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# Renewable Energy Transition for the Himalayan Countries Nepal and Bhutan: Pathways Towards Reliable, Affordable and Sustainable Energy for All

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**ABSTRACT** The Himalayan countries Nepal and Bhutan have been confronted with similar climate change and energy emergencies for quite a long time. Its influence is felt as a barrier in financial, social, infrastructural, and political development. Despite having an enormous amount of renewable energy sources, these countries are unable to fulfil their current energy demand. While the power sector is entirely dependent on hydropower, other sectors depend on fossil fuel imports from India. This study offers a pathway for energy independency, energy for all and transition towards a 100% renewables based 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 visualised, 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 levelised cost of energy is observed for the scenario without GHG emission cost, however, taxing GHG emissions will accelerate the energy transition with the levelised cost of energy 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. Solar photovoltaics and hydropower will play a dominant role 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.

**INDEX TERMS** 100% renewable energy, Nepal, Bhutan, energy transition, Himalayan countries, hydropower, solar photovoltaics.

## I. 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 [1]. Consequently, resulting in changing monsoon patterns [2], rising sea levels [3] and melting glaciers [4], [5], 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, health and general well-being across these nations [6]. Therefore, dependence on fossil fuels; a major contributor to greenhouse gases (GHG) emissions will not only accelerate these consequences, but also contribute to energy insecurity and unaffordability to the common people.

During the last few decades, Nepal and Bhutan have experienced tremendous growth in energy consumption, not only due to growing population and rising 'materialistic' standard of living, but also due to increase in industrialization and economic activities. However, this growth has resulted in

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increased dependence on fossil fuel imports, wrecking the economic balance and increase in traditional and unsustainable use of biomass (fuelwood) resources, resulting in additional GHG emissions.

Hydropower is and has been the main renewable electricity generation source in Nepal and Bhutan. While it is the main source of income for Bhutan due to hydropower export to India, Nepal has been not able to replicate this model due to various issues and utilises all its hydropower domestically [7]. In 2016, Bhutan's hydropower export provided a contribution of about 8% to its gross domestic product (GDP) [8]. Majority of the hydropower is run-of-river, depending on the monsoon and glacier melt, thus reducing the power output during the dry seasons. Even though with large hydropower potential, these countries are not able to provide uninterrupted power, with unplanned power blackouts on daily basis lasting several hours to some lasting for several days [7]. These conditions are hampering economic growth and not to forget the daily hardship faced by the common people [9].

For many years, hydropower has been promoted as the main source of electricity to provide uninterrupted power and economic development [10]. However, large hydropower projects not only face many social and environmental hinderances, but also technical and financial concerns, particularly in Nepal and Bhutan [11], due to their overdependence on one energy resource. In addition, rural electrification and extension of grid lines have been problematic due to various factors and large hydropower will amplify the problem.

Therefore, Nepal and Bhutan need to diversify their energy resource mix to accommodate remote unelectrified areas by providing electricity to 6.6 million people, uninterrupted electricity to those having access to electricity and boosting the economic growth [10]. Distributed and utility-scale solar photovoltaics (PV), wind energy, bioenergy and hydropower will not only overcome this challenge, but also broaden the portfolio of the energy generation mix making Nepal and Bhutan energy independent. Falling cost of renewables especially solar PV will make this transition faster and at an affordable cost for end-users.

This research aims to fulfill the gap in energy transition pathways towards the future for the Himalayan countries: Nepal and Bhutan. This is done by integrating solar PV, wind energy, bioenergy, and hydropower towards a high share of renewable energy in the power, heating, and transport sectors. The scenarios are optimised based on a least cost solution using the LUT Energy System Transition Model [12].

### *A. CURRENT ENERGY SITUATION IN NEPAL AND BHUTAN*

#### 1) ENERGY SUPPLY AND CONSUMPTION

The energy sector in Nepal is small, inefficient and unreliable, aptly reflected in its energy consumption and dominated by traditional energy sources [13], [14]. Nepal's per capita annual primary energy consumption was 5 MWh in 2016, which is one of the lowest in the world [15], [16], in contrast to its growing energy demand in industry and transport [8]. Bhutan had a per capita annual primary energy consumption of 23 MWh [15].

Due to no significant local deposits of fossil fuels, Nepal and Bhutan rely heavily on traditional energy resources such as firewood, agriculture residues and animal dung. In 2014, about 80% of Nepal's primary energy supply was based on biomass, whereas commercial fuels made up the remaining share (Figure 1). On the other hand, Bhutan had a comparatively, smaller share of traditional biomass in its total primary energy supply, due to its developed energy sector and higher share of electricity in final energy consumption (Figure 1). The commercial fuels, coal, diesel, and petroleum products, play an important role to satisfy the demand of industry and transport, while achieving an overall development of the country.

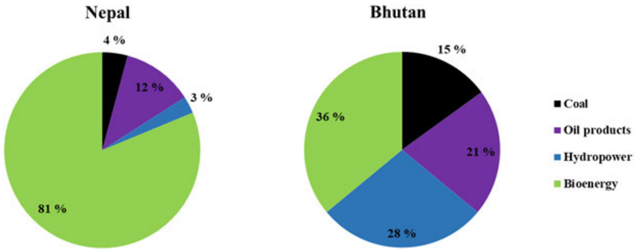

**FIGURE 1.** Primary energy supply mix for Nepal (2014) and Bhutan (2015) [8], [17].

In 2014, the residential sector had the largest share in final energy consumption (84%) in Nepal [17]. As majority of the population lives in rural areas, traditional biomass sources are used to meet the residential demand [18]. The share of industry and transport is small, however considerable growth has been observed. Between 2005 to 2014 the energy consumption in industry sector grew by a compound annual growth rate of 7.8%, while the transport sector saw the largest growth of 13.5% [17]. The rise in population, economic growth and standard of living has mainly attributed to the growing energy demand in the industry and transport sectors. Similarly, in Bhutan, the largest energy consuming sector was the residential sector with 41.6%, followed by the industry (33%) and transport sector (19%), while the remaining share was from the agriculture [8].

#### 2) DEPENDENCE ON BIOENERGY AND FUEL IMPORTS

Large percentage of the population in developing countries relies on traditional biomass for cooking and heating [10]. In Nepal and Bhutan, the situation is no different. Due to lack of access to other clean forms of energy, majority of people rely on ineffective, hazardous, time intensive energy resources such as fuelwood, agricultural residues, charcoal and animal dung [19]. More than 85% of the residential energy demand comes from biomass, used in traditional open fire cooking stoves, space heating and other purposes [8], [20]. Thus, high dependence on biomass use has given rise to excessive deforestation beyond their sustainable limits and forests are becoming scarce [21]. The use of traditional biomass as a direct fuel has severe health impacts, due to hazardous emissions. Indoor air pollution causes direct physical health risks and continuous exposure increases the risk of acute respiratory problems, lung issues, increases child mortality and other ailments [22], [23]. In Nepal alone, 15,000 women and children died due to indoor air pollution in 2013 [24]. According to [25], on average 7500 women and children die each year due to using transitional biomass for cooking and heating. On top of the hazardous consequences due to indoor air pollution, women and children spend majority of their daily time collecting fuelwood, depriving them of education and other income generating activities [22]. Hence, the governments in these countries are encouraging use of electric cooking in view of reducing biomass consumption.

According to the International Energy Agency (IEA), energy security is defined as 'uninterrupted availability of energy sources at an affordable price' [26]. Due to rising energy demand in Nepal and Bhutan, there is often a mismatch between 'local energy availability' and 'energy affordability'. This effect is compounded as these countries do not have any significant deposits of petroleum reserves nor any oil refinery for processing crude oil [10], [27]. Bhutan has some reserves of low grade coal; however, this is not used as higher grade coal and coke are imported [27]. They rely completely on India for their energy needs (petroleum products) and this creates a situation of uncertainty in supply and trade balance deficit.

This uncertainty is amplified due to extremely short storage capacity of petroleum products in Nepal of only 15 days [10]. The economic blockade of 2015 from India on goods and energy products created a severe deficit of petroleum products, slowing economic activity considerably as well as impacting daily lives of 5 million households [28]. On a national level, these kind of events raise questions on the vulnerability of countries in the turbulent times of geopolitical crises.

### 3) HYDROPOWER – A CHALLENGING RESOURCE

Hydropower is the main source of electricity generation in Nepal and Bhutan and is often promoted as the most viable option for economic development [27]. The economically exploitable potentials are estimated at 26.7 GW for Bhutan and 43 GW for Nepal [11]. Despite having a huge potential, the growth in installed hydropower capacities has been limited, especially in Nepal. Considering the first hydropower plant constructed in 1911, total installed capacity reached a meagre 856 MW in 2016 [29]. On the other hand, Bhutan has been able to tap into its hydropower potential with an installed capacity of 1614 MW at the end of 2016 [30]. An interesting fact to note here is, Nepal has 36 times the population of Bhutan, but with an installed capacity of nearly half that of Bhutan [31]. The growth in hydropower in Bhutan has been attributed to attractive policies, stable governments and its diplomatic relationship with India. On the contrary, unstable political situations in Nepal have created delays in hydropower development which have resulted in its power crises [11].

The growth in large-scale hydropower is often marred with questions on its social, economic, technical and financial impacts [32]. These impacts are often unevenly distributed, with prospects of high rewards vs high risks [33]. Most of the times the risks outweigh the rewards gained. Storage of water in reservoirs often cause biomass decomposition, producing significant amounts of greenhouse gases emissions [34]. On top of that, excessive flooding of reservoirs can cause destruction of arable land, wildlife, scenic land and residential area [34]. Most of the large hydropower projects in Nepal experience large cost and time overruns adding to the already huge initial capital investment [35]. Most of the time the overruns are due to the entire project management of Nepal Electricity Authority and the political instability in the country [36]. These factors need to be considered before starting large hydropower projects. Small-scale hydropower plants are becoming popular due to their ability to supply off-grid power to challenging remote locations.

### 4) RELIABILITY AND ACCESS TO MODERN ENERGY SERVICES

"Ensure access to affordable, reliable, sustainable and modern energy for all" is the seventh of the 17 Sustainable Development Goals of the United Nations [37]. By providing access to modern energy services it not only fulfils the basic human requirement but also secures reasonable standard of living with opportunities of human development.

This idea is farfetched in some of the developing countries like Nepal where, still, millions of people spend the majority of their time and household expenditure procuring energy for their daily livelihood and activities [38]. Despite the large hydropower potential, the share of electricity in final energy demand is low. The supply side has not been able to keep pace with the recent growth in electricity demand, as it is unable to attract large foreign investment due to the socio-political situation and long political transition after the end of the Maoist regime [28].

Nepal has one of the lowest per capita electricity consumption of 139 kWh per year compared to the world average of 3104 kWh [39]. On top of this, households having access to electricity face long hours of load shedding of about 8-16 hours on a daily basis. According to Acharya and Adhikari [28], households in Nepal are 'accustomed' to load shedding since the beginning of 2005 due to inadequate supply of electricity, amplified further by the declaration of National Energy Crisis in 2008. To overcome this situation, many households, commercial establishments and industries depend on expensive diesel generators, which creates indoor and outdoor pollution [35]. These diesel generators are expensive due to fuel import which adds to final cost of the products and reduces competitiveness of the Nepalese industry [40].

On the other hand, Bhutan has achieved universal electrification as of today, however, reliability remains an issue [8].

Like Nepal, load shedding is practiced when the peak load cannot be met by the current capacity and power imports. About 58% of households had faced one or more load shedding for at least one hour during the last seven days, with rural population facing more frequent power cuts than the urban areas [8]. These power outages have severe impact on the entire country, especially the industry sector which is the backbone of any economy.

### B. BRIEF OVERVIEW ON THE POWER, HEAT AND TRANSPORT SECTORS

The power generation mix in Bhutan and Nepal is dominated by hydropower, with some capacities from diesel-based generators. Due to load shedding on daily basis and remote locations; households and businesses must depend on diesel generators.

Bhutan's power generation capacity till end of 2017 was 1.6 GW, while total electricity generation was estimated at 7.7 TWh. Bhutan's domestic electricity requirement was only 2.2 TWh in 2017 [41]. The rest of the electricity is exported to India, which accounted for 74% of the total generation in 2017 [42]. Due to higher electricity demand and lower generation in winter, Bhutan imports some smaller amounts of electricity from India. The electricity imports from India were around 92 GWh in 2017 [43]. On the other hand, in 2016, Nepal had an installed capacity of about 856 MW, with majority of hydropower and some capacities from diesel-based generators [44]. The electricity generation was about 5.1 TWh. Due to run-of-river hydropower plants, electricity generation fluctuates and is seasonal, as a result, Nepal imported 1.6 TWh of electricity from India [17]. Still, the supply is inadequate to meet the ever-increasing demand, especially in the dry season resulting in daily load shedding.

Most of the heating requirement is based in the residential and industrial sectors. Fuelwood is the dominant fuel in the residential sector, while the industrial sector uses coal as a major fuel. There has been decrease in use of fuelwood and kerosene in Bhutan, especially in the industrial sector. Electricity has been the dominant fuel, with about 57% share in the total industrial energy demand. However, the remaining share is based on diesel and coal, which is imported [8].

In Nepal and Bhutan, the transport sector has seen tremendous growth in energy consumption due to increase in GDP per capita and rapid urbanization, with demand for petroleum fuels more than doubling from 2000s until end of 2010s [8]. The predominant mode of transport is road, due to the terrain of these countries. This has led to more motor vehicles in Bhutan, and this accounted 18.6% of total energy consumption in 2014 [45], which is about 1.2 TWh. Increasing vehicle numbers, lack of proper laws on vehicle emissions and fossil fuels has led to continuous increase in Bhutan's GHG emissions [46]. Bhutan has acknowledged the transport sector importance and increasing energy demand in the future. Thus, Bhutan introduced the 'Transport Vision 2040' [47], 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. Moreover, future plans include ways for transport-based GHG emission reduction and vehicles switching to renewable fuels and electric vehicles [48]. Similarly, Nepal's road passenger and freight has a share of about 90% in the transport sector [17]. To address the aggressive increase in transportation demand, Nepal's Government set up a national sustainable transport strategy (2015-2040) to lower GHG emissions in the transport sector. Hydrogen as a potential fuel is also studied in the country [49]. Currently, due to a lack of domestic fossil fuel reserves, Nepal and Bhutan rely heavily on expensive petroleum product imports from India [50].

### C. 'OTHER' RENEWABLE ENERGY SOURCES

Nepal and Bhutan depend on imports of energy resources, as they do not have significant reserves of petroleum and coal. The mountainous topography, price fluctuation of crude oil, unsustainable use of firewood; causing indoor air pollution and deforestation, high infrastructure cost and long delays associated with hydropower generation has prompted the governments of these countries to consider alternative energy sources, which are sustainable and affordable [21].

Nepal and Bhutan are blessed with abundant water resources and hydropower is often promoted as the most viable option [10]. Currently, hydropower dominates electricity generation, though other means of renewable energy (RE) based electricity generation are also abundantly available. Commercially exploitable hydropower potential of 26,760 MW and 42,000 MW is available in Bhutan and Nepal respectively [8], [17]. However, large hydropower projects have often been associated with environmental, social, cultural, technical, financial and economic impacts [10].

The solar resources in the mountainous terrain of Nepal and Bhutan are very promising. Nepal receives on average 300 sunshine days per year with global horizontal irradiation ranging between 1080-1860 kWh/($m^2$·a) [51]. Satellite maps show the global horizontal solar radiation vary in Bhutan from 1460-2007 kWh/($m^2$·a) [52]. Solar PV technology is extremely modular and low cost, can be installed in decentralised locations, which is a major advantage in Nepal and Bhutan. On the other hand, wind resources are quite limited and often areas with good wind speeds are in high altitude mountains tops [8]. Therefore, these areas are inaccessible for the logistic requirements of larger modern wind turbines [53]. The wind potential in Nepal and Bhutan is 3000 MW and 760 MW respectively [8], [10].

Since, agriculture and forestry form a major part of the economy in the Himalayan countries, large agricultural residues are produced. These residues together with sustainable biomass resources are potential sources of electricity production. Currently, traditional use of biomass creates indoor air pollution and associated health hazards [22], [23]. Unfortunately, these two countries have not been able to harness green energy with respect to its resource availability, except for hydropower.

**TABLE 1.** List of studies conducted on renewable energy transition scenarios for Nepal and Bhutan.

| Study | Scope | Key findings |
|---|---|---|
| Gulagi et al. [54] | SAARC | The LUT Energy System Model was used to model an overnight scenario for a 100% RE based system for the SAARC (South Asian Association for Regional Corporation) region, with Nepal and Bhutan as one of the sub-regions. The total installed capacities in 2030 for an integrated scenario is 10 GW, while the storage capacity is 1 GW. Solar PV dominates the installed capacity with about 50% share, while batteries dominate the storage capacity with 90% share. The levelised cost of electricity in 2030 will be around 63 €/MWh. |
| Shakya [55] | 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 to 16%, 15% and 14% respectively. The remaining shares is fulfilled by petroleum products, coal and solar. |
| Yangka and Diesendorf [27] | 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. |
| Jacobson et al. [56] | Nepal | The study finds that a 100% renewables based energy system is possible by 2050 utilising wind, hydropower and solar energy. The share of solar PV plants (rooftop and utility-scale) will be 64.6%, concentrating solar thermal power will be 4.8%, onshore wind will have a share of 26% and hydropower will have a share of 4.6%. Further benefits of the transition include a 62% reduction in energy demand in comparison to the current, while creating a total of 90,670 jobs. The average energy cost will be 64.6 USD/MWh (58.7 €/MWh). |

With abundant availability of solar resources across the regions of Nepal and Bhutan, these countries could tap into the enormous solar PV potential for renewable energy. A major 7.8 Richter scale magnitude earthquake in 2015 disrupted the entire energy system due to landslides and floods which destroyed poorly built hydropower plants. This example shows the vulnerability of Nepal's dependence on hydropower. Therefore, development of other RE technologies together with hydropower is the utmost way for Nepal and Bhutan to be energy independent.

For Nepal and Bhutan, there have been almost no studies capturing an energy transition of the integrated power, heat and transport sector towards a 100% renewable based energy system. Table 1 outlines the energy system studies with high RE share and their key findings. However, none of these studies consider the spatial and temporal resolution as used in this research for Nepal and Bhutan. Also, this study considers analyses on a sub-regional level, with regional interconnections via a power transmission grid.

## II. METHODS

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 are described in the following sections.

### A. LUT ENERGY SYSTEM TRANSITION MODEL OVERVIEW

The LUT Energy System Transition Model [12] 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 sum of the annual capital and operational expenditures, including ramping costs, for all the considered technologies in the modelling as given in (1). The reference year for this study was chosen as 2015, due to unavailability of the all the input data for the year 2020. The main energy balance constraint for the power sector optimisation is matching the power generation and demand for every hour of the applied transition years as shown in (2). For every hour of the year the total generation within a sub-region and electricity import cover the local electricity demand.

$$\min\left(\sum_{r=1}^{\text{reg}}\sum_{t=1}^{\text{tech}}(\text{CAPEX}_t\cdot\text{crf}_t+\text{OPEXfix}_t)\cdot\text{instCap}_{t,r}\right.$$
$$\left.+\,\text{OPEXvar}_t\cdot\text{E}_{\text{gen},t,r}+\text{rampCost}_t\cdot\text{totRamp}_{t,r}\right)\quad(1)$$

Abbreviations: capital cost of each technology ($\text{CAPEX}_t$), capital recovery factor for each technology ($\text{crf}_t$), fixed operational cost for each technology ($\text{OPEXfix}_{,t}$), variable operational cost each technology ($\text{OPEX}var_{,t}$), installed capacity in a region ($\text{instCap}_{t,r}$), electricity generation by each technology ($\text{Egen}_{t,r}$), ramping cost of each technology ($\text{rampCost}_t$), annual total power ramping values for each technology ($\text{totRamp}_{t,r}$), region (reg), and technology (tech).

$$\forall h\in[1,8760]\sum_{t}^{\text{tech}}\text{E}_{\text{gen},t}+\sum_{r}^{\text{reg}}\text{E}_{\text{imp},r}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,disch}}$$
$$=\text{E}_{\text{demand}}+\sum_{r}^{\text{reg}}\text{E}_{\text{exp},r}+\sum_{\text{t}}^{\text{stor}}\text{E}_{\text{stor,ch}}+\text{E}_{\text{curt}}+\text{E}_{\text{other}}\quad(2)$$

Abbreviations: hours ($h$), technology ($t$), all modelled power generation technologies (tech), sub-region ($r$), all sub-regions (reg), electricity generation ($\text{E}_{\text{gen}}$), electricity import ($\text{E}_{\text{imp}}$), storage technologies (stor), electricity from discharging storage ($\text{E}_{\text{stor,disch}}$), electricity demand ($\text{E}_{\text{demand}}$), electricity exported ($\text{E}_{\text{exp}}$), electricity for charging storage ($\text{E}_{\text{stor,ch}}$), electricity consumed by other sectors (heat, transport, industry) ($\text{E}_{\text{other}}$), and curtailed excess energy ($\text{E}_{\text{curt}}$).

The heat sector energy balance is defined by three equations: for industrial high temperature heat demand, for industrial high and medium temperature heat demand, and all centralised heat demand. High temperature heat can only be generated by fuel-based boilers as given in (3). Medium temperature heat can also be generated by electrical heating and can be stored in high temperature heat storage and used to produce electricity with steam turbines as given in (4). Low temperature heat can also be provided by heat pumps, electric heating rods and waste heat from other technologies as given in (5).

$$\forall h\in[1,8760]\sum_{t}^{\text{techHH}}\text{E}_{\text{gen},t}$$
$$\geq\text{E}_{\text{demandHH}}\quad(3)$$

$$\forall h\in[1,8760]\sum_{t}^{\text{techHH}}\text{E}_{\text{gen},t}+\sum_{t}^{\text{techMH}}\text{E}_{\text{gen},t}+\text{E}_{\text{stor,disch}}$$
$$\geq\text{E}_{\text{demandHH}}+\text{E}_{\text{demandMH}}+\text{E}_{\text{stor,ch}}\quad(4)$$

$$\forall h\in[1,8760]\sum_{t}^{\text{tech}}\text{E}_{\text{gen},t}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,disch}}$$
$$=\text{E}_{\text{demand}}+\sum_{t}^{\text{stor}}\text{E}_{\text{stor,ch}}+\text{E}_{\text{curt}}+\text{E}_{\text{other}}\quad(5)$$

Abbreviations: hours ($h$), technology ($t$), high temperature heat generation technologies (techHH), medium temperature heat generation technologies (techMH), all heat generation technologies (tech), industrial high temperature heat demand ($\text{E}_{\text{demandHH}}$), industrial medium temperature heat demand ($\text{E}_{\text{demandMH}}$), total centralised heat demand, including industrial, and space heating and water heating demand ($\text{E}_{\text{demand}}$).

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 demand of 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 additional important constraints used in the modelling of the energy system and prosumers: First, a restriction on 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 2 detailed description of the model can be found in Bogdanov *et al.* [12].

### B. 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 B.2 and Section B.3 respectively. The final section provides the demand growth in all sectors and the applied technologies.

#### 1) SUB-REGIONS AND GRID TRANSMISSION

The sub-division of Nepal is done based on the provincial states, which are seven regions. The districts which lies under

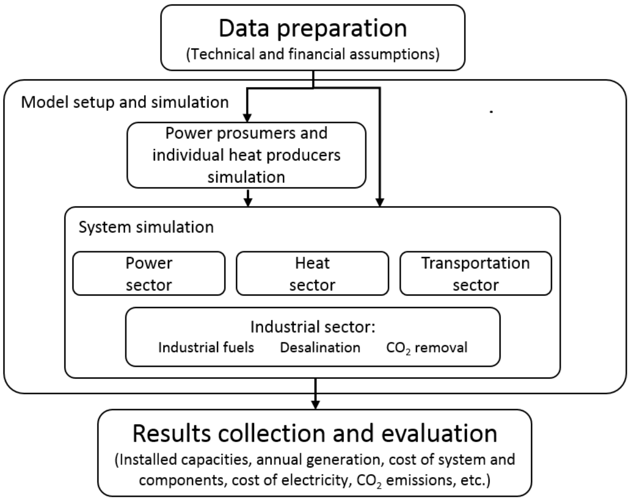

**FIGURE 2.** Process flow representation of the model input data, optimisation, and results [57].

**TABLE 2.** 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 |

each province are mentioned in Table 2. 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 the 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 3. 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. The population of Nepal and Bhutan in 2015 and projected population at every 5-year interval till 2050 is tabulated in the Supplementary Material (Table S1). Individual population projection growth rates of 1.4% for Nepal [77] and 0.61% for Bhutan [58] are applied.

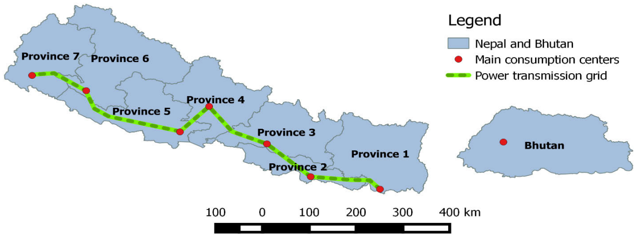

**FIGURE 3.** The seven provincial states of Nepal and Bhutan with the main power transmission grid.

### 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 Supplementary Material (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 lower risk and hence lower financial return expectations. Due to the unavailability of country specific cost projection data, financial projections were assumed to be based on a global average for all the technologies. The cost reduction in most of the RE-based technologies is following a downward curve globally and it will result in a continued capacity installation in the future [59], [60]. The price of raw materials and new installations are anticipated to decrease 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 [59], [61].

The price of electricity for three prosumer categories i.e. residential, commercial, and industrial, in the year 2015 were assumed from [7], [29], [62]. Based on a method developed by Breyer and Gerlach [63], the future electricity prices until 2050 was projected. The cost assumptions of the applied energy system technologies for Nepal and Bhutan are tabulated in the Supplementary Material (Table S8).

### 3) TECHNICAL ASSUMPTIONS

The technical lifetime and efficiencies of all applied technologies can be found in the Supplementary Material (Table S8 and S9). The installed capacities till end of 2014 for hydropower and fossil fuels are taken from [64]. 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 [11], [29], [62], [65].

### 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 wind onshore is considered. The raw data is for the year 2005 from NASA databases [66], [67] by German Aerospace Center [67] and having a resolution of 0.45°×0.45°. These data are further processed to calculate hourly capacity factor profiles as described in Bogdanov and Breyer [69] and Afanasyeva *et al.* [70]. This study does not consider increasing efficiency of solar PV systems on the land area requirements during the transition. 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.* [71]. The cost calculation for the three biomass categories were done according to the data from International Energy Agency [72] and Intergovernmental Panel on Climate Change [73]. 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 [74]. The geothermal energy potential in Nepal and Bhutan, is calculated according to the method described in Aghahosseini *et al.* [75].

The installed capacities of generation technologies in 2015 were taken from Farfan and Breyer [64] and Department of Electricity Development [76] for Nepal. 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.

### 5) DEMAND PROJECTION

The 2015 electricity demand of the 7 provinces in Nepal and Bhutan were calculated based on the electricity demand per capita and population [77]–[80]. 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 annual growth rates of 15.1%, 12.2%, 10.2%, 9.6% and 9.5% for 2015-2020, 2020-2025, 2025-2030, 2030-2035, 2035-2040 and 2040-2050, respectively, while for Bhutan a growth rate of 11.9% was assumed till 2030 and after that growth rate similar to Nepal was assumed [41]. For Bhutan, as electricity export forms a large part of its GDP, future growth in exported electricity is also considered. This study does not differentiate between flexible and inflexible demand. However, indirect flexibility to the system could be provided by electrolysers and to some extent by heat pumps. Implementation of demand response would bring in some financial savings and cost reduction to the entire energy system.

The heat demand from 2015 to 2050 was taken from Bogdanov *et al.* [57]. The final electricity and heat demand during the transition for Nepal and Bhutan are given in the Supplementary Material (Table S2). The final power sector excludes direct electricity used in heat and transport sectors.

The hourly load profile of electricity and heat for the provinces in Nepal was calculated as a fraction of the total demand in the country, while for Bhutan the country profile was used. The synthetic load profiles are taken from Toktarova *et al.* [81], while the space heating, domestic hot water, biomass for cooking, and industrial heat profiles are taken from Bogdanov *et al.* [57]. 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.* [82] and is shown in Supplementary Material (Table S25-S26).

### 6) APPLIED TECHNOLOGIES

An overview on the energy system presenting the relevant technologies for the power, heat and transport is provided in Figure 4. The technologies can be classified according

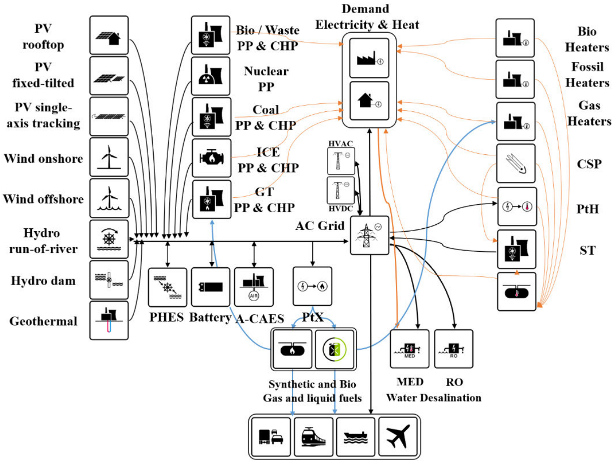

**FIGURE 4.** LUT Energy System Transition model's schematic diagram for power, heat and transportation. The diagram is adapted from [12]. Abbreviations: CHP – Combined Heat and Power; CSP – Concentrating Solar Power; GT – Gas Turbines; ICE – Internal Combustion engine; PtH – Power-to-Heat; PHES – Pumped Hydro Energy Storage.

**TABLE 3.** Detailed description of the 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 this target, certain assumptions were made. First, no new fossil fuel capacities were allowed to be installed after 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 a 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 RE capacity share cannot grow more than 20% in any 5-year time step to avoid excessive RE capacities installation in a single time step.<br>This scenario includes the potential role of prosumers (electricity and heat self-consumption), with rooftop PV-based electricity generation and 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 the 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.<br>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. |

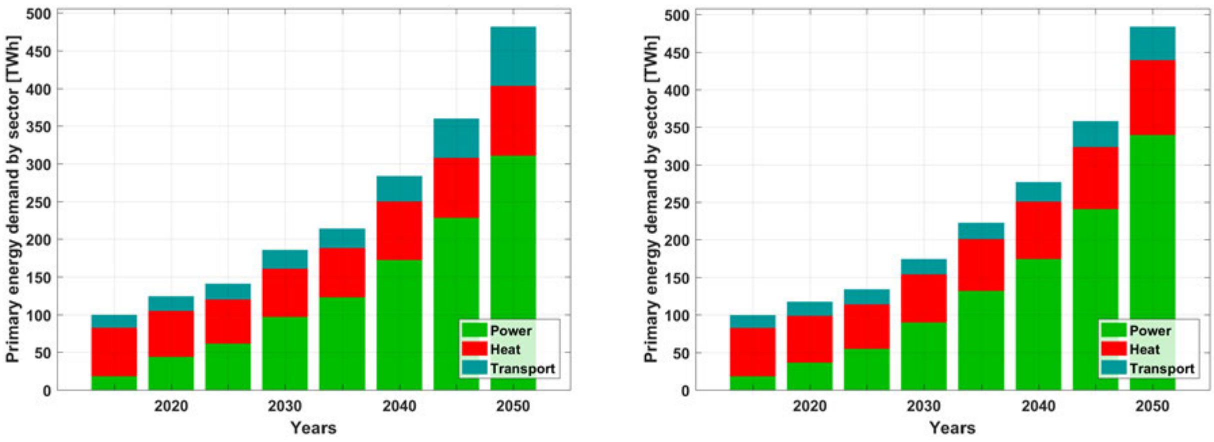

**FIGURE 5.** Primary energy demand for power, heat and transport sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

to the electricity generation from RE and fossil fuels; heat generation from RE and fossil fuels; road, rail and aviation transport modes; energy storage for electricity, heat and fuels and electricity transmission using High Voltage Alternating Current (HVAC).

### 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 3 provides a detailed description of the scenarios and specific assumptions made in each of the scenarios.

## III. RESULTS

The results obtained by applying the LUT model are presented below.

### A. PRIMARY ENERGY DEMAND DURING THE TRANSITION

Figure 5 shows the total primary energy demand by sector during 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 largest share is from the heat sector which is almost 61% in 2015 but 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 has a share of under 20% in 2015 but 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 the corresponding increase per capita energy use is the reason behind such massive growth.

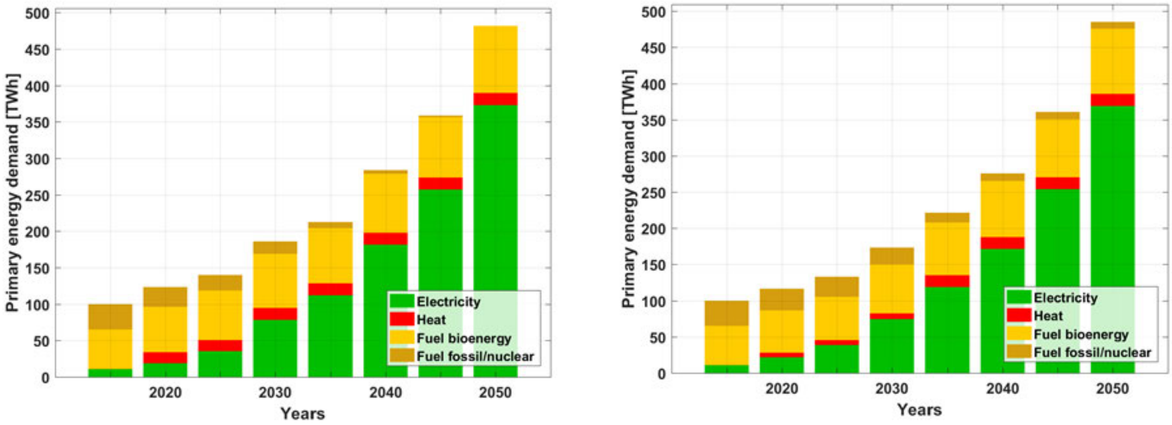

**FIGURE 6.** Primary energy demand by energy form for the BPS-1 (left) and BPS-2 (right) throughout the transition period 2015 to 2050.

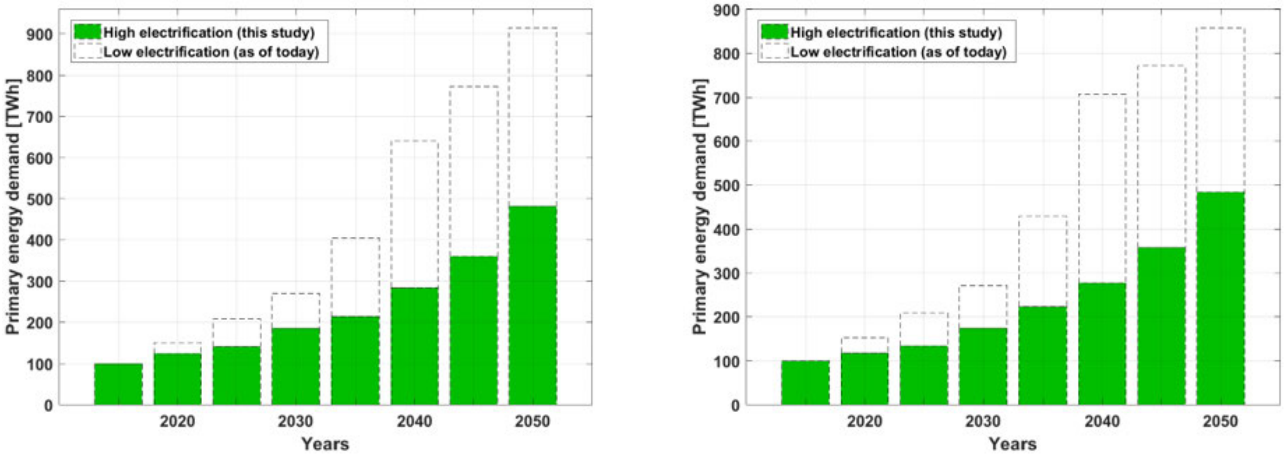

**FIGURE 7.** Efficiency gain in primary energy demand with low and high electrification in the BPS-1 (left) and BPS-2 (right) during the transition years.

Figure 6 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 resource, 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 shows the role of direct and indirect electricity use, in reducing the total primary energy demand in the two scenarios. In the BPS-1 and BPS-2, continuing with the current energy system having low electricity use in different sectors, the total primary energy demand would increase exponentially to reach 916 TWh and 858 TWh in 2050 respectively, from 100 TWh in 2015. This is around 815% increase in the BPS-1 and about 760% increase in the BPS-2. However, an energy system with high levels of electricity use across the sectors would limit the primary energy demand to only 484 TWh in 2050 for both BPS-1 and BPS-2, which is an increase of 380% from 2015. 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.

### B. INSTALLED CAPACITIES AND ELECTRICITY GENERATION

Figure 8 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.

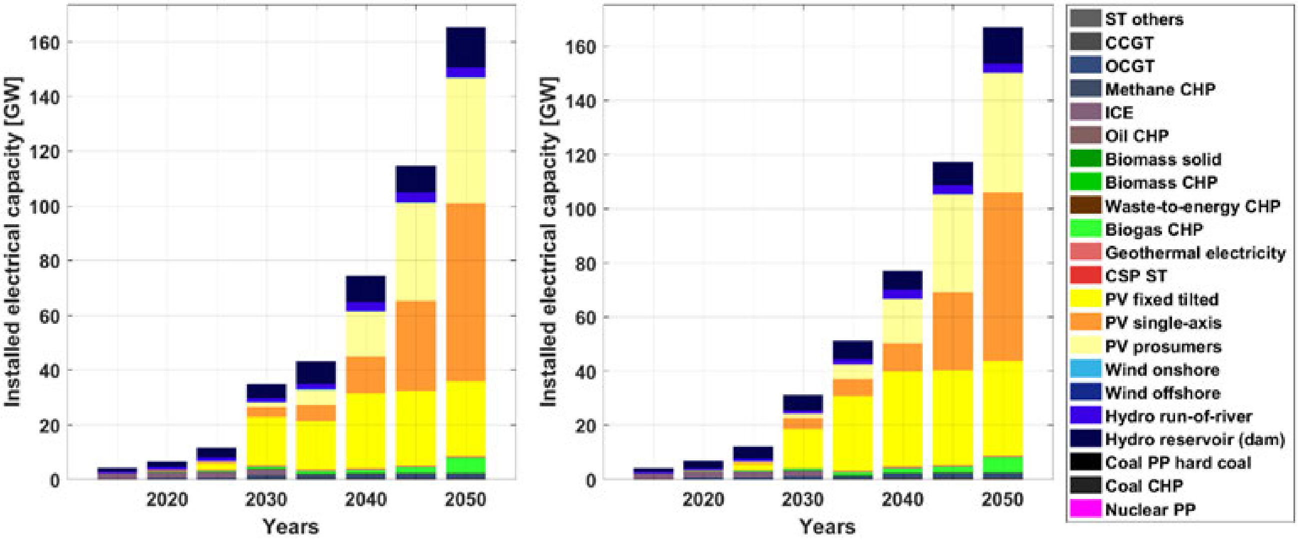

**FIGURE 8.** Cumulative installed capacities for all power generation technologies from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

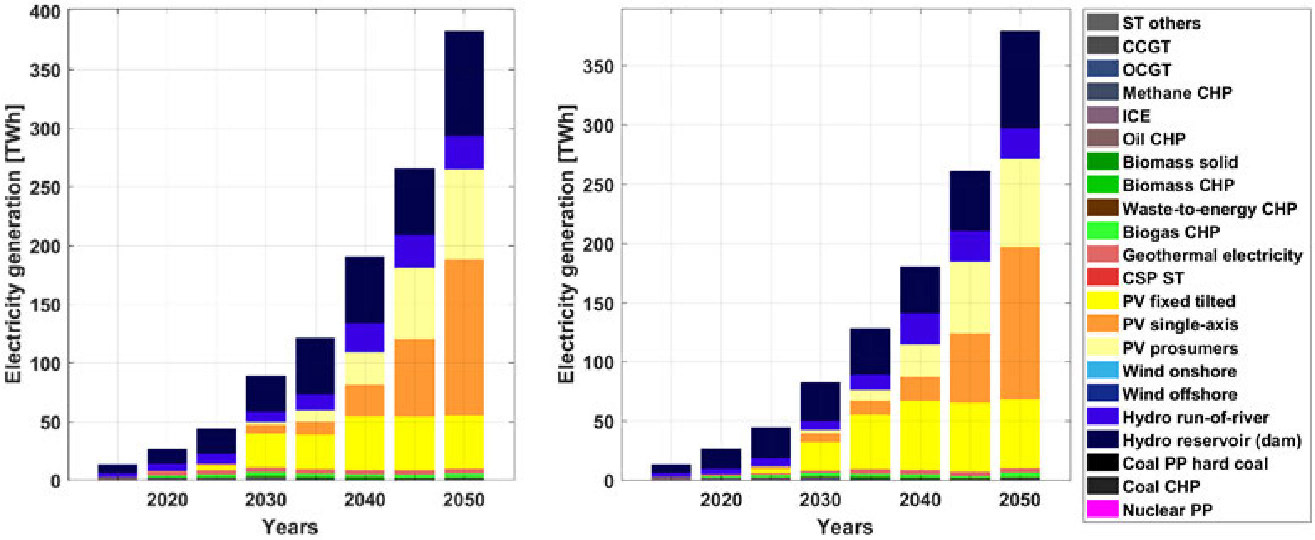

**FIGURE 9.** Technology-wise electricity generation in the BPS-1 (left) and BPS-2 (right) during the transition period.

Mostly, solar PV dominates the entire energy system starting from the year 2030 to fulfill the future energy demand. Hydropower followed by biogas based electricity compliments the energy deficit during periods of low solar irradiation in both scenarios.

The total electricity generation in the Himalayan countries is 382 TWh in the BPS-1 and 379 TWh in the BPS-2 to cover the demand of power, heat and transport in 2050. Figure 9 shows the total electricity generation in the BPS-1 and BPS-2 based on the 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 and 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 is negligible in the electricity generation in 2015. Despite having abundant hydropower as a major electricity generation source since decades, installed capacities of solar PV increases rapidly because of its extremely low cost, high modularity and fast installation time. Therefore, in 2050, electricity generation from solar PV accounts for 67% share in 2050, followed by 31% from hydropower in the BPS-1. The remaining share is contributed by wind energy, geothermal energy, and bioenergy.

As mentioned earlier in Section II, the modelling of the energy system for Nepal was done by further sub-dividing the country into provinces to analyse their detailed

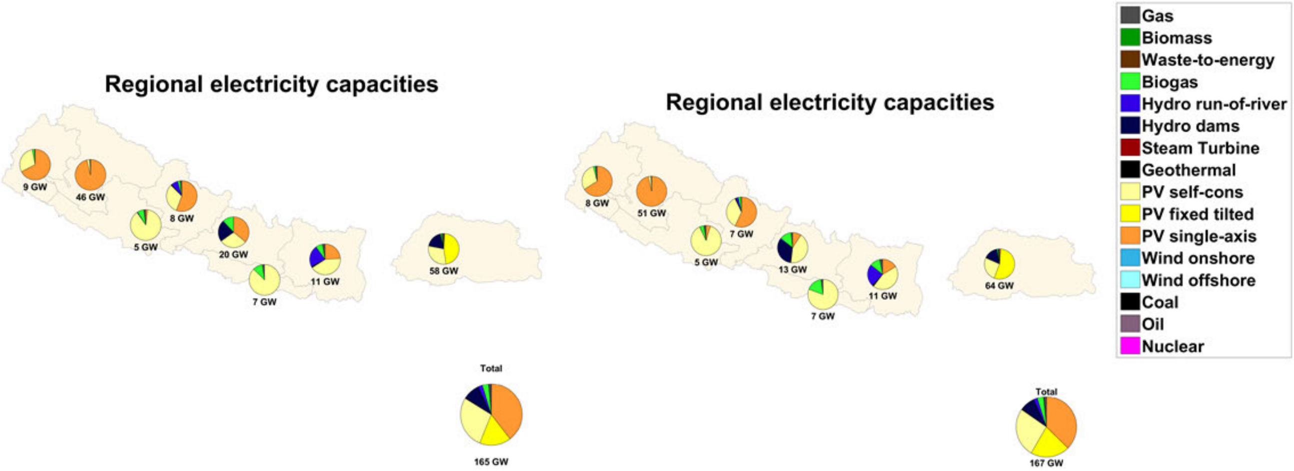

**FIGURE 10.** Installed RE capacities in the provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

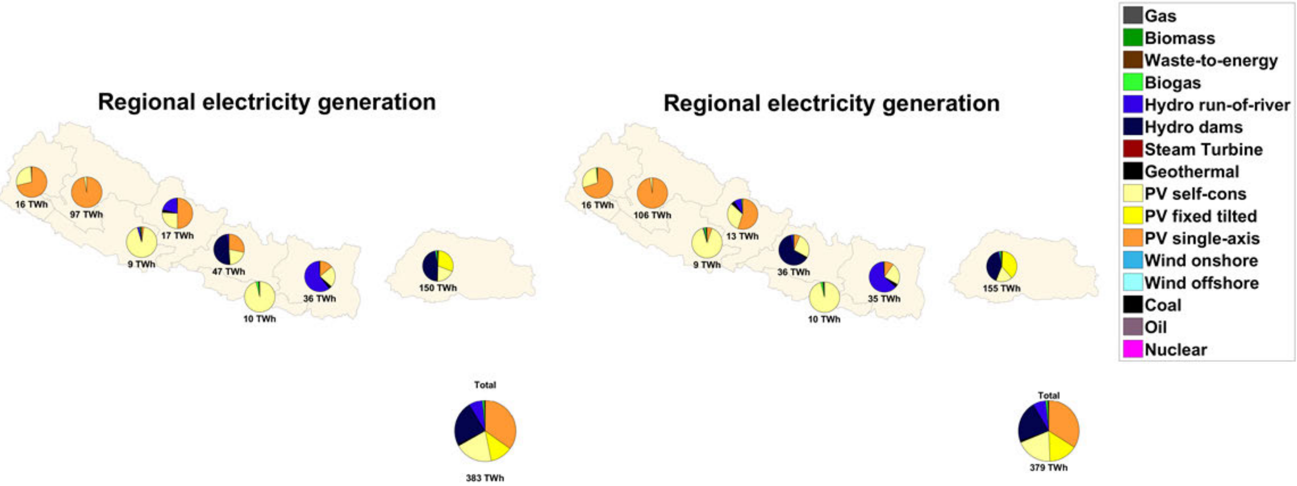

**FIGURE 11.** Installed electricity generation in provincial regions of Nepal and Bhutan in the BPS-1 (left) and BPS-2 (right) in 2050.

energy structure. Figure 10 and Figure 11 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 a 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 are observed in the BPS-2.

Solar PV plays a dominant role in total electricity generation 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 available in these regions.

The electricity in far western provinces of Nepal is solely generated by 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 11. 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 has a flat topography and it is more expensive due to the need for construction of large dams for hydropower generation. Therefore, cost-effective solar PV electricity generation is most suited in these regions.

Table S14 and S15 in the Supplementary Material provides detailed installed capacities of all technologies for the BPS-1 and BPS-2 respectively, while the electricity generation is given in Table S16 and S17 for the BPS-1 and BPS-2 respectively.

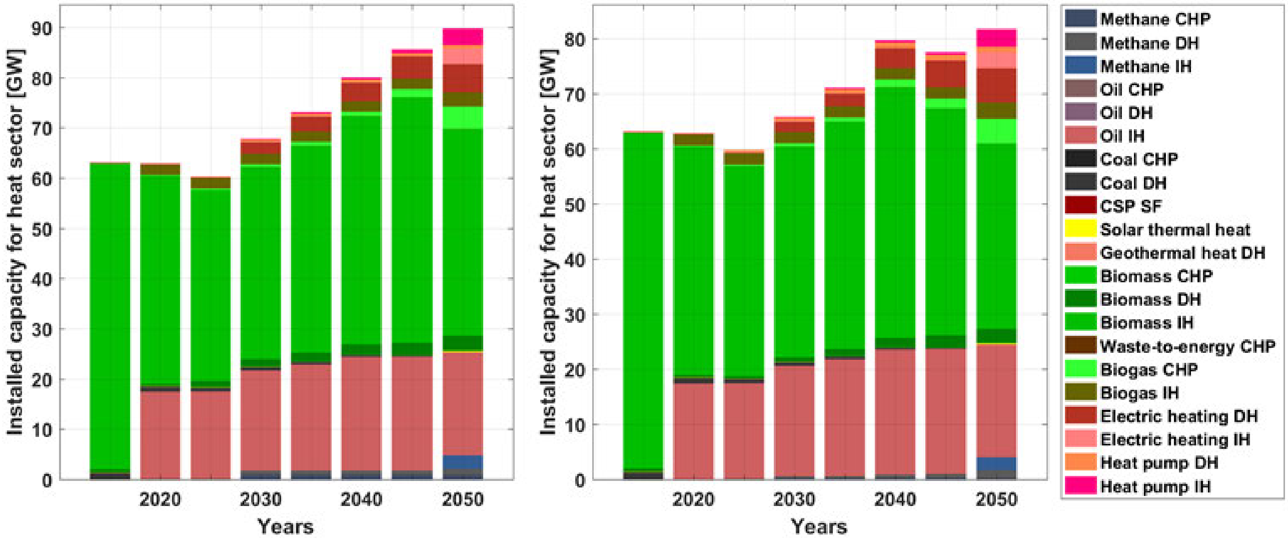

**FIGURE 12.** Installed capacity in the heat sector in the BPS-1 (left) and BPS-2 (right) in the transition years.

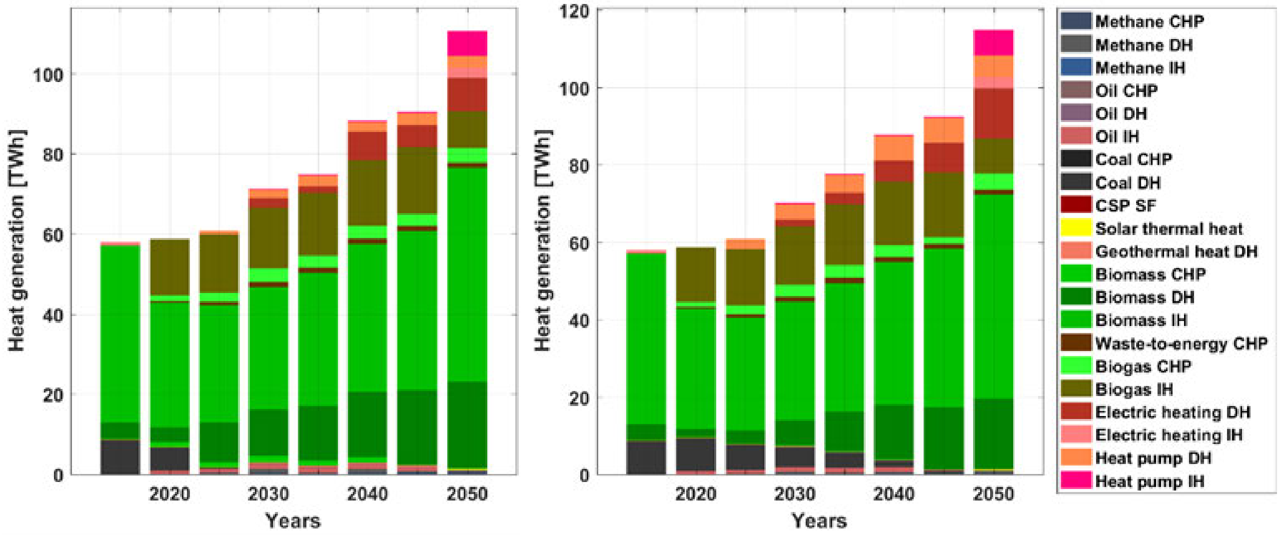

**FIGURE 13.** Heat generation in the BPS-1 (left) and BPS-2 (right) in the transition years.

### *C. HEAT GENERATION AND INSTALLED CAPACITIES*

Figure 12 and 13 shows the total installed capacities in the heat sector and total heat generation respectively by different heat generation technologies during the transition period in the BPS-1 and BPS-2.

The share of biomass-based heat generation is dominant in the heat sector in both scenarios during the transition. In 2015, 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 health hazards. However, during the transition, biomass use in cooking decreases and is replaced by electricity-based cooking. The replacement technologies could be a mix of induction and electric resistance cooking. However, detailed numbers on the mix of different cooking technologies is beyond the scope of this study. The use of agricultural and forest residues and municipal solid waste increases during the transition. In 2020, heat generation technology based on direct electricity use and oil as a transition fuel are used. 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 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. In 2050 in the BPS-1 scenario, the share of heat pumps and direct electricity-based heating in residential and commercial establishments is 10% and 4%, respectively.

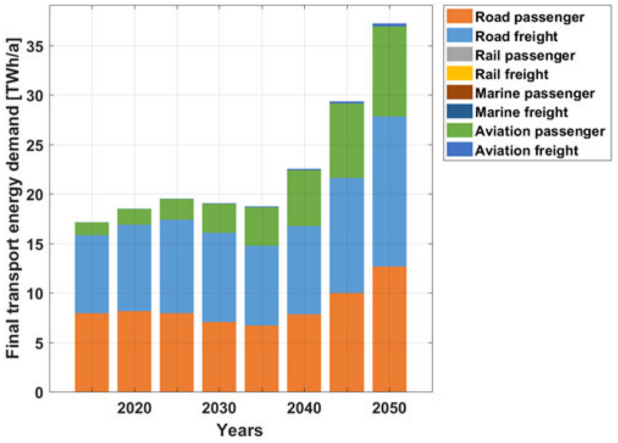

**FIGURE 14.** Final energy demand for transportation by transportation modes in the BPS-1 and BPS-2 for the transition period at generation in the BPS-1 (left) and BPS-2 (right) in the transition years.

### D. TRANSPORT SECTOR

The final energy demand for transport according to different modes for the two scenarios is shown in Figure 14 and by fuel types for the BPS-1 and BPS-2 in Figure 15. 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 of energy demand is observed for the aviation sector. The increase in energy demand is directly associated with an increase in transportation of freight and passengers.

The direct use of electricity has the largest share in meeting the final demand in transport by 2050, as shown in Figure 15. 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 increases as a result of more cost-efficient solutions.

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. The 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.

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 16. 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.

### E. 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.

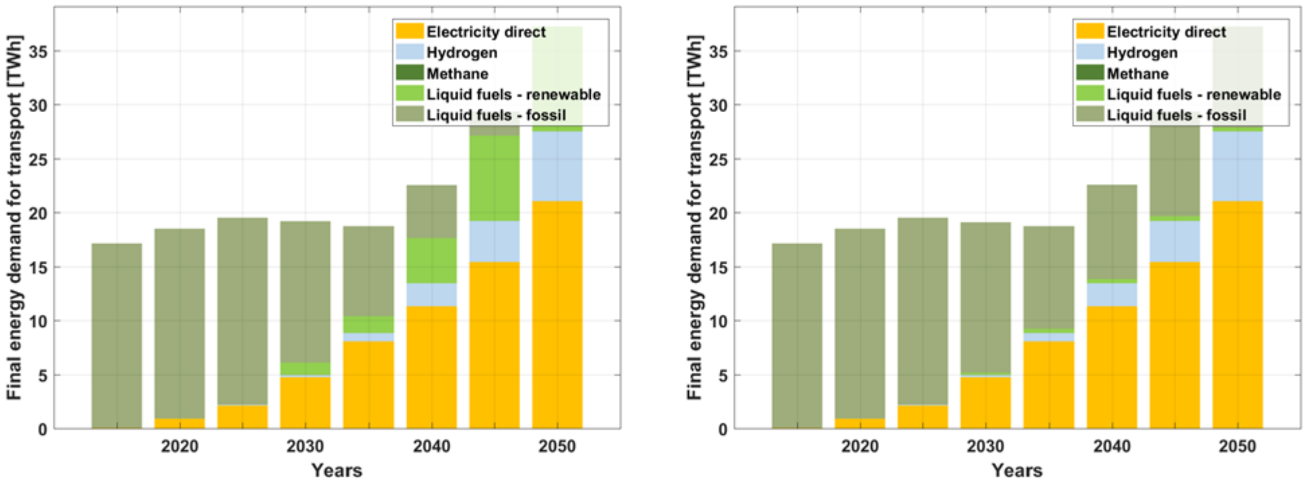

**FIGURE 15.** Final energy demand for the transportation sector by fuel in the BPS-1 (left) and BPS-2 (right) for the transition period.

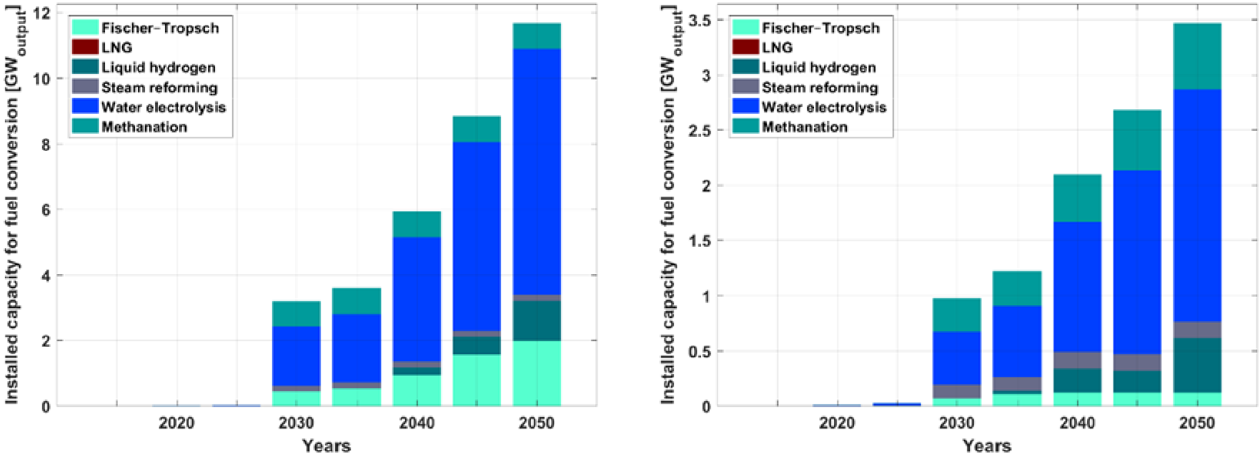

**FIGURE 16.** Installed capacity needed for transport fuel conversion in the BPS-1 (left) and BPS-2 (right) during the transition years.

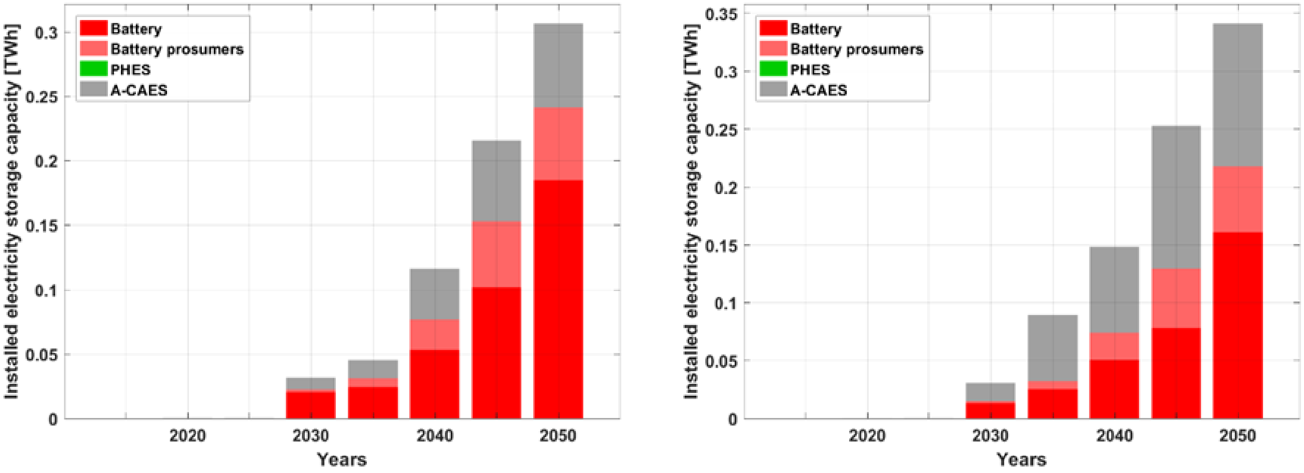

**FIGURE 17.** Installed electricity storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

The energy storage is reported in energy capacity (TWh), while the power capacity can be calculated from the Energy-to-Power ratio.

As the future energy system is solar PV dominated, batteries are necessary to maintain stability of the energy system. 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 does not arise. The total installed electricity storage capacity increases to nearly 320 GWh in 2050 in the BPS-1 as shown in Figure 17.

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 in the 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 18. The adiabatic compressed air energy storage (A-CAES) starts appearing already in 2030 with a small share and increases afterwards. Based on their location, Nepal and Bhutan have specific geologies suitable for the development of A-CAES [83]. The total electricity storage output is projected to reach 120 $TWh_{el}$ and 122 $TWh_{el}$ in the BPS-1 and BPS-2 respectively in 2050. The Energy-to-Power (h) ratio of all storage technologies is given in the Supplementary Material (Tables S10 and S11 for the BPS-1 and BPS-2 respectively).

The need for thermal energy storage (TES) is crucial for the heat sector transition. Figure 19 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. A large 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 for heat and electricity. 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, mostly for high temperature heat in industry and a small share for electricity production A steep

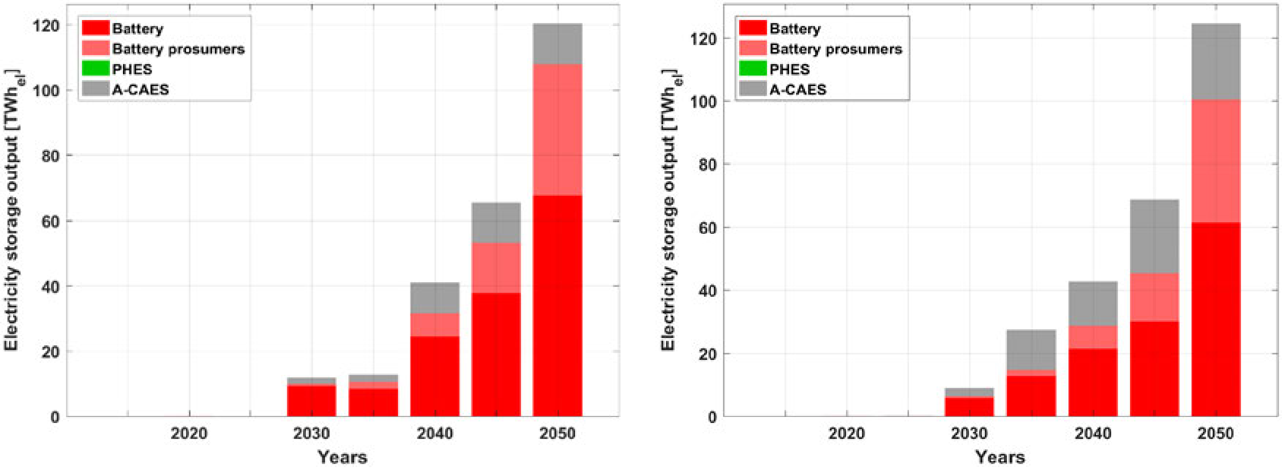

**FIGURE 18.** Electricity storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

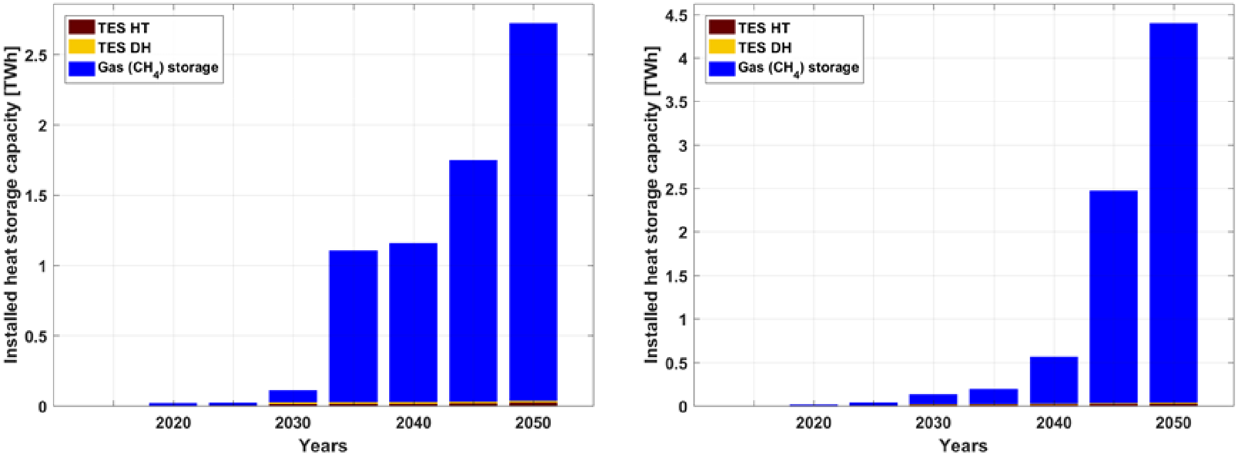

**FIGURE 19.** Installed heat storage capacity in the BPS-1 (left) and BPS-2 (right) in the transition years.

rise in heat storage output is noticed in 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 from Figure 20 during the years 2040 and 2035 respectively.

### F. ENERGY COSTS DURING THE TRANSITION

The total annual system cost and levelised cost of energy are shown in Figure 21 and 22, respectively.

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 BPS-2 does not take into consideration the GHG emissions cost and there is no constraint on the fossil fuel usage even in 2050. This can be observed from the GHG emissions (Figure 27) in 2050. The heat and the power sectors are completely defossilised, while the transport sector still uses fossil fuels in 2050 in the BPS-2. In the total annual system cost, the heat sector accounts around 5 b€, while the remaining 2 b€ comes from the power and transport sectors in 2015 for the two scenarios. The annual system cost increases for the power and transport sectors during the transition years, especially for the power sector, due to an increasing energy demand and shifting of fuel demand for electricity in transport and heat sectors. The cost of the transport sector slightly increases over the years in the BPS-1, but a large increase happens during the late 2040s due to the change in vehicle stocks, and the associated shift in corresponding fuel types and a constraint of 100% renewable energy in the transport sector. On the other hand, the BPS-2, follows the same trajectory, however the absolute annual investment in the transport sector is lower due to the utilisation of fossil fuels and no additional investments needed for the complete defossilisation of this sector. This can be clearly observed from Figure 16, where installed capacities of fuel conversion technologies are 3.5 times higher in the BPS-1. The additional installed capacities require additional annual investments, which increase the total cost of the system.

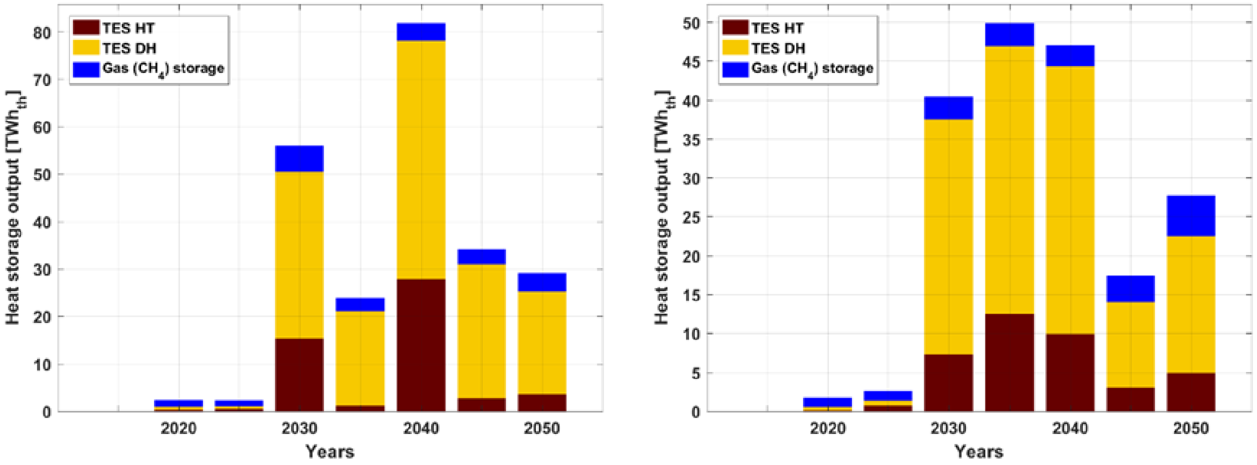

**FIGURE 20.** Heat storage output in the BPS-1 (left) and BPS-2 (right) in the transition years.

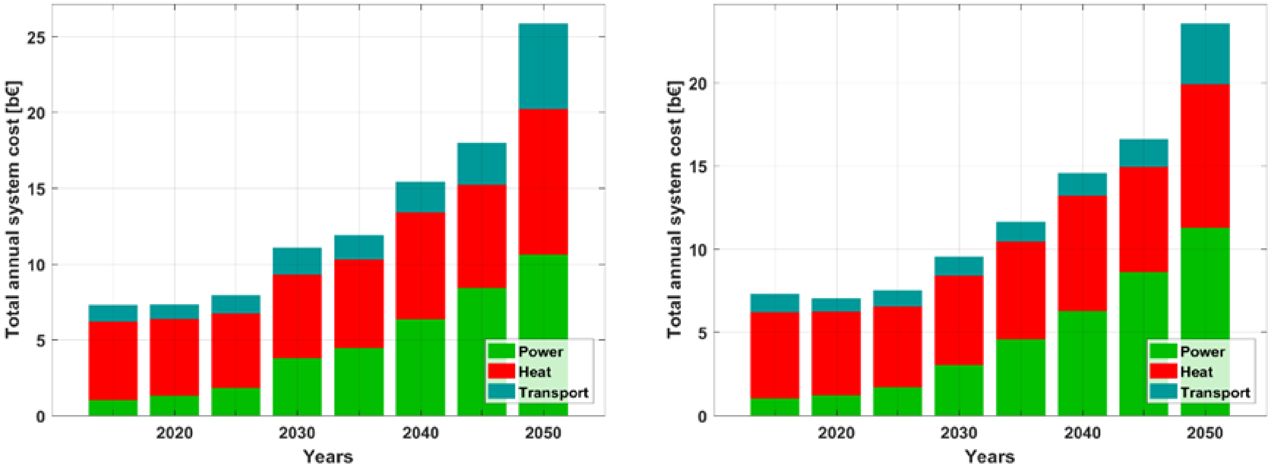

**FIGURE 21.** Total annual system cost for power, heat and transport sectors in the BPS-1 (left) and BPS-2 (right) in the transition years.

The levelised cost of energy declines to 49 €/MWh in 2050 compared to 90 €/MWh in 2015 in the BPS-1. A fully RE-based system not only offers a cost competitive solution but also an energy system with zero GHG emissions as shown in Figure 22. On the other hand, the BPS-2 follows a similar cost trajectory, however this scenario does not lead to a complete removal of fossil fuel usage from the transport sector. With no penalty on the usage of fossil fuels even in 2050, the transport sector utilises fossil fuels. However, if the emitted GHG emissions are taxed, the levelised cost of energy will increase. The high share of CAPEX implies an increase in the installation of new renewable technologies and energy storage solutions, while decreasing the cost of fuels, imported in the case of Nepal and Bhutan. 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.

The LCOE is slightly higher in the BPS-1 compared to the BPS-2 in all transition years. In both the 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 in the transport sector play a major role in having a higher share of 47% in LCOE costs in 2015. In the BPS-1 scenario in Figure 23 (left), LCOE gets reduced to 52.2 €/MWh from 90 €/MWh, in the early 2020s of the energy transition. Limiting the usage of expensive fossil fuels-based energy and the incorporated GHG emission costs are the key drivers for this reduction. The trend continues to a lower LCOE of 45 €/MWh until 2025. But in the year 2030, the LCOE rises by about 20% to 54.3 €/MWh. The rise in the LCOE is due to the installation of new power generation and storage capacities and the associated CAPEX. The solar PV and battery-based storage technology complemented by hydropower, plays an important role in the energy system which further lowers the LCOE to 49 €/MWh, a 54% reduction by the end of the transition period in 2050. The BPS-2 does not consider GHG emission cost, which is not sustainable, though the LCOE is quite low. Thus, a 100%

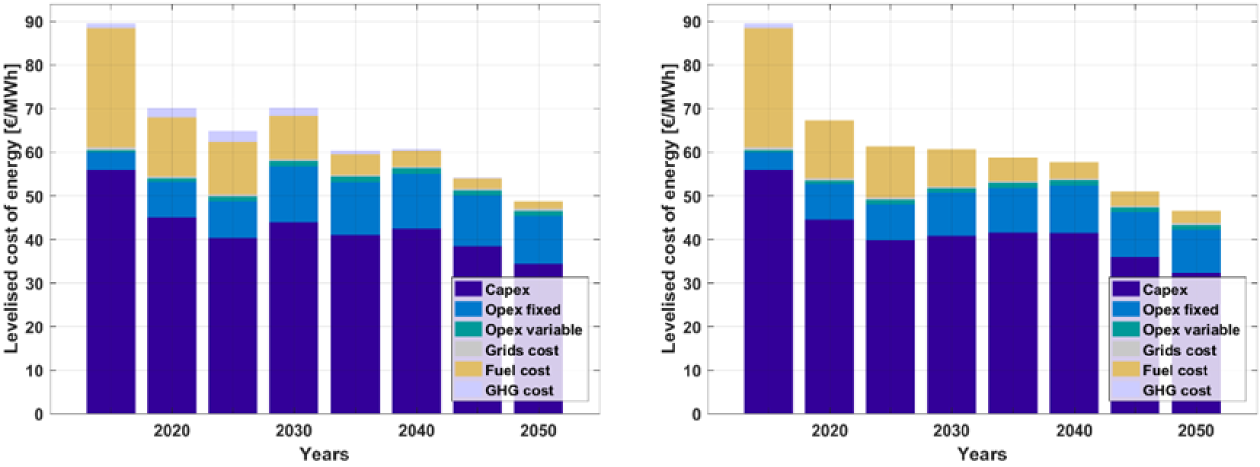

**FIGURE 22.** Breakdown of the levelised cost of energy in the BPS-1 (left) and BPS-2 (right) in the transition years.

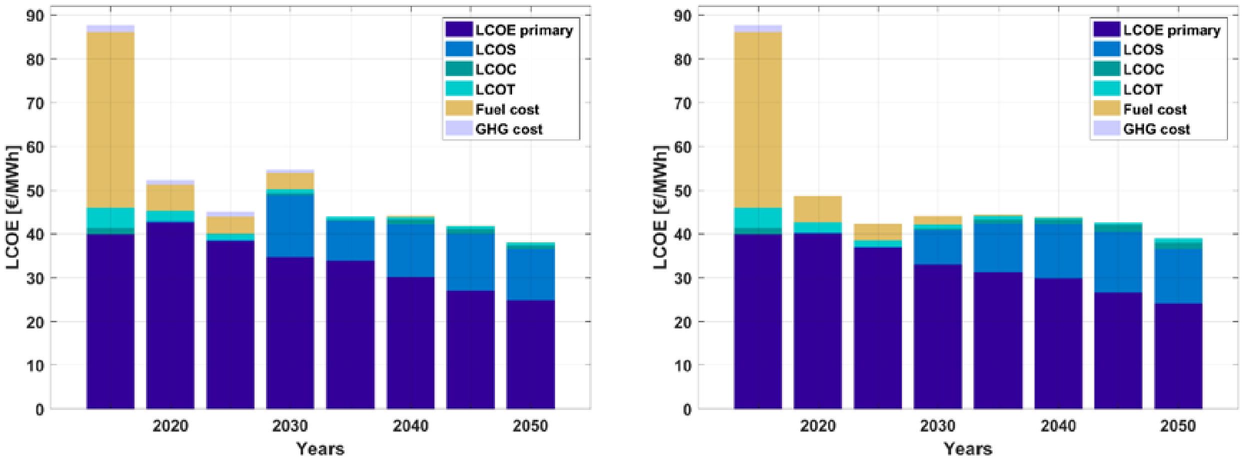

**FIGURE 23.** LCOE total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

RE-based sustainable energy system is substantially lower in cost by 2050 than the currently existing energy system.

The LCOH decreases 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 24. The LCOH remains at 80-85 €/MWh range till 2040. A decrease is observed in 2045 and again an increase in 2050 is seen in both scenarios with a LCOH of 95 €/MWh and 86 €/MWh in BPS-1 and BPS-2 respectively.

Figure 25 and Figure 26 show the final transport passenger and freight costs in the BPS-1 and BPS-2 respectively during the transition years. The final transport passenger cost declines considerably for road whereas aviation and rail transport follow a marginal decrease in the BPS-1 during the transition. In the 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 decrease substantially from 0.12 €/t-km in 2015 to around 0.03 €/t-km in 2050. In 2050, the transport passenger cost in aviation and transport freight cost in road have a major contribution towards the final transportation sector cost.

### G. GHG EMISSIONS 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 27.

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 MtCO2eq in 2050, which solely comes from the transport sector. In the case of Nepal and Bhutan, 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 MtCO2eq in 2015 achieve a steep reduction throughout the transition period. The decrease in GHG emissions is already at a faster rate starting 2020 in the BPS-1, whereas

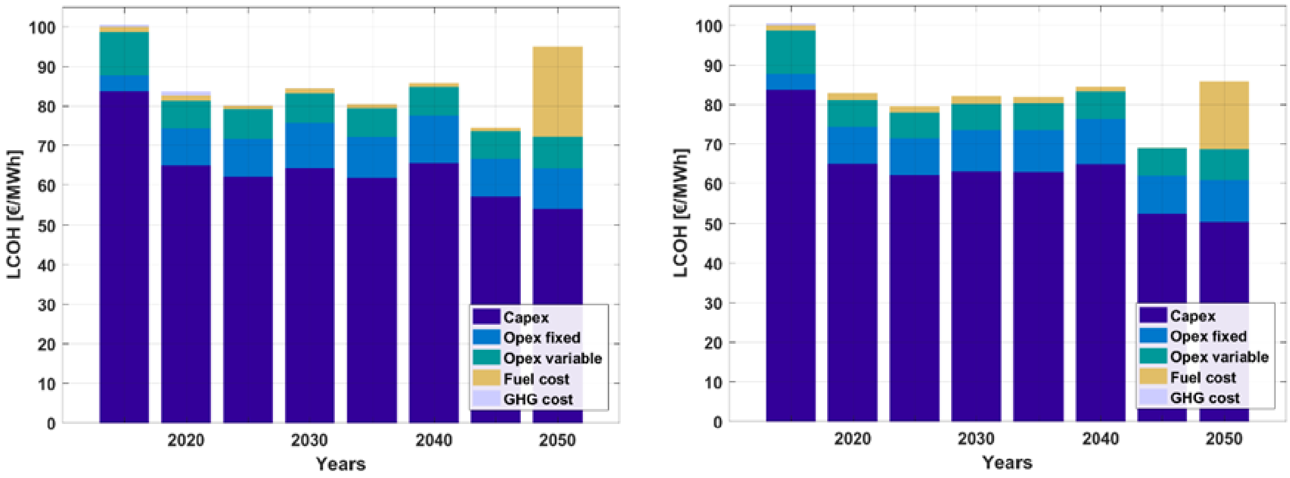

**FIGURE 24.** LCOH total cost breakdown from 2015 to 2050 in the BPS-1 (left) and BPS-2 (right).

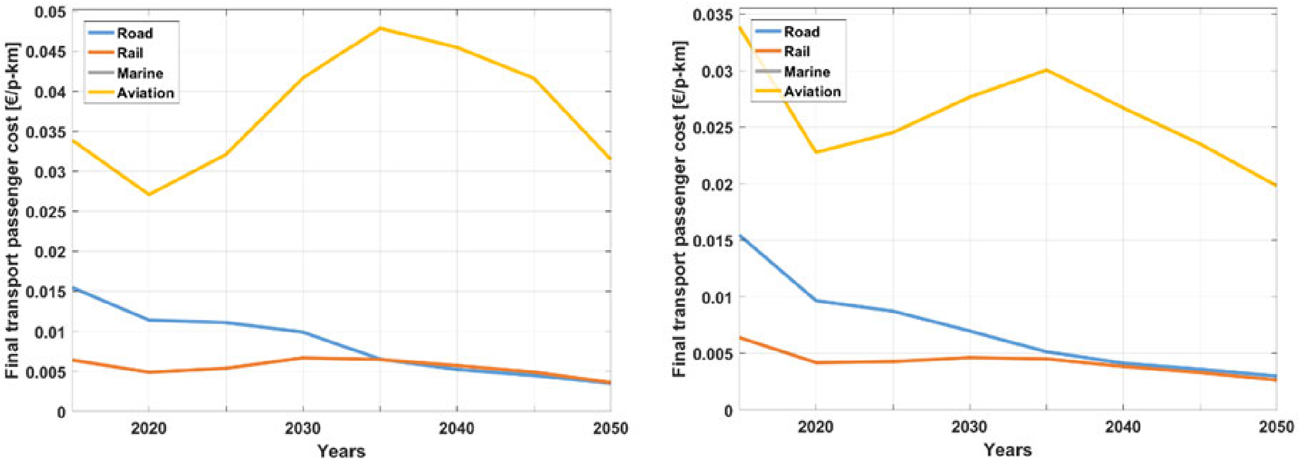

**FIGURE 25.** Final transport passenger cost per person-kilometer in the BPS-1 (left) and BPS-2 (right).

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.

## IV. DISCUSSION

### A. OVERALL RESULTS

The primary objective of this research was to demonstrate a least-cost energy system transition pathway by 2050 for Nepal and Bhutan, which is aligned to the Paris Agreement [84]. This can be achieved by using indigenous renewable resources in the country. However, missing piece of the puzzle is strong political will and long-term national policies towards integrating large shares of renewables into the energy system. This study illustrates two energy transition pathways: the BPS-1 shows a pathway towards a self-sufficient, least-cost, zero GHG emission energy system, whilst the BPS-2 shows a pathway with no GHG emission cost implemented. These two scenarios show that RE technologies, especially solar PV, would reduce unsustainable use of fuelwood. This will increase the use of direct electricity, especially in cooking [85]. Therefore, enhancing the quality of life of women and children mostly in rural areas by reducing time spent on collection of fuelwood thus creating additional opportunities for employment, heath improvement and education [86].

During the transition, the energy supply mix changes considerably from fuelwood and hydropower dominated electricity generation to solar PV electricity dominated in 2050. Solar PV dominates the installed capacity in electricity generation with 138 GW in BPS-1 and 141 GW in BPS-2. Due to the available economic potential of hydropower, addi-

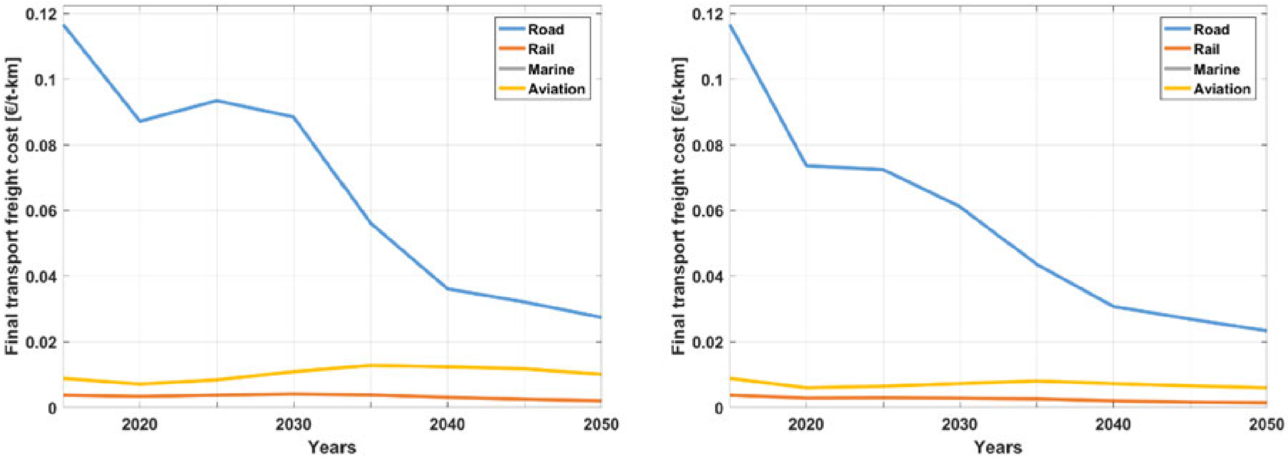

**FIGURE 26.** Final transport freight cost per ton-kilometer in the BPS-1 (left) and BPS-2 (right) in the transition years.

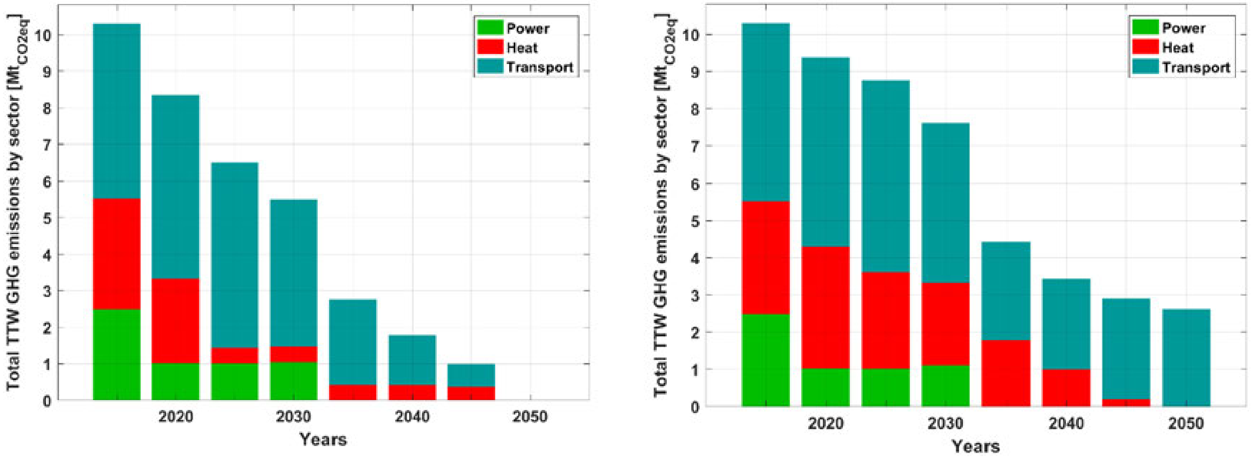

**FIGURE 27.** Sector-wise GHG emissions during the transition period in the BPS-1 (left) and BPS-2 (right).

tional capacities are installed during the transition years, as hydropower generation compliments in periods of low solar resource availability. Biogas-based CHP plants are installed from 2045 onwards, due to bio-waste availability from the increasing population. Due to flexibility provided by the integration of power, heat and transport sectors, curtailment is reduced to 4.3% in BPS-1 and 6.3% in BPS-2 of the total electricity generation in 2050. For remote locations in mountainous terrain, grid extension is often very expensive, in such cases, solar PV provides affordable electricity access in a decentralised way [87], [88]. However, care must be taken on proper cleaning mechanism of dust and other particles during periods of no rainfall, as it decreases the output considerably [89]. Almost all the provinces in Nepal and Bhutan receive excellent solar irradiation all year around, this is observed in installed capacity, as solar PV dominates installed capacity and electricity generation in each of these regions. The high share of solar PV in the BPS-1 and BPS-2 is made feasible through the current and expected cost decline of solar PV and battery energy storage systems, with manageable lithium resource supply in the future as projected by Greim *et al.* [90]. The combination of solar PV with battery storage enables electrification of remote villages located in mountainous terrain without the need for grid extension, utilising the modularity of these technologies [87]. In addition to solar PV, micro and mini hydropower provides access to electricity in remote areas not connected to the central grid [87]. However, impacts of hydropower projects on local living conditions and sustainability of the projects before and after implementation should be analysed. The biomass potential considered in this study is sustainable which consists of agricultural residues and wastes [71]. The role of biomass in electricity generation is negligible, while most of the biomass is used in the heat sector. A scenario without biomass would be possible, however the total cost of the system will be higher.

The total electricity demand grows considerably during the transition, primarily due to the projected growth in population and GDP. Additionally access to modern services and appliances will increase as these countries will try to adapt to living standards of the OECD countries. The electricity demand in 2050 will be primarily used for the basic power demand and this forms the largest share (81.6%) of the total electricity demand, while in the heat sector, electricity will be used for heat pumps and direct electricity-based heating and some for synthetic fuel production, so the electricity share in heating is 3.6% of the total electricity demand. In the transport sector, electricity is used directly by electric vehicles and indirectly for production of synthetic fuels, so the total share of electricity in transport sector is 14.8% of the total electricity demand.

The storage requirements on a daily cycle are primarily met by utility and prosumer scale lithium-ion batteries in both the scenarios in 2050, due to a low seasonality of solar resources in Nepal and Bhutan. On the other hand, A-CAES provides a buffer when solar resource is not available for some days. Lithium-ion battery recycling after their useful life enhances the sustainability as it reduces the rate of global extraction of resources and dependence on other countries. The heating sector seems to face more challenges than the power sector due to specificity and complexity of the processes. However, transitioning of the heat sector will not only reduce unsustainable fuelwood and fossil fuels consumption, but also increase the overall efficiency, making the industrial sector competitive on the global market. In 2050, in both the scenarios about 61% of the total heat demand is met by modern biomass and waste-based technologies, while the remaining demand is met by heat pumps and direct electricity based heating.

The transport sector faces a major transition due to a complete phase-out of imported fossil fuels used in this sector, according to the scenario projections. These fossil fuels are replaced by direct electricity, hydrogen, and liquid fuels generated from RE during the transition towards 2050. According to Shakya and Shrestha [91], utilising direct electricity brings various co-benefits such as emission reduction, improving energy security and employment generation. Comparing the cost of these new fuels, utilising direct electricity is the cheapest option. However, direct electricity cannot be used in all the transport modes especially in international aviation due to issues with range and weight. Within the road segment, passenger vehicles are shifted to direct electricity and hybrid plug-in solutions. On the other hand, aviation and rail transport modes utilise hydrogen and Fischer-Tropsch fuels, respectively. The cost of synthetic natural gas and especially hydrogen as fuel are quite comparable to fossil fuels. The implementation of GHG emission costs on fossil fuels used in the transport sector will greatly increase their cost, making them more expensive, which better reflects the real societal costs of these fuels. Even without GHG emission costs, the cost of fossil fuels is still higher than direct electricity in 2050, with a strong impact on all transportation options, in particular those with direct electrification. Additionally, implementation of social costs on the air pollution due to the fossil fuels would increase their total cost, while a 100% renewable based energy system would substantially reduce these cost [56].

### B. COMPARING RESULTS WITH RELATED STUDIES

The results of this study are in line with the studies presented in Table 1, comparing capacity mix, cost of generation and GHG emissions. According to Gulagi *et al.* [54], in the power sector, solar PV and batteries have the largest share in installed capacity mix in 2030 due to their expected cost decline and related assumption. This trend can also be compared with countries in the South Asian region [74], [92], [93] where solar PV and batteries form a least cost hybrid power system solution to enable the renewable energy transition. According to the results of this study, GHG emissions decrease through the transition, as fossil fuels are phased out in all the sectors and cost-competitive renewables are adopted. This was also observed by Shakya [55] and Yangka and Diesendorf [27], where a decrease in GHG emissions was observed while adopting low carbon emitting sources. According to Jacobson *et al.* [56], solar PV would have a share of 64.6% in 2050, which is line with the share of 66.7% observed in this study. Additionally, transition to a 100% renewables based energy system would create jobs and lower the cost of energy.

### C. IMPLICATIONS OF THE RESULTS

A study conducted on the role of renewable energy in Nepal [94] emphasises the need of locally available renewables to be utilised and provide electricity access in all areas and non-dependence on foreign fuel imports. Thus, an investment in locally prevailing resources such as mini hydropower and solar PV will ensure uninterrupted power in every household despite the difficult terrain and sparse household settlements in the rural areas. This also decreases GHG emissions and expensive fossil fuel purchases from India. According to the Nepalese government plan [76], a mix of different RE sources and a blend of centralised and distributed energy supply guarantees affordable energy access to every citizen. To support the government's plan, the Alternative Energy Promotion Centre (AEPC), was set up to mainstream RE capacities in Nepal. In 2016, around 30 MW of mini and micro hydropower plants were installed, and about 15 MW of solar PV systems [95]. 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 the Sustainable Development Goals and the Sustainable Energy for All programme [95].

A 100% RE-based system for Nepal and Bhutan is not only cost-competitive but also technically feasible. It ensures continuous and uninterrupted energy supply in power, heat and transport sectors. In the BPS-1, the levelised cost of energy decreases considerably to 49 €/MWh in 2050 compared to 90 €/MWh in 2015, while in the BPS-2 it further decreases to about 47 €/MWh. Due to the high shares of least cost renewables and storage technologies in the system, levelised cost of energy decreases from the levels of the current fossil fuel-based system. Specifically, the drastic cost decline of solar PV and batteries, which are projected to play a major role in electricity generation and storage, lowers the energy system cost. Therefore, Nepal and Bhutan should utilise the recent cost reductions in solar PV and tap into the growing market, while creating new jobs in manufacturing and operation and maintenance [96].

Summing up, the two scenarios show that indigenous RE resources in Nepal and Bhutan help in achieving energy independency which ensures affordable energy supply for all of their population. The respective nations 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 specific roadmaps, measures and policies. In addition, the collaboration with the neighbouring country India, which is far ahead in new renewable electricity generation, and with a whole South Asian region creates mutual benefits.

### D. LIMITATIONS OF THE STUDY

The results and main findings of this study show two of the various pathways to achieve a common goal of zero GHG emissions across the energy sectors. One of the main assumptions here was that the existing power grid available within each of the regions will supply electricity to every household, where there is a demand. A high granular data of solar and wind resources will describe the regional variability in detail. As a next step of research, sensitivity analysis of the assumptions and the input data should be done. This may alter the results, but no structural changes are expected.

## V. CONCLUSION

The Himalayan countries Nepal and Bhutan are rich in indigenous renewable resources. This is aptly reflected in the results of this study which show that a 100% RE-based system is technically possible and economically feasible by 2050 for Nepal and Bhutan with zero GHG emissions in the BPS-1 scenario. Moreover, the energy system in 2050 will be substantially more efficient than the current energy system. The renewable energy technologies and storage solutions can adequately supply energy consistently at every hour for all sectors throughout the year by 2050. The levelised cost of energy for Nepal and Bhutan decreases from 90 €/MWh in the present not sustainable energy system to 49 €/MWh and 47 €/MWh by 2050 in BPS-1 and BPS-2 respectively, documenting an increase in levels of sustainability and overall economics. Despite having huge snowmelt high current rivers and sloping terrain, which is excellent for hydropower generation, solar PV emerges as the backbone of the electricity generation supported by batteries. Excellent solar resource availability combined with the decreasing cost of PV systems and Li-ion batteries enable a transition towards a 100% RE system. Achieving a 100% renewables-based energy system enabling zero GHG emissions by 2050 demands bold, strict, and intense ambitious national policies by the two nations.

## ACKNOWLEDGMENT

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## SUPPLEMENTARY MATERIAL

Supplementary Material available under the tab "Media."

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