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The Value of Fast Transitioning to a Fully Sustainable Energy System: The Case of Turkmenistan

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ABSTRACT The Paris Agreement within the United Nations Framework Convention on Climate Change aims to mitigate effects of greenhouse gas emissions to limit global warming. Turkmenistan ratified the Agreement and is a country with absolute reliance on fossil fuels and practically zero installed renewable energy capacity. This study provides potential transition scenarios to full sustainability for Turkmenistan in power, heat and transport sectors. Vast sunny desert plains of Turkmenistan could enable the country to switch to 100% renewable energy by 2050, with prospects to have 76% solar photovoltaics and 8.5% wind power capacities in a Best Policy Scenario. Seven different transition scenarios, with different GHG emissions cost assumptions and transition rates, have been analysed to demonstrate different possible paths towards full sustainability in a cost-efficient way. The results of the study demonstrate that a 100% renewable energy system, regardless of the transition rate, will be lower in cost than a continual reliance on fossil fuels. The scenario with the highest rate of renewable energy integration enables the least cost system and quickest reduction of greenhouse gas emissions. The results are expected to serve as a guideline to policymakers in Turkmenistan. The structural results for transition speed options and respective costs and benefits from switching a practically fully fossil fuels based system to a fully renewable energy system are expected to be transferable to many countries.

INDEX TERMS 100% renewable energy, energy transition, policy scenario, sector coupling, sustainable development, Turkmenistan.

I. INTRODUCTION

The anthropogenic global warming poses an existential threat to humankind. Rising sea levels, extreme droughts, increase in occurrences of extreme weather events, among other things, can adversely alter life on Earth [1]. Humanity has a great responsibility to address the issue of climate change in an urgent manner and the highest priority is to reduce and eliminate anthropogenic emissions of greenhouse gases (GHG). As the energy sector is the biggest contributor of carbon dioxide, a transition to renewable energy sources can sharply reduce GHG emissions, and enable to reach ambitious climate targets, preferably the 1.5°C limit to global warming above pre-industrial levels [2]. However, this challenge requires the cooperation of all nations with no exceptions, and Turkmenistan cannot continue heavily relying on fossil fuels.

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Turkmenistan is a Central Asian country with a population of 5.5 million people and an area of 488,100 km^2 mostly covered by arid deserts. The electricity consumed in Turkmenistan in 2019 was 25.7 TWh, which equals 4,392 kWh/person per year, a relatively high consumption compared to its Central Asian neighbouring countries [3], thanks to high electricity penetration over 99%. People of Turkmenistan have had access to free utilities since the end of Soviet Union until very recently, when electricity price was set in place at 0.0065 €/kWh in 2014. Turkmenistan is self-sufficient energy-wise and one of the few countries with absolute dependence on fossil fuels, with the sixth largest proven natural gas reserve in the world [4]. Natural gas fired power plants provide 99% of the electricity in the country, while the remaining 1% is covered by a small hydropower plant of 1.2 MW in the Mary region and some individual diesel power generators. Electricity generation, transmission and distribution are controlled by Turkmenenergo State Corporation, as a single vertically integrated entity [5].

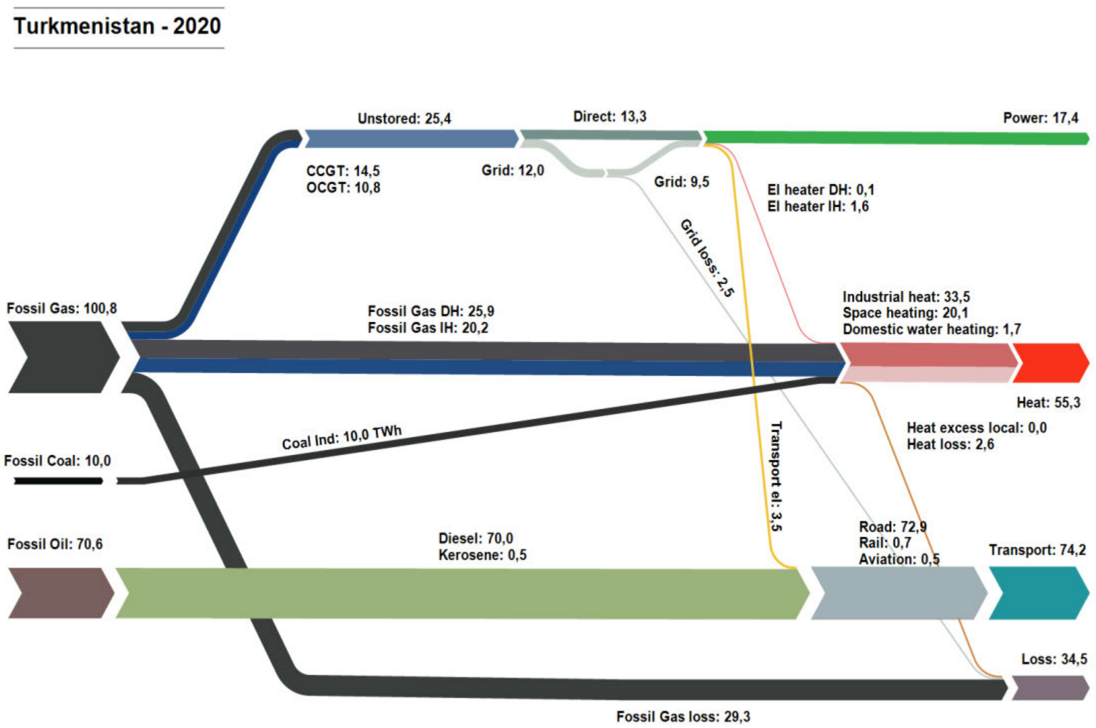

FIGURE 1. Energy flows in the energy system of Turkmenistan for the year 2020. All units are in TWh.

The state-owned oil company TurkmenNebit supplies heavily subsidised fuel for the transportation needs of Turkmenistan. Heating demands are covered by individual gas boilers in 95% of households and the remaining 5% is covered by electricity. There is insufficient political and social will to change the state of the current energy system in Turkmenistan. Heavily subsidised utilities and lack of awareness have kept the citizens ignorant regarding the environmental effects of the reliance on fossil fuels. There are little to no incentives for citizens to consider energy efficiency and the conscientious use of resources. The historically high level of corruption [6] and inefficient legal and regulatory frameworks have barely attracted foreign investments in renewable energy (RE).

The current energy system is presented in Fig. 1, tracing the energy flow from primary fuels to final energy demands. The figure shows the relatively straightforward energy flow with almost non-existent sector coupling. The losses mostly consist of inefficiencies from generating electricity in gas turbines but do not include the losses from oil use in the transport sector. The losses in the transport sector vary greatly depending on transport mode [7] and are harder to quantify for presentation purposes.

Despite having vast potential for solar and wind power, 655 GW and 10 GW respectively [8], there is practically zero installed RE capacity in Turkmenistan [4], [9]. The vast desert plains, with close to 300 days of sunshine at a global horizontal irradiation of 4.72 kWh/(m^2·day), or 1722 kWh/(m^2·a) [10] and a wind power generation potential of up to 222 W/m^2 at 50 m hub height [11], can potentially enable enormous RE-based electricity generation to cover domestic demand and may even enable electricity export to neighbouring countries.

The intended nationally determined contribution (INDC) of Turkmenistan within the United Nations Framework Convention on Climate Change (UNFCCC) [12] highlighted sustainable development and energy efficiency investments, however little tangible actions have been undertaken in the country so far. Practically zero new RE capacity was installed in Turkmenistan since the hydropower plant installation in Mary in 1913 [9], besides the experimental few kW solar PV installed by the Institute of Solar Energy "Gun". However, there may be a few MW of independent PV systems, as Werner *et al.* [13] have indicated, with a different method based on international tariffs data, about 5 MW at the end of 2017. The national strategy represents the government's vision on the issue of climate change in vague terms, but no effective legal frameworks have been established so far.

No updates or reports have been published by the government of Turkmenistan since the INDC report, to the knowledge of the authors. However, some international organisations and corporations have assessed Turkmenistan's current state and current policy scenarios through work such as the energy sector assessment [5], a holistic review of energy efficiency and RE sectors in Central Asia [14], and a survey of the current state of infrastructure developments [15]. The European Bank for Reconstruction and Development [5] provides an analysis of the legal and regulatory frameworks in Turkmenistan and concludes that the current institutional structure favours fossil fuels. Korpeyev [16] provides an overview on the benefits of switching to RE in Turkmenistan, such as increasing standards of living, creating local jobs, addressing the short-term issues of providing energy to remote settlements and helping the country to realise its environmental protection liabilities. All aforementioned reports further confirm the inadequacy of the development towards sustainability in the country. The aim of this research is to analyse energy system pathways for Turkmenistan for power, heat and transport sectors to design a cost-optimal fully sustainable energy system aimed for the mid-century.

II. MATERIALS AND METHODS

A. MODEL

LUT Energy System Transition Model [17], [18] was utilised to simulate Turkmenistan's energy transition fully integrating power, heat and transport sectors.

The model takes as input the current state of the energy system and RE resource availability potentials. The current power, heat and transport energy demands are first applied to the model. Then, renewable energy potentials, including solar, wind, bioenergy, geothermal and hydropower, are considered. Energy infrastructure, including currently installed power capacities, grid connections and power flow between the regions of Turkmenistan, is taken into account. In addition, population density and distribution and electricity market prices are included. The model allows to set different assumptions regarding costs of various electricity production and storage technologies and the pace of the transition such as the rate of integration of RE technologies. It is also possible to set different constraints such as CO_2 emissions cost, area availability, biomass potential, etc. The model utilises linear optimisation with a spatial resolution of solar and wind resources of $0.45° \times 0.45°$. The target function is to achieve a least cost energy system given the constraints.

The fundamental structure of the LUT Energy System Transition Model is displayed in Fig. 2. The model simulates not only the power sector, but also heat and transport sectors and the interplay between the sectors. It also considers prosumers' interplay with the system, i.e., the consumers of electricity that produce their own electricity on-site.

The model considers 108 different generation and storage technologies and their corresponding costs of installation, fixed and variable operational costs, operational lifetime, costs for fossil fuels and biofuels and renewable energy potentials for solar, wind and hydro resources. The main energy system components are displayed in Fig. 3.

The three energy sectors are divided into different types of demand. The power sector consists of residential, commercial and industrial end-users. Prosumers are divided in a similar way, where residential houses, commercial facilities and industrial sites can install rooftop solar PV systems and batteries on-site. The heat sector consists of space

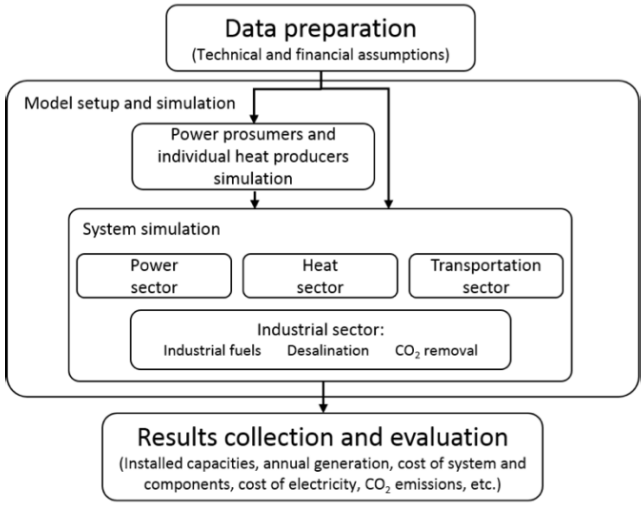

FIGURE 2. Fundamental structure of the LUT Energy System Transition Model [17].

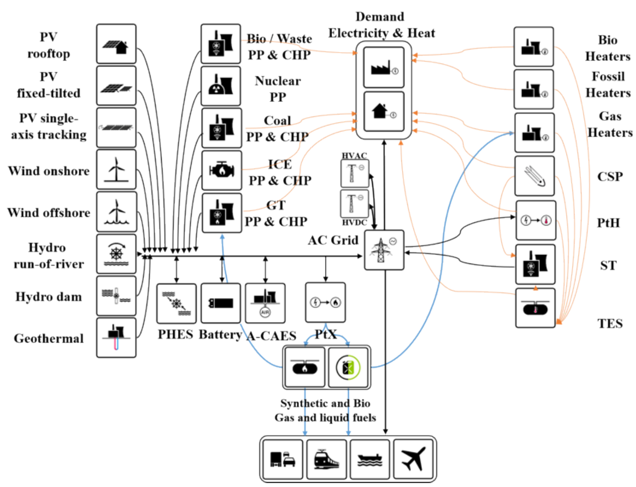

FIGURE 3. Schematic of the LUT energy system transition model for power, heat and transport sectors [19].

heating, domestic hot water, industrial process heat demand and biomass for cooking. However, the heat needed for these subsectors is not equal. Whereas space heating may require ∼25 °C of heat and domestic hot water demand may range and top at 70 °C, industrial processes can usually require an order of magnitude higher temperatures in hundreds or more than thousand degrees Celsius. Therefore, heat is further divided into low-, mid- and high temperature heat. The transport sector is also subdivided into passenger and freight transportation. The two transportation demands are met by different modes of transport and respective final energy requirements, according to Khalili *et al.* [7]:

Passengers road transport (Light Duty Vehicles, busses, 2-3 wheelers) and freight road transport (Medium Duty Vehicles, Heavy Duty Vehicles):

- BEV – battery electric vehicle;
- FCEV – fuel cell electric vehicle;

- PHEV – plug-in hybrid electric vehicle;
- ICE – internal combustion engine.

Passengers and freight rail transport:

- electricity;
- liquid fuel.

Passengers and freight aviation:

- electricity;
- hydrogen;
- liquid fuel.

The model outputs possible scenarios which are optimised towards full sustainability on an hourly basis in five-year intervals from the year 2020 to 2050. This includes the shares of individual renewable energy resources and costs of implementing such a transition and related greenhouse gas emissions, assuming projected population growth, energy demand growth, energy storage demand, diversified energy mix and minimisation of reliance on fossil fuels. The model had been described in great detail in [17], [18], [20].

B. DATA

In the absence of up-to-date and reliable data from state institutions of Turkmenistan, various secondary international sources, databases, fact books and organisations, such as United Nations [8], [21], the Central Intelligence Agency of the United States [22], International Energy Agency [23] and several others [3], [24], [25] have served as data sources for this research.

This study was conducted primarily relying on data from secondary sources. Demographic data was taken from international organisations, as the census report from the state of Turkmenistan was not possible to obtain. The demographics data used in this study may be out of date and distorted [21], as it fails to account for the latest trends in the country such as a mass emigration of people abroad in search for jobs, or migration between the administrative regions inside the country in the face of economic difficulties. Nevertheless, the study was conducted based on accessible demographic data.

The data regarding current installed power capacity and power plants were taken from governmental internet portals and websites of contractors of said power plants [26]–[29].

C. ASSUMPTIONS

The future power load projection was calculated based on methods from Toktarova *et al.* [30]. The heating demand was found based on population and average space heating demand per person and average hot water demand per person [31]. Biomass for cooking demand is set to zero, as there is no reason for households to use biomass due to subsidised supply of fossil gas almost everywhere with a well-developed gas infrastructure. Final heat demand projections are presented in Fig. 4 divided by temperature levels and heat segments. Absolute energy demand for the heat sector is expected to grow due to the growing population and increasing industrial heat demand from 55 TWh in the year 2020 to 90 TWh in 2050. The relative share of subsectors of heat demand are not expected to change with industrial heat demand having the largest share at around 60% of total demand, followed by space heating demand representing 37%, and domestic water heating demand having the smallest share of all at only 3% of total demand.

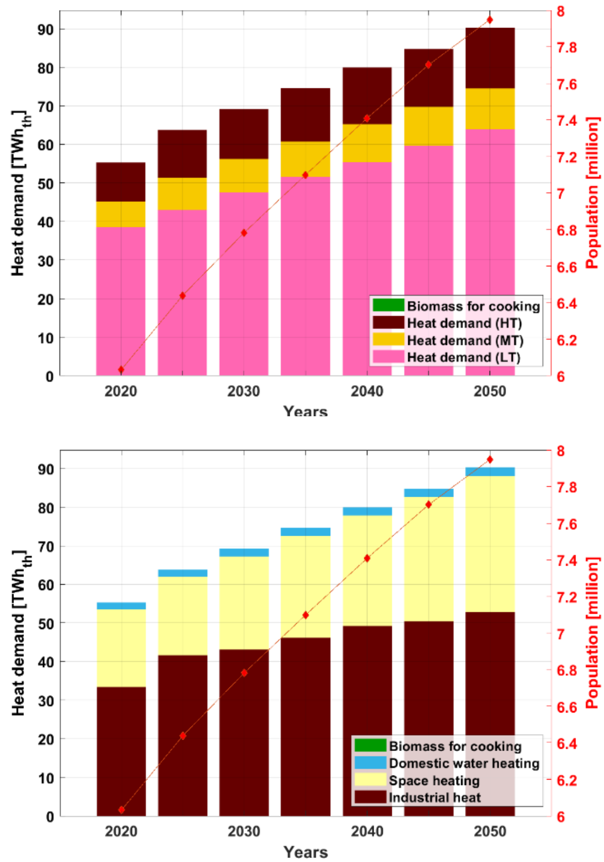

FIGURE 4. Heat demand projections by temperature levels (top) and by segment (bottom) through the transition.

Final transport passenger and freight demand are expected to grow along with the population, from 13 billion p-km and 42 billion t-km to over 22 billion p-km and 63 billion t-km by mid-century (Fig. 5). Road and rail modes make up the majority of the total demand and represent about 40% and 56% of total passenger transport demand and about 85% and 5% of total freight transport demand, respectively. Share of aviation among the different transport modes is very small at the beginning of the energy transition period, but is expected to grow in the future, both in passenger and freight transportation. Demand for marine transport is not considered in this study for Turkmenistan, as no reliable source of marine transport demand was found. The future growth trajectories of various transport segments were obtained from Khalili *et al.* [7].

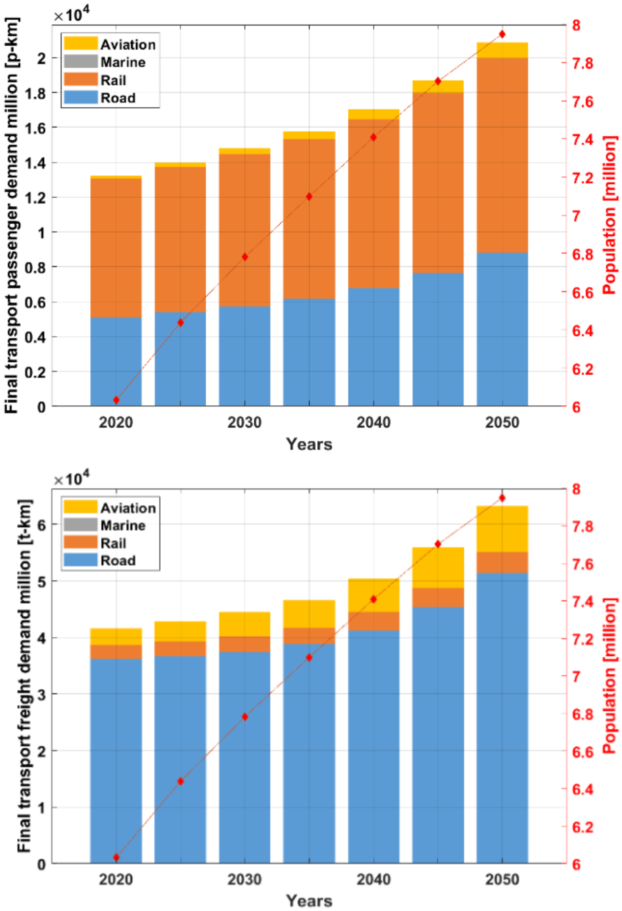

FIGURE 5. Final transport passenger (top) and freight (bottom) demand projections through the transition.

D. RENEWABLE RESOURCE POTENTIALS

The renewable resource potentials were calculated based on available area, average annual solar irradiation and real-world historical weather data. The country was subdivided into five demand centres according to administrative regions: Ahal, Balkan, Dashoguz, Lebap, Mary (Fig. 6).

FIGURE 6. Turkmenistan and administrative regions.

The solar PV resource potential was calculated based on the area of each region, assuming an alternating current capacity density of 75 MW/km^2 and 18% PV module efficiency in 2020 and linearly increasing up to 30% efficiency and a respective capacity density of 125 MW/km^2 in 2050, according to the projection in Vartiainen *et al.* [32]. Similarly, the wind turbine installation density was assumed to be 8.4 MW/km^2, which was determined by Bogdanov and Breyer [20] based on a 3 MW E-101 wind turbine. Wind turbine power ratings have been steadily increasing year-by-year and are expected to continue increasing upwards [33]. There is a strong positive correlation between nameplate power ratings and blade diameters, as manufacturers have been achieving greater power ratings thanks to bigger swept area of the rotor. However, an optimal wind turbine installation requires a distance between each turbine of about 5 to 7 times the rotor diameter, thus bigger rotor diameters require bigger distances between each turbine, thereby counteracting the power ratings gain when it comes to area density. Therefore, the aforementioned 8.4 MW/km^2 is assumed throughout the transition until 2050. The fixed tilted solar PV and onshore wind resource potential maps are displayed in Fig. 7.

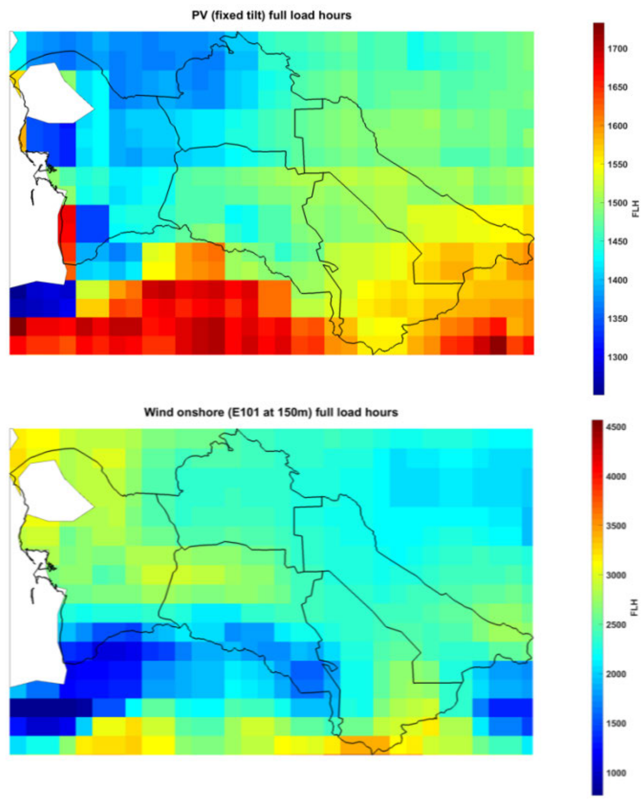

FIGURE 7. Fixed tilted solar PV (top) and onshore wind (bottom) resource potentials in Turkmenistan.

The data regarding biomass were taken from United Nations Food and Agriculture Organization [25], which in fact was statistically imputed based on data from neighbouring Central Asian states. The biomass potential consists of crop and forest residues, biowaste and municipal solid waste. The applied method is detailed in Mensah *et al.* [34].

More detailed data regarding financial and technical assumptions can be found in the Supplementary Material (Tables S1-S10).

E. ENERGY TRANSITION PATHWAYS

The consequence of heavy government subsidies is relatively very low costs of electricity and gas in the country and these numbers were used as inputs for the model. The abnormally low prices and unusual absolute reliance on gas turbines in the power sector necessitated a slightly different approach in simulation. Seven different scenarios were simulated to accommodate the transition challenges. TABLE 1 that shows the details of different scenarios studied. The different scenarios enabled deeper understanding of the possible future paths for energy transition in Turkmenistan. First, a Current Policy Scenario (CPS) was simulated with business-as-usual assumptions, with no objective to cut GHG emissions or switch to sustainable energy resources. The CPS describes the consequences of state inaction towards climate change and serves as a baseline in the discussion. Next, the CPS30 scenario was simulated assuming introduction of RE technologies in the year 2030, to imitate a scenario where the country is left with no choice but to start transitioning in the future with increasing international pressure. As the leading developed countries in the world are expected to be in later stages of their energy transition and as people around the world start experiencing extreme natural events more frequently, it is expected that the pressure will start mounting on environmentally underperforming nations such as Turkmenistan. Next, a Best Policy Scenario Standard (BPS-St) was simulated with a gradually increasing pace of RE integration: maximum 3% per year RE share in total capacity increase between 2020-2025 and 4% afterwards, until 100% RE in 2050. Similarly, BPS-3, BPS-4 and BPS-5 scenarios were simulated to better understand the effects of different RE integration rates, with 3%, 4% and 5% maximum RE share in total capacity increase per year, respectively. Finally, a Best Policy Scenario without Carbon Costs (BPSwoCC) was simulated to understand the impact of a carbon emissions pricing on the energy transition pace and costs.

TABLE 1. Energy transition scenarios applied.

Scenario	RE integration rate [%]	GHG emissions cost [€/tCO_{2eq}]	Fischer-Tropsch [yes/no]
CPS	0%	0	No
CPS30	2020-2030: 0% 2030-2050: 4%	2020-2030: 0 2035: 68 2040: 75 2045: 100 2050: 150	Yes, after 2030
BPS-St	2020-2025: 3% 2025-2050: 4%	2020: 28 2025: 52 2030: 61 2035: 68 2040: 75 2045: 100 2050: 150	Yes
BPS-3	3%		Yes
BPS-4	4%		Yes
BPS-5	5%		Yes
BPSwoCC	4%	0	Yes

III. RESULTS

All seven scenarios were modelled based on the Turkmenistan specific input data for the period from 2020 to 2050 using the LUT Energy System Transition Model in full hourly resolution. The model outputs, the energy system structure and hourly operation profiles for all technologies were postprocessed to calculate additional metrics of the system performance such as system cost, levelised cost of electricity, total primary energy supply (TPES), electrification rate, etc. A methodological flow chart is presented in Fig. 8.

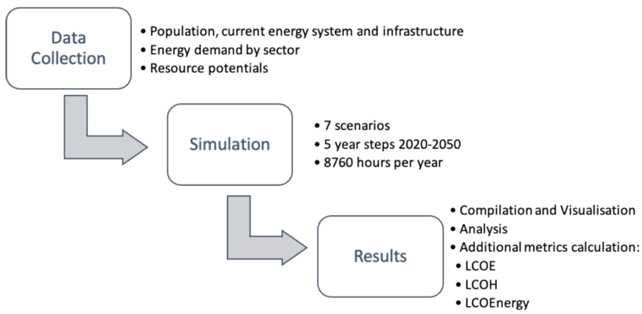

FIGURE 8. Methodological flow chart.

The results of all scenarios are presented in a concise manner as follows: overview of the scenarios are presented and general trends are noted in section A, section B presents how electricity generation and storage across all sectors develop throughout the transition; it is followed by energy supply for power, heat and transport sectors in section C, and finally, annualised energy system costs and GHG emissions are presented in section D.

A. GENERAL TRENDS IN THE APPLIED SCENARIOS

Among the seven scenarios, the BPS-5, that had the most rapid rate of renewable energy integration, enables the least levelised cost of energy, fastest reduction of GHG emissions and thus the least cumulative GHG emissions in 2050. The BPS-5 reaches the second lowest cumulative pathway cost. Only the BPSwoCC is lower in cost, as cost for GHG emissions are not considered. Henceforth, the BPS-5 scenario shall be used as the benchmark.

Final energy demand goes through a phase of lower demand mid-transition and grows again to the initial level in 2050. Fig. 9 (top) demonstrates that final energy demand falls to 133 TWh in 2035 thanks to efficiency gains related to reduction in fuel consumption in the transport sector due to fast efficiency gains in road transport and grows again to 148 TWh in 2050. The electricity consumption per capita grows from slightly less than 4 MWh up to 5.4 MWh (Fig. 9, bottom). Primary energy demand per capita can be found in the Supplementary Material (Fig. S37).

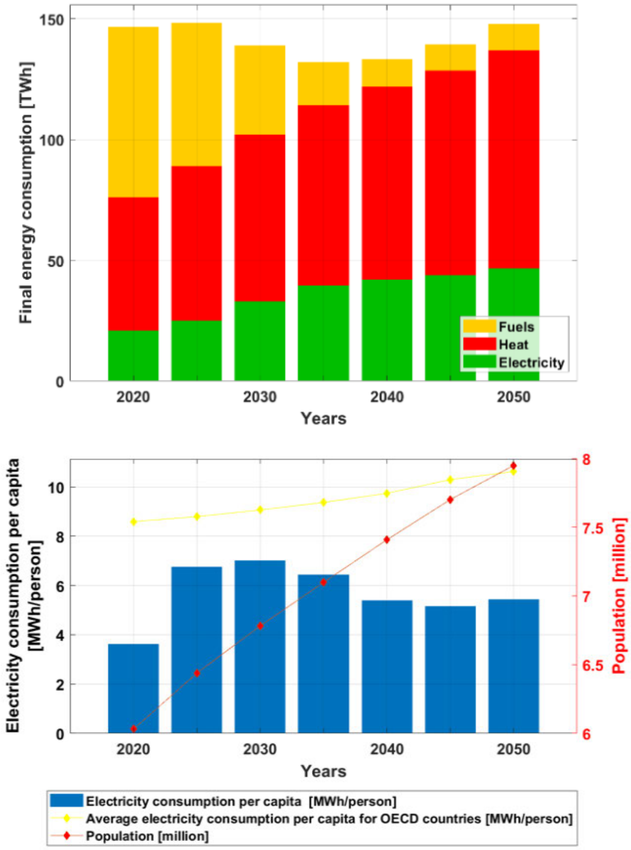

FIGURE 9. Final energy demand (top) and electricity consumption per capita with population (bottom) through the transition in the BPS-5.

The final energy demand and electricity per capita growth is limited as Turkmenistan already has achieved high electricity penetration and has subsidised access to fuels for heating and transportation. Thus, the final energy demand only slightly increases with rising population.

Fig. 10 shows the energy flow in Turkmenistan's 2050 energy system in the BPS-5. The energy system becomes much more complex with intensive sector coupling. Majority of primary energy is used in the form of electricity, mostly from solar PV and wind. Heat demand is mostly satisfied by environmental heat via heat pumps. Transport sector final energy demand is much lower in contrast to the year 2020 (Fig. 1) and it is mostly satisfied by electricity and some synthetic fuels. Losses mostly consist of heat losses in fuel conversion units producing hydrogen and synthetic fuels, and some curtailment in the power sector. The losses and curtailment are recoverable, and they may be further reduced with industry integration and international power exchange. Curtailment during the transition and ratio of curtailment to generated electricity can be found in the Supplementary Material (Fig. S13).

Due to high electrification of the entire energy system and subsequent energy efficiency gains (Fig. 11), primary energy demand is projected to decrease in almost all scenarios, except for the CPS, for which fossil fuel use and its overall low efficiency level is continued without changes (Fig. 12). The composition of primary energy supply shifts from fossil gas, oil and coal today to RE sources in 2050 in the BPS-5. RE sources, such as solar PV and wind, supply electricity as primary energy at the first point of extraction from nature and thus electrify the primary energy supply. Direct electricity supply from renewables removes one major point of losses where usually fossil fuels are converted to electricity in thermal power plants with efficiencies less than 40%. This electrification happens uniformly in all BPS variations, except the BPSwoCC where the rate dwindles down in later years because there are no incentives to fully get rid of fossil fuels in this scenario. The CPS continues relying on fossil fuels thus the electrification does not happen in primary energy supply, whereas CPS30 starts electrifying as soon as it is allowed to install renewables in 2030.

High electrification also takes place in the heat and transport sectors, as electric heat pumps and electric resistance heaters become major heat generation technologies and BEVs replace ICE cars. The electric counterparts offer efficiency gains of several factors. The electric resistance heaters convert all consumed electric energy into heat, therefore offering 100% efficiency. Heat pumps allow to utilise the "free" ambient heat of the environment, providing 3.2 kWh and 4.5 kWh of heat for each kWh of electricity for district heating and individual heating heat pumps, thus effectively offering a coefficient of performance of 3.2 and 4.5, respectively. Similarly, electric drives convert almost all electric current into kinetic motion, with some losses related to electricity inversion, storage and friction, in practice offering >80% efficiency [35]. In addition, renewable sources of electricity, such as solar PV and wind, enable a much more direct extraction of energy from nature and for the highest possible exergy level, as electricity is generated directly, thus eliminating many conversion losses, compared to relatively inefficient fossil fuel fired thermal power and heat plants. Accordingly, primary energy demand falls sharply in all scenarios mid-transition in 2040, except CPS and CPS30. Though primary energy demand grows later in 2050, due to overall growth of final energy demand, it still remains below the primary energy demand as of today and CPS in 2050. Fig. 11 (bottom) demonstrates the reduction in primary energy demand due to the high electrification rate in the BPS-5; the solid bars show the potential gains in efficiency relative to the business-as-usual path (dashed). The primary energy demand breakdown by fuel and sector can be found in the Supplementary Material (Fig. S36 and Table S17).

The BPSwoCC demonstrates the least primary energy demand in 2050. The absence of carbon pricing in this scenario removes the pressure to switch away from fossil fuels, therefore the transport sector, that is harder to electrify (aviation), continues relying on fossil kerosene and marine fuel, instead of switching to RE-based Power-to-X fuels [36], [37].

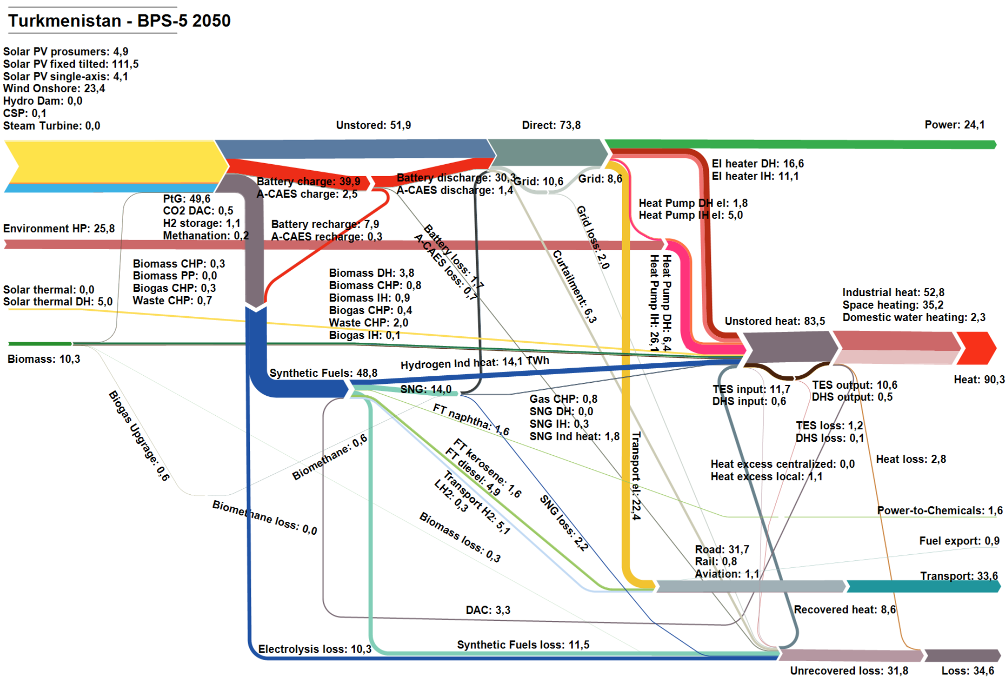

FIGURE 10. Energy system of Turkmenistan in 2050 in the BPS-5. All units are in TWh.

B. ELECTRICITY GENERATION AND ENERGY STORAGE

While solar PV and wind power provide over 90% of electricity in 2050 in all BPS variations (Fig. 13), except BPSwoCC, gas turbines continue playing a vital role in the energy system of Turkmenistan and are run with RE-based synthetic natural gas (SNG) with zero net GHG emissions, as the CO_2 is provided by direct air capture units [38]. In the BPS-5, electricity from gas turbines solely comes from combined-cycle gas turbines (CCGT) at about 640 full load hours (FLH) in 2050, while the fuel used is RE-based. Notably, in the BPSwoCC gas turbines still constitute an even higher share of about 20% of electricity generation capacity mainly CCGT at 730 FLH and some open-cycle gas turbines (OCGT) at very low FLH in 2050, because there is less economic pressure to cut GHG emission in this scenario. The CPS30 follows the CPS until the year 2030, but swiftly installs RE capacities and majority of electricity comes from solar PV and wind sources by 2050, cutting GHG emissions and reducing levelised cost of electricity (LCOE).

Wind electricity generation dominates RE generation in the beginning of the transition, providing over 80% of renewable electricity in 2030. However, solar PV overtakes all other forms of electricity generation and becomes the major electricity supply source by 2040 in all scenarios except the CPS, thanks to ever declining costs and improving efficiencies, as described in Vartiainen *et al.* [32]. Solar PV provides over 75% of electricity in all BPS variations and almost 60% in the BPSwoCC in 2050. Over 47% of electricity comes from solar PV in the CPS30, overtaking all other forms of electricity generation in mere 20 years.

Unsurprisingly, bioenergy plays a miniscule role in electricity generation among all scenarios through the transition, owing to the fact that there is little biomass available in Turkmenistan.

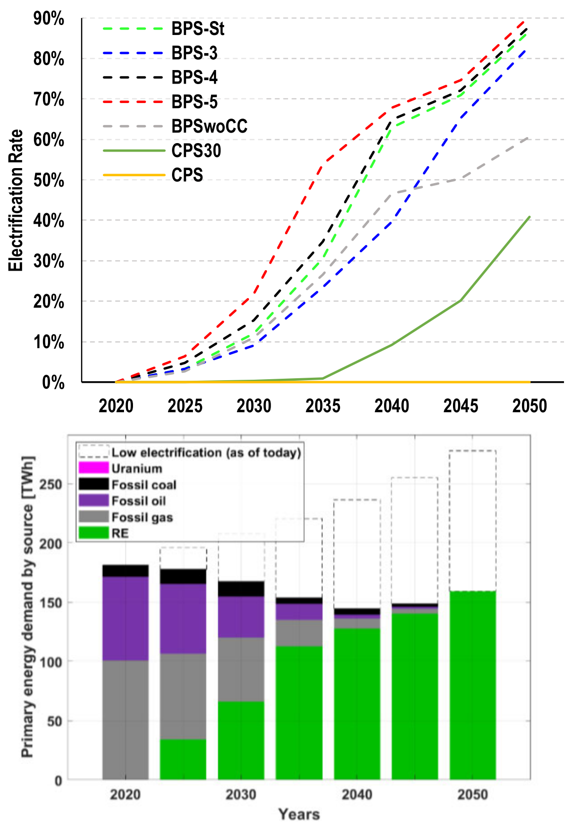

FIGURE 11. Electrification rate among all scenarios (top) and efficiency gains in primary energy demand in the BPS-5 (bottom) through the transition. Electrification rate is defined as the share of electricity in total primary energy demand.

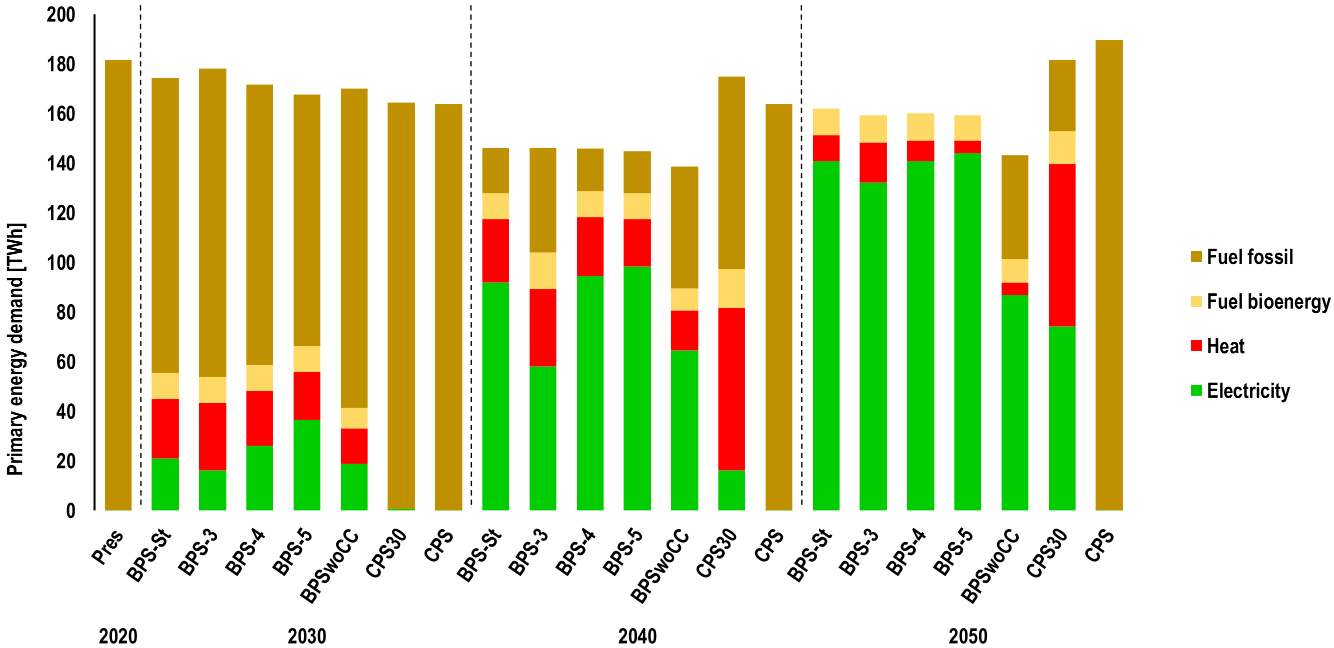

FIGURE 12. Primary energy demand among all scenarios through the transition.

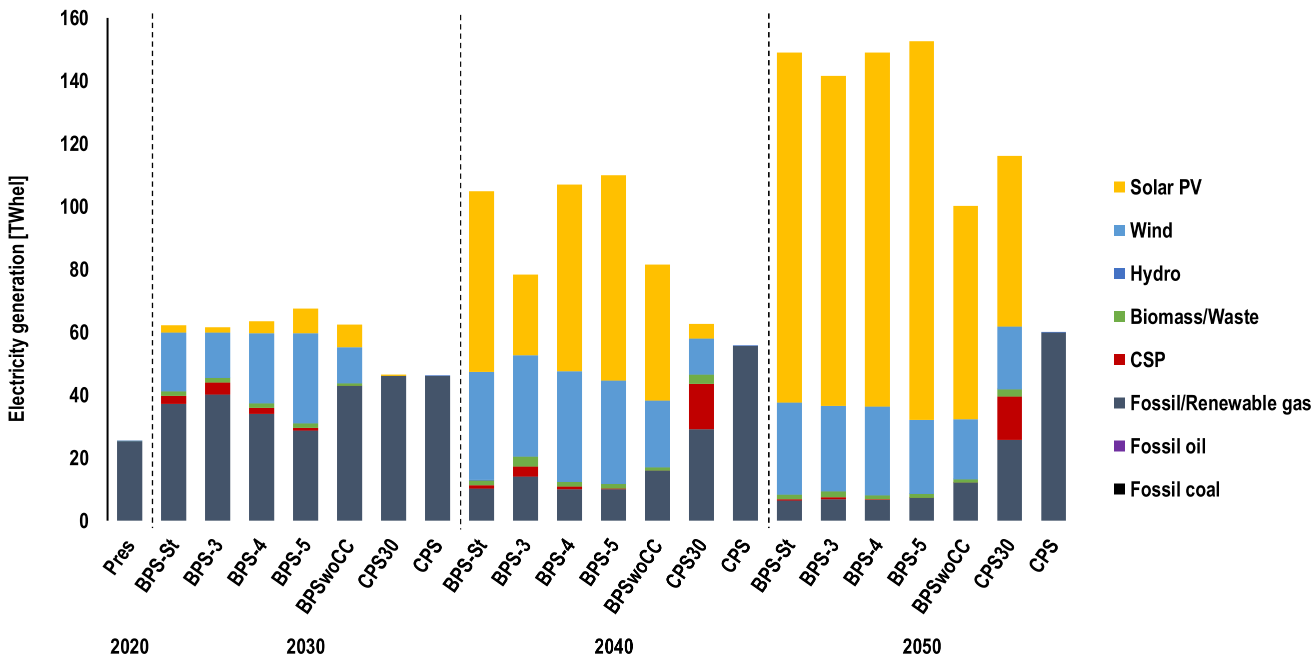

FIGURE 13. Electricity generation among all scenarios through the transition.

Hydropower electricity generation is nearly absent in all scenarios. No new hydroelectric power plant installations are planned in Turkmenistan owing to the limited resource availability. Only one currently existing 1.2 MW hydropower plant is operating in all scenarios. Hydro resource availability is infinitesimal next to solar and wind resources in Turkmenistan.

Breakdown of electricity generation over the transition by sector can be found in the Supplementary Material (Fig. S11).

The transition away from dispatchable thermal power plants necessitates utilisation of flexibility options which can be provided by sector coupling, in particular by electrolysers, but also by installing energy storage technologies. Considering that no geothermal, hydropower, or almost no bioenergy is present in any of the scenarios, and as the energy system is mainly based on variable wind and solar PV, adequate storage technologies and capacities are very important, next to other flexibility options, as detailed in [39], to be able to sustain stable and secure electricity supply especially in times when neither of the main energy sources are available. One way to secure a stable supply of electricity is open cycle gas turbines that stay in the system from the pre-transition period. Their advantage is that open cycle gas turbines with short start-up time provide flexibility in ensuring electricity supply for peak-demand and the used fuel can be fully switched from fossil gas to biomethane and SNG. Storage technologies such as utility-scale batteries are necessary in order to store the direct electricity of solar PV and wind turbines. Learning rates are high and so the costs are declining rapidly [32]. Thus, utility-scale batteries become the dominant energy storage option in terms of throughput in almost all scenarios, except the CPS30 and CPS. While capacity-wise gas storage stands out as the largest energy storage capacity (Fig. 14, top), batteries cover diurnal energy needs, going through full cycles every day, thus making up the majority of storage throughput (Fig. 14, bottom).

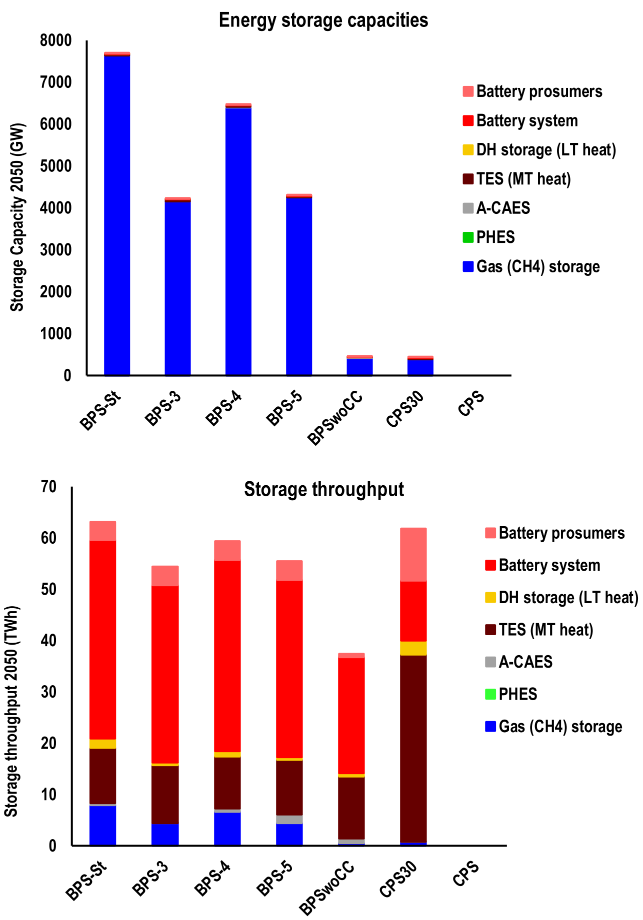

FIGURE 14. Energy storage capacities (top) and storage throughput (bottom) in 2050 among all scenarios.

Gas storage ensures energy availability for seasonal and heating needs. It is important to notice that gas storage here does not refer to underground reservoirs for fossil gas, but storage for synthetic natural gas. In order to cut net GHG emissions, it is important to phase out fossil gas usage in power and heat sectors and use electricity-based Power-to-X methane to power gas turbines, next to biomethane.

Fig. 15 (top) demonstrates the state-of-charge pattern for gas storage in Turkmenistan throughout a year in the BPS-5 in 2050. As can be seen, gas storage starts being discharged in the winter months when there is less sunshine available for solar PV electricity generation, and it starts being charged in mid-spring as more and more sunshine is available to power water electrolysis and methanation plants to produce SNG for charging the storage.

In contrast, battery storage demonstrates a daily charging and discharging profile (Fig. 15, bottom). Charging periods are during the sunshine hours and discharging starts in the later afternoon hours.

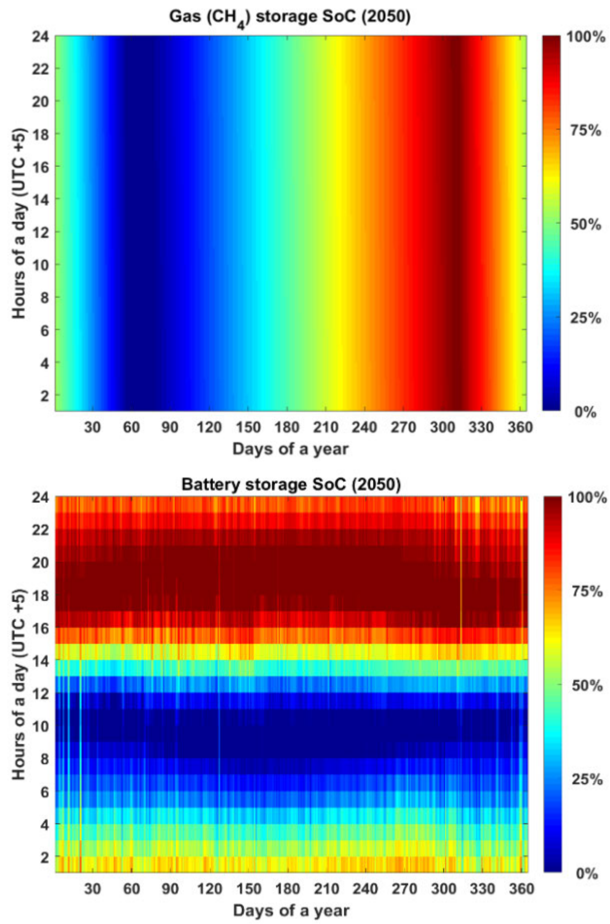

FIGURE 15. Gas (top) and battery (bottom) storage annual state-of-charge patterns in the BPS-5 in 2050.

In addition to electricity storage, heat storage technologies will also play a significant role in the energy system to match heat supply and demand in an optimised way (Fig. 16). Thermal energy storage covers about 15% of heat demand at 11 TWh of the total 75 TWh in the BPS-5 in 2050. Heat generation and storage stands out in the CPS30 due to the fact that the CPS30 heavily leans on concentrated solar power (CSP) installations, therefore heat contributes more to

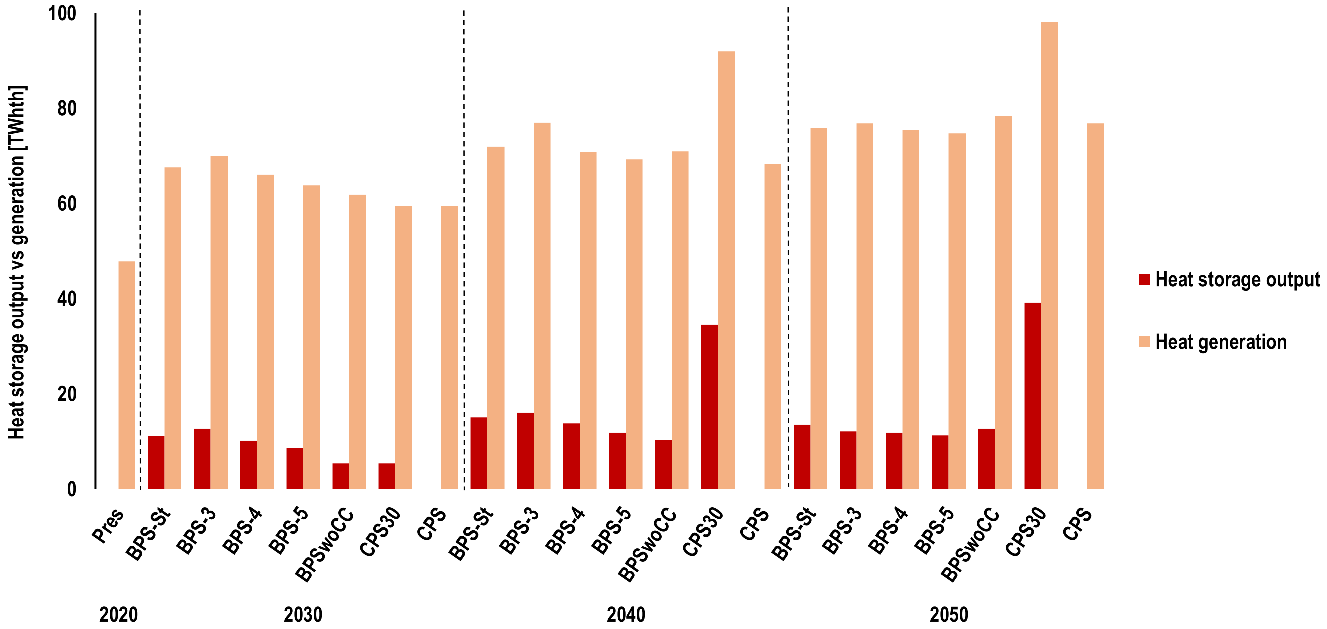

FIGURE 16. Heat storage output vs. heat generation among all scenarios through the transition.

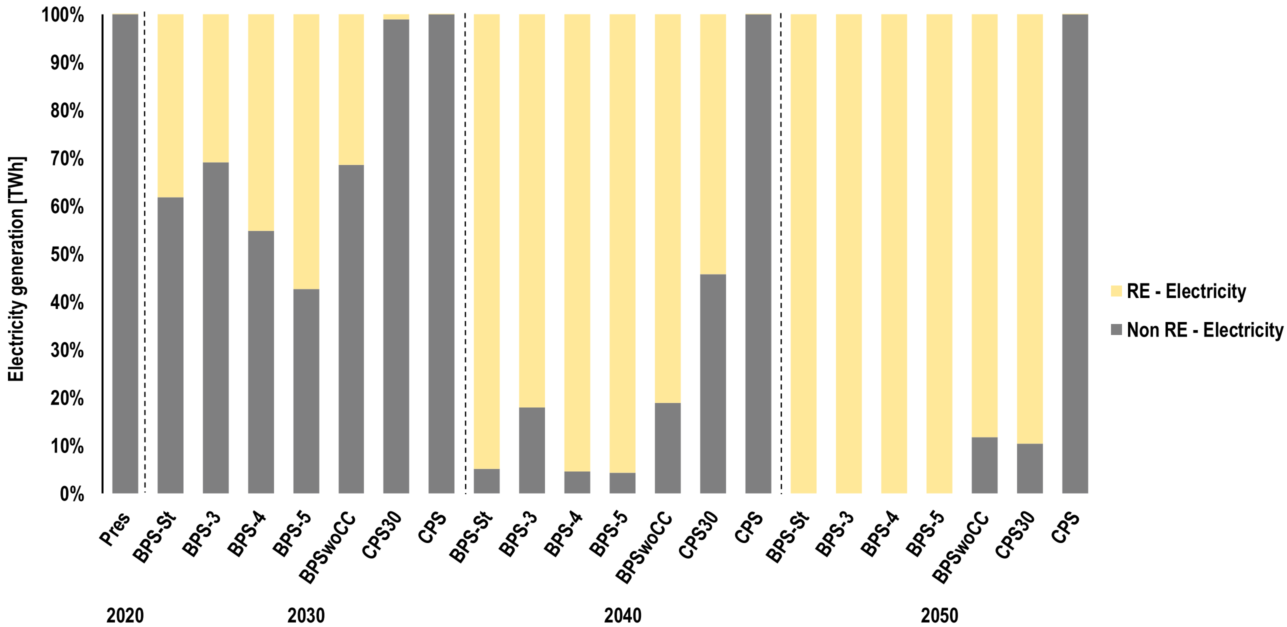

FIGURE 17. Electricity generation among all scenarios through the transition.

primary energy supply (Fig. 12). The high CSP share in the CPS30 is related to the high LCOE (Fig. 23), which blocks Power-to-Heat routes. Subsequently, more heat storage is utilised in the CPS30 compared to other scenarios.

C. ENERGY SUPPLY FOR POWER, HEAT AND TRANSPORT

Primary energy demand decreases due to high electrification in all scenarios, excluding the CPS. High electrification is simply inevitable as electric appliances and technologies offer much higher efficiencies compared to their non-electric counterparts. As can be seen in Fig. 17, it is possible to reach 100% renewable electricity generation if right incentives and mechanisms are set in place, as in the BPS variations.

In the BPS variations the power sector undergoes a radical transformation from fossil fuel thermal power plants to renewable energy and inverter-based technologies. As can be seen in Fig. 18, the majority of newly installed RE capacities consist of wind power at 3.5 GW in 2025 and 7 GW in 2030 in the BPS-5, whereas utility-scale solar PV takes off from 2035 onwards as the least cost option, totalling 79 GW in 2050 in the BPS-5. Subsequently, almost all electricity is supplied by solar PV and wind power in the BPS-5 in 2050.

The installation of CAPEX dominated RE technologies and diminishing use of fossil fuels has a strong impact on the LCOE structure, as discussed in section 3.4.

Wind power consists of onshore wind, as offshore territories of Turkmenistan were not considered in this study. Moreover, the best sites for wind power are found in the north-western region of Turkmenistan, with consistent winds above 6 m/s [11], [16].

Among solar PV technologies, fixed-tilted PV power plants at an optimal tilt angle constitute the majority of installations, compared to single-axis tracking and rooftop PV (Fig. 18). Though on average single-axis tracking PV systems are economically better performing globally [40], fixed-tilted PV is able to deliver electricity in Turkmenistan at lower cost in the energy system.

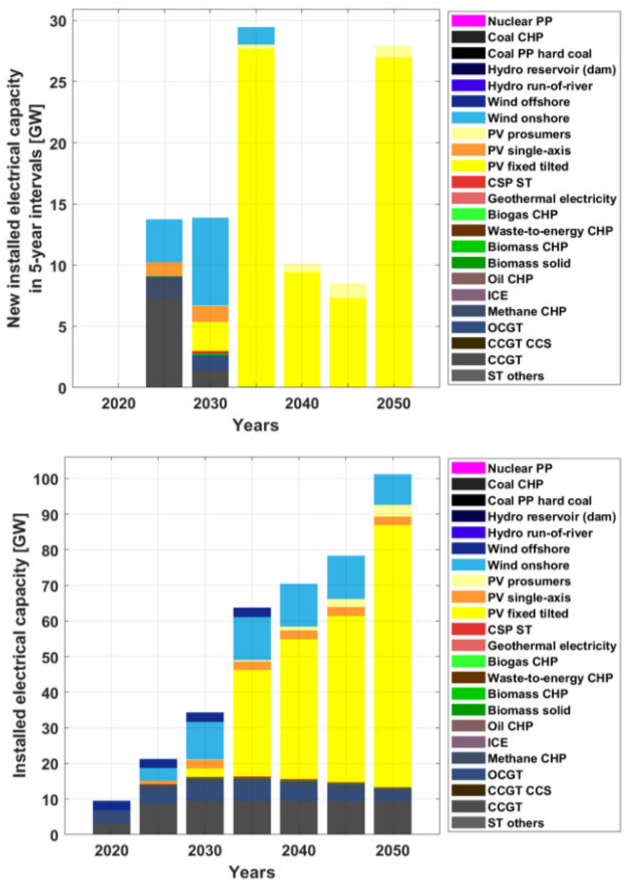

FIGURE 18. New installations (top) and cumulative (bottom) electricity generation capacities in 5-year intervals in the BPS-5 through the transition.

The heat supply mix is expected to change significantly from today's fossil gas-powered boilers to mostly electric, solar thermal and biomass heaters in 2050 in all scenarios, except the CPS (Fig. 19). This supply mix helps to cut GHG emissions in the heat sector [41]. Electric heating includes electric resistance heaters and heat pumps. Electrification is inevitable, as the electric counterparts offer much higher efficiencies. Solar thermal heat supply includes solar thermal collectors and concentrated solar thermal plants. The CPS30, in contrast to other scenarios, relies strongly on solar thermal heat generation, which coincides with substantially higher LCOE. CPS30 has similar technical and financial assumptions as in the BPS variations, however, due to the delayed RE technologies introduction in 2030, the LCOE suffers from early high-cost investments, blocking more use of direct electric heat supply options. Still solar thermal is a very good zero GHG emissions replacement to fossil gas heat boilers that takes advantage of high direct solar irradiance availability in Turkmenistan.

Final heat energy demand breakdown by fuel can be found in the Supplementary Material (Fig. S25 and Table S14).

With high electrification, final energy demand for transport sector is expected to fall significantly in all scenarios, from 74 TWh today to slightly more than 30 TWh in 2050 (Fig. 20). Highly efficient electric vehicles will cover the land mobility needs of future Turkmens while simultaneously cutting GHG emissions [41]. Final transport energy demand breakdown by fuel can be found in the Supplementary Material (Fig. S26 and Table S15).

Aviation energy demand will be covered by sustainably sourced hydrogen and Fischer-Tropsch fuels (Fig. 22). Weight sensitive aircrafts rely on fuels with high energy density, where lithium-ion batteries with relatively low energy density of the fuel, i.e., stored electricity, are not optimal. Power-to-Fuels technologies, such as water electrolysis and the Fischer-Tropsch process [36] allow to move from fossil to sustainable fuels in the transport sector and cut GHG emissions. Newly installed fuel conversion technologies, mainly water electrolysis, CO_2 direct air capture and Fischer-Tropsch units (Fig. 21) will enable to produce 7 TWh of electricity-based kerosene-type jet fuel and diesel (Fig. 22). However, the fuel conversion technologies will increase the cost of fuel for the aviation sector and it is reflected in final transportation costs, shown in the next section. A more detailed breakdown of final energy demand of the transport sector can be found in the Supplementary Material (Fig. S1-S5).

Notably, the BPSwoCC continues relying on some amount of fossil fuels for transportation. Switching to Power-to-X fuels would not be the best economic option in this artificial scenario, where there are no societal costs of emitting CO_2. More importantly, even this scenario switches the majority of transportation to electricity as it is economically disadvantageous to continue relying on traditional internal combustion engines [41].

D. ANNUALISED ENERGY SYSTEM COSTS AND GHG EMISSIONS

All scenarios that introduce renewable energy into the energy mix demonstrate lower LCOE (Fig. 23, top) and lower total annualised cost (Fig. 23, bottom), thanks to ever falling costs of RE technologies and practically infinite supply of solar irradiation and wind. The BPS-5 with the highest share of renewables can reach LCOE of less than 45 €/MWh in 2050. Solar PV technology, the main energy supply source in the BPS variations, has demonstrated a steady decline in cost

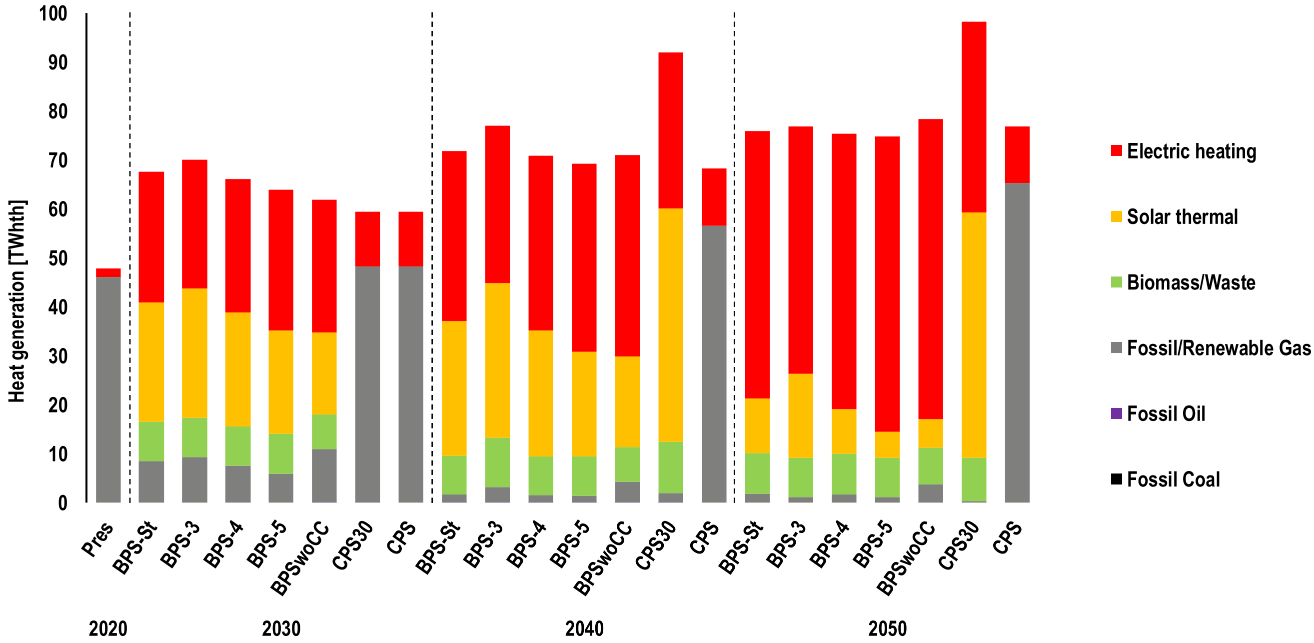

FIGURE 19. Heat generation among all scenarios through the transition.

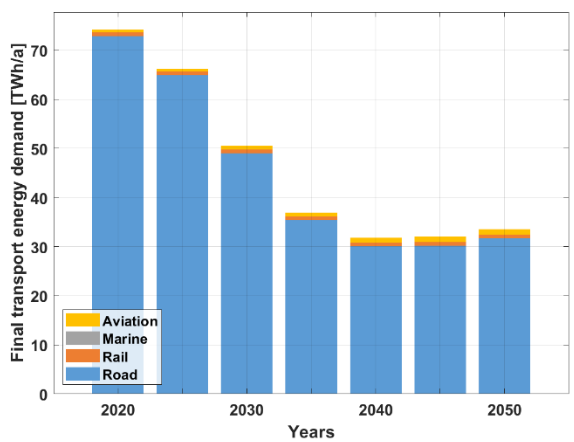

FIGURE 20. Final energy demand for transport through the transition.

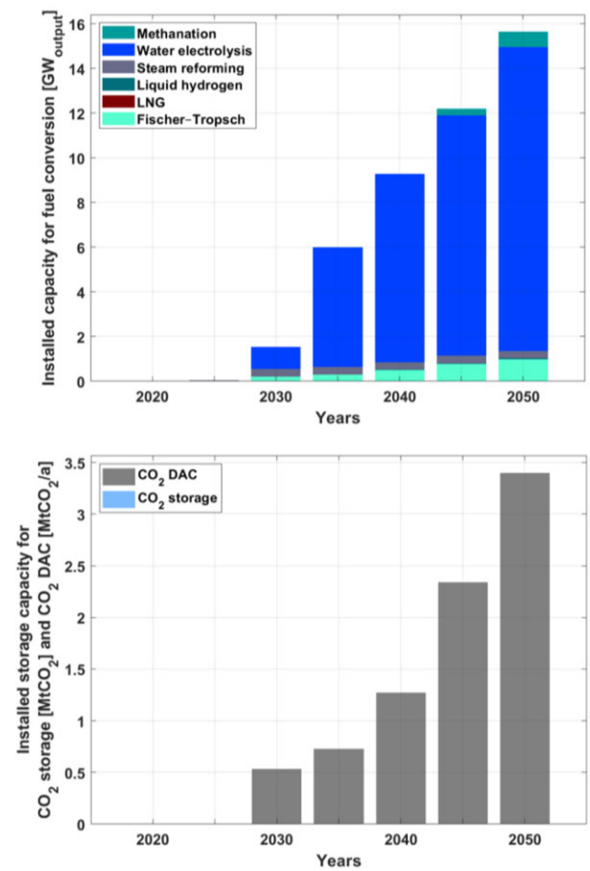

FIGURE 21. Installed capacities for fuel conversion technologies (top) and CO_2 direct air capture and CO_2 storage (bottom) in the BPS-5 through the transition.

over the last few decades and is already more cost-effective in comparison to fossil fuel generation sources today and it will certainly continue to decline in cost even further [32], [42]. Wind power converting technologies have also demonstrated a steady decline in electricity generation costs. The trends in the wind turbine industry will enable further cost reduction per unit of energy, due to larger blade diameters, higher hub heights, more efficient power electronics and better wind forecasting systems [33]. The main takeaway among the scenarios in this study is that RE-based energy system reduces the LCOE and annualised system costs relative to the CPS regardless of the rate of integration of RE technologies.

The BPS variations result in lower cumulative costs by 2050 than the CPS (Fig. 24). The BPSwoCC has even lower annualised cost but that is due to the fact that it artificially does not include CO_2 costs. It leads to least cumulative pathway costs but that could only be thinkable if there were no impacts from GHG emissions.

A more detailed breakdown of transition costs can be found in the Supplementary Material in Tables S11-S12 and Fig. S6-S10, S15 for the power sector, Table S13 and

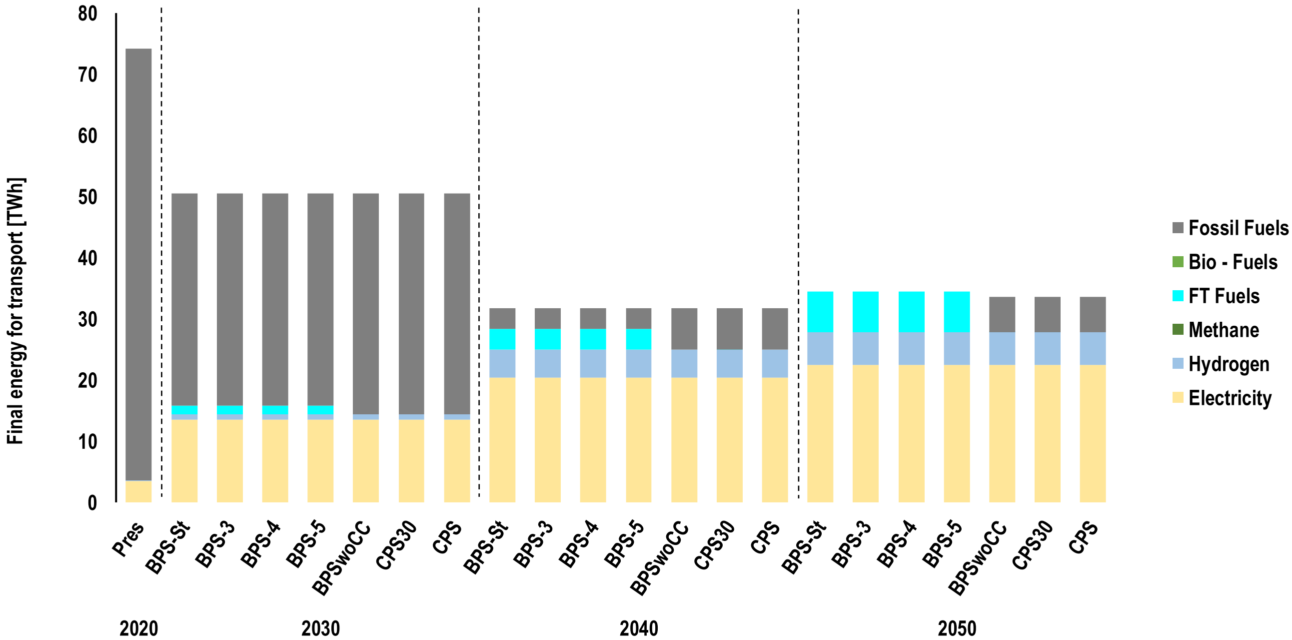

FIGURE 22. Final energy demand for the transport sector by sources among all scenarios through the transition.

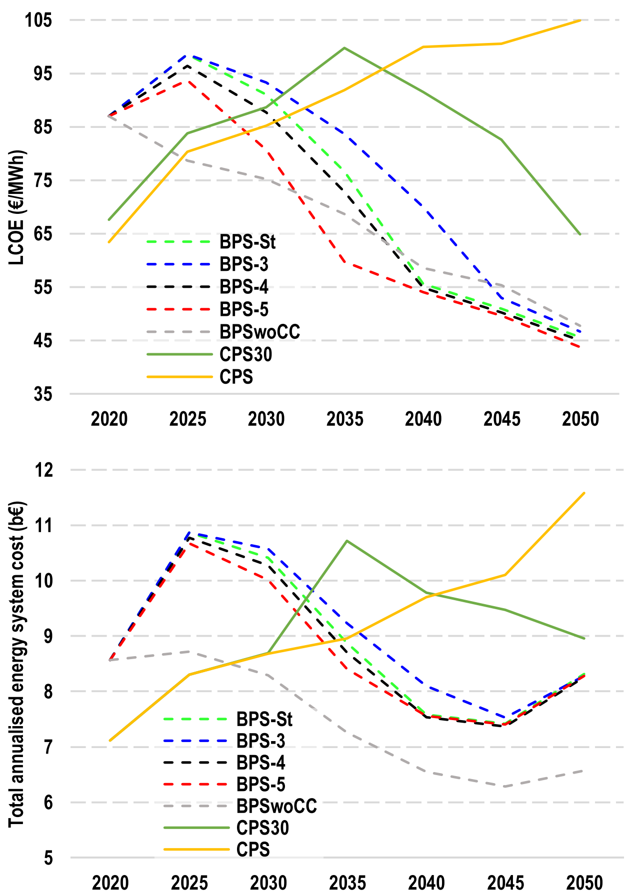

FIGURE 23. Levelised cost of electricity (top) and total annualised energy system cost (bottom) among all scenarios through the transition.

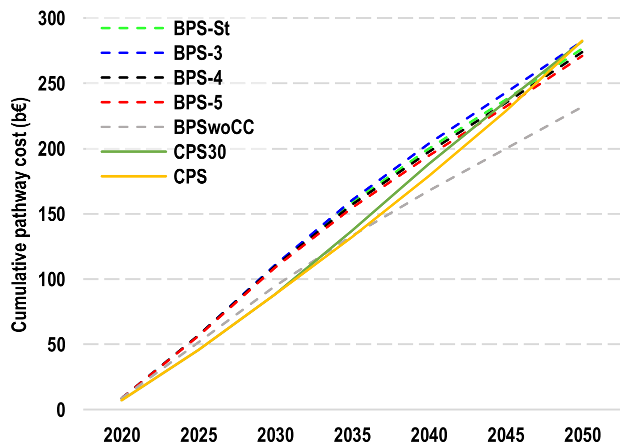

FIGURE 24. Cumulative pathway costs among all scenarios through the transition.

Fig. S17-S19, S21, S22, S24 for the heat sector, Fig. S27-S32 for the transport sector and Fig. S38 for total annual system cost.

The composition of the levelised cost of energy is expected to move from fuel and GHG emissions cost dominance today and become dominated by capital and operational expenditures by 2050 (Fig. 25, top). Though a 100% RE system allows to decrease the overall cost per unit of energy, from over 58 €/MWh to 56 €/MWh, the renewable energy and storage technologies require higher capital investments per MWh compared to the fossil fuel powered counterparts (Fig. 25, bottom). Capital investments in the order of more than 10 b€will be required in the upcoming decades to upgrade the fossil fuel-based energy system to a RE-based system. As can be seen in Fig. 25 (bottom), the investments are not only in power generation technologies, such as wind and solar PV, but also in heat generation, energy storage and fuel conversion technologies. The increase in fixed operational expenditure entails more local jobs in operations and maintenance that are required to keep the energy system up and running, resulting in another indirect benefit of switching to a 100% RE-based system [43].

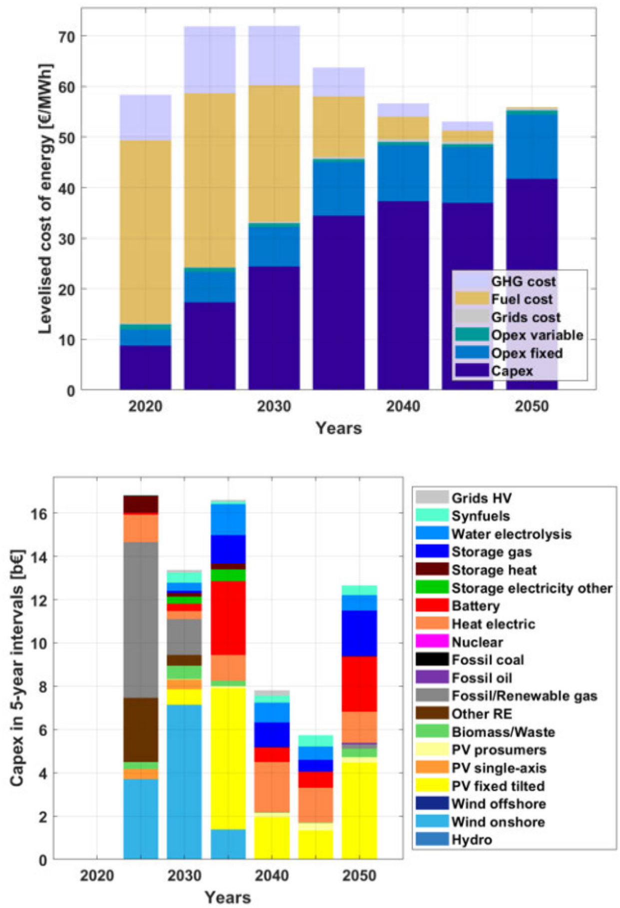

FIGURE 25. **Levelised cost of energy (top) and capital expenditures in 5-year intervals (bottom) in the BPS-5 through the transition.**

The decrease in final energy demand in the transport sector helps to decrease the final transport energy cost as well, from 3.8 b€today to 2.3 b€in 2050 (Fig. 26).

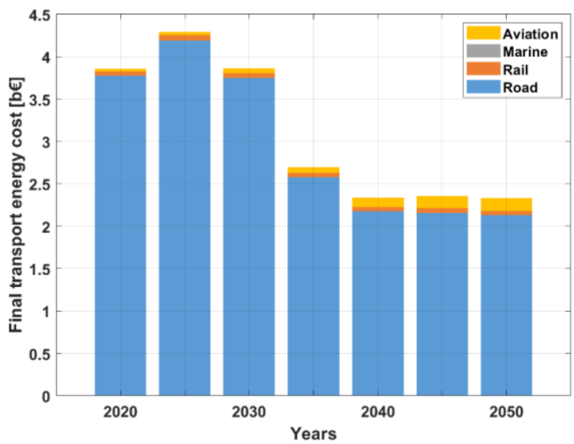

FIGURE 26. **Final transport energy cost in the BPS-5 through the transition.**

Moreover, thanks to high electrification, the cost of transport per kilometre is also expected to drop (Fig. 27, bottom). While the cost of road transport per kilometre drops by over 50%, both in passenger and freight transport, the aviation cost per kilometre slightly rises, because the switch to Power-to-X fuels is expected to increase the cost of fuel for aviation.

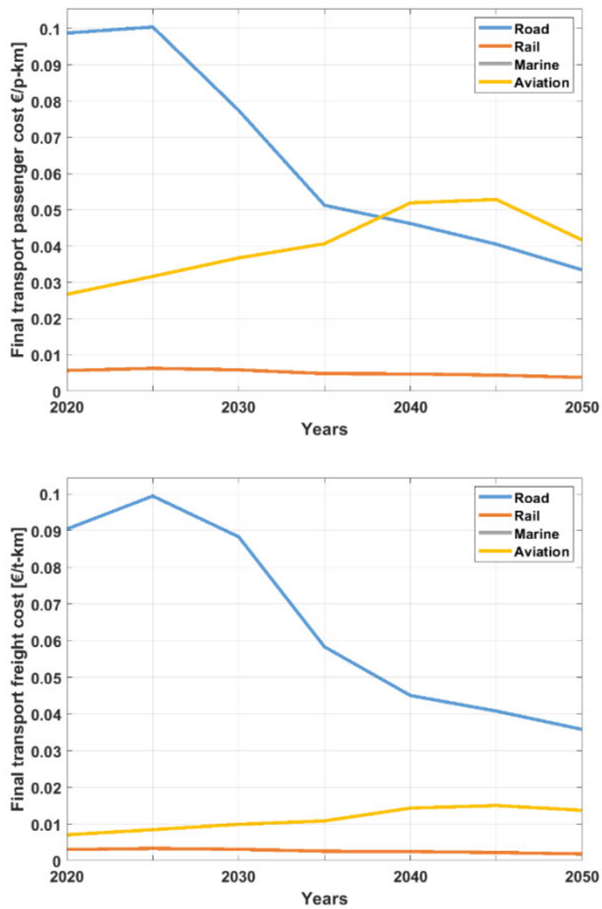

FIGURE 27. **Final transport passenger (top) and freight (bottom) kilometer costs in the BPS-5 through the transition.**

The CPS results in over 47 $MtCO_{2eq}$ annual emissions (Fig. 28, top) and leads to over 1300 $MtCO_{2eq}$ cumulative emissions by 2050 (Fig. 28, bottom). While short-term emissions may fall thanks to high electrification and efficiency improvements in combined cycle gas turbines, such as the recently installed Mary-3 combined cycle power plant, long-term emissions will remain at unsustainable levels. The introduction of low to zero GHG emitting RE technologies will help to significantly cut GHG emissions as seen in all other scenarios. The CO_2 emissions related to solar PV and wind power converting technologies only occur during their manufacturing phase [44]. Without a fundamental breakthrough in energy storage technologies, the aviation transport mode is expected to continue relying primarily on jet fuel. However, Power-to-X technologies, such as the well understood Fischer-Tropsch process developed in the beginning of 20th century, allows to cut the GHG emissions of the transport sector to zero. It is worth noting the GHG emissions in the CPS30 compared to the BPSwoCC in 2050: the CPS30 is capable of reaching lower annual GHG emissions in 2050 even though it only starts introducing RE technologies a decade later than the BPSwoCC. BPSwoCC fails to cut

GHG emissions down to zero as there is no economic pressure to do so and for this reason it is important to include societal costs of emitting GHG to fully get rid of them.

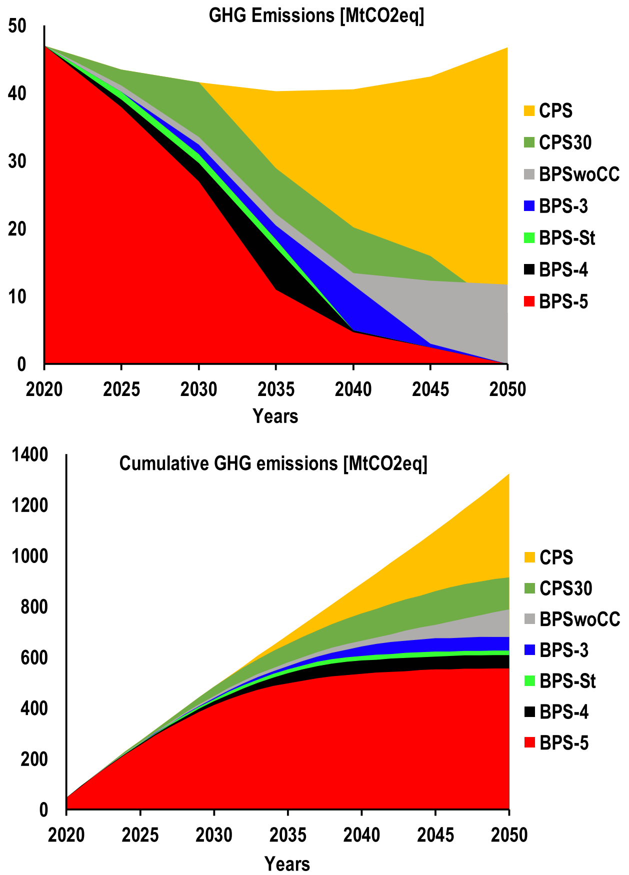

FIGURE 28. **Annual (top) and cumulative (bottom) GHG emissions among all scenarios through the transition.**

A more detailed breakdown of GHG emissions can be found in the Supplementary Material in Fig. S14-S15 for the power sector, Fig. S23-S24 for the heat sector, Fig. S33 for the transport sector and Fig. S39 and Table S18 for total GHG emissions.

IV. DISCUSSION

A. OVERALL FINDINGS

This study with various transition pathways demonstrates that a 100% RE system in Turkmenistan is economically viable and technically feasible. Seven scenarios demonstrate the effects of different rates of RE integration into the energy system and can help policymakers, potential investors, and other stakeholders in Turkmenistan to shape the future development in the country. All scenarios, except the CPS, demonstrate that it is possible to quickly switch to renewable sources of energy in Turkmenistan in a cost-effective way. The CPS confirms this fundamental finding, since it is the least efficient and highest cost option among all scenarios and the CPS30 demonstrates the positive effects of these two key system metrics, if the energy system receives more freedom from the year 2030 onwards to switch to a RE dominated system. Turkmenistan, awash with solar irradiation year-round and with its desert plains with strong winds, is one of the best regions for solar PV systems and wind power, with FLH of up to 1710 and 2733 for solar PV and wind energy, leading to LCOE of 80.6 €/MWh in 2030 and 44 €/MWh in 2050, respectively.

Growing population along with a growing economy, increasing standards of living and access to low-cost energy is projected to result in both relative and absolute growth in final energy demand in all scenarios. Continual reliance on fossil fuels as primary energy supply will result in growth of fossil fuel consumption and ever increasing GHG emissions and associated costs. As demonstrated in the BPS and CPS30 scenarios, switching to RE resources helps to cut primary energy demand and minimise GHG emissions. Thus, transitioning towards 100% RE systems is a key element to reach the Clean Energy target of the United Nations Sustainable Development Goals, however an accelerated RE introduction can be an integral element of policies needed to reach other Sustainable Development Goals as discussed for cases of Indonesia [45] or Indian states [46].

In this study, BPS variations and the CPS30 demonstrate that the introduction of RE not only helps to cut GHG emissions but also it is economically advantageous to switch to renewable sources of energy. The BPS-5 scenario with a 5% rate of increasing the capacity share of annual RE integration not only enables the lowest LCOE but also the least total annualised costs, in addition to quickly cutting GHG emissions down to zero. However, it needs to be noted that such a high RE phase-in has not been observed yet anywhere in the world, as more than 3% of annual capacity share growth of RE is hardly found [47]. One of the fastest RE ramps in generation ever recorded has been Uruguay with generation increase from 60% to 98% renewables within eight years, which reveals a phase-in rate of 4.75% for the increase of annual generation shares.

PV will play the most significant role in the energy transition of Turkmenistan, representing up to 74-79% of all electricity generation in 2050 in the BPS variations. The energy demand and supply balance is found for each hour in this variable RE based system, mainly via using battery storage and flexible energy supply for PtX. This shows that 100% RE systems can also be built in countries with good solar resources, but weak to moderate wind potentials as India, Indonesia and other Sun Belt countries. Several of these countries are currently major fossil fuels exporters, and local energy systems of many of them are also mostly based on fossil fuels. However, the results of the modelling show, that if local fossil fuels subsidies are not taken into account and fuels prices are on open market levels, then RE cost outrivals the cost of traditional fossil fuels based generation.

This study also demonstrates the effects of different RE integration rates into an energy system that relies solely on fossil gas power generation. The common thread among all scenarios is that any rate of RE integration cuts costs on top of reducing GHG emissions. There is neither environmental nor economic advantage of continuing the reliance on fossil fuels. However, all scenarios imply a strong uncertainty of possible future paths of Turkmenistan's national energy system and it is impossible to predict the actual development with high certainty. Besides the assumptions made in this study, several other factors will influence and shape the future development such as social acceptance of RE investments and installations or acceptance of continuing the present path of destroying economic value for the country in avoiding RE investments, while uncertainties related to the economic health of the nation may influence both fundamental policy options. Some factors, such as an almost inevitable increase in frequencies of extreme natural events [1], may even urge the government to switch to renewable sources of energy in a quicker manner than the most rapid scenario in this study.

The abundance of natural resources and relatively recent investments in gas turbines and gas infrastructure lead to some interesting results. This built-out gas infrastructure continues to play a vital role in the energy system of Turkmenistan in all scenarios. As can be seen in results, gas turbines can facilitate the transition to variable renewable energy sources by providing flexibility to the system. In short to mid-term, fossil gas can serve as a crucial balancing option during particularly cloudy or windless days in a cost-optimal way while simultaneously avoiding becoming stranded assets.

Flexibility and energy storage as a key flexibility option will play a vital role in a 100% RE system, enabling temporal shift in energy supply and thus providing flexibility for variable RE. With continuously declining cost, batteries become the main energy storage technology in all scenarios, except the CPS and CPS30. On top of that, thermal energy storage technologies facilitate the integration of variable renewable heat generation resources, such as solar heat collectors and concentrating solar power plants. Smart charging of BEV and vehicle-to-grid (V2G), an emerging new approach to flexibility and energy storage, was not considered in this study, although it may play a relevant role in 100% RE energy systems of the future [48]. It is demonstrated in [49] and [50] that high V2G participation can help decrease the need for peak power capacity, long-term gas storage, water electrolysis and fuel conversion capacities and subsequently lower total annualised costs. The curtailment in the BPS variations reaches values between 4.1% to 4.8% in 2040 (except the BPS-3 with only 1.2% due to a slow RE phase-in) and 5.0% to 5.9% in 2050. Such values are regularly observed in sector coupled 100% RE systems [51], [52] and further confirm the RE penetration-storage-curtailment nexus found on the case of Israel [53], which has similar resource conditions as Turkmenistan.

Theoretically, Turkmenistan should be able to bypass utilising energy storage all together, thanks to huge proven reserves of fossil gas. Gas turbines would be able to supply power absent the sunshine or wind. However, that would entail more GHG emissions and the associated costs of GHG emissions, while it would block least cost energy system solutions. The combination of RE sources and storage technologies is the best environmental and economic option even for a country with domestic fossil fuel supply such as Turkmenistan as an existing domestic energy supply option is substituted with an even more beneficial sustainable domestic energy supply option.

The transport sector shall undergo a radical transformation, switching to much more efficient vehicles and cutting final energy demand by half. Though transportation demand rises overall, the final energy demand decreases due to electrification of the road vehicles fleet thanks to efficiency gains of several factors. Direct electrification of the aviation sector will be possible for short distance flights after 2030 [7] whereas longer distance aviation can be indirectly electrified thanks to Power-to-X technologies. Indirect electrification does not have a strong negative effect on efficiency, but it helps to cut GHG emissions of the aviation sector. The Power-to-Fuels technologies allow to create liquid hydrocarbons by combining carbon from the CO_2 captured from the atmosphere and hydrogen from the water. However, it is important to have sustainably sourced carbon and hydrogen in order to have zero net-emissions of CO_2. CO_2 direct air capture [38] or point source CO_2 capture technologies, such as for cement mills [54], will be able to provide sustainable or otherwise unavoidable carbon, whereas water electrolysis will allow to create hydrogen by the well-known water electrolysis process. In addition, these energy-intensive PtX technologies convert large amounts of electricity from solar PV and wind turbines into hydrocarbons, while providing a very high flexibility to the entire energy system [19], [52], which also effectively limits curtailment of electricity. Fig. 29 shows the operational dynamics of the entire energy system and in particular of electrolysers providing the green hydrogen for the PtX routes. The best and worst week of the BPS-5 for the 2050 energy system design is shown and documents the enormous flexibility enabled by electrolysers, but also the diurnal energy storage function of batteries.

B. RELATED STUDIES

The results of this study are in line with the findings of recent energy transition studies in other countries around the world, specifically the dominance of solar PV in electricity generation [19], [55]–[57] and cost savings related to transitioning to sustainable forms of energy [58]. Breyer *et al.* [55] investigate the role of solar PV in energy transition on a global level, employing high temporal and high spatial modelling and conclude that solar PV technology will emerge to be the "most relevant source of energy in the mid-term to long-term for the global energy supply" thanks to ever decreasing costs of PV systems and battery storage technologies. Bogdanov *et al.* [17] identified that the global average of solar PV share in electricity generation can be expected to reach about 70% in mid-century, while this can reach levels beyond 90% in Sun Belt countries [51], [59]–[63]. Tavana *et al.* [56] studied the RE potential for the energy

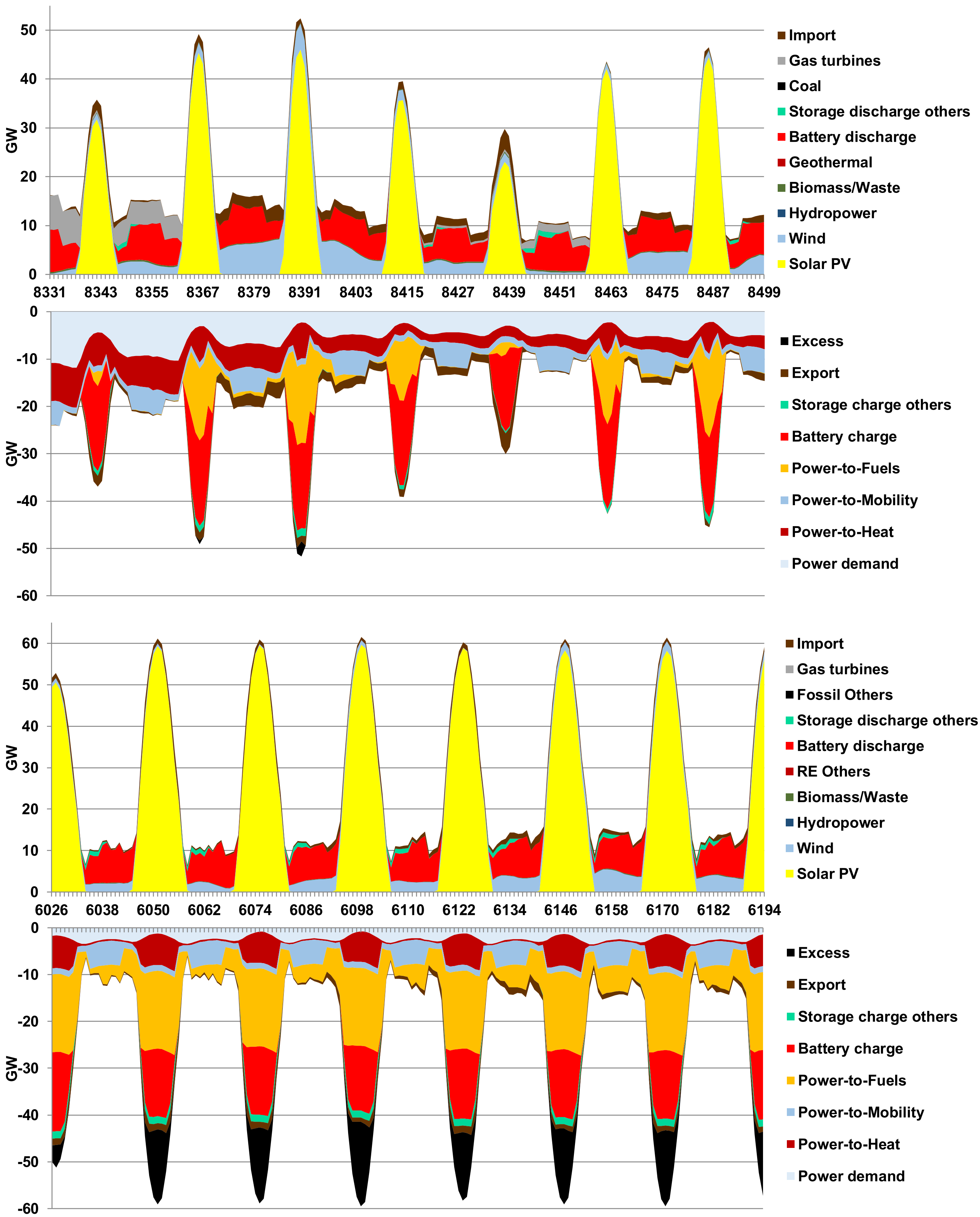

FIGURE 29. Worst (top) and best (bottom) week of solar electricity production in Turkmenistan in the BPS-5 in 2050.

transition of Iran, a geographically similar country to Turkmenistan with a comparable energy system heavily dependent on fossil fuels. Tavana *et al.* [56] similarly present several transition scenarios with different RE integration rates and demonstrate the high potential of solar PV and wind power technologies and that they are technically and economically feasible, albeit with slightly conservative solar PV cost and efficiency assumptions. Ghorbani *et al.* [57] have undertaken a detailed energy transition study for Iran in high geo-spatial resolution to determine cost-optimal pathways towards full sustainability of Iran's energy system; though only power sector and desalination sectors along with non-energetic gas sector were simulated, the authors similarly conclude that solar PV will dominate the electricity supply in the BPS in 2050.

C. IMPLICATIONS

Turkmenistan's lack of national determination towards concrete sustainability targets is alarming and should be addressed immediately. Specifically, more focus must be paid to the promotion of RE technologies. The current business-as-usual case is unsustainable, and high in cost as clearly documented by the CPS. A renewables-based energy system enables progress on all three pillars of sustainability: environment, economy and society.

The results for the case of Turkmenistan strongly indicates that accelerated phase-in policies for renewables are of high economic relevance in a general perspective. Empirical data indicates that only a few countries had been able to phase-in RE capacities at an annual rate of 3% increase in relative capacity share over periods of five years or longer, while only Uruguay is known for ramping the relative RE generation share close to 5% for almost a decade. However, the BPS-5 for the case of Turkmenistan shows that such a very high RE phase-in rate is the economically most beneficial case, while it reduces the GHG emissions in the fastest way. Given the fast decline in remaining carbon budgets, it is of highest relevance that very fast declining GHG emissions pathways positively coincide with economic performance.

The results also show that without considering direct or indirect fossil fuels subsidies and the fuels cost set on the global market level, the cost of RE-based generation is lower than the cost of traditional fossil gas based generation already today. The example of Norway may be a blueprint for the government of Turkmenistan: achieving highest levels of RE utilisation for domestic least cost energy supply, while maximising exports of fossil gas to laggard countries in the energy transition. This obviously seems to be a strategy for generating highest societal welfare.

It is important to note the cumulative GHG emissions in the BPS variations in later years of the transition – they flatten out and remain almost constant throughout the later years (Fig. 28, bottom). According to Rogelj *et al.* [64], intended nationally determined contributions by members states of UNFCCC will not be enough to keep the global warming below 2°C, while stating that "substantial over-delivery on current INDCs" will be needed to achieve the goal of keeping global warming below 2°C and even further efforts to keep it below 1.5°C. Meanwhile, the remaining carbon budgets further decline due to triggered feedback loops of the planetary climate system [65]. The CO_2 emitted to the atmosphere will have to go down and be either utilised or stored, for which CO_2 direct air capture is a major option as it may enable massive utilisation of CO_2 as a raw material and in a second phase the transition to negative CO_2 emissions in the future [66].

These results are achieved for conditions of Turkmenistan but can be also applied to other countries with similar solar irradiation conditions: 100% RE systems can be built mostly on basis of solar PV, with rather limited shares of other resources such as wind, hydropower and bioenergy. Nevertheless, the energy demand and supply balance is found for every hour and reliable operation of the variable RE based system can be reached at a cost level lower than in the current fossil fuel based energy system.

D. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study is one of the first of its kind for investigating the pathway options of Turkmenistan's energy system, for which more research is required. There is a dire need to study the energy system of Turkmenistan from different perspectives with more granular data. The data used in this study, such as energy demand profile and population, may not fully match the latest numbers. As an example, the unusual bulge in the electricity per capita mid-transition (Fig. 9, bottom) is probably related to mismatch between real population and data used for this study. A 100% renewables based energy system potentially offers even more benefits to the nation when considering job creation [43], water desalination [67], industry sector integration [19] and power exchange over regional cross-border grids [68]. The results of this research clearly indicate that it would be beneficial to conduct further studies on societal benefits of RE-based energy system, grid capacity requirements within Turkmenistan and international cross-border grid capacity, but also water demand, supply and desalination aspects in Turkmenistan.

V. CONCLUSION

Turkmenistan has been blessed with natural fossil fuel resources and it is awash in renewable energy resources to an even greater extent. The LUT Energy System Transition Model was used to analyse seven different energy system pathways for Turkmenistan, employing a multi-node high resolution sector coupling approach. The results of this study show that RE, sector coupling, and storage technologies can sufficiently cover the national energy demand at every hour throughout a year. Solar PV and wind power can lead the transition to a fully sustainable 100% renewable energy system in Turkmenistan, cutting GHG emissions to zero. Low-cost solar PV and wind electricity, efficiency gains and effective energy sector coupling can enable a reduction in levelised cost of electricity in Turkmenistan from 87 €/MWh in 2020 to 44 €/MWh in 2050, while the overall levelised cost of energy in 2050 will stay on the same level as in 2020. Pathways of delayed or blocked renewable energy investments lead to higher energy system cost and higher GHG emissions. Direct and indirect electrification of heat and transport sectors will help to cut GHG emissions in these sectors to zero and reduce the cost for the entire energy system. The fast worsening of climate change may lead to international attention to Turkmenistan's inadequate actions regarding GHG emissions sooner or later, and this might enforce drastic measures on Turkmenistan's energy policy. Decision-makers in Turkmenistan should strongly consider enabling investments in RE through solid frameworks and legislation, as this enhances the welfare of the country.

SUPPLEMENTARY MATERIALS

Supplementary Material available under the tab ''Media''.

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