42	0.42	0.42
OCGT	**[GW]**	0.00	0.43	0.44	0.57	0.75	0.98	1.02	1.02
ST others	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass PP	**[GW]**	0.00	0.00	0.00	0.08	0.08	0.08	0.08	0.08
Biogas dig	**[GW]**	0.00	2.52	2.87	3.22	3.22	3.22	3.22	3.22
Biogas Upgrade	**[GW]**	0.00	0.21	0.23	0.48	0.49	0.32	0.29	0.39
Coal PP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ICG	**[GW]**	2.10	2.07	2.05	2.05	0.00	0.00	0.00	0.00
Methane CHP	**[GW]**	0.00	0.01	0.01	0.67	0.67	0.67	0.67	0.67
Oil CHP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Coal CHP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GW]**	0.00	0.07	0.07	0.12	0.12	0.12	0.05	0.05
Waste to energy CHP	**[GW]**	0.00	0.02	0.05	0.09	0.09	0.09	0.09	0.07
Biogas CHP	**[GW]**	0.00	0.24	0.36	0.68	0.92	1.04	2.05	5.56
Electric heating DH	**[GW]**	0.04	0.05	0.05	2.32	2.92	3.72	4.43	5.62
Heat pump DH	**[GW]**	0.00	0.00	0.13	0.41	0.57	0.57	0.67	0.67
Methane DH	**[GW]**	0.00	0.04	0.06	0.74	0.75	0.76	0.76	1.16
Oil DH	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal DH	**[GW]**	1.27	1.03	0.80	0.64	0.48	0.32	0.16	0.00
Biomass DH	**[GW]**	0.62	0.43	1.18	1.47	1.76	2.09	2.53	3.01
Electric heating IH	**[GW]**	0.24	0.24	0.20	0.15	0.10	0.05	0.00	3.13
Heat pump IH	**[GW]**	0.00	0.00	0.00	0.15	0.25	0.44	0.75	3.31
Methane IH	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.65
Oil IH	**[GW]**	0.00	17.37	17.37	19.99	21.18	22.66	22.72	20.56
Biomass IH	**[GW]**	60.90	41.43	38.08	38.24	41.19	45.42	48.83	41.15
Biogas IH	**[GW]**	0.00	2.05	2.05	2.05	2.07	2.08	2.08	2.83
Battery RES	**[GW]**	0.00	0.00	0.00	0.20	0.63	2.20	4.90	5.71
Battery RES	**[GW]**	0.00	0.00	0.00	0.06	0.16	0.62	1.34	2.82
Battery IND	**[GW]**	0.00	0.00	0.00	0.08	0.22	0.63	1.27	2.34
Battery SC	**[GW]**	0.00	0.00	0.00	0.33	1.01	3.44	7.52	10.87
Battery System	**[GW]**	0.00	0.02	0.02	5.03	5.76	11.33	17.76	28.96
Battery	**[GW]**	0.00	0.02	0.02	5.36	6.77	14.78	25.28	39.84

PHES	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TES HT	**[GW]**	0.00	0.30	1.19	11.63	13.28	13.65	16.81	22.17
TES DH	**[GW]**	0.00	0.42	0.64	12.14	12.20	12.62	13.71	14.27
A-CAES	**[GW]**	0.00	0.01	0.01	1.68	1.95	5.58	7.95	7.95
Gas (CH4) storage	**[GW]**	0.00	17.86	19.03	87.72	1079.63	1131.70	1716.75	2687.12

Table S18: Installed capacity: power, heat and transportation sectors in the BPS-2.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV prosumers RES	**[GW]**	0.00	0.03	0.22	1.03	3.62	10.44	23.66	25.23
PV prosumers COM	**[GW]**	0.00	0.01	0.03	0.24	0.81	2.72	6.24	8.06
PV prosumers IND	**[GW]**	0.00	0.01	0.04	0.33	1.06	3.21	6.09	10.66
PV prosumers total	**[GW]**	0.00	0.04	0.28	1.59	5.49	16.37	35.99	43.96
PV fixed-tilted	**[GW]**	0.01	0.06	2.12	14.48	27.64	35.05	35.05	35.00
PV single-axis	**[GW]**	0.00	0.00	0.82	4.02	6.29	10.41	28.86	62.30
CSP ST	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind onshore	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.14	0.14	0.14
Hydro run-of-river	**[GW]**	0.62	0.76	1.02	1.14	1.74	3.33	3.33	3.33
Hydro reservoir (dams)	**[GW]**	1.48	2.77	4.45	5.68	6.90	6.94	8.66	13.54
Geothermal electricity	**[GW]**	0.00	0.18	0.19	0.26	0.51	0.53	0.54	0.55
CCGT	**[GW]**	0.00	0.02	0.02	0.13	0.31	0.61	0.69	0.73
OCGT	**[GW]**	0.00	0.73	0.73	0.81	0.89	1.40	1.40	1.40
ST others	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Biomass PP	**[GW]**	0.00	0.00	0.00	0.07	0.20	0.21	0.21	0.21
Biogas dig	**[GW]**	0.00	2.52	2.87	3.22	3.22	3.22	3.22	3.22
Biogas Upgrade	**[GW]**	0.00	0.18	0.19	0.40	0.43	0.30	0.29	0.48
Coal PP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ICG	**[GW]**	2.10	2.07	2.05	2.05	0.00	0.00	0.00	0.00
Methane CHP	**[GW]**	0.00	0.00	0.00	0.07	0.09	0.10	0.10	0.10
Oil CHP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal CHP	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GW]**	0.00	0.00	0.00	0.04	0.04	0.05	0.04	0.04
Waste to energy CHP	**[GW]**	0.00	0.02	0.05	0.08	0.08	0.09	0.09	0.07
Biogas CHP	**[GW]**	0.00	0.21	0.35	0.68	0.95	1.72	2.14	5.60
Electric heating DH	**[GW]**	0.04	0.04	0.05	1.80	2.23	3.64	4.84	6.22
Heat pump DH	**[GW]**	0.00	0.00	0.37	0.62	0.78	0.95	1.08	0.99
Methane DH	**[GW]**	0.00	0.01	0.07	0.48	0.48	0.69	0.83	1.50
Oil DH	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal DH	**[GW]**	1.27	1.03	0.80	0.64	0.48	0.32	0.16	0.00
Biomass DH	**[GW]**	0.62	0.42	0.42	0.83	1.31	1.79	2.26	2.59
Electric heating IH	**[GW]**	0.24	0.24	0.20	0.15	0.10	0.05	0.00	2.91
Heat pump IH	**[GW]**	0.00	0.00	0.00	0.15	0.25	0.44	0.44	3.23
Methane IH	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.39
Oil IH	**[GW]**	0.00	17.37	17.37	19.99	21.18	22.66	22.66	20.44
Biomass IH	**[GW]**	60.90	41.43	38.08	38.24	41.19	45.42	41.16	33.58

Biogas IH	**[GW]**	0.00	2.05	2.05	2.05	2.07	2.08	2.08	2.94
Battery RES	**[GW]**	0.00	0.00	0.00	0.20	0.63	2.20	4.93	5.81
Battery RES	**[GW]**	0.00	0.00	0.00	0.06	0.16	0.62	1.34	2.42
Battery IND	**[GW]**	0.00	0.00	0.00	0.08	0.22	0.63	1.28	2.34
Battery SC	**[GW]**	0.00	0.00	0.00	0.33	1.01	3.44	7.54	10.57
Battery System	**[GW]**	0.00	0.01	0.02	3.41	6.33	11.09	15.15	25.76
Battery	**[GW]**	0.00	0.01	0.02	3.74	7.34	14.53	22.69	36.33
PHES	**[GW]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TES HT	**[GW]**	0.00	0.06	1.78	7.56	8.72	11.44	17.62	22.91
TES DH	**[GW]**	0.00	0.69	0.89	7.91	8.01	10.26	10.41	11.50
A-CAES	**[GW]**	0.00	0.00	0.01	2.56	8.16	9.17	13.24	14.02
Gas (CH4) storage	**[GW]**	0.00	11.17	33.33	115.93	177.84	541.06	2442.98	4365.24

Table S19: Electricity generation: power, heat and transportation sectors in the BPS-1.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV prosumers RES	**[GWh]**	0.01	43.12	363.01	1731.40	6102.38	17518.72	39434.28	45426.82
PV prosumers COM	**[GWh]**	0.00	11.94	45.39	401.09	1380.93	4588.57	10504.07	13469.68
PV prosumers IND	**[GWh]**	0.00	16.80	72.16	555.68	1799.37	5452.35	10306.99	18096.24
PV prosumers total	**[GWh]**	0.01	71.86	480.56	2688.18	9282.68	27559.64	60245.34	76992.74
PV fixed-tilted	**[GWh]**	11.67	111.61	3591.89	29284.01	29278.58	45463.71	45458.96	45359.02
PV single-axis	**[GWh]**	0.02	62.22	1312.60	6866.25	11218.49	26887.53	66336.25	132937.19

CSP ST	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind onshore	**[GWh]**	0.00	0.16	0.16	341.19	341.19	341.25	341.43	341.43
Wind offshore	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro run-of-river	**[GWh]**	3280.66	6293.18	8459.12	8692.41	13502.06	24600.88	27864.58	27864.57
Hydro reservoir (dams)	**[GWh]**	7482.41	12180.93	21545.18	30382.48	48426.62	56622.66	56966.60	89499.86
Geothermal electricity	**[GWh]**	0.06	3612.03	3613.05	3870.46	3834.84	3874.65	3845.30	3918.98
CCGT	**[GWh]**	0.00	418.60	172.75	1164.77	568.89	643.11	622.24	625.66
OCGT	**[GWh]**	0.00	228.11	229.00	484.12	392.49	52.69	51.14	204.32
ST others	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass PP	**[GWh]**	0.04	6.79	0.00	313.54	161.05	276.40	192.75	130.51
Biogas Upgrade	**[GWh]**	0.00	1460.96	1332.69	2432.63	2677.63	1768.81	1813.51	2796.16
Coal pp hard coal	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ICG	**[GWh]**	2666.40	1087.90	1076.91	1112.17	0.00	0.00	0.00	0.00
Methane CHP	**[GWh]**	0.06	60.84	50.23	485.86	352.42	563.96	979.77	938.90
Oil CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GWh]**	0.06	562.34	553.45	814.84	602.19	708.34	107.39	43.53

Table S20: Electricity generation: power, heat and transportation sectors in the BPS-2.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV prosumers RES	**[GWh]**	0.01	43.12	363.01	1731.40	6102.38	17518.72	39602.94	42263.90

PV prosumers COM	**[GWh]**	0.00	11.94	45.39	401.09	1380.93	4588.57	10498.41	13573.06
PV prosumers IND	**[GWh]**	0.00	16.80	72.16	555.68	1799.37	5452.35	10342.56	18096.24
PV prosumers total	**[GWh]**	0.01	71.86	480.56	2688.18	9282.68	27559.64	60443.91	73933.20
PV fixed-tilted	**[GWh]**	11.67	99.76	3511.67	23999.13	45799.62	58086.71	58080.47	57992.38
PV single-axis	**[GWh]**	0.02	2.11	1527.45	7501.17	11735.60	20126.10	58753.17	128755.29
CSP ST	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wind onshore	**[GWh]**	0.00	0.28	0.28	2.80	3.08	216.16	215.87	215.87
Hydro run-of-river	**[GWh]**	3280.66	4918.03	7025.78	7827.91	12841.10	26015.15	26015.15	26015.15
Hydro reservoir (dams)	**[GWh]**	7482.41	16535.40	26066.24	32542.43	39132.43	39443.80	50549.14	82058.01
Geothermal electricity	**[GWh]**	0.06	1498.71	1617.34	1816.61	3886.18	3872.42	3843.22	3907.29
CCGT	**[GWh]**	0.00	125.55	47.02	320.46	647.32	742.73	1159.32	1263.09
OCGT	**[GWh]**	0.00	383.66	384.95	489.45	487.47	137.59	384.64	789.05
ST others	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass PP	**[GWh]**	0.04	5.28	10.91	296.04	749.06	410.99	71.25	211.48
Biogas Upgrade	**[GWh]**	0.00	1199.02	1232.31	2286.43	2598.41	1842.84	1571.35	3195.16
Coal pp hard coal	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ICG	**[GWh]**	2666.40	1088.39	1079.04	1182.97	0.00	0.00	0.00	0.00

Methane CHP	**[GWh]**	0.06	6.70	10.20	288.32	123.54	308.29	144.41	146.80
Oil CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GWh]**	0.06	10.73	15.53	202.83	163.26	154.73	4.45	12.17

Table S21: Electricity storage output for the BPS-1.

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	**[TWh]**	0.00	0.02	0.00	9.86	10.43	31.60	53.11	107.88
PHES	**[TWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A-CAES	**[TWh]**	0.00	0.00	0.00	1.85	2.33	9.40	12.33	12.47
TES	**[TWh]**	0.00	0.29	0.47	15.35	1.12	27.82	2.71	3.54

Table S22: Electricity storage output for the BPS-2.

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	**[TWh]**	0.00	0.01	0.03	6.28	14.68	28.65	45.39	100.40
PHES	**[TWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A-CAES	**[TWh]**	0.00	0.00	0.01	2.65	12.70	14.00	23.24	24.10
TES	**[TWh]**	0.00	0.07	0.70	7.25	12.46	9.89	3.03	4.89

Table S23: Heat generation-heat sector in the BPS-1.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Methane CHP	**[GWh]**	0.02	40.52	36.05	214.03	167.79	273.65	501.13	446.22
Oil CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Coal CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GWh]**	0.07	1222.25	1221.34	1531.73	1279.57	1401.60	136.13	51.29
Waste-to-energy CHP	**[GWh]**	0.00	393.55	845.80	1390.80	1327.74	1387.70	1332.21	1273.35
Biogas CHP	**[GWh]**	0.00	1372.57	2313.84	3283.80	2929.03	3141.04	2946.96	3712.31
Electric heating DH	**[GWh]**	51.67	5.08	0.00	2477.54	1574.05	7193.31	5374.11	8201.64
Heat pump DH	**[GWh]**	0.03	5.43	986.37	2150.45	2722.68	2369.47	3112.02	3010.55
GAS DH	**[GWh]**	0.04	49.50	363.12	1125.68	187.25	1071.80	216.62	595.99
Oil DH	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal DH	**[GWh]**	8582.27	5851.79	430.58	157.42	86.46	58.04	38.97	0.00
Biomass DH	**[GWh]**	4197.42	3600.19	9851.19	11563.72	13722.47	16252.78	18576.45	21626.81
Electric heater IH	**[GWh]**	856.06	1.43	1.15	0.87	0.46	0.10	0.00	2486.63
Heat pump IH	**[GWh]**	0.00	0.01	0.01	200.68	286.16	268.30	326.60	6230.58
GAS IH	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	2.20
Oil IH	**[GWh]**	0.00	810.97	910.68	1285.16	1327.45	1342.92	1201.07	0.98
Biomass IH	**[GWh]**	44184.19	31137.72	29251.44	30571.97	33146.90	36920.09	39695.94	53415.18
Biogas IH	**[GWh]**	0.00	14115.41	14506.70	15084.87	15734.57	16317.42	16738.88	9183.16

Table S24: Heat generation: heat sector in the BPS-2.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**

Methane CHP	**[GWh]**	0.02	2.42	3.76	115.57	49.23	124.17	56.51	57.68
Oil CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal CHP	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass CHP	**[GWh]**	0.07	12.51	19.28	242.04	219.88	182.13	5.80	14.45
Waste-to-energy CHP	**[GWh]**	0.00	395.39	851.95	1292.70	1441.28	1320.28	1352.58	1297.86
Biogas CHP	**[GWh]**	0.00	1318.37	2218.91	3119.89	3257.08	3085.09	1675.03	4178.20
Electric heating DH	**[GWh]**	51.67	5.69	14.83	1724.85	2998.60	5494.22	7660.01	12936.42
Heat pump DH	**[GWh]**	0.03	4.49	2755.16	4070.80	4592.30	6414.81	6433.97	5603.51
GAS DH	**[GWh]**	0.04	10.83	183.24	447.34	354.52	390.99	292.62	891.12
Oil DH	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal DH	**[GWh]**	8582.27	8579.50	6609.60	5216.29	3907.07	1668.27	543.44	0.00
Biomass DH	**[GWh]**	4197.42	2151.35	3478.02	6491.42	10259.55	14069.50	16170.86	18194.90
Electric heater IH	**[GWh]**	856.06	1.43	1.15	0.87	0.46	0.10	0.00	3027.54
Heat pump IH	**[GWh]**	0.00	0.01	0.01	200.68	286.16	268.30	298.54	6584.18
GAS IH	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.65
Oil IH	**[GWh]**	0.00	810.97	910.68	1285.16	1327.45	1342.92	0.00	1.01
Biomass IH	**[GWh]**	1853.50	1588.50	1704.91	2208.68	2694.48	3138.15	3047.25	5206.56
Biogas IH	**[GWh]**	1970.91	1677.64	1780.15	2290.52	2800.50	3254.69	3152.15	5430.94

Table S25: Heat storage output in the BPS-1.

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
TES	**[TWh]**	0.00	0.29	0.47	15.35	1.12	27.82	2.71	3.54
DH	**[TWh]**	0.00	0.62	0.49	35.14	19.97	50.26	28.20	21.63
Gas (CH4) storage	**[TWh]**	0.00	1.47	1.34	5.52	2.81	3.66	3.27	3.95

Table S26: Heat storage output in the BPS-2.

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
TES	**[TWh]**	0.00	0.08	0.77	8.06	13.85	10.99	3.37	5.45
DH	**[TWh]**	0.00	0.46	0.66	30.27	34.41	34.47	10.97	17.63
Gas (CH4) storage	**[TWh]**	0.00	1.20	1.26	2.88	2.98	2.65	3.44	5.22

Table S27: Sustainable fuel production: transport sector in the BPS-1.

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyser	**[GWh]**	0.02	35.13	89.81	6495.28	4014.48	12853.06	21318.71	27178.77
Methanation	**[GWh]**	0.01	4.17	10.48	3090.05	130.99	1893.45	1458.69	1153.03
FT	**[GWh]**	0.00	11.47	0.60	1445.99	1947.26	5239.27	9895.71	12152.85
FT kerosene	**[GWh]**	0.00	3.97	0.21	391.47	613.12	2447.67	4822.25	5605.33
FT diesel	**[GWh]**	0.00	5.21	0.27	765.32	944.68	1743.74	3094.32	4116.95
FT naphtha	**[GWh]**	0.00	2.29	0.12	289.20	389.45	1047.85	1979.14	2430.57
LNG	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LH2	**[GWh]**	0.00	0.00	0.00	0.00	62.47	380.05	1243.25	3024.76

Table S28: Sustainable fuel production: transport sector in the BPS-2.

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyser	**[GWh]**	0.02	19.83	113.76	1380.02	2053.93	3960.61	7131.70	9861.91
Methanation	**[GWh]**	0.01	3.30	23.32	592.53	381.89	809.44	1866.01	2022.05
FT	**[GWh]**	0.00	2.50	5.22	259.34	497.69	494.00	565.77	458.43
FT kerosene	**[GWh]**	0.00	0.89	1.82	91.80	180.73	177.69	278.24	212.70
FT diesel	**[GWh]**	0.00	1.11	2.35	115.67	217.42	217.51	174.37	154.04
FT naphtha	**[GWh]**	0.00	0.50	1.04	51.87	99.54	98.80	113.15	91.69
LNG	**[GWh]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LH2	**[GWh]**	0.00	0.00	0.00	0.00	62.47	380.05	1243.25	3024.76

Table S29: Final transport energy demand by mode, segment and vehicle type in the BPS-1.

Technology	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Road LDV ICE fuel	**[TWh,th]**	2.80	3.21	3.22	2.49	1.29	0.93	0.78	0.58
Road LDV BEV elec	**[TWh,el]**	0.00	0.02	0.08	0.38	0.86	1.28	1.76	2.49
Road LDV FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.02	0.04	0.15	0.38	0.53
Road LDV PHEV fuel	**[TWh,th]**	0.00	0.01	0.03	0.03	0.04	0.05	0.07	0.09
Road LDV PHEV elec	**[TWh,el]**	0.00	0.01	0.05	0.06	0.07	0.10	0.13	0.18
Road 2,3W ICE fuel	**[TWh,th]**	0.93	0.78	0.85	0.72	0.59	0.50	0.47	0.34

Road 2,3W BEV elec	**[TWh,el]**	0.04	0.15	0.20	0.38	0.62	0.98	1.49	2.25
Road 2,3W FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road 2,3W PHEV fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road 2,3W PHEV elec	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road Bus ICE fuel	**[TWh,th]**	4.16	3.55	2.38	0.96	0.41	0.42	0.44	0.43
Road Bus BEV elec	**[TWh,el]**	0.00	0.40	1.09	1.97	2.66	3.26	4.21	5.40
Road Bus FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Road Bus PHEV fuel	**[TWh,th]**	0.00	0.01	0.02	0.04	0.07	0.11	0.17	0.26
Road Bus PHEV elec	**[TWh,el]**	0.00	0.01	0.01	0.02	0.03	0.05	0.07	0.10
Road MDV ICE fuel	**[TWh,th]**	6.81	7.15	7.34	5.41	2.37	0.99	1.05	1.03
Road MDV BEV elec	**[TWh,el]**	0.00	0.29	0.61	1.80	3.46	4.85	6.47	8.54
Road MDV FCEV H2	**[TWh,th]**	0.00	0.00	0.05	0.13	0.42	1.11	1.51	2.04
Road MDV PHEV fuel	**[TWh,th]**	0.00	0.03	0.07	0.12	0.20	0.34	0.55	0.85
Road MDV PHEV elec	**[TWh,el]**	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.12

Road HDV ICE fuel	**[TWh,th]**	1.08	1.23	1.27	1.34	1.00	0.34	0.15	0.15
Road HDV BEV elec	**[TWh,el]**	0.00	0.01	0.05	0.12	0.30	0.64	0.87	1.15
Road HDV FCEV H2	**[TWh,th]**	0.00	0.00	0.02	0.05	0.24	0.48	0.65	0.86
Road HDV PHEV fuel	**[tWh,el]**	0.00	0.01	0.01	0.02	0.04	0.11	0.28	0.39
Road HDV PHEV elec	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
Rail pass fuel	**[tWh,th]**	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Rail pass elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Rail freight fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rail freight elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LNG	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Marine freight elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight LNG	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation pass fuel	**[TWh,th]**	1.28	1.59	2.09	2.92	3.80	5.17	6.00	5.39
Aviation pass elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.02	0.10	0.32	0.77
Aviation pass LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.06	0.37	1.21	2.94
Aviation freight fuel	**[TWh,th]**	0.02	0.03	0.04	0.06	0.09	0.13	0.18	0.22
Aviation freight elec.	**[TWh, el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation freight LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.09

Table S30: Final transport energy demand by mode, segment and vehicle type in the BPS-2.

Technology	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Road LDV ICE fuel	**[TWh,th]**	2.80	3.21	3.22	2.49	1.29	0.93	0.78	0.58
Road LDV BEV elec	**[TWh,el]**	0.00	0.02	0.08	0.38	0.86	1.28	1.76	2.49
Road LDV FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.02	0.04	0.15	0.38	0.53

Road LDV PHEV fuel	**[TWh,th]**	0.00	0.01	0.03	0.03	0.04	0.05	0.07	0.09
Road LDV PHEV elec	**[TWh,el]**	0.00	0.01	0.05	0.06	0.07	0.10	0.13	0.18
Road 2,3W ICE fuel	**[TWh,th]**	0.93	0.78	0.85	0.72	0.59	0.50	0.47	0.34
Road 2,3W BEV elec	**[TWh,el]**	0.04	0.15	0.20	0.38	0.62	0.98	1.49	2.25
Road 2,3W FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road 2,3W PHEV fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road 2,3W PHEV elec	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Road Bus ICE fuel	**[TWh,th]**	4.16	3.55	2.38	0.96	0.41	0.42	0.44	0.43
Road Bus BEV elec	**[TWh,el]**	0.00	0.40	1.09	1.97	2.66	3.26	4.21	5.40
Road Bus FCEV H2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Road Bus PHEV fuel	**[TWh,th]**	0.00	0.01	0.02	0.04	0.07	0.11	0.17	0.26
Road Bus PHEV elec	**[TWh,el]**	0.00	0.01	0.01	0.02	0.03	0.05	0.07	0.10
Road MDV ICE fuel	**[TWh,th]**	6.81	7.15	7.34	5.41	2.37	0.99	1.05	1.03
Road MDV BEV elec	**[TWh,el]**	0.00	0.29	0.61	1.80	3.46	4.85	6.47	8.54

Road MDV FCEV H2	**[TWh,th]**	0.00	0.00	0.05	0.13	0.42	1.11	1.51	2.04
Road MDV PHEV fuel	**[TWh,th]**	0.00	0.03	0.07	0.12	0.20	0.34	0.55	0.85
Road MDV PHEV elec	**[TWh,el]**	0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.12
Road HDV ICE fuel	**[TWh,th]**	1.08	1.23	1.27	1.34	1.00	0.34	0.15	0.15
Road HDV BEV elec	**[TWh,el]**	0.00	0.01	0.05	0.12	0.30	0.64	0.87	1.15
Road HDV FCEV H2	**[TWh,th]**	0.00	0.00	0.02	0.05	0.24	0.48	0.65	0.86
Road HDV PHEV fuel	**[tWh,el]**	0.00	0.01	0.01	0.02	0.04	0.11	0.28	0.39
Road HDV PHEV elec	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
Rail pass fuel	**[tWh,th]**	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Rail pass elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Rail freight fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rail freight elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine pass LNG	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Marine freight fuel	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Marine freight LNG	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation pass fuel	**[TWh,th]**	1.28	1.59	2.09	2.92	3.80	5.17	6.00	5.39
Aviation pass elec.	**[TWh,el]**	0.00	0.00	0.00	0.00	0.02	0.10	0.32	0.77
Aviation pass LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.06	0.37	1.21	2.94
Aviation freight fuel	**[TWh,th]**	0.02	0.03	0.04	0.06	0.09	0.13	0.18	0.22
Aviation freight elec.	**[TWh, el]**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aviation freight LH2	**[TWh,th]**	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.09

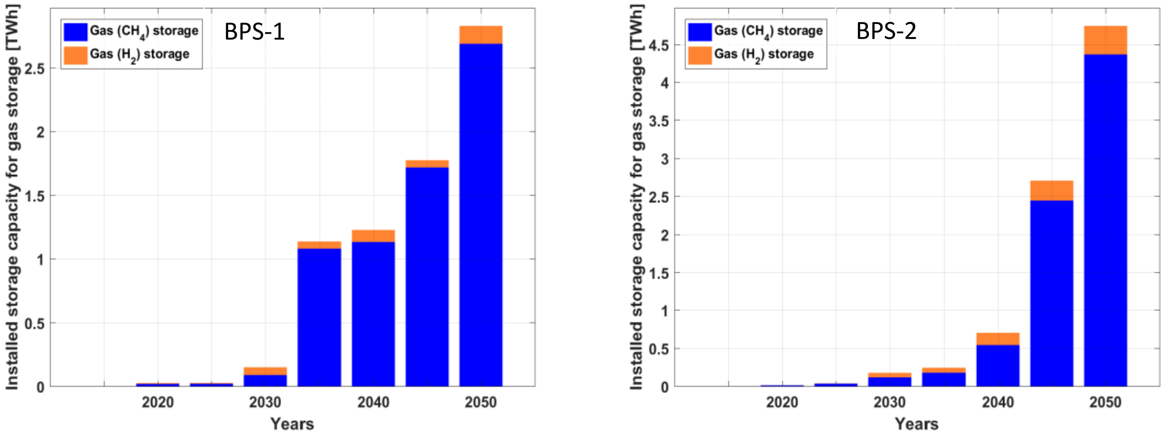

Figure S48: Transport sector: Installed capacity for gas storage in the BPS-1 and BPS-2.

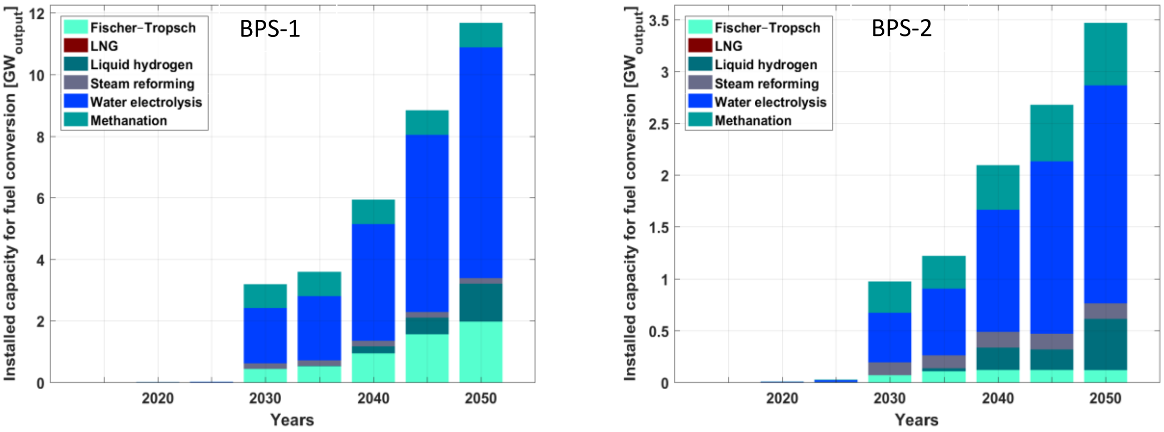

Figure S49: Transport sector: Installed capacity for fuel conversion in the BPS-1 and BPS-2.

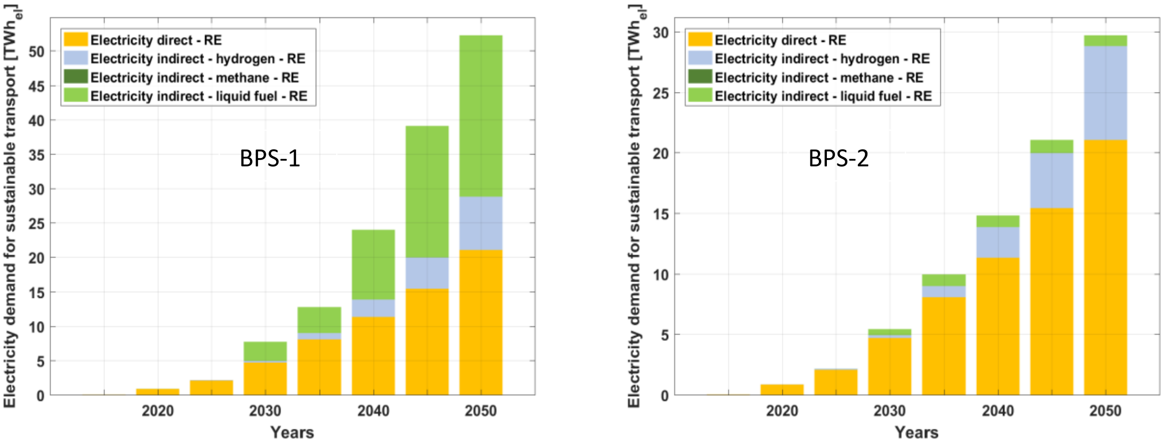

Figure S50: Electricity demand for sustainable transport in the BPS-1 and BPS-2 during the transition period.

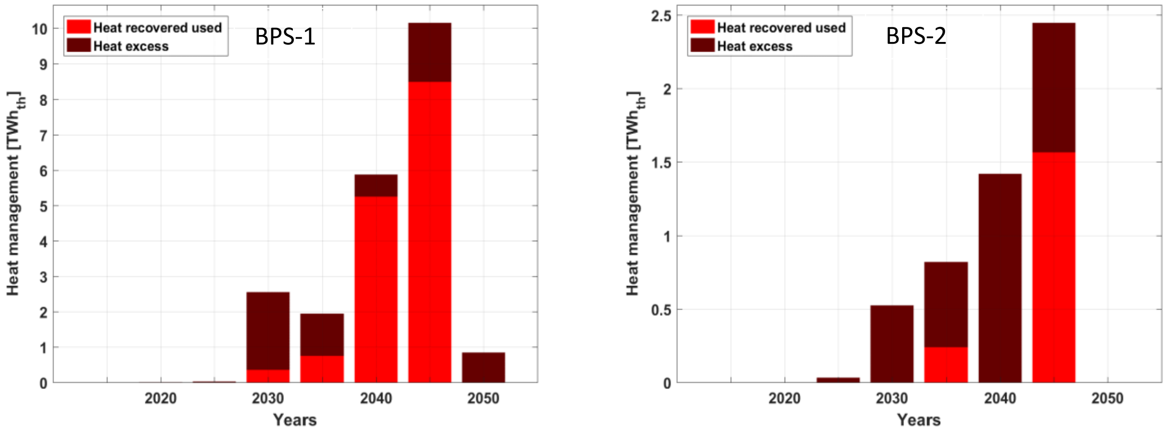

Figure S51: Transport sector: Installed capacity for heat management in the BPS-1 and BPS-2.

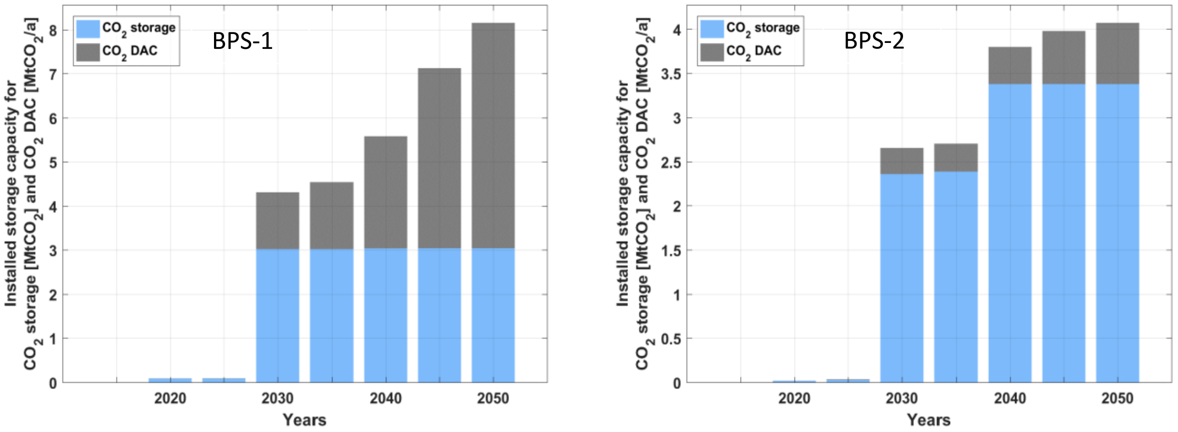

Figure S52: Transport sector: Installed capacity for CO_2 direct air capture and CO_2 storage in the BPS-1 and BPS-2.

Table S31: Electricity costs in all sectors in the BPS-1.

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
LCOE - Generation	**[€/MWh]**	79.45	49.42	43.20	38.66	33.79	30.36	27.00	24.64
LCOC - Curtailment	**[€/MWh]**	3.24	0.00	0.00	0.59	0.21	1.15	1.06	0.86
LCOS - Storage	**[€/MWh]**	0.00	0.41	0.28	14.38	9.11	12.00	13.06	11.68
LCOT - Transmission	**[€/MWh]**	4.99	2.39	1.56	0.99	0.76	0.50	0.62	0.78
LCOE total	**[€/MWh]**	87.68	52.22	45.05	54.62	43.87	44.01	41.75	37.97
GHG emissions cost	**[€/MWh]**	1.67	1.08	1.19	0.74	0.00	0.00	0.00	0.00
Fuel cost	**[€/MWh]**	39.72	6.58	4.07	3.76	0.00	0.29	0.08	0.00

Table S32: Electricity costs in all sectors in the BPS-2.

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
LCOE - Generation	**[€/MWh]**	79.45	45.78	40.40	34.76	31.44	29.59	26.55	24.06
LCOC - Curtailment	**[€/MWh]**	3.24	0.00	0.01	0.32	0.86	1.04	1.52	1.50
LCOS - Storage	**[€/MWh]**	0.00	0.30	0.27	7.85	11.18	12.42	13.90	12.39
LCOT - Transmission	**[€/MWh]**	4.99	2.47	1.62	1.04	0.81	0.57	0.56	0.95
LCOE total	**[€/MWh]**	87.68	48.55	42.29	43.97	44.29	43.62	42.53	38.91
GHG emissions cost	**[€/MWh]**	1.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fuel cost	**[€/MWh]**	39.72	5.74	3.57	1.80	0.29	-0.30	-0.22	-0.11

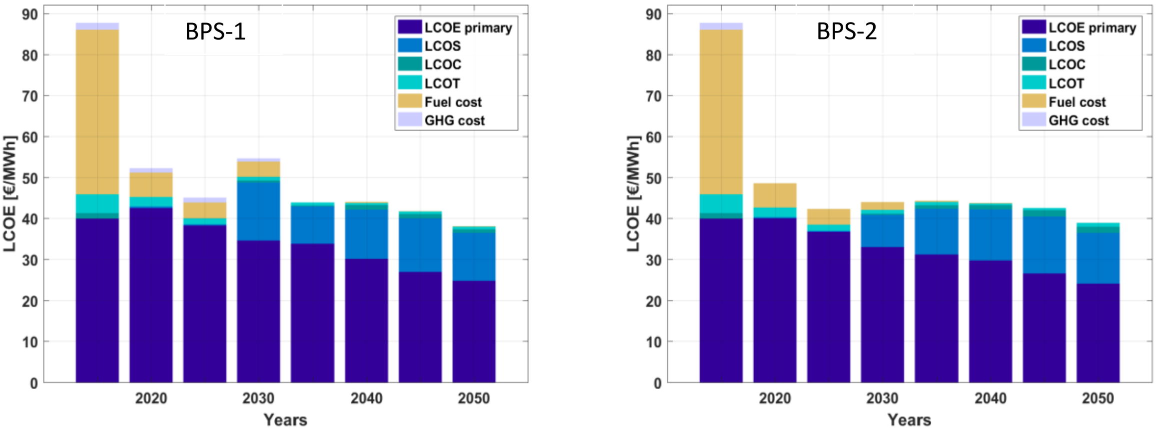

Figure S53: Levelised cost of electricity by main categories in the BPS-1 and BPS-2.

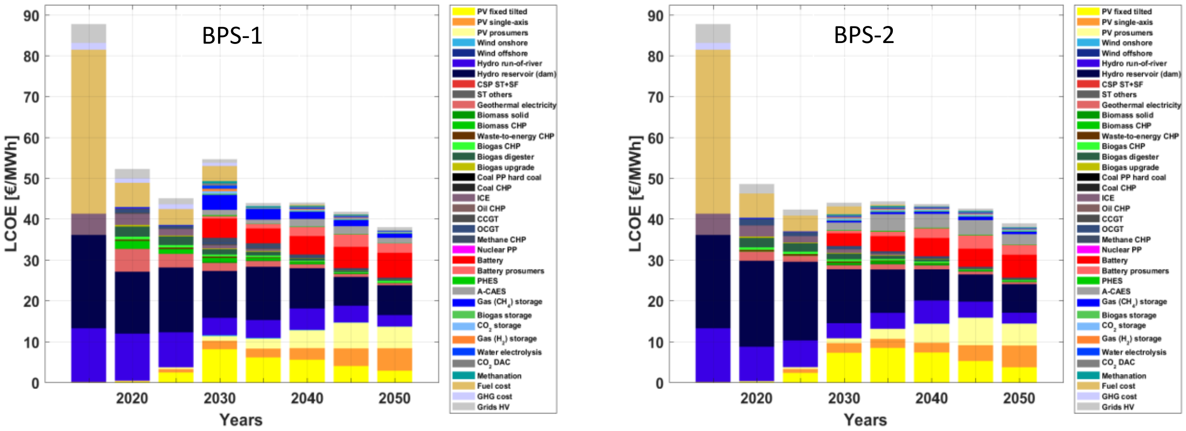

Figure S54: Levelised cost of electricity by technology type in the BPS-1 and BPS-2.

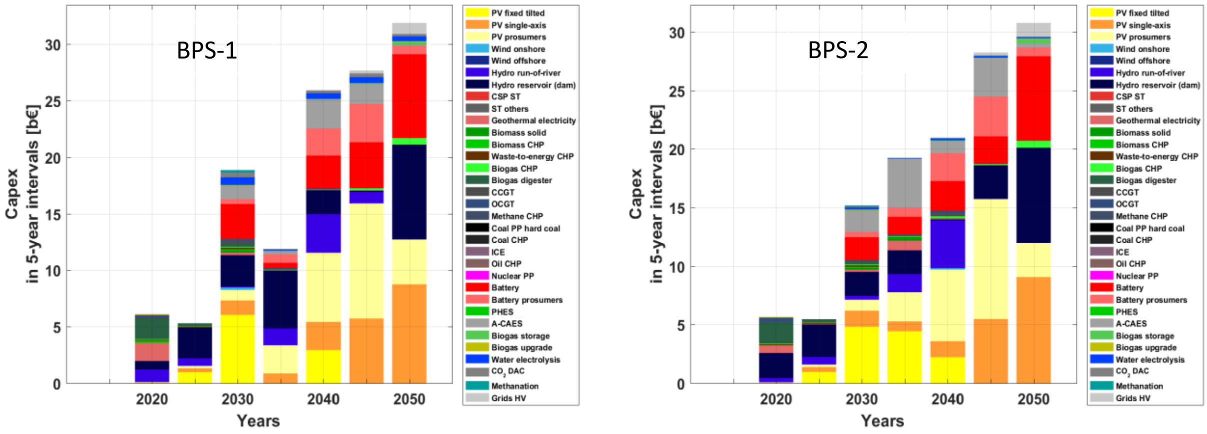

Figure S55: Power sector-capex in 5-year intervals in the BPS-1 and BPS-2.

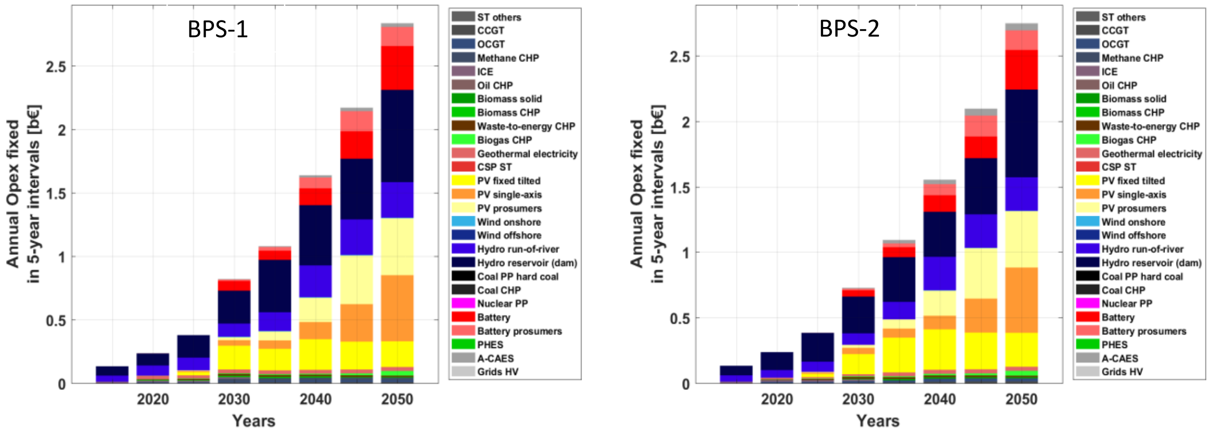

Figure S56: Power sector: annual opex fixed in 5-year intervals in the BPS-1 and BPS-2.

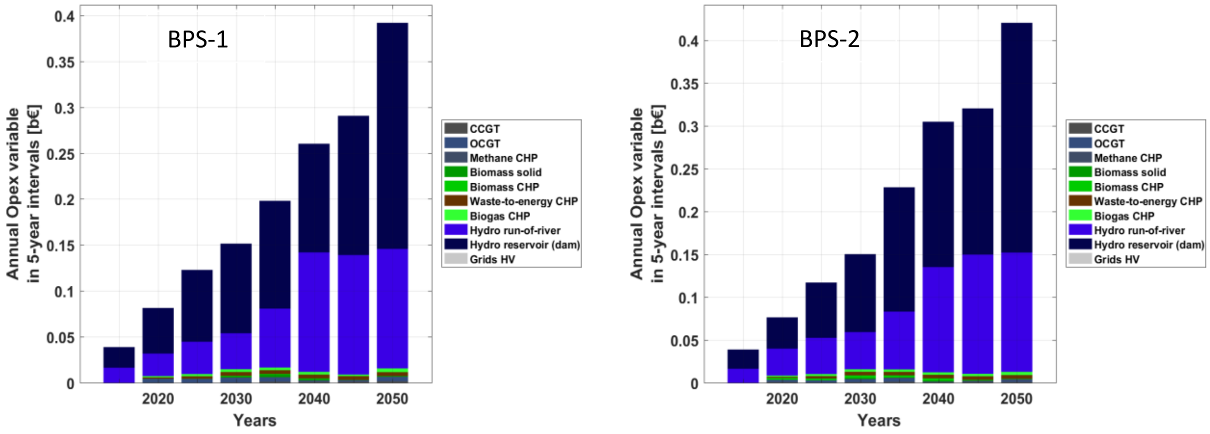

Figure S57: Power sector: annual opex variable in 5-year intervals in the BPS-1 and BPS-2.

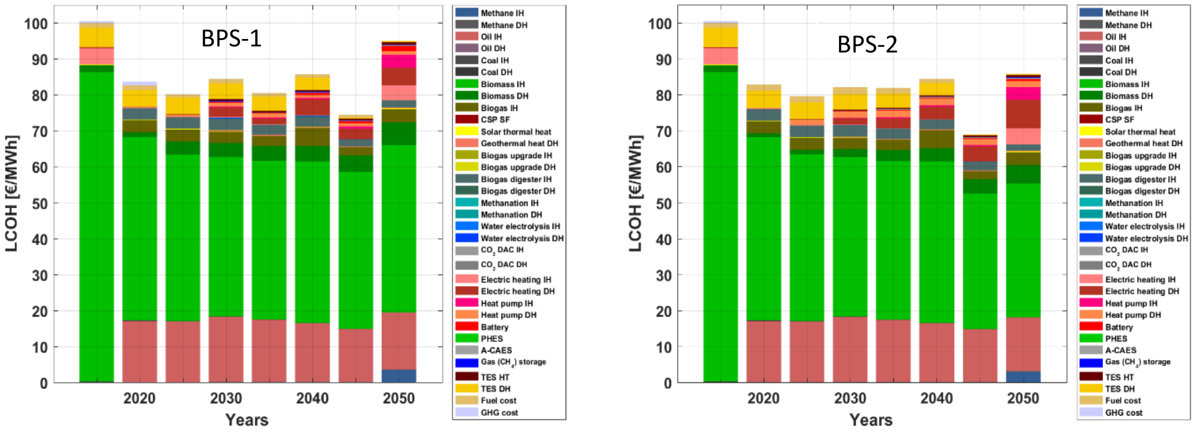

Figure S58: Heat sector: Levelised cost of heat in the BPS-1 and BPS-2.

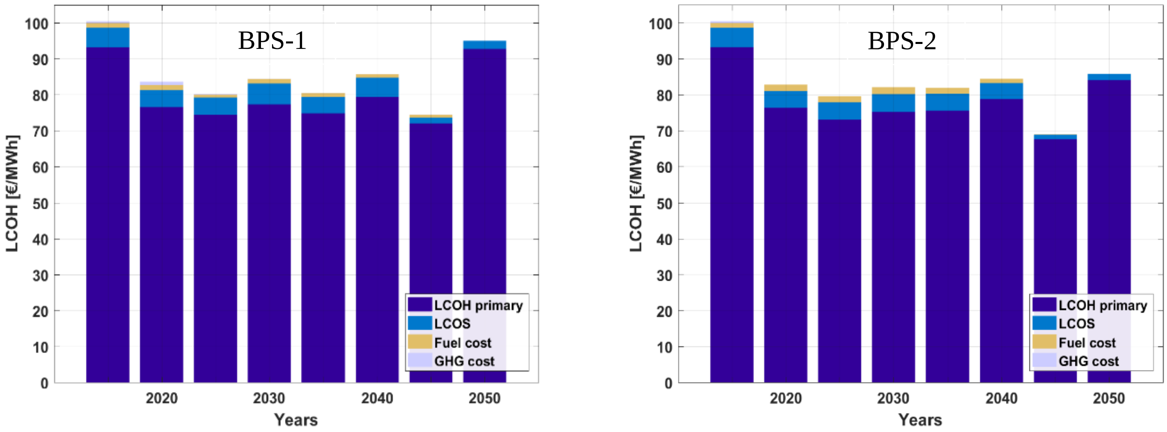

Figure S59: Heat sector: Levelised cost of heat by cost distribution in the BPS-1 and BPS-2.

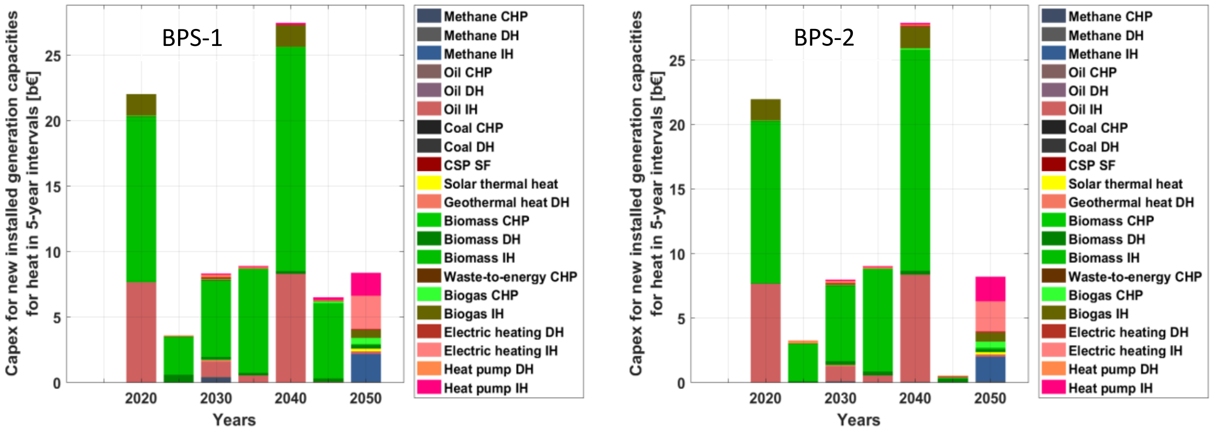

Figure S60: Heat sector: Capex for new installed generation capacities for heat in 5-year intervals in the BPS-1 and BPS-2.

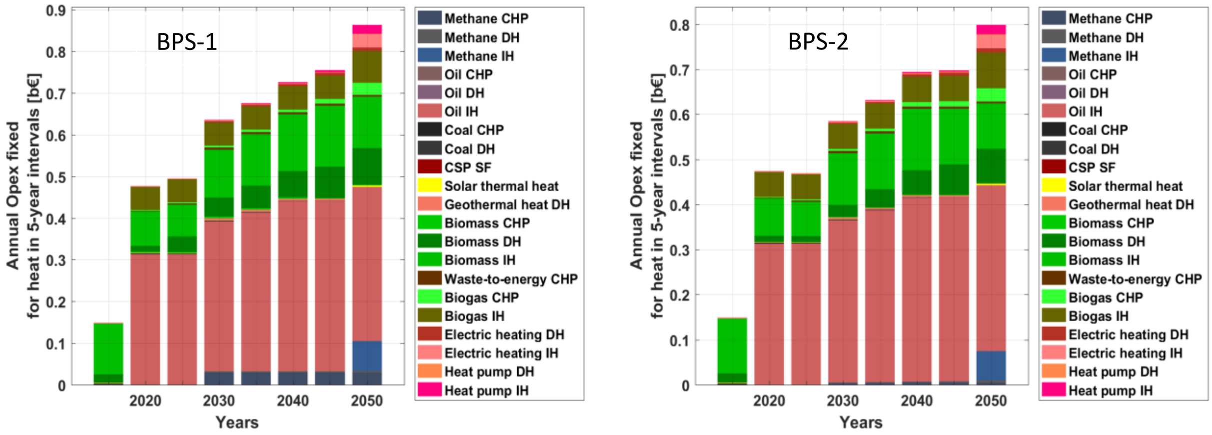

Figure S61: Heat sector: Annual opex fixed for heat in 5-year intervals in the BPS-1 and BP- 2.

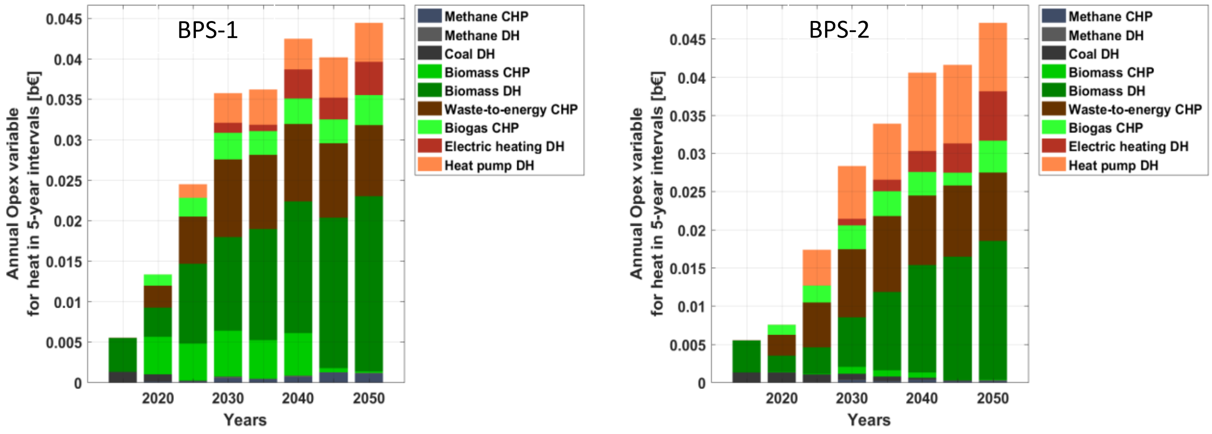

Figure S62: Heat sector: Annual opex variable for heat in 5-year intervals in the BPS-1 and BPS-2.

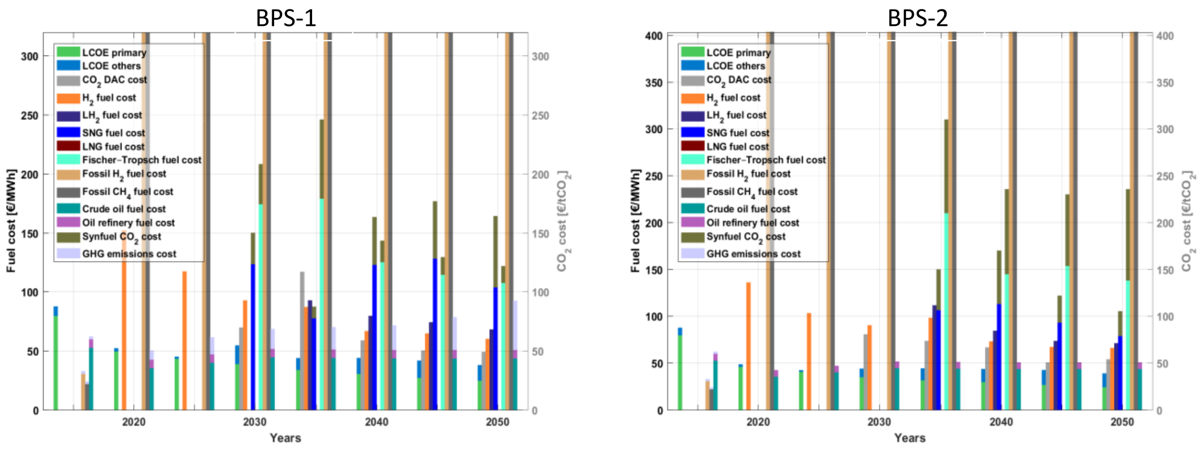

Figure S63: Fuel costs for the transport sector during the transition period from 2015-2050 in the BPS-1 and BPS-2.

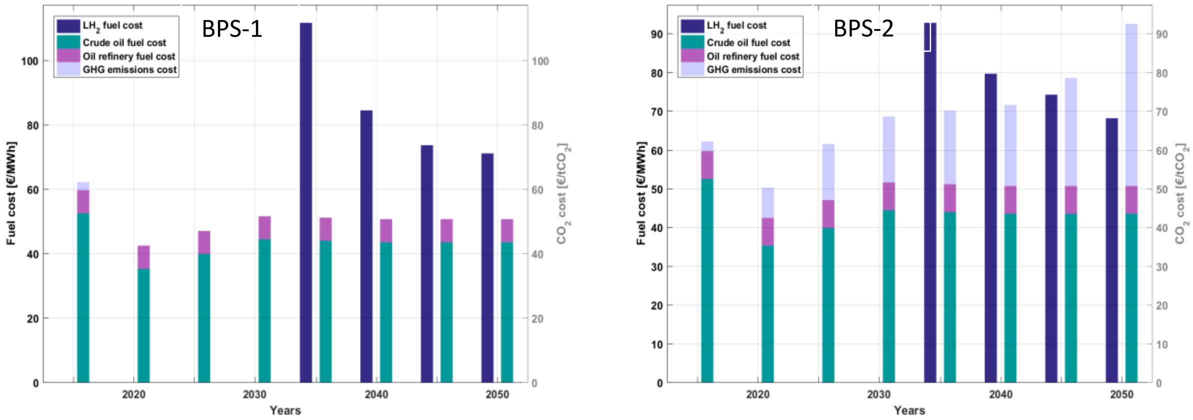

Figure S64: Fuel costs during the transition period from 2015-2050 in the BPS-1 and BPS-2.

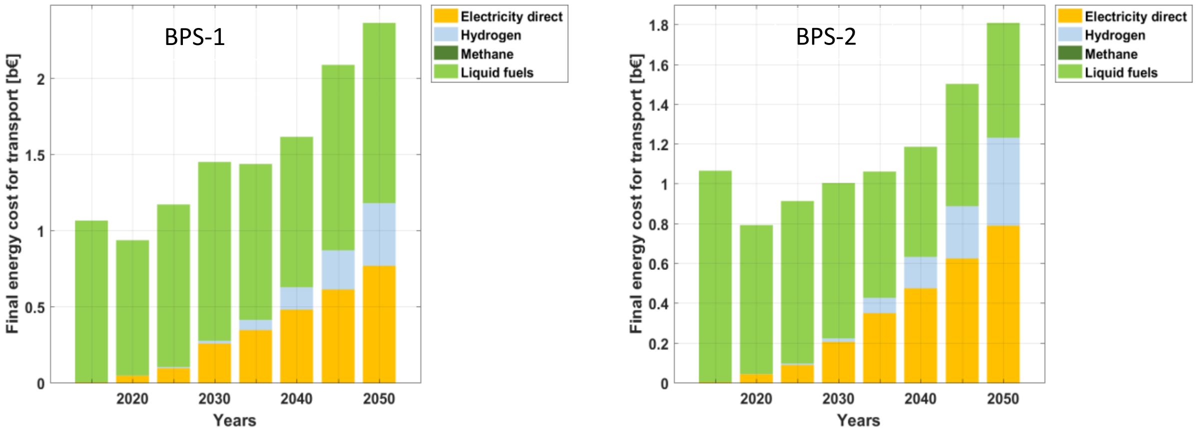

Figure S65: Final transport energy costs based on fuel form in the BPS-1 and BPS-2.

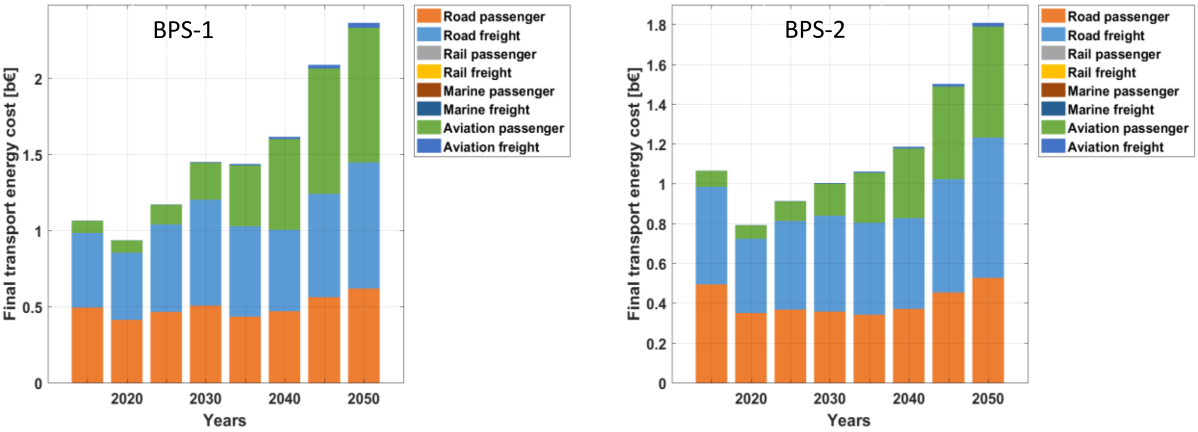

Figure S66: Final transport energy costs based on mode of transport in the BPS-1 and BPS-2.

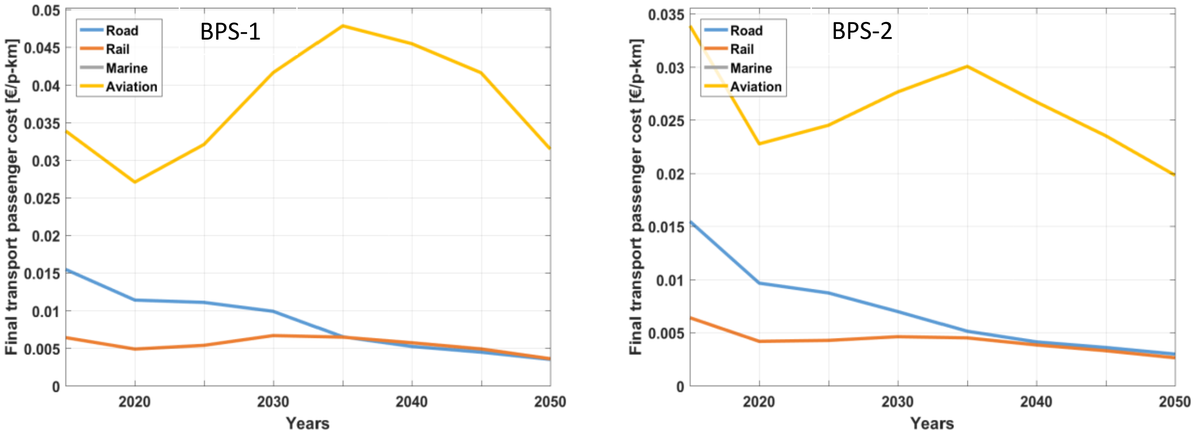

Figure S67: Final transport passenger cost by mode in the BPS-1 and BPS-2.

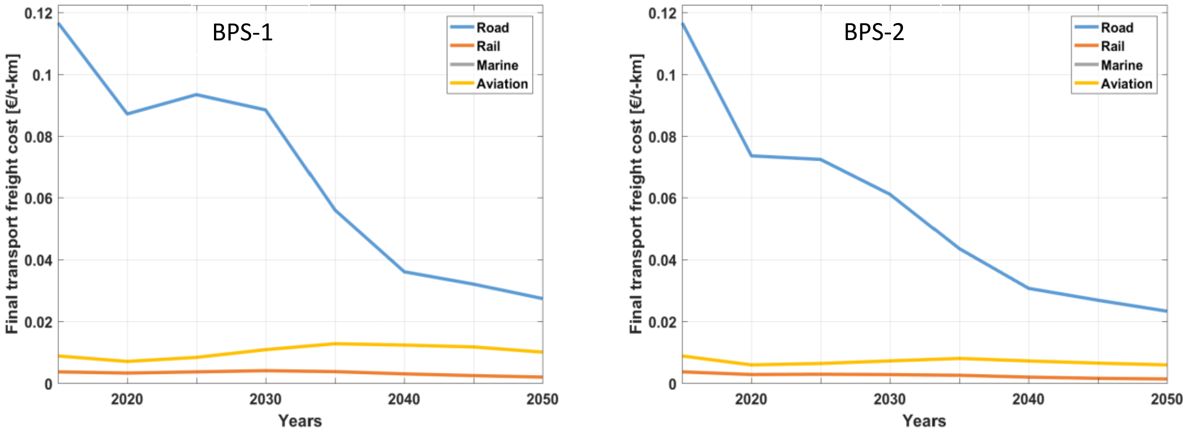

Figure S68: Final transport freight cost by mode in the BPS-1 and BPS-2.

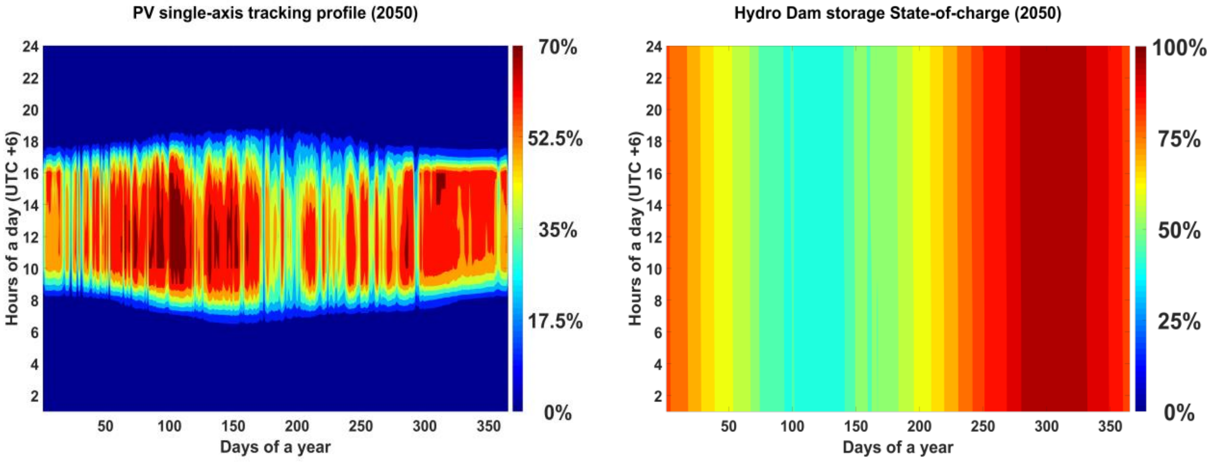

Figure S69: PV single-axis tracking profile (left) and hydro dam storage state of charge (right) in 2050.

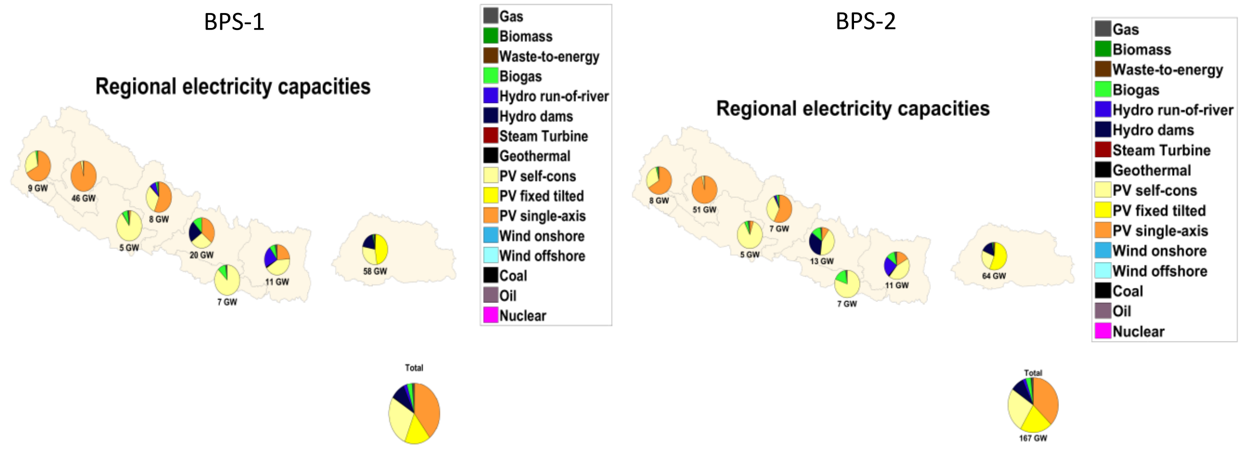

Figure S70: Regional electricity capacities in Nepal and Bhutan by energy resource type in the BPS-1 and BPS-2 in 2050.

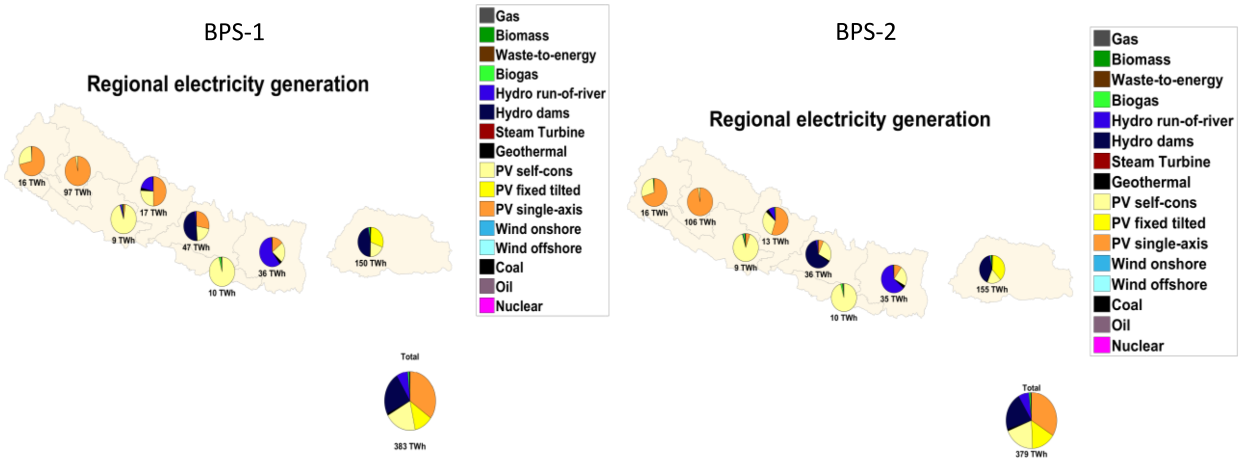

Figure S71: Regional electricity generation in Nepal and Bhutan by energy resource in the BPS-1 and BPS-2 in 2050.