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Just transition towards defossilised energy systems for developing economies: A case study of Ethiopia

Ayobami Solomon Oyewo*, A.A. Solomon, Dmitrii Bogdanov, Arman Aghahosseini, Theophilus Nii Odai Mensah, Manish Ram, Christian Breyer

LUT University, Yliopistonkatu 34, 53850, Lappeenranta, Finland

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ABSTRACT

This article explores the transition to renewable energy for all purposes in developing countries. Ethiopia is chosen as a case study and is an exemplary of developing countries with comparable climatic and socioeconomic conditions. The techno-economic analysis of the transition is performed with the LUT Energy System Transition model, while the socio-economic aspects are examined in terms of greenhouse gas emissions reduction, improved energy services and job creation. Six scenarios were developed, which examine various policy constraints, such as greenhouse gas emission cost. The Best Policy Scenarios cost less than the Current Policy Scenarios and generate more job. The results of this research show that it is least costing, least greenhouse gas emitting and most job-rich to gradually transition Ethiopia's energy system into one that is dominated by solar PV, complemented by wind energy and hydropower. The modelling outcome reveals that it is not only technically and economically possible to defossilise the Ethiopian energy system, but it is the least cost option with greatest societal welfare. This is a first of its kind study for the Ethiopian energy system from a long-term perspective.

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1. Introduction

Globally, the need for coordinated efforts to mitigate the threat of climate change and to eradicate widespread energy poverty is evident in the perspectives of the Paris Agreement on climate change and Sustainable Development Goal 7 (SDG 7) [1]. Progressive decarbonisation is widely apparent as today's energy system violates social, economic and environmental sustainability criteria [2]. In 2011, Ethiopia launched a Climate Resilient Green Economy (CGRE) strategy, with the clear objective to become a middle-income country by 2025, and to achieve this through economic growth that is both resilient to negative impacts of climate change and results in no net greenhouse gas emissions [3]. This article explores how developing countries can transition to renewable energy (RE) for all purposes. Ethiopia is chosen as a case study, as the country reflects the current situation in many sub-Saharan African (SSA) countries, which includes limited infrastructure, growing population, dependence on fossil fuel, high use of unsustainable biomass and vulnerability to climate change.

Ethiopia is a landlocked country located in the Horn of Africa. With an expanding population of above 100 million, Ethiopia is the second most populated country in Africa, and the fastest growing economy in the region [4]. However, it is also one of the poorest in the world, with per capita income of 790 USD in 2018 [4] and is ranked 173rd of 189 in terms of human development index [5]. Despite the vast energy resources, such as hydropower, solar, wind, biomass, geothermal, natural gas and coal, Ethiopia is still unable to develop, transform and utilise these resources for optimal economic development [6]. Over 50 million (55%) Ethiopians are unelectrified and 98.9 million people rely on biomass for cooking in 2018 [7]. Biofuel accounts for the largest share (87%) of the total primary energy supply, hydrocarbons 10% and electricity 3% in 2017 as illustrated in Fig. 1 [8].

Recognising energy development as a vital enabler of socioeconomic development, the Ethiopian government aims at investing in RE sources to curb energy crisis and vulnerability to climate change [3,6]. In doing so, Ethiopia is committed to developing solar and wind energy alongside its massive hydropower, and investment in geothermal and bioenergy to complement these variable energy sources [3,6]. Despite the high vulnerability to extreme weather variability, especially erratic rainfall [3,9]; there are existing plans to increase the hydropower capacity from 3.8 GW

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* Corresponding author.
E-mail address: solomon.oyewo@lut.fi (A.S. Oyewo).

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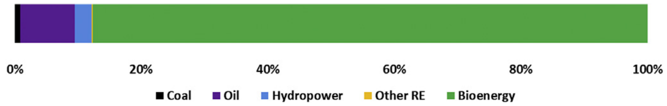

Fig. 1. Ethiopian total primary energy supply in 2017.

in 2018 to 22 GW by 2030 [10]. However, climate change might pose significant challenges to hydropower generation [11–13]. Beyond environmental and social impacts of hydropower projects, these projects are often susceptible to substantial financial risks due to cost overruns and scheduled spills [14–16]. Further, countries hosting large hydropower dams have shown the ineffectiveness of a 'hydropower strategy' as an option to improving electrification access, particularly in rural areas [17].

Ethiopia shows an excellent prerequisite for a nearly 100% RE supply [18]. With the fast decline in RE costs and excellent resource conditions in Ethiopia, countless opportunities exist in the country for low-cost energy supply [18]. Solar PV, wind energy and hydropower are anticipated to experience strong growth in the country's energy mix [6,18]. However, these power sources are variable in nature [19]. Nevertheless, the variability can be overcome by designing an optimal system [20], with appropriate enabling technologies, if resources scarcity enforces dependence on limited variable RE (VRE) resources [21–23] and that exploit resource complementarity to reduce its impact and the need for enabling technologies for regions with diverse resources [18,19]. So far, there is a lack of high temporal and spatial resolution energy transition studies on regional and country resolution in SSA, which consider the impact of high shares of RE in meeting the rising energy demand [24]. Further, a systematic understanding of national energy transition is vital, especially for developing countries like Ethiopia. Thus, the need for energy system modelling is essential to understand the underlying behavioural pattern and dynamics of energy systems, particularly when integrating high shares of VRE resources in the context of SSA [25–28].

Recent studies have demonstrated the technical feasibility and economic viability of achieving a fully renewable electricity system in general [26] and in particular for cases such as South Africa [25], Nigeria [26], Ghana [27], West Africa [28], SSA [23] and the world [30]. The SDG 7, Africa Vision 2063 [31], Ethiopia CGRE Vision 2025 [3] and the Paris Agreement can be achieved by the deployment of RE technologies, in tackling the two major challenges of the 21st century: widespread energy poverty and climate change [1,3,6].

For these reasons, the techno-economic analysis of the Ethiopian energy transition is performed, and a socio-economic footprint is examined in terms of greenhouse gas (GHG) emissions, improved energy services and job creation. The analysis for Ethiopia serves as an exemplary of developing countries with similar climates and socioeconomic conditions. The energy transition is modelled in 5-year intervals within the time span of 2015–2050, by applying linear optimisation modelling to determine a cost optimal generation mix to meet the demand based on projected costs and technologies. Six scenarios were developed to fully understand the transition pathway options under certain policy constraints. These scenarios could cater to policy decisions for defossilising the Ethiopian energy system within the time horizon of 2050.

2. Literature review: state of 100% renewable energy research in sub-saharan africa

A brief review on the state of research for 100% RE systems in SSA countries is presented in Table 1. The literature review considers only peer-reviewed articles. In total, 16 articles have been identified and analysed, including country, regional and global studies. However, only global studies with focus on SSA countries or high regional resolution are included in this review.

Most of the studies listed in Table 1, have a predominant focus on the power sector, while less attention is given to other energy sectors. Some of the studies reviewed focus on 100% RE systems analysed in the overnight approach, which may lack sufficient insights that could cater for decision making in transitioning to a fully RE system. In addition, most of the RE policies in SSA are focused on the power sector, while little or no policy framing exists for other sectors to enable comparable progress [32]. Furthermore, several countries in SSA aim at 100% renewable electricity by 2050 including Ethiopia, Rwanda, Senegal, Kenya, Malawi, Ghana, Madagascar and Burkina Faso. Cape Verde has a highly ambitious target set for 2025 [32]. A recent review article on 100% RE systems, which covers 180 articles published until end of 2018, shows that Africa, in particular SSA, is one of the major regions in the world that is not yet covered well by 100% RE research [24]. This limited research creates less support for policymakers when designing the future RE policy frameworks. Up to now, there is no study for SSA with high spatial resolution for the entire energy system, in full hourly resolution and describing transition pathways. To fill this research gap, a comprehensive sector-coupled energy system assessment covering demand from power, heat, transport, and desalination sectors, is performed for the case of Ethiopia, within the time horizon of 2015–2050 in 5-year intervals. This study applies a novel technology-rich, multi-nodal, multi-sectoral, and cost-optimal analysis, with high geo-spatial and full hourly resolutions for Ethiopia. The LUT model, as identified by Prina et al. [33] as a leading energy system transition model, maintains the top position as the most used energy system model for 100% RE analyses for SSA in scientific articles as presented in Table 1.

3. Methods

The Ethiopian energy system optimisation was performed with the LUT Energy System Transition model described in Refs. [30,47]. Fig. 2 illustrates the geographical scope of this study.

3.1. Model description

The LUT Energy System Transition model is a linear optimisation tool, which can handle an hourly sequential temporal resolution for an entire year [30,47]. The key function of the optimisation algorithm is to minimise the total annual system cost of the integrated energy system. To compute the lowest system cost, the model seeks to optimise the sum of installed capacities of each technology, operational expenditures, and costs of generation ramping. The Ethiopian energy transition is simulated in 5-year time intervals under certain constraints. Fig. 3 illustrates the schematic of the process flow associated with utilising the model.

In addition, the energy system considers power prosumers and individual heating systems. Individual heating and power prosumers are optimised exogenously in hourly resolution. The target function includes annual costs of the prosumers power generation and storage, and heating equipment, the cost of electricity required from the distribution grid and the cost of fuels required for boilers, income via electricity feed-in to the distribution grid is deducted from the total annual cost.

The following constraints are taken into consideration to establish a sound basis for the energy system transition analysis:

- No new nuclear, coal and oil-based power and heat generation capacities could be built after 2015. However, gas turbines could

Table 1
Review on the status of 100% renewable energy system studies for SSA. The used model is indicated in brackets.

Coverage Study	Study /year/model	Geography	Sector	Pathway	Multi-node	Hourly resolution	Remark
Country	Timmons et al. [34] 2019 (OSeMOSYS)	Mauritius	Power	O	×	×	This study modelled a fully renewable electricity supply for Mauritius by 2040. The research demonstrates that such a system can provide sufficient electricity to meet demand in each day and night of the year, at a price similar to the current electricity generation.
	Timmons et al. [35] 2020 (OSeMOSYS)		Power	O	×	×	This study analyses the economics of electrical energy storage in a fully RE power system for Mauritius by 2040. Results show that at the current prices, the cost minimising solution relies exclusively on pumped hydro energy storage (PHES) and account for 7% of the electricity supply. However, with large cost reductions, batteries are more competitive, but do not greatly reduce total cost compared to the base case using PHES.
	Bouckaert et al. [36] 2014 (TIMES)	Réunion island	Power	T	×	×	This research provides insight on the dynamic operation of a fully RE power system for Réunion island by 2030. The research provides valuable insights on the role of energy storage in achieving a reliable power system.
	Drouineau et al. [37] 2015 (TIMES)		Power	T	×	×	This research analyses the capability of achieving a 100% RE power system for Réunion island by 2030. The results show that the island can achieve electricity autonomy by 2030 with available RE resource potential and provides a generation mix ensuring a reliable power supply.
	Maïzi et al. [38] 2018 (TIMES)		Power	T	×	×	A 100% renewable and reliable power system was researched for Réunion island until 2030. The article describes conditions for reliable operations using the Kuramoto model to assess the synchronism condition over the whole power grid.
	Selosse et al. [39] 2018 (TIMES)		Power	T	×	×	This article analysed a 100% renewable electricity mix by 2030. The transition scenarios show that by 2030, electricity from biomass advantageously replaces electricity from coal, representing 50% of the electricity generation.
	Selosse et al. [40] 2018 (TIMES)		Power	T	×	×	Pathways towards a 100% renewable and local electricity mix by 2030 was analysed for Réunion. This research highlights the role of energy policy in fostering renewable technologies to supply electricity.
	Mensah et al. [27] 2021 (LUT model)	Ghana	Power	T	✓	✓	This research examines the grid balancing role of bioenergy in a fully RE power system by 2050, using Ghana as a case study. The results clearly show that bioenergy can provide a substantial share of the needed grid balancing requirement in a fully RE power system. With bioenergy in the system, results show a reduction in cumulative installed capacity, total generation, storage output, curtailment, and cost of electricity.
	Oyewo et al. [25] 2018 (LUT model)	Nigeria	Power	T	✓	✓	This research explores pathways to a fully RE electricity supply for Nigeria by 2050. The results show that a PV-battery system emerges as the least cost combination in a fully RE powered system for Nigeria.
	Tambari et al. [41] 2020 (TIMES)		Power	T	×	×	A transition to 100% renewable electricity by 2050 is a cheaper option compared to the conventional pathway, and it could potentially create around 1.54 million jobs for Nigerians by 2050.
	Oyewo et al. [25] 2019 (LUT model)	South Africa	Power	T	✓	✓	The results indicate that a 100% renewable energy system is the least-cost, least-water intensive, least-GHG-emitting and most job-rich option for the South African energy system in the mid-term future. No new coal and nuclear power plants are installed in the least-cost pathway, and existing fossil fuel capacities are phased out based on their technical lifetimes.
	Ferreira et al. [42] 2020 (Cape Verde planning model)	Cape Verde	Power	T	×	×	This research analysed different scenarios towards a 100% renewable electricity supply for Cape Verde, in monthly time steps for a 20-year planning period. The authors conclude that a RE power system will lead to an increase in total system cost and a significant decrease in both CO_2 and external energy dependency of the country.
Region	Oyewo et al. [28] 2020 (LUT model)	West Africa	Power	T	✓	✓	Pathways towards a fully RE power system was analysed for West Africa by 2050. Results show that transitioning to a fully RE-based system will not only deliver the lowest cost but also emits less GHG and creates more jobs in West Africa. Cooperation of electricity exchange within the region can reduce cost by about 10%.
	Oyewo et al. [11]. 2018 (LUT model)	SSA	Power	O	✓	✓	This research analysed impact of the Grand Inga project and synthetic inertia in a 100% RE power system for SSA, based on an overnight approach for the year 2030 and 2040. The results show that when the cost escalation for the Grand Inga hydropower project exceeds 35% in 2030 and -5% in 2040 assumptions, the project becomes economically non-beneficial. Integration of synthetic inertia in a system dominated by VRE is confirmed as an attractive option for SSA in a 100% renewable power system.
	Barasa et al. [23] 2018 (LUT model)		Power	O	✓	✓	This research work establishes that a 100% renewable resource based power system is a technically and economically practical solution for SSA, based on an overnight approach for 2030.
Global	Breyer et al. [43] 2017 (LUT model)	Global	Power	O	✓	✓	A 100% RE power system was researched based on an overnight approach for 2030, the study capture SSA as a region subdivided into 16 sub-regions. The results show that solar PV and wind drives a fully RE system for the region.
	Breyer et al. [18] 2018 (LUT model)		Power	T	✓	✓	A cost-optimised transition pathway towards 100% RE in the power sector by 2050 was analysed for Ethiopia and 7 other representative countries in the world. The results show that Ethiopia is a representative Sun Belt country with growing demand and solar PV emerge as the choice technology for low-cost bulk energy supply in the power sector.
	Bogdanov et al. [30] 2019 (LUT model)		Power	T	✓	✓	This research describes a global 100% RE electricity system by 2050. In this study SSA is structured into 16 sub-regions. This study is the first transition research that analysed the SSA power sector within the time horizon of 2015–2050. The results show that the SSA power sector can achieve a 100% carbon-neutral RE power system by 2050, and that such a system is economically viable.
	Bogdanov et al. [44] 2021 (LUT model)		All	T	✓	✓	This research examines the technical feasibility and economic viability of 100% RE systems across the globe by 2050. This study includes SSA in 16 regional resolution. The results show that SSA has the required RE resources to achieve an affordable, efficient, sustainable, and secure energy system.
			All	O	✓	✓	

Table 1 (*continued*)

Coverage Study	Study /year/model	Geography	Sector	Pathway	Multi-node	Hourly resolution	Remark
	Jacobson et al. [45] 2017 (LOADMATCH)		All	O	✓	✓	This research covers 139 countries in the world including SSA countries. No electricity trade among the countries. A 100% RE energy system was analysed based on an overnight approach for 2050.
	Jacobson et al. [46] 2019 (LOADMATCH)						A 100% RE system was analysed for 143 countries globally, including SSA countries based on an overnight approach for 2050. The results show that transitioning to RE system should substantially reduce energy needs, reduce costs, create jobs, reduce air-pollution mortality, and reduce global warming.

Indicator: Yes (✓), No (×), Transition (T), Overnight (O).

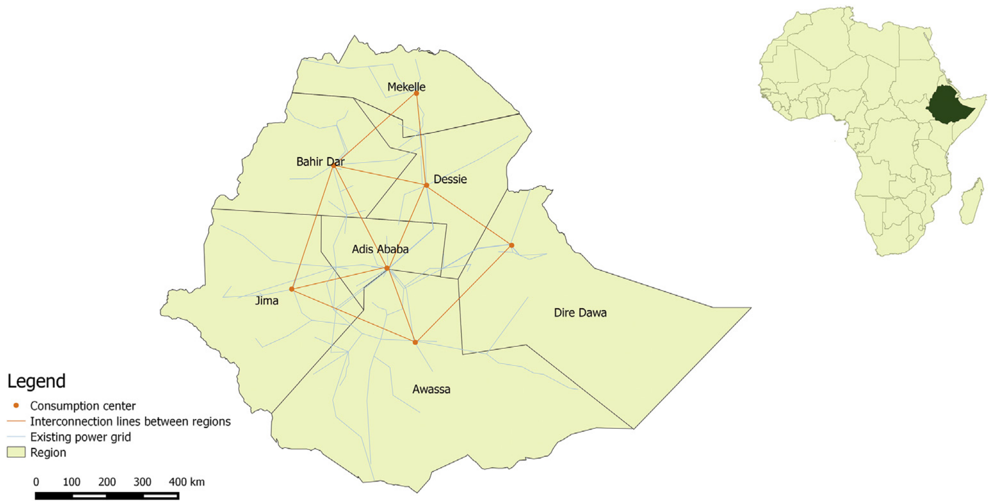

Fig. 2. The different sub-regions of Ethiopia applied in this research.

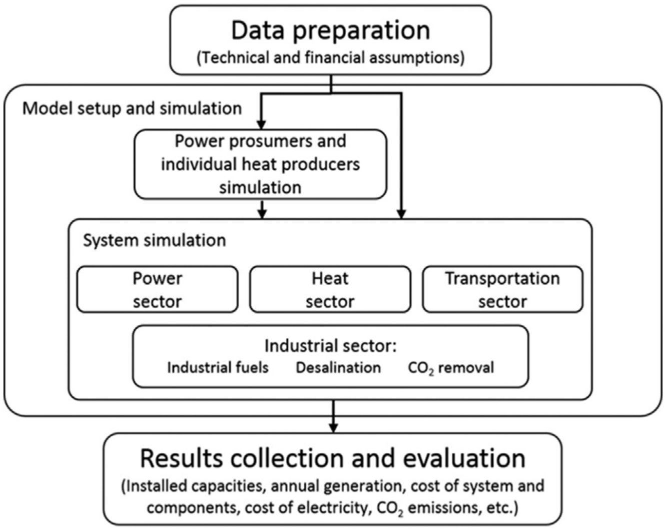

Fig. 3. LUT Energy System Transition data flow schematic [30].

be built due to their lower GHG emissions, higher efficiency and possibilities to use synthetic gas and biomethane in the later phase.

- Pumped hydro energy storage and hydropower plants are refurbished every 35 years and never decommissioned based on empirical observation [48].
- In order to avoid system disruptions, the RE capacity share increase cannot exceed 4% per year (3% per year from 2015 to 2020) based on empirical observation [48].
- Maximum PV prosumers share is limited to 20% of total power sector demand, but half of total PV prosumer electricity generation can be fed in the grid for small financial compensation. Prosumer generation is constrained in a step-wise progression from a maximum of 3% in the initial time step to 6%, 9%, 15%, 18% and 20% in the subsequent time steps.
- Fischer-Tropsch fuels contribution in the transport sector is constrained in a step-wise progression from 3% in 2030, 10% in 2035, 43% in 2040, 77% in 2045, and 100% in 2050.

The socio-economic footprint of the transition is analysed mainly in terms of job creation, GHG emissions reduction and improved energy services. The direct energy jobs created during the transition are estimated using the employment factor approach for the entire energy sector. Direct employments created across the value chain including manufacturing, construction and installation, operation and maintenance, transmission, decommissioning and fuel supply. A detailed description of the methods for the power sector is presented in Ram et al. [49] and the energy sector including power, heat, transport and desalination sectors in Ram et al. [50]. Further, the GHG emission pathways for all scenarios are analysed. Since the main goal of the Paris Agreement and the Ethiopian GCRE is the reduction of GHG emissions, costs of GHG emissions is considered during the transition. Improved energy services are anticipated as end-use services are satisfied in a sustainable manner across the various sectors.

3.2. Model setup

The model has integrated all crucial aspects of an energy system, which includes power, heat, desalination and transport sectors. Technologies introduced to the model include the following: electricity generation, heat generation, energy storage, transmission, transport, fuel conversion, fuel storage, desalination and sector bridging technologies. Detail description of the model setup can be found in Refs. [30,44,47]. All sectors are integrated and optimised together in full hourly resolution. Fig. 4 illustrates the LUT Energy System Transition design.

3.3. Main input parameters for modelling

- **Financial and technical assumptions**: Financial assumptions for all generation, storage, transmission and conversion technologies are critical parameters in determining a cost optimal energy transition pathway. Technical parameters include lifetimes and efficiencies of all technologies. The financial and technical assumptions introduced in the model are provided in the Supplementary Material (Table S1–S4). In all the scenarios examined, a 7% weighted average cost of capital (WACC) was assumed, whereas 4% WACC is set for residential PV self-consumption. A lower WACC is assumed for the PV self-consumption, as financial return expectations are lower. The residential, commercial and industrial consumers electricity prices were estimated till 2050 based on methods described in Refs. [51,52]. Electricity prices are provided in the Supplementary Material (Table S5).

  The RE technologies upper limits were estimated based on the method described in Ref. [53], existing installed capacities until 2015 are taken from Ref. [48] and set as lower limit. Absolute numbers of the upper and lower limits of all technologies are provided in the Supplementary Material (Tables S6–S7). The transmission and distribution grid losses were considered according to Sadovskaia et al. [54].

- **Renewable energy resource potential**: This includes hourly generation profiles of solar, wind and hydropower. Region average generation profiles for optimally fixed-tilted PV, single-axis tracking PV, concentrated solar power (CSP) and wind energy are calculated based on methods described in Ref. [53], from the generation profiles in 0.45 × 0.45° nodes resolution. Profiles for single-axis tracking PV are calculated according to Ref. [55], based on resource data of NASA [56,57], reprocessed by the German Aerospace Centre [58]. The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005 [59]. The sustainable and economic hydropower potential is obtained from Ref. [60]. The potentials for biomass and waste resources were calculated based on the method described in Ref. [27] and further classified into categories of solid wastes, solid residues and biogas. Geothermal energy potential is estimated according to the method described in Ref. [61]. Maps of Ethiopia showing annual full load hours of resources can be found in the Supplementary Material (Figure S1).
- **Demand:** The hourly electricity load profile is calculated as a fraction of the total demand for each sub-region based on synthetic load data weighted by the sub-region's population [62]. The power demand is categorised into residential, commercial and industrial end-users. Heat demand was divided into domestic hot water heating, biomass for cooking and industrial processes. The heat demand profiles were generated according to Barbosa et al. [63]. Further, the heat demand is classified as low, medium and high temperatures. The transport sector demand is classified according to Khalili et al. [64] into road, rail, marine and aviation. The desalination demand is projected as a function of water stress index and total water demand is estimated for each year during the transition, according to Caldera

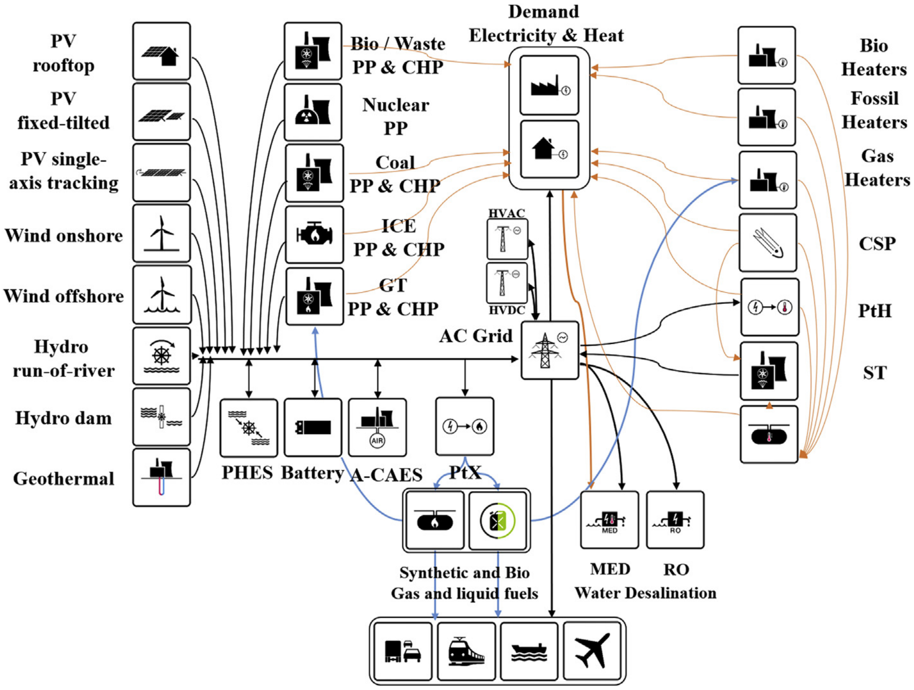

Fig. 4. Schematic of the LUT Energy System Transition design. Abbreviations: PP, power plant, ST, steam turbines, PtH, power-to-heat, ICE, internal combustion engine, GT, gas turbines, A-CAES, adiabatic compressed air storage, PtG, power-to-gas, PHES, pumped hydro energy storage, TES, thermal energy storage, CHP, combine heat and power, PtX, Power-to-X, CSP, concentrated solar power, AC, alternating current, HVAC, high voltage alternating current, HVDC, high voltage direct current. The diagram is in analogy to Ref. [47].

and Breyer [65]. All demand data are available in the Supplementary Material (Table S8, Figures S2–S6).

3.4. Scenario analysis

Six scenarios are considered to better analyse the transition pathway options. Detailed description of these scenarios is presented in Table 2.

4. Results

This section presents mainly results of scenarios with GHG emission costs including BPS-1, BPS-2 and CPS, however, results of scenarios without GHG emission costs are only mentioned or discussed where deemed fit.

4.1. Analysis of the power capacity and generation mix

The cumulative installed power capacities through the transition across various scenarios is shown in Fig. 5. Absolute capacity numbers are available in the Supplementary Material (Table S9–S11). The total installed capacity grows massively from over 2 GW in 2015 to 144 GW in BPS-1, 136 GW in BPS-2 and 105 GW in CPS by 2050. Hydropower dominates in all scenarios till 2030, however from 2035 onwards, a more diversified technology mix is observed. In 2050, the share of installed solar PV is around 67–115 GW, wind energy is 10–12 GW and hydropower is 10–22 GW. While, other RE resources such as bioenergy have some shares in the energy mix, with a complementary role through the transition. Electricity generation increases to meet the steadily increasing demand as shown in Fig. 6. Electricity is expected to experience rapid growth in developing economies like Ethiopia. Hydropower dominates the generation mix until 2030 in the BPSs and till 2035 in the CPS. From 2035 onwards, solar PV emerges as the default technology for bulk energy supply. In 2050, solar PV accounts for 50–66% of electricity generation, followed by 10–27% for hydropower and 9–14% for wind energy. Additional graphical results on sub-regional electricity generation, installed capacities, regional storage capacities and regional storage annual throughput in 2050 can be found in the Supplementary Material (Figures S7–S12).

4.2. Analysis of energy system flexibility components

Assessment of flexibility and supply security is vital in energy systems with high penetration of VRE resources. A portfolio of flexibility options such as energy storage, power transmission and sector coupling are analysed in this section.

4.2.1. Energy storage

The relevance of storage increases with the shares of RE during the transition, providing flexible and quick response to effectively manage variability in generation and load. The share of electricity demand covered by storage through the transition is visualised in Fig. 7. In 2050, the electricity demand covered by storage is around 1.05 TWh_{el} in the CPS and is over 50 TWh_{el} in the BPSs. Utility-scale and prosumer batteries contribute the entire share of electricity storage output by 2050. Batteries are anticipated to become an important storage technology for the energy transition, however, the scenarios vary structurally in the phase-in of storage.

Similarly, heat storage plays an important role in covering the heat demand across all sectors as shown in Fig. 8. Heat storage output covers about 110 TWh_{th} and 40 TWh_{th} of the total heat demand in the BPSs and CPS respectively by 2050 as shown in Fig. 9. The ratio of heat demand covered by energy storage to heat generation increases significantly to around 70%–78% in the BPSs and about 25% in the CPS by 2050. Thermal energy storage emerges as the prime heat storage technology with around 96% and 91% in the BPS and CPS respectively by 2050. Power-to-Gas contributes around 4% and 9% of heat storage output in the BPSs and CPS respectively by 2050.

4.2.2. Power transmission

The extent of grid utilisation varies from one scenario to another. Fig. 10 illustrates the grid utilisation profiles for the BPSs and CPS. The grid utilisation appears to be positively related to solar PV and hydropower generation in the BPSs. In the CPS, hydropower plants are site specific and require a maximum grid utilisation in shifting energy across the country. A good mix of RE sources and a more decentralised system is observed in the BPSs and most of electricity can be supplied locally, which result in lower grid utilisation in comparison with the CPS. In all the scenarios, grid utilisation appears to be vital due to a high penetration of RE generators. Fig. 11 shows the directions and amounts of electricity transmitted across the country in BPS-1 and CPS-1. The net grid export between the sub-regions ranges from 40 to 45 TWh in the BPSs, and 62–64 TWh for the CPSs.

4.2.3. Sector coupling

Electricity will play a major role in Ethiopia's future energy system and will be the energy of choice for most end-uses. Electricity as new primary energy carrier allows coupling of previously separated end-use sectors, allowing synergy effects across the energy sector. In this sub-section, power-to-heat, power-to-water, power-to-mobility and power-to-fuel is analysed. Additional flexibility is harnessed in the system by coupling low cost RE electricity to energy services including heat, desalination and transport.

4.2.3.1. Power-to-heat. In 2050, heat demand accounts for 33% of the total final energy demand (TFED), whereas 77% and 23% of all

Table 2
Scenario description.

Scenario	Description
Best Policy Scenario 1 (BPS-1)	This scenario adheres to all constraints listed in section 2.1. The Best Policy Scenario naming is considered based on 100% RE and zero GHG emissions.
Best Policy Scenario 1 no GHG emissions costs applied (BPS-1noCC)	This scenario is like BPS-1, but no GHG emissions costs are assumed.
Best Policy Scenario 2 (BPS-2)	This scenario is like BPS-1, but without PV prosumers.
Best Policy Scenario 2 no GHG emissions costs applied (BPS-2noCC)	This scenario is like BPS-2, but no GHG emissions costs are assumed.
Current Policy Scenario (CPS)	The CPS is designed based on the country performance targets [10].
Current Policy Scenario (CPSnoCC)	This scenario is like CPS, but no GHG emissions costs are applied.

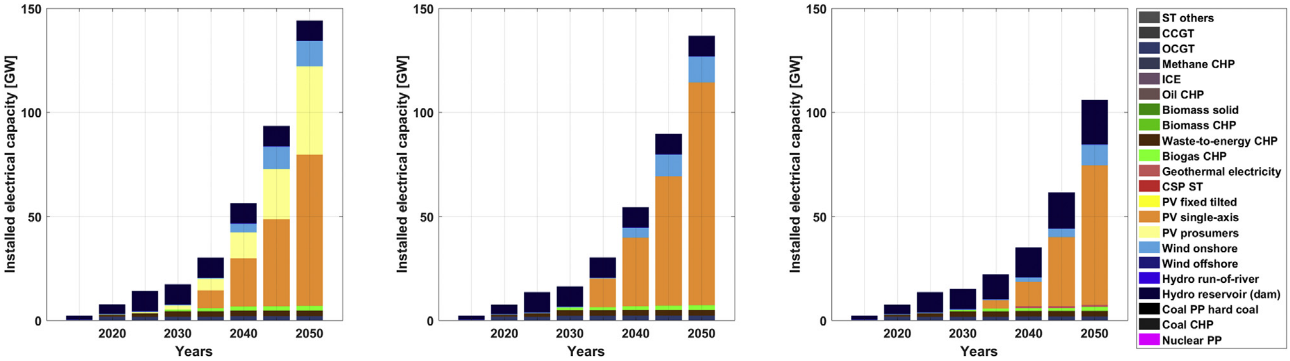

Fig. 5. Technology-wise installed electrical capacity for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

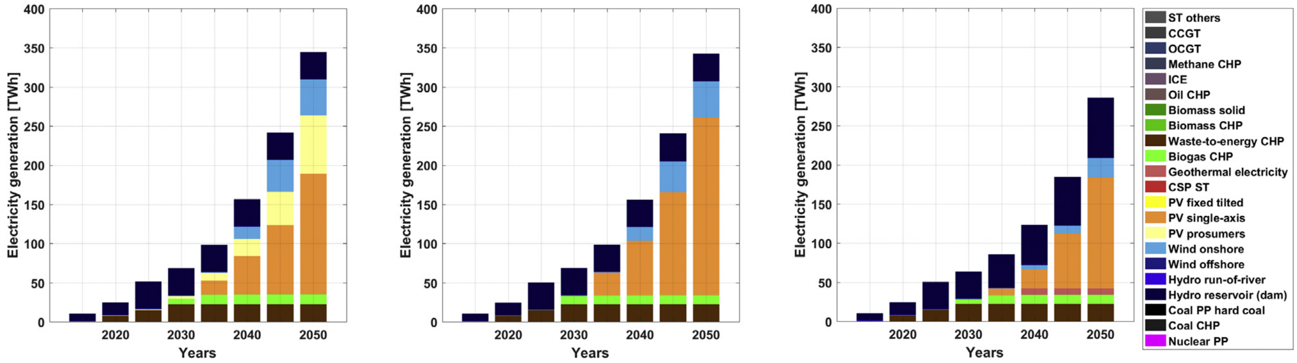

Fig. 6. Electricity generation mix for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

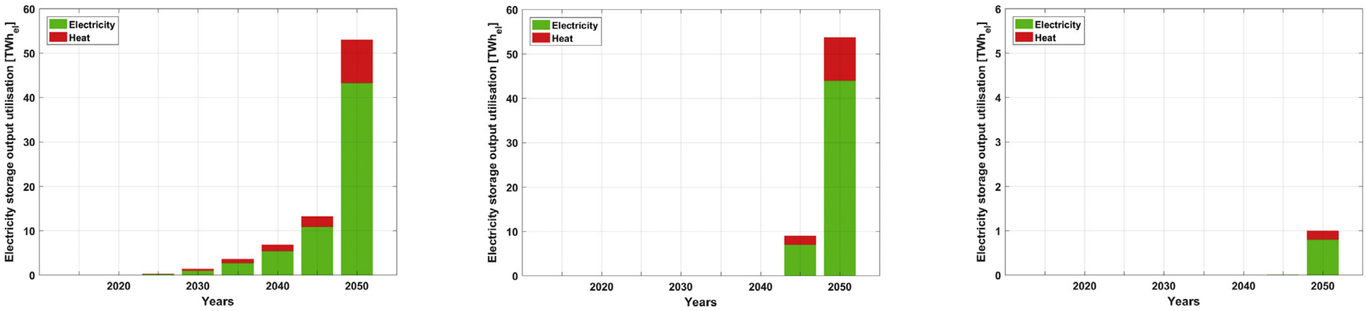

Fig. 7. Electricity storage utilisation for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

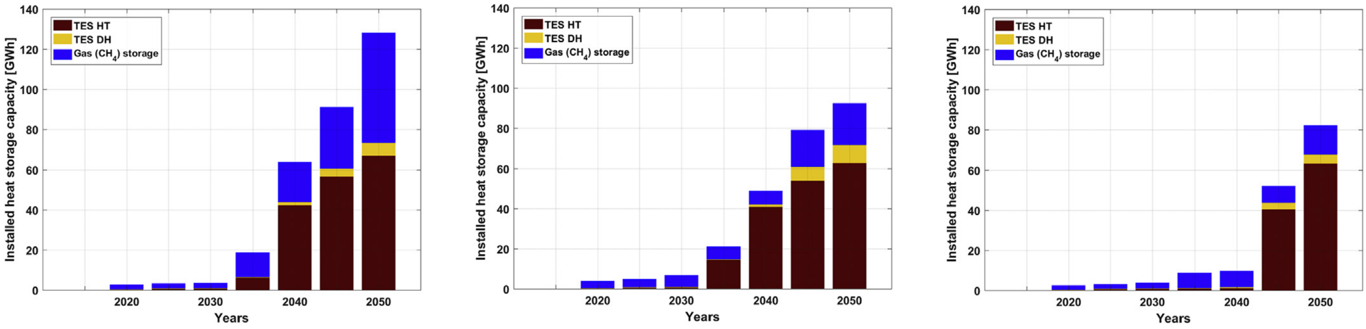

Fig. 8. Technology-wise heat storage capacity in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

electricity generation is required for direct and indirect supply for the heat sector. As illustrated in Figs. 12 and 13, an increase in the share of RE electricity leads to steady increase in electrification of the heat sector. Fossil and unsustainable biomass dependent heat

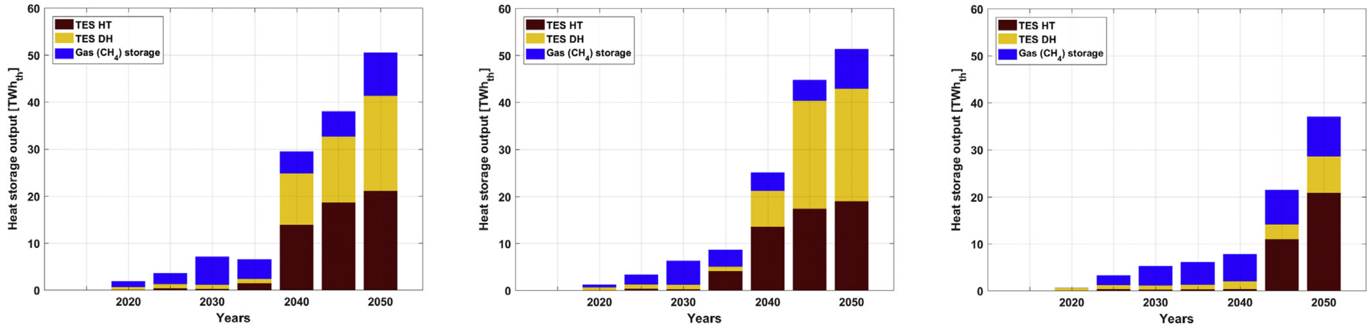

Fig. 9. Technology-wise heat storage output for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

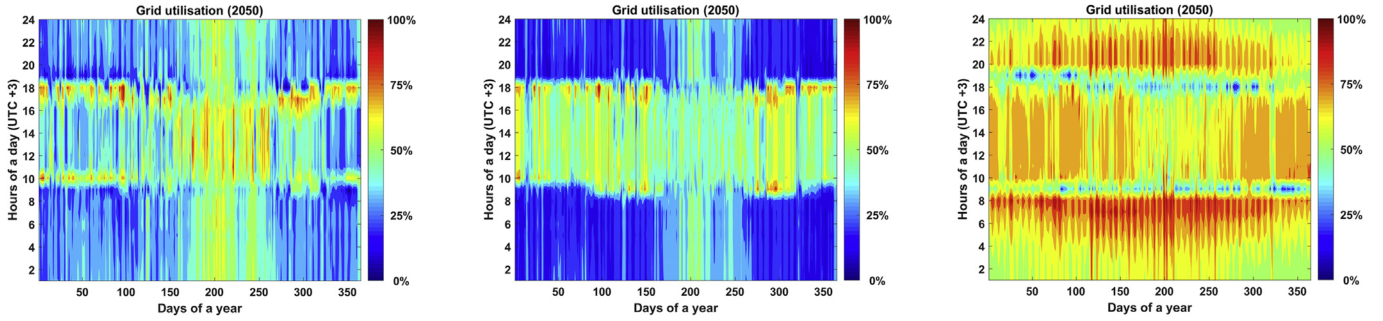

Fig. 10. Grid profiles for BPS-1 (left), BPS-2 (centre) and CPS (right) for 2050. Grid profile is the hourly distribution of electricity transmitted across sub-regions over the entire year.

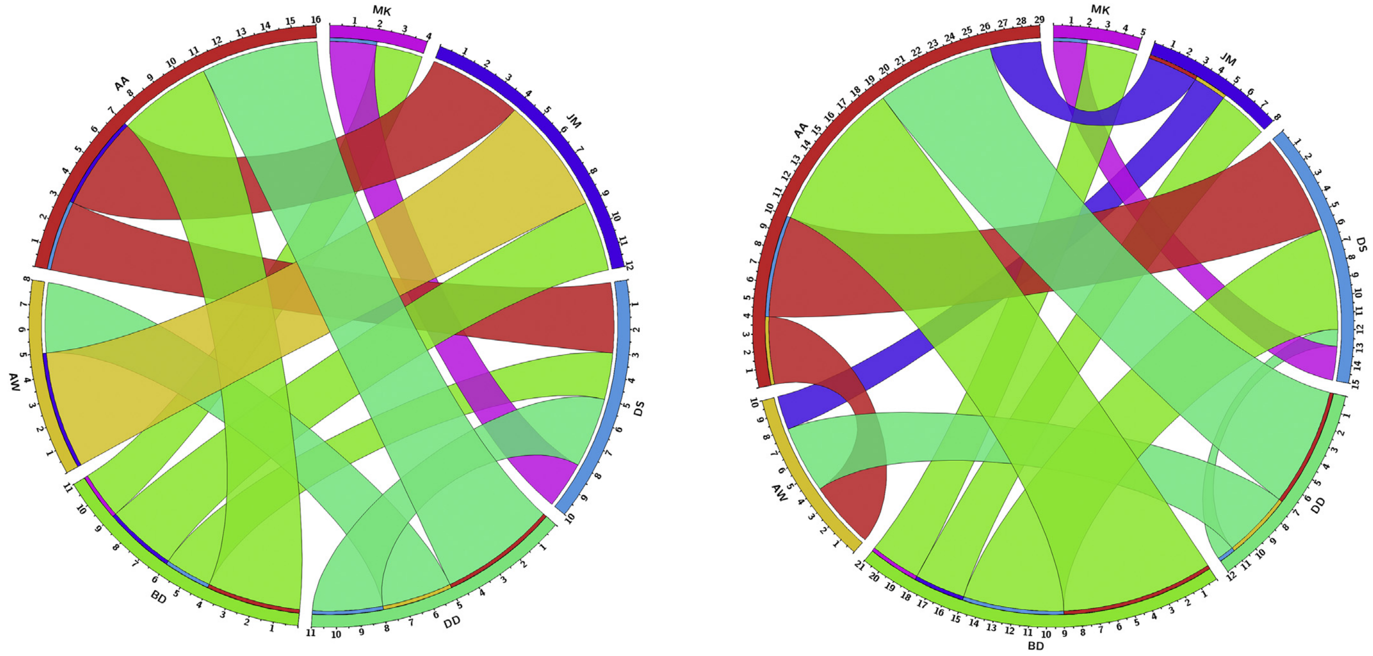

Fig. 11. Electricity transmission among the sub-regions for 2050 in the BPS-1 (left) and CPS (right).

generation is gradually replaced with electric heating, heat pumps, geothermal and sustainable biomass-based heating. In 2050, electric heat and heat pumps account for 34%–37% of heat generation, 10%–13% for geothermal, 11%–24% for gas and 26%–40% for biomass heating across various scenarios. Additional graphical results on heat capacities and generation is available in the Supplementary Material (Figures S13–S14).

4.2.3.2. Power-to-water. Another source of demand is seawater desalination plants, which are also coupled with low cost RE electricity. The desalination demand is low for the case of Ethiopia. Desalination demand increases from 0.6 mil m^3 in 2015 to 4.0 mil m^3 in 2050, while total electricity demand for desalination increases from 3 GWh in 2015 to 14 GWh in 2050, which is equivalent to 0.003% of TFED. The heat for MED is accessible form recovered waste heat from other processes, mainly synthetic fuel production.

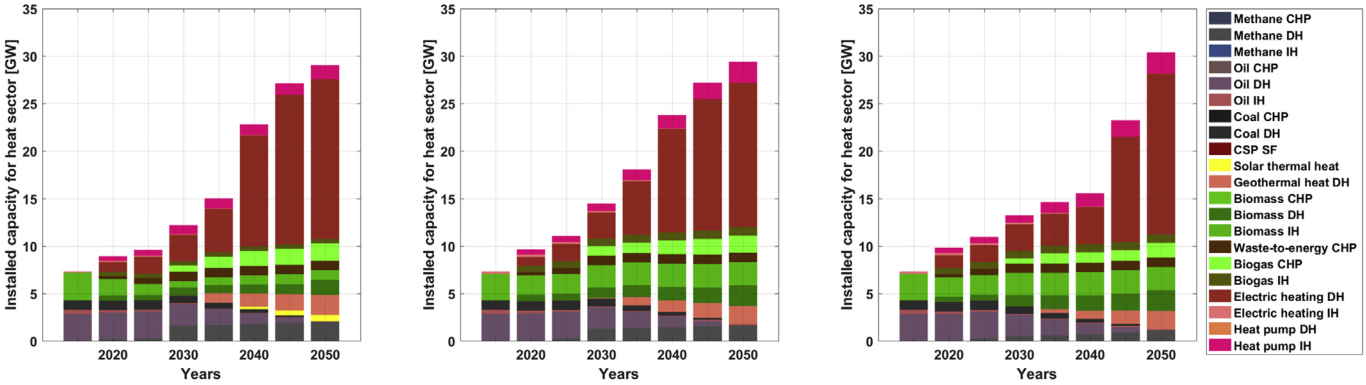

Fig. 12. Technology-wise heat generation capacity for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

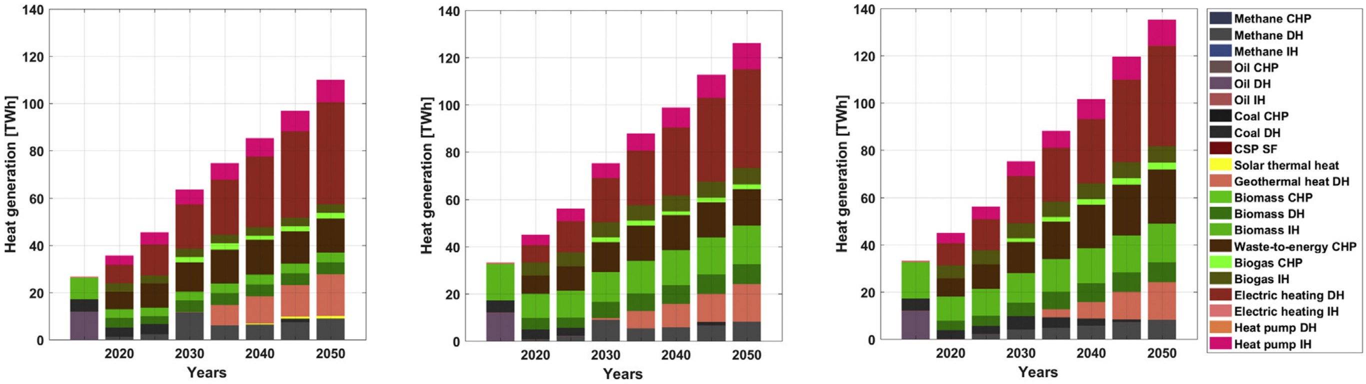

Fig. 13. Technology-wise heat generation for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

The required installed desalination capacity and demand for desalinated seawater is shown in Fig. 14.

4.2.3.3. Power-to-mobility. Ethiopia's low-cost RE electricity generation is a key enabler for coupling with the transport sector. In 2050, transport demand accounts for 15% of the TFED, whereas 31% and 69% of all electricity generation is required for direct and indirect supply of the transport sector. Power-to-mobility is realised in a direct way mainly through road vehicles such as battery-electric and plug-in hybrid electric for light, medium and heavy duty vehicles, buses and 2,3-wheelers, but also electrified railway, all-electric ferries and short distance all-electric flights, in the later period [64]. In addition, indirect electrification of transportation demand is realised via electricity-based synthetic fuels, such as hydrogen, or Fischer-Tropsch fuels (diesel, gasoline, jet fuel). In 2050, electrification of the transport sector creates a demand of around 80 TWh_{el} and 20 TWh_{el} in the BPSs and CPS respectively as shown in Fig. 15. The final energy demand of the transport sector across various scenarios is shown in Fig. 16, which remains in the range of 40–56 TWh in the BPSs and 40–97 TWh in the CPS through the transition. Transport demand appears to be stable during the transition due to substantial efficiency gains through electrification in the BPSs compared to the inefficient prevailing combustion systems in the CPS.

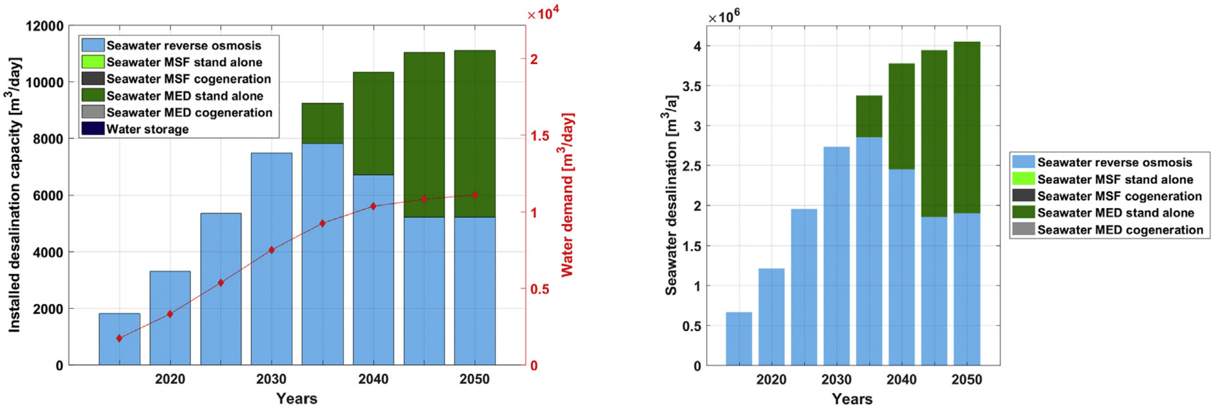

Fig. 14. Development of installed desalination capacity (left) and seawater desalination (right) through the transition.

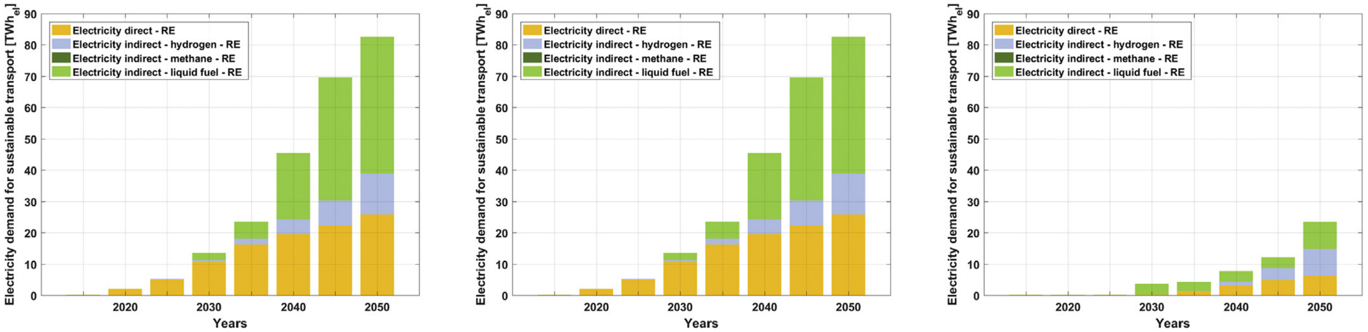

Fig. 15. Electricity demand for sustainable transport in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

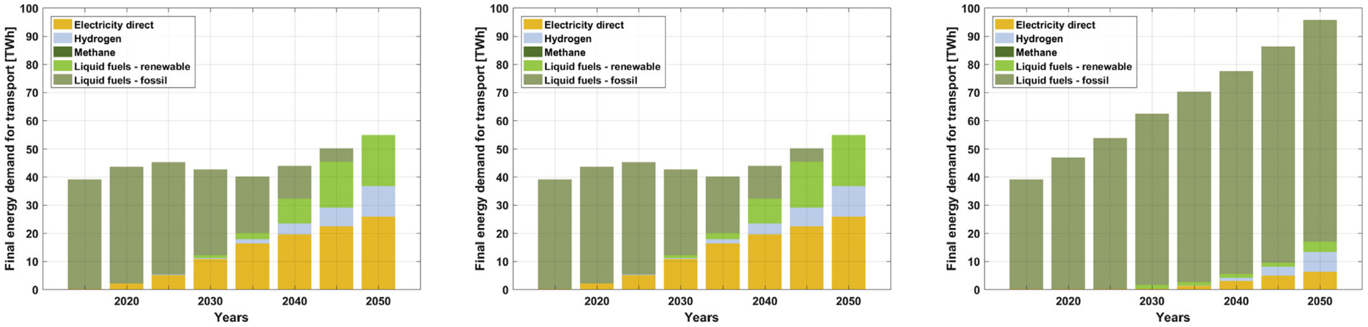

Fig. 16. Final energy demand for the transport sector in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

4.2.3.4. Power-to-fuel. Synthetic fuel production is a highly effective option for a deep defossilisation and energy sector coupling strategy. Synthetic fuels, such as hydrogen, methane, diesel, gasoline and jet fuel, are used to supply residual demand that cannot be covered directly by electricity. Massive demand for synthetic fuels is observed from 2040 onwards, especially in the BPSs. This is predominantly used to cover demand that is not possible to defossilise using all-electric solutions, in particular in aviation for long distance international flights, but also for high-temperature heat applications. As illustrated in Fig. 17, the installed capacities of fuel conversion technologies increase from 2030 to 2050. In 2050, the required fuel consumption installed capacities is over 20 GW in the BPSs and nearly 12 GW in the CPS.

Further, gas storage is vital in the production of synthetic fuels. The installed storage capacity for gas increases to about 0.12 TWh_{th} in BPSs and 0.04 TWh_{th} in CPS by 2050 as shown in Fig. 18. Water electrolysis forms the majority share of fuel conversion capacities through the transition, followed by hydrogen liquefaction units and Fischer-Tropsch synthesis plants. As well, heat is required during the production of synthetic fuels, primarily for energy-efficient CO_2 direct air capture (DAC) [66], and this is cost-efficiently enabled by managing and recovering of process heat, such as excess heat from Fischer-Tropsch synthesis units. Heat utilisation is around 25 TWh_{th} and 8 TWh_{th} in the BPSs and CPS respectively by 2050, which is comprised of recovered and excess heat, as illustrated in Fig. 19. The CO_2 DAC and CO_2 storage are important in the production of synthetic fuels. The installed capacity for CO_2 DAC and CO_2 storage increases up to around 8 $MtCO_2$ in BPSs and over 2 $MtCO_2$ in CPS by 2050 as shown in Fig. 20.

4.2.3.5. Energy flows in strong sector coupling. The Ethiopian energy system reaches high levels of efficiency and cost competitiveness due to access to low-cost RE and highly efficient utilisation of electricity across the entire energy system via Power-to-X (PtX) processes. Fig. 21 visualises the strongly sector coupled energy system, which links least cost RE and valuable flexibility options in the sectors heat and transport, particularly enabled by flexible electrolysers used for hydrogen production. This characterises the

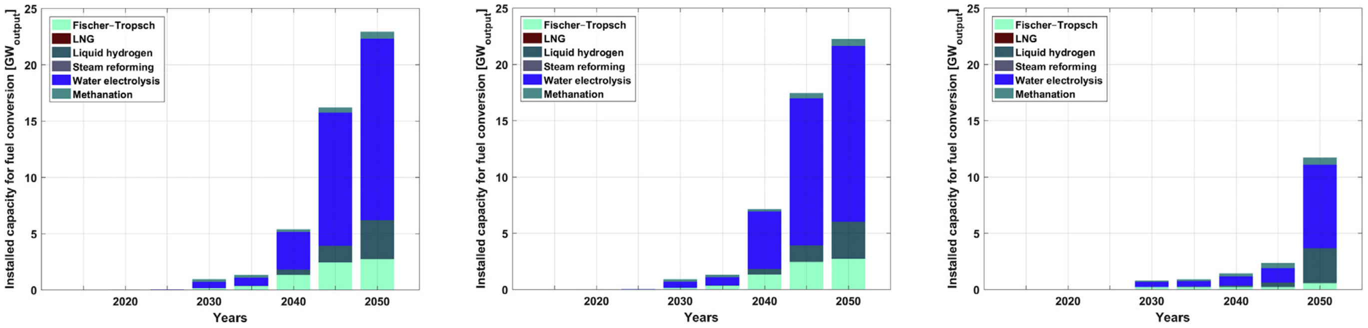

Fig. 17. Total installed capacity for fuel conversion for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

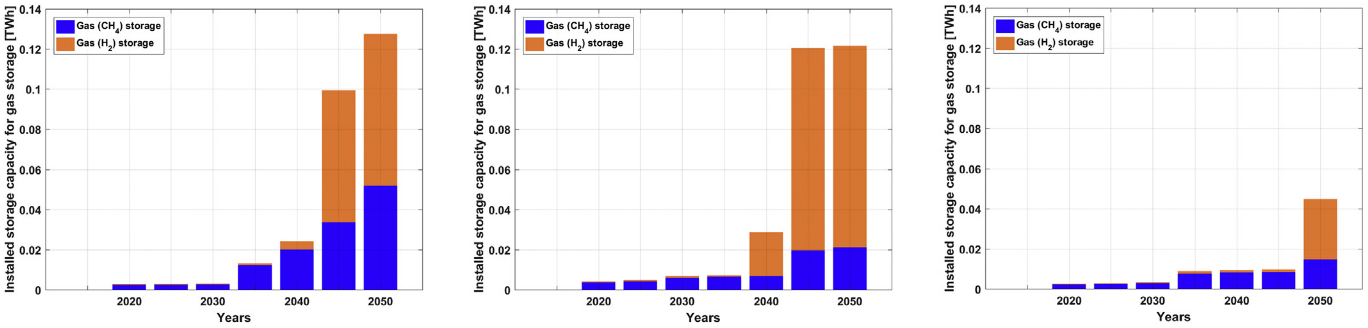

Fig. 18. Total installed capacity for gas (methane and hydrogen) in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

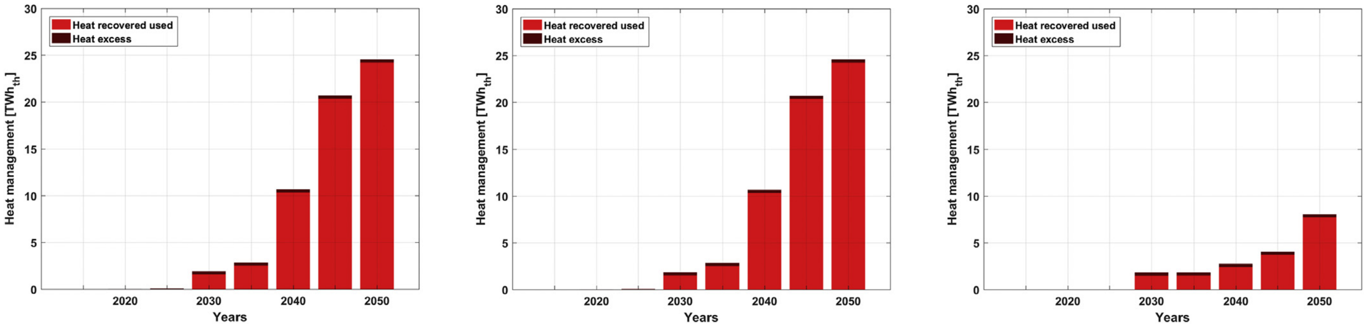

Fig. 19. Heat management in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

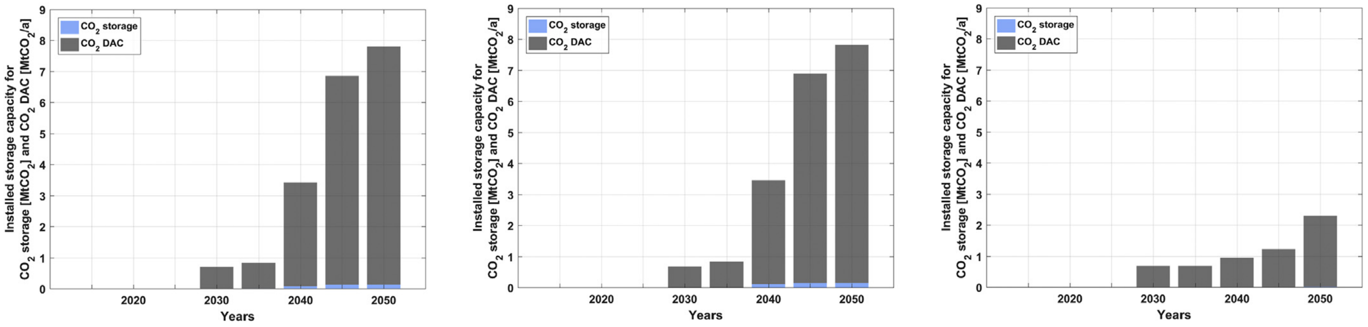

Fig. 20. CO_2 direct air capture and CO_2 storage in BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

future energy system: direct electrification as much as possible and indirect electrification in harder-to-abate segments, very often including hydrogen in the energy conversion routes as the second most important energy carrier. Additional energy flow diagrams are available in the Supplementary Material (Figures S15–S17).

4.3. Analysis of socio-economic footprint of the transition

Undoubtedly, energy transition cannot be considered in isolation, the energy sector is inextricably linked to the socio-economic system, which changes its socio-economic footprint and offers multiple co-benefits such as GHG emissions reduction, job creation and societal welfare.

4.3.1. Greenhouse gas emission trajectory

The GHG emissions trajectory through the transition is shown in Fig. 22. The power sector defossilisation occurs earlier, whereas for the heat and transportation sectors this occurs mostly between 2030 and 2050 in the BPSs. The BPSs indicate a sharp decline in GHG emissions until 2050, reaching zero GHG emissions by 2050 across various sectors. The GHG emissions decline from 16 $MtCO_{2eq}$ in 2015 to zero by 2050 in the BPSs. The GHG emissions trend in the CPS is visualised in Fig. 22 (right). In the CPS, GHG emissions increase from 16 $MtCO_{2eq}$ in 2015 to around 21 $MtCO_{2eq}$ in 2035, and further increased slightly to 22 $MtCO_{2eq}$ in 2050, dominated by GHG emissions in the transport sector. Additional graphical results on GHG emissions are available in the Supplementary Material (Figures S18–S21).

4.3.2. Employment projections during the transition

Employment provides an important linkage between economic growth and poverty alleviation by allowing the poor to generate income. Job creation is one of the socio-economic footprints to measure the performance of the energy transition. Figs. 23 and 24 depict the direct energy jobs created during the energy transition for the BPS and CPS. Jobs will be created in different value chains including manufacturing, construction and installation, operation and maintenance, decommissioning and fuel supply. The assumed

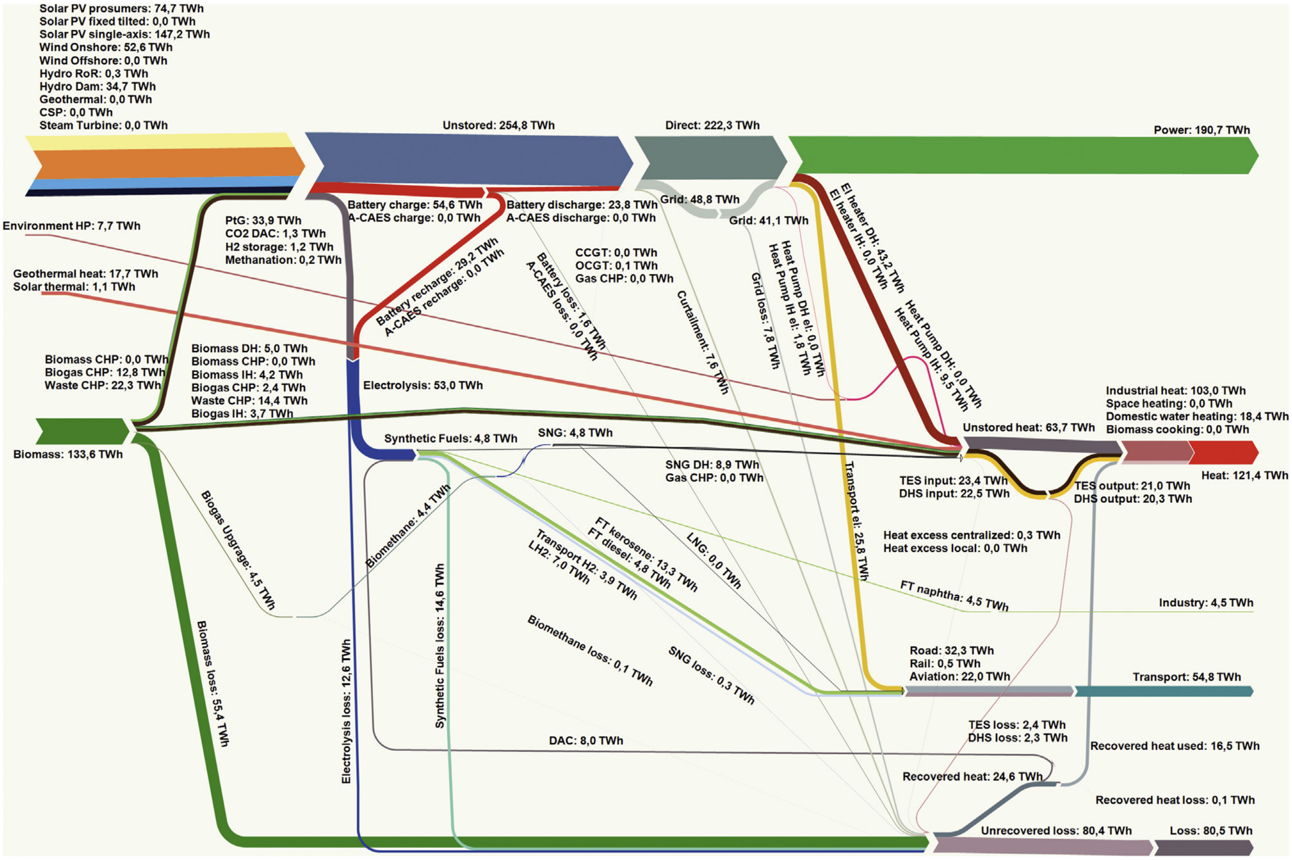

Fig. 21. Energy flow of the system in 2050 for BPS-1. All numbers displayed are in TWh.

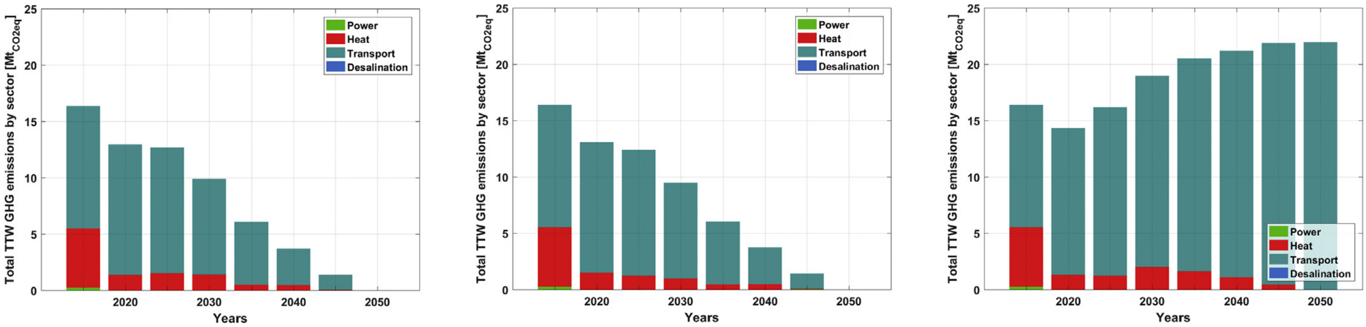

Fig. 22. Sector-wise GHG emissions for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

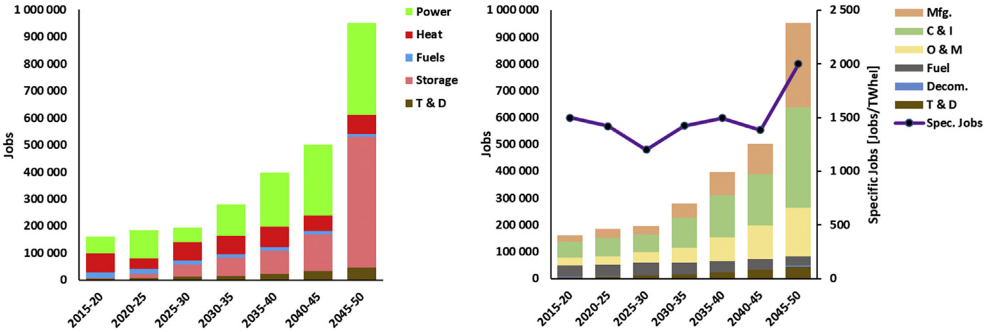

Fig. 23. Jobs created by the various energy system technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Ethiopia for the BPS. Abbreviations: Mfg. – Manufacturing, C&I – Construction and Installation, O&M – Operation and Maintenance, Decom. - Decommissioning, T&D – Transmission and Distribution, Spec. Jobs – Electricity demand specific jobs.

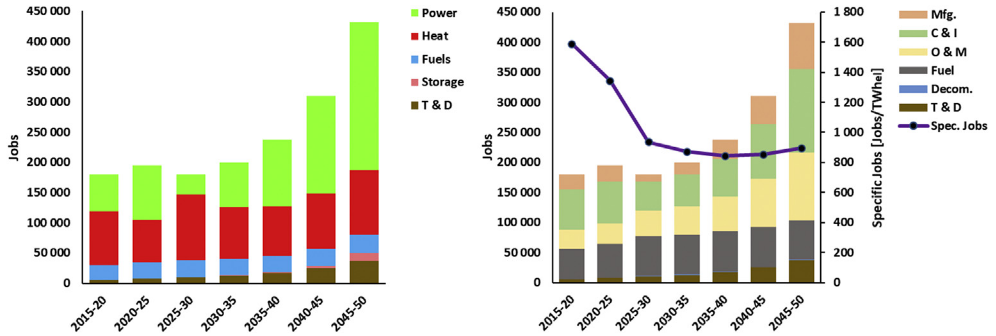

Fig. 24. Jobs created by the various energy system technologies (left) and jobs created based on different categories with the development of electricity demand specific jobs (right) during the energy transition from 2015 to 2050 in Ethiopia for the CPS. Abbreviations: Mfg. – Manufacturing, C&I – Construction and Installation, O&M – Operation and Maintenance, Decom. - Decommissioning, T&D – Transmission and Distribution, Spec. Jobs – Electricity demand specific jobs.

employment generation factors and jobs created by various technologies across the power, heat, fuels and storage sectors can be found in the Supplementary Material (Table S12, Figures S38–S41).

Unemployment and underemployment continue to be serious social problems in Ethiopia despite some improvements in recent years. This is mainly a result of rapid population and labour force growth (on the supply side) and limited employment generation capacity of the modern industrial sector of the Ethiopian economy (on the demand side) [67]. In this regard, job estimations on the basis of the results of this study and adopting the method from Ram et al. [50] shows that the energy transition in Ethiopia has huge employment benefits. The total number of direct energy jobs across Ethiopia is observed to increase from just around 160 thousand in 2015 to over 950 thousand by 2050 in the BPS and just over 430 thousand in the CPS, as indicated in Figs. 23 and 24. Power and heat sectors create the most jobs through the transition, complemented by jobs in the storage, transmission and distribution technologies as highlighted in Fig. 23. In addition, renewable electricity based synthetic fuels production creates some jobs from 2040 onwards.

Figs. 23 and 24 also indicate the distribution of jobs across the different categories during the transition period in Ethiopia for the BPS and CPS. With rapid installation of capacities in the BPS, the bulk of the new jobs are created in the construction and installation of power, heat and storage facilities. Manufacturing jobs have a relatively lower share in the initial periods, as the share of imports is high. From 2025 onwards, as domestic production capabilities build up, a higher share of manufacturing jobs are observed until 2050. Whereas manufacturing jobs are much lesser in the CPS. The shares of fuel related jobs continue to diminish from 2020 onwards through the transition period, as fossil fuels are replaced with synthetic fuels in the BPS. While fuel jobs have a steady share in the CPS until 2050. Transmission and distribution jobs increase through the transition in both the BPS and CPS until 2050. This means more stable jobs are created in the BPS for a country suffering from high unemployment amongst the youth [68].

The combined challenges of growing energy demand and expanding labour force, present Ethiopia not only with an opportunity to diversify the energy mix, but also to help mitigate high youth unemployment and assist in creating higher-skilled jobs. The final energy demand specific jobs increase from around 1500 jobs/TWh in 2015 to nearly 2000 jobs/TWh in 2050 in the BPS, with the rapid ramp up in renewable energy installations. Whereas specific jobs decline steadily from about 1600 jobs/TWh in 2015 to around 900 jobs/TWh by 2050 in the CPS. It is quite clear as to which pathway is far more job intensive and socially as well as economically beneficial, the BPS has the potential to nearly double the jobs over the CPS by 2050. This further indicates that jobs lost in conventional fossil fuels can be replaced by a substantial number of jobs created in renewables and other sustainable technologies. However, this implies challenges of reskilling and training of personnel to enable switching jobs from the conventional fossil fuels based jobs to advanced renewables based jobs.

4.4. Analysis of cost and investments through the transition

Investments in zero GHG emission technologies are needed during the transition. The total annual costs increase through the transition for all scenarios and are well distributed across the major sectors of power, heat and transport, as desalination demand in Ethiopia is relatively low. As illustrated in Fig. 25, the total annual costs increase from around 4 b€ in 2015 to around 14 b€ in the BPSs and about 19 b€ in the CPS.

The levelised cost of energy, defined by the total annualised cost divided by the total final energy demand, for all scenarios is visualised in Fig. 26. The levelised cost of energy reaches its peak in 2025 and gradually declines afterwards until 2050. From 2025 onwards, the levelised cost of energy declines, as low-cost RE dominates the energy system, particularly in the BPSs. The levelised cost of energy declines from 51 €/MWh in 2015 to around 36 €/MWh in the BPSs and relatively lesser decrease, to about 47 €/MWh in the CPS by 2050. Fuel and GHG emission costs account for nearly 40% of the levelised cost of energy in the CPS by 2050.

The aforementioned stark decline in levelised cost of energy is mainly driven by a steady decline in levelised cost of electricity (LCOE) as shown in Fig. 27. This low-cost RE is available via a comprehensive direct and indirect electrification of the entire energy system enhanced by modern sector coupling. The relatively high cost for power transmission grids in the beginning of the transition period can be well shared by a fast growing electricity demand during the transition. Additional graphical results on costs are available in the Supplementary Material (Figures S22–S31).

5. Discussion

This study demonstrates how developing countries of similar climatic and socioeconomic conditions, such as Ethiopia, can defossilise their energy system in a sustainable manner. Ethiopia can progressively defossilise its energy sector by coupling low-cost renewable electricity to the entire energy system, in particular the sectors of heat and transport.

5.1. Electricity generation mix and climate vulnerability consciousness

Ethiopia is a representative Sun Belt country, with a strong growing energy demand and an evolving dominant solar PV share,

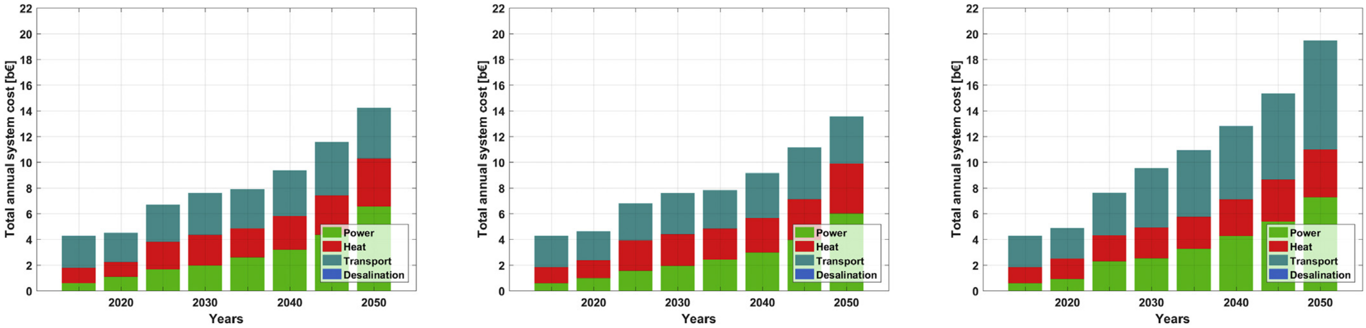

Fig. 25. Sector-wise total annualised costs for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

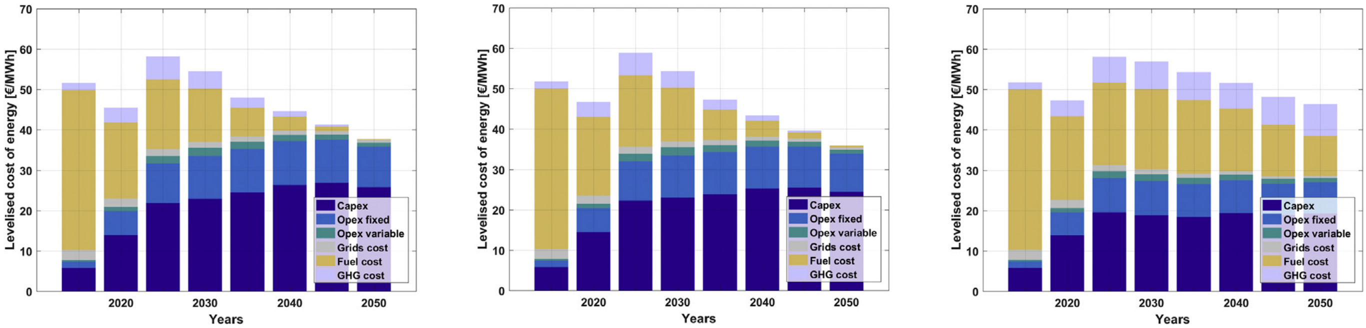

Fig. 26. Levelised cost of energy for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

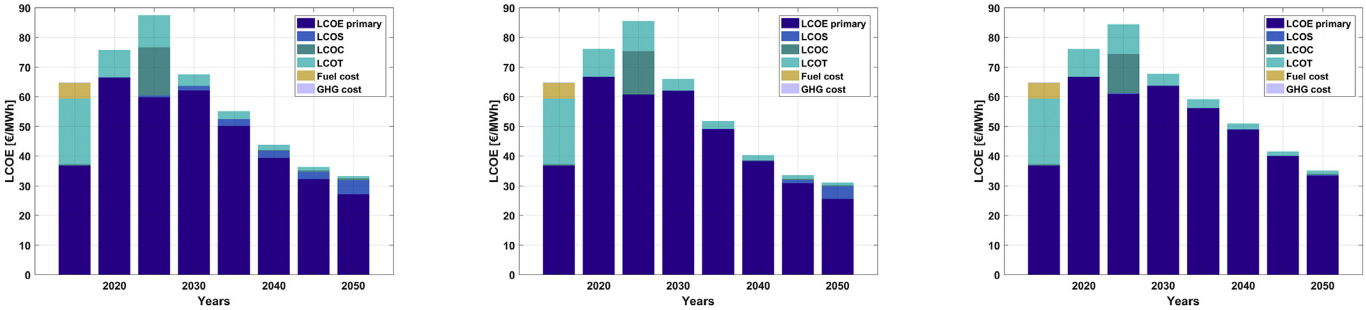

Fig. 27. Levelised cost of electricity for BPS-1 (left), BPS-2 (centre) and CPS (right) during the transition.

as observed for the entire SSA [23]. Comparable results have been published for South Africa [25], Nigeria [26] and West Africa [28]. The total solar PV electricity generation share obtained in this study for the entire energy system is the highest ever reported for Ethiopia, only comparable to an earlier power sector analysis [18], which suffered from a limited understanding of hydropower and sustainable bioenergy potential. Solar PV emerges as the default technology for bulk electricity supply during the transition, which is strongly supported by the decline of solar PV cost [69]. The heavy dependency on hydroelectricity can be substituted by a mix of RE technologies, which reduces the vulnerability of climate change induced hydropower supply risks [13] and increases the resilience of the Ethiopian energy system that improves the overall energy security [70]. The energy system optimisation results show that it is least-cost to supply about 66% of electricity demand with solar PV, 14% with wind and 10% with hydropower for the BPSs by 2050. The results of the BPSs are comparable to the findings of Jacobson et al. [46] for Ethiopia. According to [46], solar PV tops the power capacity mix with 63%, followed by wind energy with 28% and hydropower with 5%. In 2050, the CPS generation mix is about 50% for solar PV, 9% for wind and 27% for hydropower. It is worth mentioning that Ethiopia has the land resources to technically host a generation mix led by VRE, since only 0.1% of the land is required for ground-mounted solar PV and a further 0.1% for wind energy. The required land can be used for agriculture and PV [71] or in co-location with hydropower and reservoirs [72], whereas wind farms can be also operated in co-location to agriculture. Such combined usage increases societal welfare and enables increased income for communities.

The CPSs result is comparable to the findings of Mondal et al. [73] for Ethiopia. In 2050, power generation capacity from large hydropower is found to be in the range of 19–31 GW across the scenarios examined in Ref. [73]. According to the IEA [10], Ethiopia plans to expand hydropower capacity to 13.5 GW by 2040 and would make the country the second largest hydropower producer in Africa. Nonetheless, large scale hydropower developments are, largely, contentious and controversial due to their social, environmental and financial impacts [11]. In view of the Ethiopian Government's intention to heavily invest in hydropower, possible negative social and environmental effects of such massive deployment of hydropower should be considered [74]. More importantly, hydropower plants are vulnerable to climate variability as precipitation patterns are projected to change across the world [13]. In most parts of Africa, hydropower plants may experience a shortfall in generation due to reduction in rainfall, and extreme water shortage could leave these assets stranded [13,75]. The sensitivity of the Ethiopian power system to extreme weather was investigated by applying an integrated reservoir and power system dispatch [12]. The authors conclude that the power system is poorly resilient to climate change [12]. Beyond the social and environmental impacts, studies have shown that hydropower development is susceptible to schedule spills and cost overruns [14–16]. However, advocates of hydropower are predictably over-optimistic about schedule, cost and often exaggerate on multiple public benefits of large dam development, disregarding the true risk of the project on fragile economies of developing countries [15,16]. A statistical test of six hydropower hypotheses was analysed by Sovacool and Walter [76]. These hypotheses test how hydropower is related to internal conflicts, poverty, economic growth rates, rates of public debt, corruption and GHG emissions [76]. The results of the analyses show that hydropower does not increase internal conflict experience and reduces GHG emissions per capita. However, all other hypotheses confirm that hydropower to some extent increases poverty, decreases GDP per capita, increases public debt and increases corruption [76]. It is noteworthy that hydropower sits at a critical junction in countries or regions where capacity is yet to be built [76].

The BPSs results show that solar PV will emerge as the dominating technology of the Ethiopian future energy system. Based on the forgoing discussion, solar energy is less vulnerable than hydropower to climate change risks [13], which is an important fact for Ethiopia. Emodi et al. [13] conclude that climate change will have serious implications on energy systems, which will lead to changes in energy demand and supply. Solar PV systems are more resilient to climate change when compared to other RE sources. Thus, solar PV is anticipated to play a vital role in mitigating GHG emissions and adapt the energy system to future climatic conditions [13]. Additionally, solar PV systems are least at risk to cost overruns [77]. According to Sovacool et al. [77], decentralised, modular and scalable systems such as solar PV and wind would see fewer cost escalations. The IEA [78] also concludes that more modular systems run lower risks of technical systems failures. Developing countries like Ethiopia should prefer agile energy alternatives to mega hydropower projects that can be built over short time horizons. This will finally improve resilience and other metrics of energy security [70].

Solar PV generation in 2050 is around 66% of total generation in BPSs, relatively composed of 22% PV prosumer and 44% utility-scale PV in BPS-1, whereas in BPS-2 utility-scale PV supplies the entire solar PV generation. Decentralised power systems at the consumer end, notably rooftop PV is growing at an accelerated pace and is expected to shape the future power system [79]. Solar PV prosumers may be one of the very important enablers of the energy transition [79]. Solar PV prosumers with batteries may not require as much electricity from the central grid. Results indicate that Ethiopian PV prosumers with batteries can reduce their consumption from the grid by 38 TWh (19%), while increasing the energy system resilience. The continuous decline in the cost of solar PV will prompt further cuts in LCOE for PV prosumers, which will stimulate the PV prosumer sector in the nearest future. Solar PV electricity generation is key to achieving a deep defossilisation of the Ethiopian energy system and is comparable for other Sun Belt countries [23,25–28,30,44].

5.2. No technical showstoppers to the transition

Security of energy supply is persistently expressed as a concern in power systems dominated by VRE. This study demonstrates how a renewable-led generation can overcome the challenge of grid instability and available solutions are discussed in this section. The Ethiopian generation mix demonstrates a tendency towards greater flexibility and complementarity. The future mix of hydropower and wind energy can balance the rainy period, when generation from solar PV, the prime source of electricity is limited. Additional flexibility in the energy system is provided by storage technologies, grid interconnections, generation curtailment and sector coupling.

Storage technologies provide flexibility in the energy system, the contribution of both electricity and heat storage increases significantly towards the end of the transition. Electricity storage installed capacity and output is dominated by battery storage. In BPS-1, prosumer battery dominates until 2045, utility-scale battery becomes relevant only in 2050. Prosumer battery output increases from around 0.2 TWh in 2025 to 20 TWh in 2050, whereas utility-scale battery output increases from less than 0.01 TWh in 2045 to 33 TWh in 2050. In BPS-2, utility-scale battery output increases from around 0.01 TWh in 2045 to 53 TWh in 2050. Through most of the transition available hydropower dams capacity and flexibility from PtX technologies are adequate to balance the centralised power system generation and demand. PV-battery hybrid systems emerge as the least cost option, as observed in the BPSs. The possibility of PV-storage hybrid systems dominating the future energy system is also highlighted in recent studies [80,81]. Battery costs have declined by roughly 85% between 2010 and 2018 [82]. Further cost reduction of batteries is expected [83,84], which will drive PV growth [18,69], in addition, PV cost declines continue as projected by Vartiainen et al. [69]. Regarding heat storage, TES and gas storage contribution increases significantly from 2035 onwards. TES dominates from 2040 until 2050 and is supported by gas storage. Storage requirement through the transition is low, rather dispatchable RE, especially hydropower acts as virtual storage in the energy system. In the CPS, battery storage output is less than 1 TWh through the transition. Similarly, heat storage requirements are low in the CPS compared to the BPSs. The plausible reason for low storage requirements in the CPSs is due to a very high share of hydropower and fossil fuel contribution. It is worth mentioning that supply side flexibility of the Ethiopian power system is largely linked to the flexibility of the dammed hydropower plants in the country.

Grids provide additional operational flexibility. The transmission interconnection facilitates the penetration of RE by increasing the use of geographically distributed resources across the country. Grid utilisation is also observed to be vibrant during the rainy periods for all scenarios, due to reduced output from solar PV. Hourly generation in the best and worst weeks, regarding renewable electricity supply is available in the Supplementary Material (Figures S32–S33). In sum, grid utilisation appears to be more positively related to solar PV and hydropower generation. The hydropower flexibility would have been locked, if there were not enough grid capacities to connect load centres to regions of low-cost supply. Energy curtailment is another operational strategy to stabilise the grid and improve energy system flexibility. Curtailment is usually anticipated to grow with high shares of variable RE [85–87]. Generation curtailment increases especially in the BPSs from 2035 until 2050. In 2050, curtailment of electricity generation is 6–8 TWh (2%) in the BPSs and is around 4 TWh (2%) in the CPSs. A certain level of curtailment in optimally managed energy transition brings techno-economic opportunities to the system [85]. Notably, the found level of curtailment of the strongly sector coupled Ethiopian energy system is one of the lowest ever reported for a 100% system mainly based on VRE. Graphical results on curtailment through the transition is provided in the Supplementary Material (Figure S34).

The findings of this study consolidate the move of scientific insights towards the concept of electrification of almost everything [44,88]. An electricity-based supply, as observed in this study, increases energy system flexibility by coupling decarbonised electricity to all energy sectors. PtX options are very important for deep defossilisation and energy sector coupling strategy. Demand that cannot be directly electrified can be supplied by PtX solutions. It is noteworthy that Ethiopia having abundant and cheap RE resources could create new industrial opportunities in the production of hydrogen-rich chemicals and synthetic fuels, as found earlier for the Maghreb region [89,90].

The need for flexibility will continue to increase in RE dominated energy systems, especially when VRE sources become the dominating technologies [28]. Grid instability in energy systems with a low share of synchronous generators can be remedied with flexible gas turbines or engines and other emerging technologies [29,87,91]. Integration of synthetic inertia in a system dominated by VRE is confirmed as an attractive option for SSA in a 100% renewable power system [11].

5.3. Comparison of key parameters in best policy scenarios and currents policy scenarios in 2050

This section compares the BPSs and CPSs. Table 3 highlights the key differences in selected parameters for 2050. This research shows that a fully defossilised energy system is the cost optimal solution for Ethiopia by 2050, which is an important finding for developing economies of similar climatic and socioeconomic conditions.

Primary energy reduction is one of the fundamental features of an energy system primarily based on electricity, as observed in this study, especially in the BPSs. The primary energy reduction stems from moving to renewable-based electricity and electrification of energy services in comparison to the current inefficient combustion driven system, powered by fossil fuels. The findings of this research consolidate the important role of electricity in the future energy system [44,88]. According to IEA, electricity comprises of 40% of final energy demand in 2040, global electricity demand is expected to increase by 60%, with developing economies accounting for over 85% of the global growth [92]. With GHG emissions cost, the BPSs show approximately 12% less primary energy demand, 43% less total annualised cost, 9% less levelised cost of energy than the CPS. Similarly, the BPSs show about 15% less primary energy demand, 23% less total annualised cost, 6% less levelised cost of energy than the CPS, without GHG emissions cost. The total annualised cost of the energy system through the transition is shown in Fig. 28. Additional graphical results on primary energy demand and efficiency gains are available in the Supplementary Material (Figures S35–S37).

5.4. Energy justice and zero GHG emissions solutions for ethiopians

Ethiopia's zero GHG emissions energy future includes off-grid electrification and access to clean cooking [6]. Many households in Ethiopia can be classified as fuel poor, due to difficulties in affording clean and adequate energy [93]. The number of Ethiopians without access to clean cooking is over 90 million and around 59 million are without access to electricity in 2018 [7]. The Ethiopian National Electrification Program (NEP) aims at 100% electrification by 2025, relatively composed of 35% off-grid and 65% grid, and 96% grid connections are expected by 2030 [10]. Access to modern energy systems could present millions of Ethiopians with opportunities to improve experiences of using energy [93]. There are stark disparities in the rates of access to electricity in urban and rural areas, over 90% have access to electricity in urban areas, while access remains low at 30% in rural areas [7]. Rural dwellers in Ethiopia rely mainly on traditional biomass for cooking and heating [93].

The results of this research highlight the significant role of solar PV in Ethiopia's future energy system. Solar PV systems are modular and durable source of electricity, ranging from watts to gigawatts, these features make PV systems suitable for off-grid electrification [94,95]. On the positive side, solar PV users in remote areas can also benefit more by storing electricity in battery

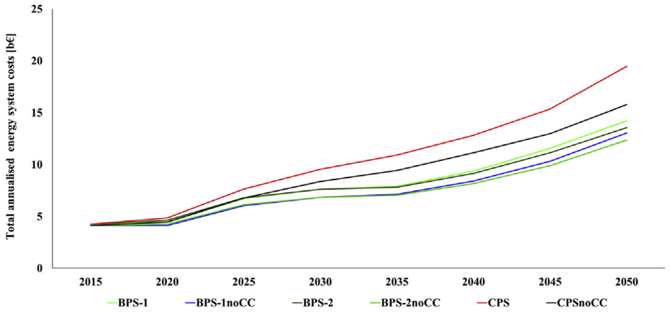

Fig. 28. Trajectory of total annualised energy system costs per year through the transition for all scenarios.

Table 3
Differences in key energy system parameters and financial outcomes in 2050 for all scenarios.

	Unit	BPS-1	BPS-1noCC	BPS-2	BPS-2noCC	CPS	CPSnoCC
Financial outcome							
Levelised cost of energy	[€/MWh]	39	36	38	34	47	38
Total annual system cost	[b€]	14	13	14	12	20	16
Cumulative system cost	[b€]	274	248	271	244	346	302
Energy parameters							
RE share in PE	[%]	67	58	66	57	49	45
Demand	[TWh]	333	280	333	280	280	260
Generation	[TWh]	345	290	343	288	286	267
Installed capacity	[GW]	144	118	137	108	105	96
Primary energy demand	[TWh]	460	440	470	448	510	520
Primary energy demand per capita	[MWh/person]	2.4	2.3	2.5	2.3	2.6	2.7
GHG emissions							
Baseline	$MtCO_{2eq}$	16					
Emissions 2050	$MtCO_{2eq}$	0	11	0	10	22	28

or for water heating purpose [95]. The continuous decline in PV cost will make off-grid solar PV technologies relevant for rural electrification, particularly in remote areas where grid connections are prohibitively expensive or national budgets for electrification are limited [23].

For unelectrified rural areas, solar PV system appears the better option for providing modern energy supply [94,95]. Bertheau et al. [96] modelled two scenarios to investigate the effects of future grid expansion plans in SSA, using geospatial methods. In the first scenario based on the existing grid, electrification options are composed of 40% solar home systems (SHSs), 5% mini-grids and 55% grid extensions. The second scenario, in which modelling was based on the planned grid, 35%, 4% and 61% can be electrified by SHSs, mini-grids, and grid extensions, respectively, hence more by grid extensions as shown in Fig. 29. Another study on electrification planning in Ethiopia [97], distinguishes three categories of technology penetration, 1%–33% grid, 34%–66% mini-grid and 67%–100% stand-alone systems to provide universal access by 2030.

Further, access to clean cooking and heating remains a challenge in Ethiopia, over 95% of households continue to depend on polluting fuels and technologies, especially biomass, which results in health and environmental problems [93]. Ethiopia's emissions from burning wood fuel is projected to increase from 25 $MtCO_{2eq}$ in 2010 to over 40 $MtCO_{2eq}$ in 2030 [93]. Household energy consumption in Ethiopia will shape the future emission pathways of the country, energy policies in the country should consider households as vital stakeholders in the decarbonisation plan. Tackling climate change means shifting away from unsustainable biofuel for cooking and fossil fuels for lighting to zero emission innovations. In general, households through their consumption behaviours account for 72% of global GHG emissions [98]. Decarbonising household energy in Ethiopia provides opportunities to improve energy services that will eliminate fuel poverty and polluting fuel use. Policies, programmes and plans to tackle energy injustice and promote economic development in Ethiopia should be based on sound principles of respect, sustainability, affordability and equity.

5.5. Benefits of the energy transition

The benefits of this transition are discussed through the lens of three interconnected sustainability dimensions, namely environmental, social and economic benefits.

Renewable energy transition will dramatically transform the Ethiopian economy. The economic benefits are discussed in terms of investments and employment creation during the transition. Investments in RE will stimulate socio-economic development, especially job creation in Ethiopia. Electrification of energy services will provide many new jobs. Sceptics of renewable energy frequently question if the sector can realistically create the numbers of jobs as in the fossil-based system [88]. The results of this study show that a shift to a sustainable energy system will create far more jobs as observed in the BPSs than in the CPS. A 100% RE system would employ nearly 1 million people in Ethiopia and solar PV emerges as the major job creating sector, employing over 275 thousand in 2050. Jobs increase by 10 and 5 times more in 2050 compared to 2015, in the BPS and CPS respectively. In the CPS, most of the jobs in the heat and transport sectors are related to fuel supply, due to partial decarbonisation in these sectors. Several studies [46,49,50,88] indicate that RE transition will create more jobs, which is comparable to the findings of this research.

The environmental benefit is discussed in terms of GHG emissions reduction through the transition under various scenarios. Examining the application of GHG emissions costs during the transition, particularly in the BPSs results in a rapid transition and gradual GHG emissions reduction and reaches zero GHG emission in 2050, as shown in Fig. 30. The results show a slower energy transition and GHG emissions reductions without GHG emissions costs. Furthermore, without GHG emissions costs, zero GHG emission was unattained across all scenarios, as shown in Fig. 30. In the CPSs, zero GHG emission was not reached by 2050. However, with emissions costs, GHG emissions reduced by about 27% in the CPS. With GHG emissions costs, the remaining cumulative GHG emissions are approximately 67% lower in the BPS compared to CPS (0.2 $GtCO_{2eq}$ vs 0.6 $GtCO_{2eq}$), without GHG emissions costs it is about 43% lower in the BPSs compared to CPS (0.4 $GtCO_{2eq}$ vs 0.7

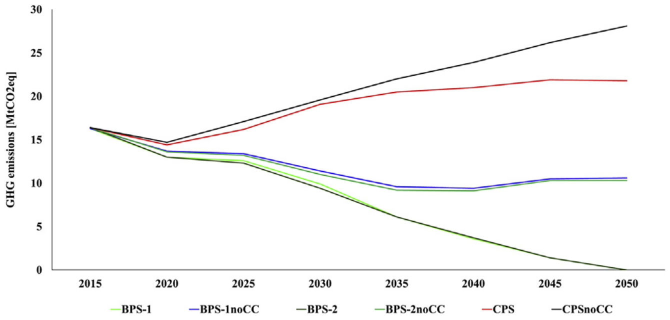

Fig. 30. Trajectory of GHG emissions through the transition for all scenarios.

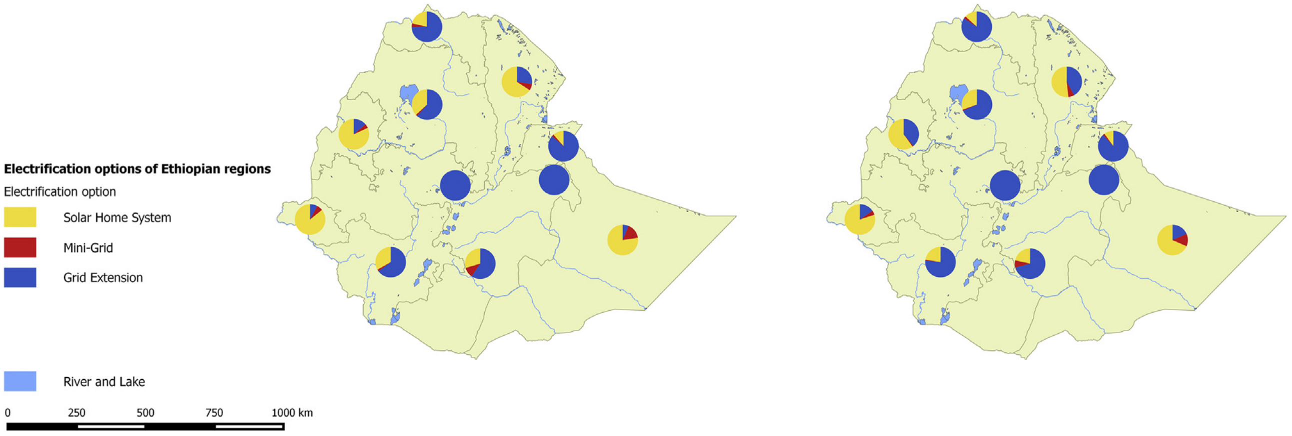

Fig. 29. Electrification options for Ethiopia - existing grid (left) and planned grid (right) [90].

$GtCO_{2eq}$), and is aggregated from 2018 to 2050.

The social benefits are discussed in terms of improved energy services. Energy is vital to socio-economic development. Results of this study show that Ethiopia can migrate from being an energy poor to an energy rich country. The primary energy demand with high electrification is expected to increase as observed in this study. Correspondingly, the average per capita energy demand increases from around 0.8 MWh/person in 2015 to nearly 2.5 MWh/person in 2050, while the population is expected to grow from 100 million in 2015 to 191 million in 2050. Furthermore, improved energy services for domestic purposes such as heating and cooking is anticipated in this study. Advancing a green energy system as illustrated in this research will enable millions of Ethiopians to overcome poverty and improve their livelihoods in a sustainable manner. Policies to drive social equity are vital for all stakeholders to enjoy the benefits of the energy transition. Such policies should ensure social inclusiveness and capture the principles of energy justice described in Refs. [1,99], especially for rural households due to their vulnerability to energy poverty. Further, there is a need for sustained dedication to alleviating energy poverty through national government policies [100]. On the technology side, deployment of RE technologies as observed in the BPSs supports environmental sustainability and makes the society more self-reliant.

5.6. Influence of varying cost parameters on results

This research is primarily focused on a cost optimisation of the future energy system. A combination of both market development and scientific literature is adopted in deriving the technical and financial parameters of various technologies, which are crucial in determining a cost optimal energy transition pathway. The modelling outcome shows that the PV-battery hybrid system emerges as the backbone of the least-cost generation mix by 2050, owing to the anticipated decrease in CAPEX. The applied PV CAPEX is comparable to that of the World Energy Outlook (WEO) 2020 for 2040 [101]. Latest insights from the WEO 2020 technology cost projection for all technologies including fossil fuels, deliver a clear message that the fossil age is gradually disappearing.

Nevertheless, it must be acknowledged that changing cost parameters would have an impact on the technology roll-out, as it seems that the cost and rate of capacity installation are directly correlated, which is a crucial aspect of a cost optimal energy system. The impact of technology cost sensitivity is not explicitly stated; however, scenario variations are the means to compare the impacts of some assumptions. The costs of investments in the BPSs are offset by savings in fuel and GHG emission costs in the CPSs. It is worth mentioning that the cost assumed maybe too conservative or too optimistic over time. On the other hand, system solutions would not be structurally different, as solar PV and battery would still emerge as the backbone of the future energy system.

6. Conclusions and policy implications

Greening the Ethiopian energy system comes with multiple co-benefits including job creation, improved energy services and human welfare. The benefits of energy transition transcend the energy sector itself, given the many-sided links and interactions with the broader economy. There are no technical showstoppers in pursuing a sustainable energy system in Ethiopia, but a strong political will is crucial to delivering this kind of energy transition. This study depicts the possibility of achieving Ethiopia's GRCE Vision 2025, which is an important fact for African countries to realise the Africa Vision 2063, SDG 7 and contribute to the Paris Agreement.

The massive roll-out of RE capacities in BPSs is the least cost option for Ethiopia without subsidies. However, subsidisation might be inevitable if a policy-triggered deviation from this techno-economic least-cost path is followed. A well-designed policy framework with clear RE targets in a long-term perspective and comprehensive energy market reforms are needed. Energy policy in Ethiopia should consider investments in scalable and modular RE technologies in order to achieve rapid electrification, especially in remote areas where grid connection is prohibitively expensive. Investments in large scale hydropower projects in Ethiopia should consider the susceptibility of such projects to climate change. Beyond the susceptibility of hydropower to climate change, hydropower projects often suffer schedule spills and cost overruns. To this end, hydropower planning may require a recheck and reconsideration on underlying assumptions to capture and evaluate associated risks, especially in developing economies like Ethiopia.

The BPS offers multiple social co-benefits including access to modern energy services for cooking, heating and other purposes. Energy policy in Ethiopia should consider social inclusiveness, especially for rural households due to their vulnerability to energy poverty. Such a policy should be based on sound principles of energy justice, so that energy services can be available, accessible and affordable for all. Further, jobs creation during the transition is instrumental in achieving a broader societal goal and stability. Jobs created during the transition is noteworthy for the government and policy makers in Ethiopia. The BPS creates more jobs and costs less than the CPS.

Transition to a sustainable energy system is a real policy option for Ethiopia, where solar PV emerges as the bulk energy supplier, complemented by hydropower and wind energy. Energy policy in Ethiopia should have at its core, energy resource diversification, rather than developing one resource as the current system relies on hydroelectricity. From the energy supply side, a good mix of energy resources, as observed in this study, is vital for ensuring stable energy supply, increased resilience, and improved energy system flexibility, which is an important aspect for systems with high shares of RE. An optimal resource mix will reduce the vulnerability of the energy system to climate change. An electricity-based energy system is achievable, and it is characterised by a reduced primary energy demand as observed in this research. Ethiopia can progressively defossilise its energy sector by coupling its low-cost RE electricity to desalination, heat and transport sectors. Also, the abundant and cheap RE electricity could create new industrial opportunities in producing synthetic fuels, which are equally important for sectors that cannot be directly decarbonised by RE electricity.

Enabling energy related-policies and political will at all levels of governance in Ethiopia is fundamental in promoting the deployment and integration of RE. Sound policies are vital to generate maximum benefits of the energy transition. The findings of this research are noteworthy for energy planners and policymakers in Ethiopia, and an important reference for developing economies especially in SSA. This study is an example of how developing economies with similar climatic as well as socioeconomic conditions can transition to renewable energy for all purposes without violating the fundamentals of sustainability.

CRediT authorship contribution statement

Ayobami Solomon Oyewo: Data curation, Conceptualization, Writing – original draft, Modelling, Visualisation, Investigation. **A.A. Solomon:** Validation. **Dmitrii Bogdanov:** Methodology. **Arman Aghahosseini:** Resources. **Theophilus Nii Odai Mensah:** Data curation. **Manish Ram:** Methodology, Formal analysis. **Christian Breyer:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they do not have any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2021.05.029.

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