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Setting the Pace for a Sustainable Energy Transition in Central Africa: The Case of Cameroon

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ABSTRACT Sustainable energy systems form an indispensable component of sustainable development especially in developing economies. Therefore, understanding the system wide techno-economics of sustainable energy systems becomes critical in shaping the energy system mix within a region or country. This paper explores Cameroon's progressive and optimal pathways towards a fully sustainable energy system by 2050 in power, heat, and transport sectors as a representative case study for the Central Africa region. Six key scenarios are modelled with the LUT Energy System Transition Model to capture key policy and sustainability constraints. Results from the study show that the optimal least-cost technology combination for a fully sustainable energy system for Cameroon with net-zero greenhouse gas emissions in 2050 is dominated by solar PV (86%), complemented by hydropower (8%), and bioenergy (5%). These results show that a fully sustainable energy system for Cameroon is feasible from both the technical and economic perspectives if policy commitment is oriented towards these low-cost energy solutions. The results of this research provide a reliable reference for planning transitions towards a 100% renewable energy-based energy system in countries within the Central Africa region.

INDEX TERMS Energy system modelling, Cameroon, Central Africa, 100% renewable energy, sustainable energy transition.

I. INTRODUCTION

The 1.5°C target of the Paris Agreement projects a net-zero carbon economy by 2050 and emphasizes on the need for timely actions to combat anthropogenic climate change [1]. In this vein, as the need for a global energy system transition becomes indispensable, planning of this transition at national levels are priorities [2], [3]. A key aspect of these national government actions pivots on the defossilisation of the energy system to provide clean, affordable, and reliable energy based on Sustainable Development Goal (SDG) 7 and to support attainment of the other 16 SDGs [4]. In sub-Saharan Africa (SSA), research on the progressive transition to a 100% renewable energy (RE) system on national regimes has proven to be the best option in the three spheres of sustainability (economic, social, and environmental). This is in particular for South Africa [5], Nigeria [6], West Africa [7], Ethiopia [8], and Ghana [9]. Similarly, 100% RE systems are also the most attractive energy system solution on regional regimes [10]. Drawing inspiration from these studies [5]–[10], this paper investigates a system wide energy transition, in an hourly resolution, for the Central African region using Cameroon as a case study. The modelling outcome of this study can steer relevant and cross-national comparable policy towards achieving sustainable energy system transitions in Cameroon and other Central African countries.

A. ENERGY AND POLICY CONTEXT

The United Nations Statistics Division (UNSD) [11] classifies the Central Africa region to consist of nine countries, namely: Angola, Cameroon, Central African Republic (CAR), Chad, Congo Democratic Republic (DRC), Congo Republic, Equatorial Guinea, Gabon, and Sao Tome and

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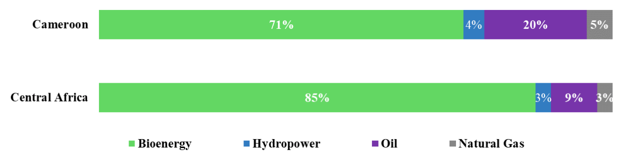

FIGURE 1. TPES for Cameroon and Central Africa in 2017.

Principe. The region's population in 2020 is estimated at 180 million inhabitants and is projected to reach 383 million by 2050 [12]. Cameroon is the third most populous country in the region after DRC and Angola with a population estimated at 26.5 million in 2020 and projected to reach 50.6 million by 2050 [12]. Compared to other regions in the continent, Central Africa has the least access to electricity, the least installed power generation infrastructure, and very little regulatory policies to boost the development of sustainable energy systems [13]. The region's electricity access rate in 2018 was estimated at 26% which is comparatively lower than the electricity access rates for West and Southern Africa estimated at 53% and 48% respectively [14]. Within this region, Cameroon is the sole country out of the nine regional countries to have regulatory policies and fiscal incentives promoting the development and integration of renewables [15]. Cameroon is therefore chosen as case study because of its potential to stimulate and lead a sustainable transition within the region.

Traditional biomass dominates the total primary energy supply (TPES) in both Cameroon and Central Africa accounting for 71% and 85% respectively [16] as illustrated in Figure 1.

Central Africa's total installed power capacity is 5.5 GW [13], with hydropower generation capacity estimated at 4.2 GW [17], representing 76% of the generation capacity. So far, the region has largely relied on electricity generation from hydropower and there has been very little development of other variable renewable energy (VRE). Regarding the case study of interest within this region, Cameroon established a strategic national vision for growth and development (DSCE) to become an emergent economy by 2035 [18]. Government actions are therefore consolidated to foster sustainable development and to simultaneously eradicate extreme poverty within the country following the Poverty Reduction Strategy (PRSP) jointly established with the International Monetary Fund (IMF) [19]. Three strategic government plans have been enumerated relating to energy access, energy security and environmental sustainability; the energy sector development plan (PDSE) [20]; the rural electrification masterplan (PDER) [21], and the renewable energy master plan (REMP) [22]. Furthermore, in 2015, Cameroon submitted a plan of its Intended Nationally Determined Contributions (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC) on the country's targets and intended contributions by 2035 to the global efforts on climate change [23], [24]. These plans are principally oriented towards developing the hydropower (reservoir and run-of-river) resource potential in the country and extending the grid networks to remote areas, while solar, wind and bioenergy have received very little attention in the government's proposed energy mix [22]. Hydropower development in many parts of the world either suffers from cost overruns or project schedule extensions [25], [26], same is the case in Cameroon [27]. Furthermore, hydropower development painstakingly meets the energy demands of the rural inhabitants who have little access to the electricity grid [28]. The holistic nature of this research therefore integrates all the available energy resources in Cameroon to form an energy mix that meets the SDG 7 goal of accessibility, affordability, and environmental sustainability.

B. A REVIEW OF THE STATE OF 100% RE RESEARCH IN SSA

This section presents the state of the art on research towards 100% RE systems in SSA as a precursor to a comprehensive assessment of the transition to 100% RE in Cameroon. A comprehensive review on the status of 100% RE systems highlights Africa as the region with the least coverage [29], prompting the need for an extended spatial coverage of research to 100% RE systems in the region. The most prominent 100% RE transition studies in SSA are those of Oyewo *et al.* [5]–[8], [30] and Barasa *et al.* [31]. Few studies have also analysed a 100% RE transition for countries in SSA, mainly applying an overnight approach for Réunion island [32]–[34], Mauritius [35], Cape Verde [36], and Nigeria [37]. It is worth noting that the studies of Breyer *et al.* [38], [39], Bogdanov *et al.* [40], [41], as well as those of Jacobson *et al.* [10], [42] carried out at a global level include selected countries and regions in SSA. Results from Oyewo *et al.* concluded that, by 2050, a 100% RE system is the least-cost, least GHG emitting energy supply option for Nigeria [6], West Africa [7], South Africa [5], and Ethiopia [8] which is similar to the findings of Mensah *et al.* [9] for Ghana. Furthermore, in the case of South Africa, West Africa, and Ethiopia, the results show that a 100% RE system also is the most job-rich energy system configuration. Barasa *et al.* [31] also found similar results depicting a 100% RE system as technically and economically feasible and practical solution for SSA by 2030. To the knowledge of the authors, no research has so far been solely conducted on transitions to sustainable energy systems on hourly resolution in Cameroon or Central Africa. Most of the studies in this region carried out on Cameroon principally focus on estimating the renewable energy resource potential and the role of policy in renewable energy deployment, as will be reviewed in the following section.

C. REVIEW OF THE RENEWABLE ENERGY SITUATION IN CAMEROON

This section reviews the most prominent literature on RE resource potential, and the role policy has in developing these renewable resources in Cameroon. On resource estimation, Abanda [43] reviewed the potential benefits and enabling environments of various renewable energy sources in Cameroon. He concluded that solar and biomass energy are abundant throughout the country, and wind energy is in few regions. The abundant solar potential in Cameroon is marked by high global horizontal irradiation, which ranges from 2190 kWh/($m^2 \cdot a$) in the northern parts of the country to 1537 kWh/($m^2 \cdot a$) in the southern parts of the country [44], with an average value of 1789 kWh/($m^2 \cdot a$). Similarly, Abanda concluded that, wind is available in selected parts, especially in the country's northern parts with wind speeds ranging between 2.8-4.1 m/s and decreases towards the southern parts with average wind speeds ranging from 1.2-1.8 m/s. Kwaye *et al.* [45] further confirmed the findings of Abanda, emphasising the trend of decreasing wind speed moving from northern to the southern parts of Cameroon. However, they mentioned that in some cities in the southern parts of the country, especially in Ngambe in the Littoral region and Kribi in the South region, average wind speeds of 2.6-4.1 m/s can be obtained. Furthermore, Tansi [46] assessed the wind and solar resource potentials throughout the 10 regional cities in Cameroon using RETScreen software. His findings align with those obtained by previous authors with abundant solar, bioenergy and hydropower potential. Several authors also confirm the abundance of hydropower resources in Cameroon [43], [47], [48]. Some authors argue that the geothermal resource in Cameroon needs to be effectively assessed [43], [48], [49]. Aghahosseini and Breyer [50] estimated the enhanced geothermal system (EGS) potential excluding water stress and economic constraints at 1.62 GW of power capacity for Cameroon as part of a global estimation of the ESG potential for countries grouped into 145 regions. More research is therefore needed to evaluate the actual potential of geothermal energy in Cameroon. In addition, Kenfack *et al.* [13] assessed the available RE resources within Central Africa, including Cameroon and identified actions to promote their development. One key finding worth noting from their research is that weakness of institutions is a critical obstacle to RE development within the region. Muh *et al.* [47] also reviewed the energy policies in Cameroon and concluded that a blend of adequate policies, regulations and off-grid RE investments are needed to improve the country's access to RE. In addition, Kenfack *et al.* [51] reviewed the potential for hydropower development in Cameroon under the vision of the Central Africa Power Pool (CAPP). Their conclusions are strongly inclined towards hydropower as a sustainable energy solution for Cameroon. However, they acknowledged the slow development of many hydropower projects in Cameroon which poses significant bottlenecks to curb the country's energy problems. The authors further report poor visibility on information about the hydropower potential in Cameroon. Such information should take into account changing hydrological patterns due to climate change [51]. The low exploitation of the available renewable resource potential is highlighted by Tangka [52]. He further explained that some laws have been so far responsible for the poor performance of the energy sector, however, with ratified international climate treaties, Tangka believes Cameroon is ready to start the exploitation of these renewable sources. Fossong *et al.* [53] also stressed that RE will be a major driver of economic growth both in the short and long term in Cameroon. Several institutional actors are therefore expected to drive the implementation of strategies for such a RE future [47], [54], [55].

The narrative drawn from the literature points to abundant renewable resources, especially for solar energy and the need for efficient policies to drive a sustainable energy strategy in Cameroon. These strategies should also allow for off-grid electrification to cater to rural communities out of which only 14% have access to electricity [48]. As such, it is key to review the status of off-grid electrification in Cameroon.

D. STATUS OF OFF-GRID ELECTRIFICATION IN CAMEROON

Remote communities, especially those in developing countries, are often isolated from the central electricity infrastructure due to the high cost of grid extension. As these high costs in grid extension cannot be balanced by the remote communities, grid extension endeavours are economically not viable [56]. Off-grid electrification plays a vital role in providing access to electricity in rural areas of developing countries using a decentralised generation strategy, suitable for small and mid-size electricity generation projects [57], [58]. With the attractiveness of off-grid electrification as a vital solution for the electrification of rural communities, several remote areas are adopting this electrification strategy. Table 1 reviews various off-grid projects implemented throughout the national territory of Cameroon. The major literature findings show that hybrid off-grid configurations are effective for rural electrification in Cameroon. In addition, solar PV and diesel generators are seen as essential technologies in the hybrid configurations for Cameroon based on the 10 studies reviewed as shown in Table 1.

E. RESEARCH NOVELTY

So far, the reviewed literature on energy system analyses for Cameroon comprises either resource estimations, the role of policy on developing the energy infrastructure, or small-scale system configuration for off-grid electrification. These studies are vital in establishing baselines for which energy resources require policy attention or designing small-scale energy systems. However, from a broader national perspective, they do not address the technical and economic feasibility of developing these energy resources over time in terms of capacity installations and energy system cost. This article analyses the techno-economics of a transition to a fully sustainable energy mix for Cameroon on hourly resolution and for a fully sector-coupled system. This research is the first of its kind for Cameroon with concise feasibility of energy system cost evolution based on transparent assumptions. The underlying thinking for this research is that least-cost energy systems are highly attractive for policy adoption globally [59] and could therefore be highly attractive for Cameroon as well. The outcome of this research is therefore geared in steering policy towards a progressive transition to a 100% RE system

TABLE 1. Review of the off-grid electrification literature for Cameroon.

Study/year	Location	Technologies	Model	Description
Muh and Tabet, 2019 [60]	Wum as representative of Southern part of Cameroon	PV, wind, micro hydro turbine, diesel generator, battery storage, charge controllers, and inverters	Homer	This study assessed the feasibilities of nine hybrid systems using Homer for remote application. A PV-diesel-(small)hydropower-battery hybrid configuration was found to be a most economically viable option with a 0.443 $/kWh (0.368 €/kWh) energy cost.
Ayerbe, 2020 [61]	Akak Bitetele (Endom District) in the Centre Region	Solar, micro hydro, battery storage, and diesel generator	RAMP and MicroGrids.Py	The study analysed a micro hydro, solar PV based generation and a hybrid configuration comprising hydro and PV using the RAMP model and MicroGrids.Py. A hydropower-based system was found to be the most economical solution but needed a generator backup during dry seasons. A hybrid configuration of hydropower, solar and battery storage eliminated the need for backup generators but increased the system cost.
Nfah, 2013 [62]	Remote villages in Far North	Solar, battery storage, and diesel generators	HOMER	A hybrid system was designed consisting of a 12.5 kW diesel generator, a solar PV system ranging from 15.3-21.42 kWp and a battery storage of 274.56 kWh capacity for both varying and constant daily energy demands. The optimal configuration for the hybrid system had more than 88% RE fractions for both constant and varying energy demands.
Nfah and Ngundam, 2009 [63]	Villages in the South region for scenario 1 and villages in the North region for scenario 2	Pico-hydro, solar PV, battery storage, biogas generator	HOMER	Two hybrid configurations are tested to analyse their economic viable. Scenario 1 comprised of a pico-hydro-biogas-battery system while in scenario 2, the pico-hydro of scenario 1 is replaced with solar PV. The authors found that the cost of energy for both scenarios were in 0.352 €/kWh for scenario 1 and 0.396 €/kWh for scenario 2. The authors conclude that the off-grid electrification option based on RE resources including biogas could compete favourably with grid extension.
Nfah et al., 2008 [64]	Villages in the Southern parts of Cameroon and villages in the Northern parts of Cameroon	Micro-hydro generator, LPG generator, solar PV, battery storage	HOMER	Four hybrid systems are investigated in this study. Of these four hybrid systems, a micro hydro-LPG-battery system is the most economically viable option for villages in the southern parts. For the northern villages, a PV-LPG-battery system is the most viable option when the solar irradiation is greater than 2028 kWh/(m^2·a). The authors conclude of the possibility of an off-grid electrification based on RE resources in remote villages in Cameroon.
Nfah et al., 2007 [65]	Remote areas in the Far North	Solar PV, battery storage, diesel generator	Modelling in Matlab	An optimal hybrid configuration of PV-diesel-battery was designed with 350 Wp module power, 2.5 kW diesel generator, and 5.4 kWh battery storage capacity to meet an annual energy demand of 300 kWh. The renewable energy fraction of generation in the hybrid configuration was greater than 83%.
Mbaka et al., 2010 [66]	Remote villages in the Far North of Cameroon	Solar PV, battery system, and diesel generator	Net present value technique modelling	A comparative analysis is done for a hybrid system (comprising a PV, battery, and diesel generator), a standalone PV and a standalone diesel generator. The study concludes that the hybrid configuration was a more economically viable option than standalone PV or diesel generators.

TABLE 1. *(Continued.)* **Review of the off-grid electrification literature for Cameroon.**

Falama et al., 2021 [67]	Three towns in the northern part of Cameroon (Maroua, Garoua and Ngaoundéré)	Solar PV, battery storage and grid connection	Firefly optimisation algorithm	A PV-battery grid-connected hybrid system presented a long-term viable option for these three towns in the northern part of Cameroon. The results also found that, such a system reduced considerably the grid dependence with a PV-battery hybrid system providing 60-70% load supply in Maroua, 59-72% load supply in Garoua, and 62-73% load supply in Ngaoundéré.
Nsafon et al., 2020 [68]	Northern part of Cameroon (Touboro Community)	Solar PV, hydro, wind, diesel generator and wind turbine	HOMER	Simulation analysis of the six hybrid configurations were performed with Homer. Selection of the best hybrid alternative based on experts' interview was further carried out on the six hybrid configurations using the multi criteria decision analysis. Based on energy production, unmet load, net present cost and renewable energy fraction, results from the multicriteria yielded a hybrid system comprising hydro-wind-PV as the best suited energy system configuration for the northern villages.
Talla Konchou et al., 2021 [69]	Makenene in centre region	Solar PV, wind, battery storage, diesel generator	Multi-objective particle-swarm optimisation technique	This study analysed 7 hybrid configurations and a PV-battery-diesel generator was the most viable option with the lowest loss of power, least-cost of electricity, least net present cost and least annual emissions.
Bertheau et al., 2017 [70]	All countries in SSA	Electricity grids, mini-grids, and solar home systems (SHS)	Scenario modelling with Python 2.7 and QGIS.	This study modelled two scenarios to investigate suitable electrification options for countries in SSA, using geospatial methods. In a first scenario based on the existing grid, electrification options are composed of 25.7% SHS, 5.7% mini-grids and 68.5% grid extensions for Cameroon. The second scenario, in which modelling was based on the planned grid 18.9%, 3.7% and 77.4% can be electrified by SHS, mini-grids and grid extensions, respectively.

for Cameroon in 2050. This research also sets the pace for such a transition within the Central Africa region as most of the countries within this region possess similar energy contexts to those of Cameroon.

II. RESEARCH METHODS

Strategically located at the equator between latitudes 2° and 13°N and longitude 8° and 16°E, Cameroon consist of 10 political regions which are grouped into six key nodes as shown in Figure 2.

The six key nodes (NT, NA, ES, CN, LT, NSW) shown in Figure 2 represent geographic regions which are grouped for the modelling configuration. These six nodes are interconnected by optimised transmission networks.

The population projection for each node in Figure 2 and for the whole country from 2020 to 2050 is displayed in Table S1 of Supplementary Material.

A. ENERGY SYSTEM TRANSITION MODEL

Cameroon's energy system is modelled using the LUT Energy System Transition model, a linear optimisation model compiled in MATLAB with precise constraints and working on an hourly resolution for an entire year. The mathematical functions describing the LUT model as well as constraints and parameters are fully explained in reference [71]. The principal constraint of the model worth noting is that the model matches energy supply and demand for every hour throughout the entire year. In addition, the model is developed with excellent synergies between power generating technologies, storage, and sector coupling technologies. The objective function of the optimisation model is to minimize the total annual energy system cost, computed by summing annual costs of installed capacities of each technology, costs of electricity generation, and costs of generation ramping, for all technologies required for the covered energy sectors.

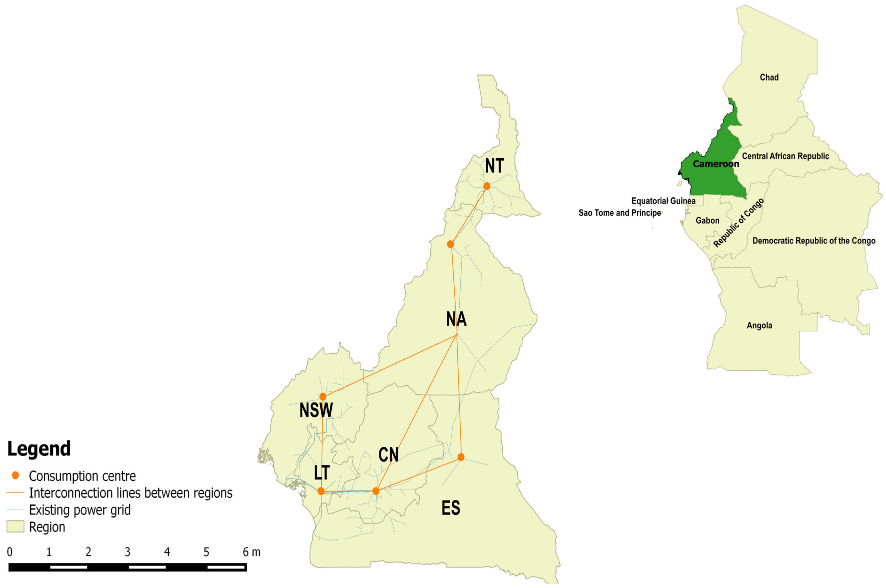

FIGURE 2. Geographic location of Cameroon. Abbreviations. NT: Extreme North; NA: North and Adamawa; ES: East and South; CN: Centre; LT: Littoral; NSW: North West, South West and West.

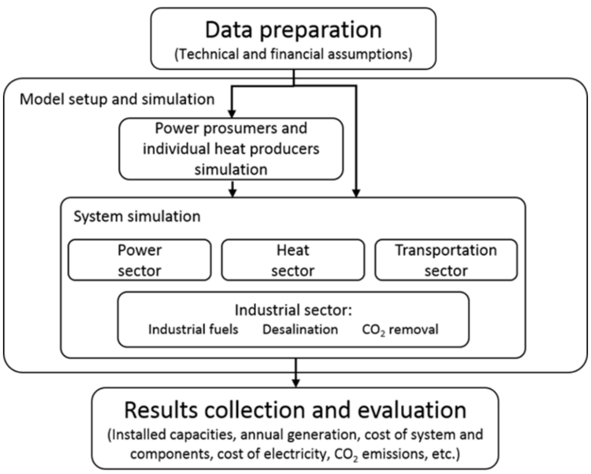

FIGURE 3. LUT energy system transition model schematic flow [38]–[41], [73].

The transition simulation was performed for the period from 2020 to 2050 in 5-year time steps. Figure 3 represents the structure of the LUT Energy System Transition Model. The LUT model was ranked highest among long-term energy transition models [72].

Included in the LUT model is the self-generation and consumption of heat (individual heating user system) and electricity (power prosumers) for end-users. The objective function of power prosumers and individual heating user systems is to minimize the annual cost calculated by the sum of the cost of prosumer power generation and storage, heating equipment, the cost of electricity required from the distribution grid, the cost of fuels required for boilers, and income of electricity feed-in to the distribution grid. Sold electricity is assumed to be remunerated with 20 €/MWh.

The following constraints which govern the model's operation are worth noting. Firstly, for each 5-year time step, the renewable energy installed capacities share cannot grow more than 20% of the total power generation capacities [74]. This is to avoid power system disruptions. Secondly, the system is constrained not to build any new coal or oil-based power plants after 2020, for avoiding stranded assets. However, installation of gas turbines is allowed as they have lower GHG emissions, higher efficiencies, and in particular, possibilities of accommodating synthetic gas and biomethane. Thirdly, hydropower plants are never fully decommissioned but refurbished after every 35years [74]. In addition, the model constrains the Fischer-Tropsch contribution for liquid hydrocarbon fuels in the transport sector to a stepwise progression from 3% in 2030 to 10% in 2035, 43% in 2040, 75% in 2045 and 100% in 2050. This does not compromise potential biofuel supply. The constraints apply mainly to Best Policy Scenario conditions but can be varied to other scenario types. The energy sectors considered in the LUT model are grouped into power, heat, and transport sectors. Technologies introduced into the model include electricity generation, heat generation, energy storage, transmission, transport, fuel conversion, fuel storage and sector coupling technologies and the model is fully described in [73]. The model setup is illustrated in Figure 4.

B. MODEL ASSUMPTIONS

1) FINANCIAL AND TECHNICAL ASSUMPTIONS

The LUT Energy System Transition model is a data-driven optimisation model with hourly resolution. It operates on robust technical and financial assumptions shown in Tables S2-S5 of Supplementary Material. The weighted

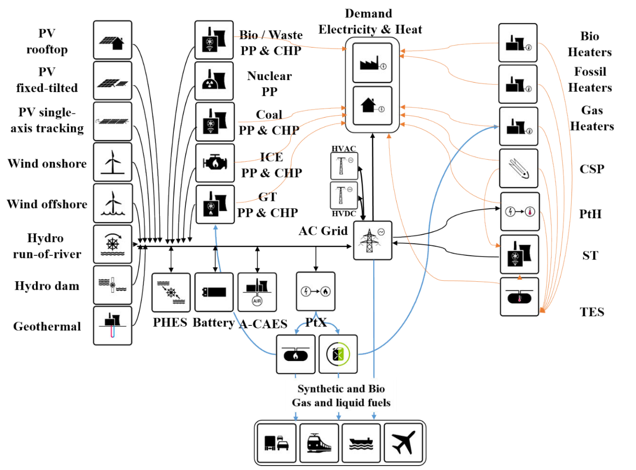

FIGURE 4. **Schematic of the LUT energy system transition model. Abbreviations: PP, power plant, ST, steam turbines, PtH, power-to-heat, ICE, internal combustion engine, GT, gas turbines, A-CAES, adiabatic compressed air storage, PtG, power-to-gas, PHES, pumped hydro energy storage, TES, thermal energy 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.**

average cost of capital (WACC) was assumed at 7% for all technologies except for residential PV prosumer which was assumed at 4% due to lower financial requirements. The electricity prices for residential, commercial, and industrial end-users are provided in the Supplementary Material (Table S6) and are projected from 2020 to 2050 based on a methodology formulated in [59], [75]. In addition, lower limits for RE installed capacities for 2020 are taken from [74], while the upper limits are calculated based on methodology in [40] and [76]. Values of the upper and lower limits of all technologies are shown in the Supplementary Material (Table S7-S8).

2) RENEWABLE ENERGY RESOURCE POTENTIAL

The hourly generation profiles for optimally fixed-tilted PV, single-axis tracking, and wind energy are calculated according to Bogdanov *et al.* [40] and Afanasyeva *et al.* [77] based on resource data obtained from the National Aeronautics and Space Administration (NASA) [78], [79], which is further processed by the German Aerospace Space Center [80]. The hydropower feed-in profile used in the model was based on precipitation data for the year 2005 [81]. The sustainable and economic hydropower potential is obtained from [82]. Biomass and waste potential for Cameroon were calculated using the method described in [9]. Maps of Cameroon showing annual full load hours of solar and wind resources can be found in the Supplementary Material (Figure S1).

3) ENERGY DEMAND

The electricity demand for each node and each year up to 2050 is calculated exogenously based on cumulative annual growth rates taken from [14]. 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 [83]. Transmission and distribution grid losses are estimated by the method from [84]. Heat demand profiles classified as low, medium, and high temperature heat are generated according to the method established in [85]. The transport sector is classified into road, rail, marine and aviation following reference [86]. All demand data are available in the Supplementary Material (Table S9, Figures S2-S9).

C. SCENARIO DEFINITIONS

This study models six distinct scenarios for an integrated energy system combining power, heat, and transport sectors for Cameroon. These scenarios are:

- **Best Policy Scenario (BPS):** The BPS aims for a 100% RE system by 2050. In this scenario, the model constraints are respected to allow a 100% penetration of renewables into the energy mix by 2050. This scenario targets no fossil use in the energy mix by 2050 and consequently zero GHG emissions. This scenario, therefore, complies with the Paris Agreement of net-zero GHG emissions from the energy sector by 2050.
- **Best Policy Scenario no Carbon Cost (BPSnoCC):** The BPSnoCC is like the BPS, however, in this scenario, no GHG emission cost is allocated to fossil fuel use.
- **INDC Scenario**: This scenario is developed based on Cameroon's intended nationally determined contributions which target a 32% reduction in the energy sector GHG emissions by 2035 compared to the projected business as usual scenarios of the base year 2010. This scenario aligns with the REMP [22], [23].
- **INDCnoCC Scenario**: This scenario is like the INDC except for the exclusion of a carbon pricing for fossil fuel use.
- **Current Policy Scenario (CPS):** The CPS is designed based on Cameroon's current performance targets [22].
- **Current Policy Scenario no Carbon Cost (CPSnoCC):** The CPSnoCC is the same as the CPS except no carbon pricing is applied to fossil fuel use.

In these six scenarios, as defined above, the model targets a holistic approach both from the financial, technical and sustainability points of view. Modelling the scenarios with and without GHG emission cost gives an integral understanding of externalities which are often neglected in techno-economics of energy systems.

III. MODELLING RESULTS

This section presents the results of the six scenarios analysed in this research. The main scenarios discussed in this section are the BPS, the INDC and the CPS. Graphical results of the BPSnoCC, the INDCnoCC, and the CPSnoCC are displayed in the Supplementary Material for comparative analysis and discussed where necessary.

A. TRENDS IN THE TOTAL PRIMARY ENERGY DEMAND

The total primary energy demand (TPED) by 2050 across the three scenarios is evaluated at 152 TWh for the BPS,

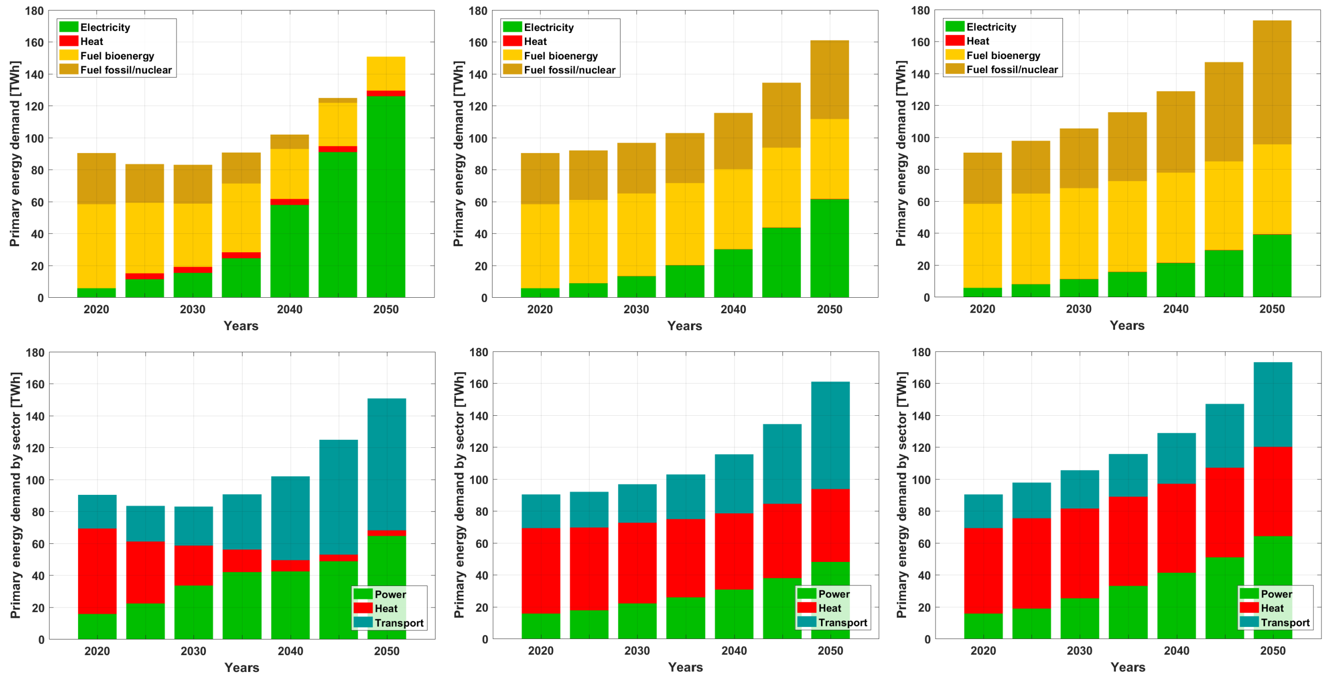

FIGURE 5. Total primary energy demand by energy sources used (top) and by sector (bottom) for BPS (left), INDC (centre), and CPS (right).

160 TWh for the INDC, and finally 173 TWh for the CPS. Figure 5 (top) depicts the TPED as a function of the energy sources used, while Figure 5 (bottom) shows the sector-wise TPED. On the sectoral assessment, there is a progressive reduction of the primary energy demand in the heat sector in the BPS while demand in the power and transport sectors increase steadily. The energy demand in the heat sector declines slightly in the INDC and remains constant in the CPS. Electricity forms the bulk of the TPED in the BPS beyond 2040, accounting for approximately 83% of the TPED by 2050 complemented by sustainable bioenergy and heat from renewable sources. Final energy demand figures across the scenarios can be found in the Supplementary Material (Figure S2). Massive electrification in the BPS results in a highly efficient energy system, thereby contributing to an overall reduction in the TPED as opposed to the INDC and the CPS (38% and 23% of electricity in the TPED respectively by 2050), which use significant portions of low efficient fossil fuels throughout the transition. The effect of efficiency gains on the primary energy demand across scenarios can be found in the Supplementary Material (Figure S3).

B. TRENDS IN THE POWER SECTOR

The cumulative installed capacity through the transition across scenarios is depicted in Figure 6. Absolute values of the installed capacities and annual generation for all scenarios are available in the Supplementary Material (Tables S10-S21, Figures S10-S11). In the BPS, the cumulative installed power capacity increases by a factor of 36 from a value of 1.8 GW in 2020 to 64 GW in 2050. In the INDC scenario and the CPS, the cumulative installed power capacity grows from 1.8 GW in 2020 to respectively 16 GW and 9 GW by 2050. For the BPS, beyond 2035, solar PV provides the bulk of the installed capacity which reaches 60 GW by 2050, with PV single-axis tracking accounting for 50 GW (78% of total installed capacity) and PV prosumers 10 GW (15% of total installed capacity). In contrast to the BPS, the INDC and the CPS have relatively lower shares of installed PV capacity by 2050 (49% and 38%, respectively), while hydropower remains dominant in the electricity mix throughout the transition and is complemented by fossil fuel-based power plants, wind and bioenergy. Electricity generation increases steadily to meet the demand, as shown in Figure 7. In the BPS, electricity generation from solar PV dominates from 2040 and beyond accounting for about 69% and 86% in 2040 and 2050 respectively, complemented by hydropower (8%) and bioenergy (5%) by 2050. In contrast, electricity generation in the INDC and CPS is dominated by hydropower up to 2050 accounting for 68% in the INDC and 66% in the CPS. The emergence of solar PV as the prime source of electricity generation in the BPS steers the pathway towards an efficient, highly decentralised, flexible and demand-driven system.

C. TRENDS IN THE HEAT SECTOR

A significant contrast is observed in the evolution of the heat demand in the BPS on the one hand and the INDC and the CPS on the other hand, as shown in Figure 8. As renewable electricity generation increases significantly in the BPS, the use of electricity in the heat sectors through appropriate power-to-heat technologies also increases with

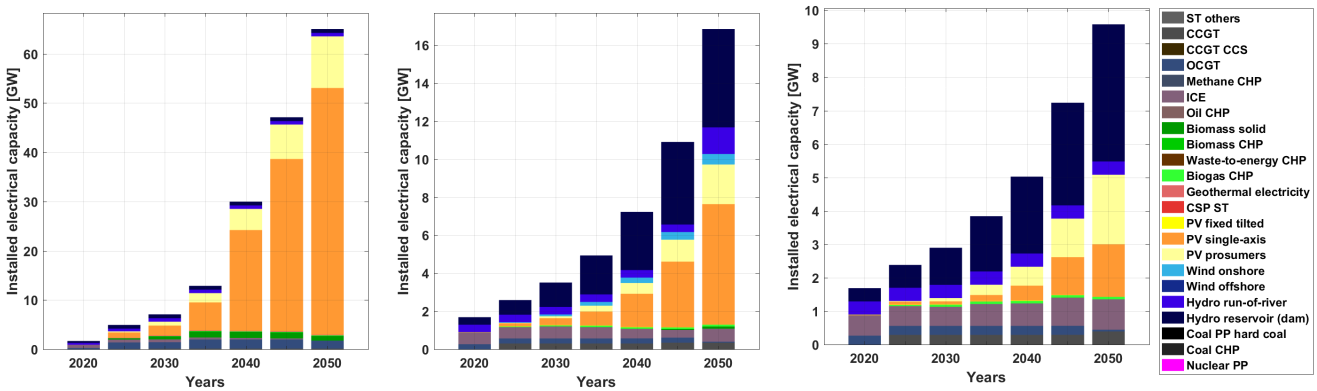

FIGURE 6. Installed electrical capacities for the BPS (left), INDC (centre), and CPS (right).

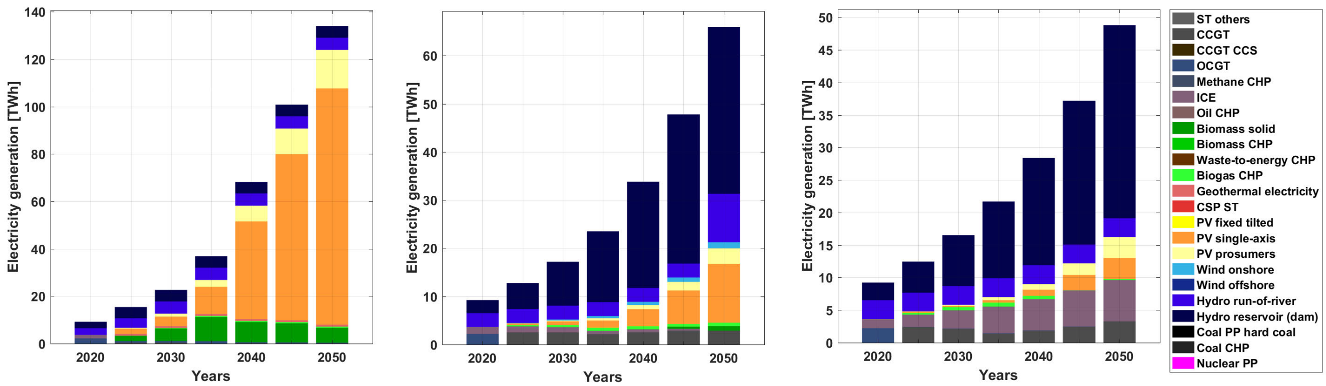

FIGURE 7. Electricity generation mix for the BPS (left), INDC (centre), and CPS (right).

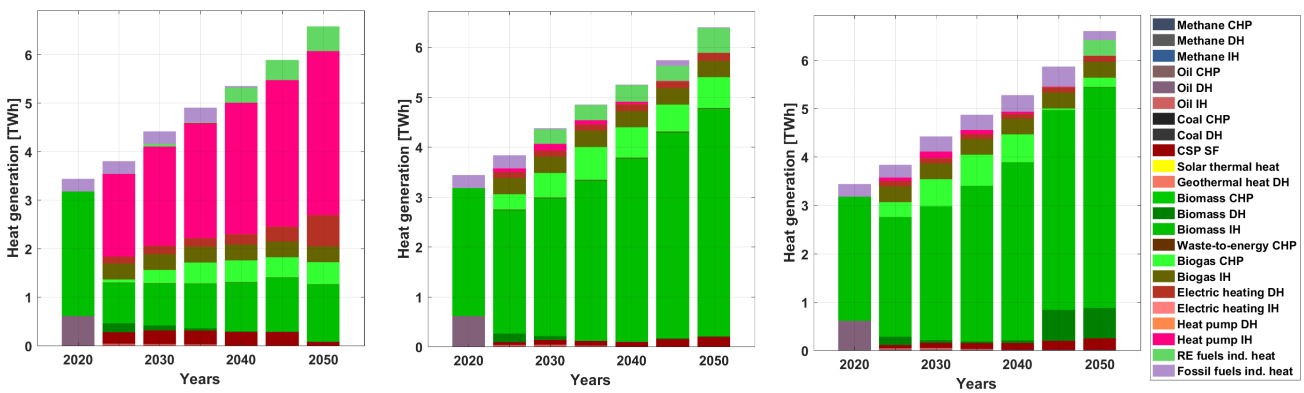

FIGURE 8. Heat generation technology wise in the BPS (left), INDC (centre), CPS (right).

the deployment of electric heating and heat pumps. Electric heating and heat pumps constitute 69% of total heat demand by 2050, with sustainable biomass heating providing 30% in the BPS. On the contrary, in the INDC and the CPS scenarios, heating demand is supplied by biomass (86% of total demand in both scenarios) complemented by fossil fuels. Additional figures for the heat generation for all scenarios are further displayed in the Supplementary Material (Figure S12).

D. TRENDS IN THE TRANSPORT SECTOR

The energy demand of the transport sector of Cameroon by 2050 is predominantly marine freight as shown in Figure 9

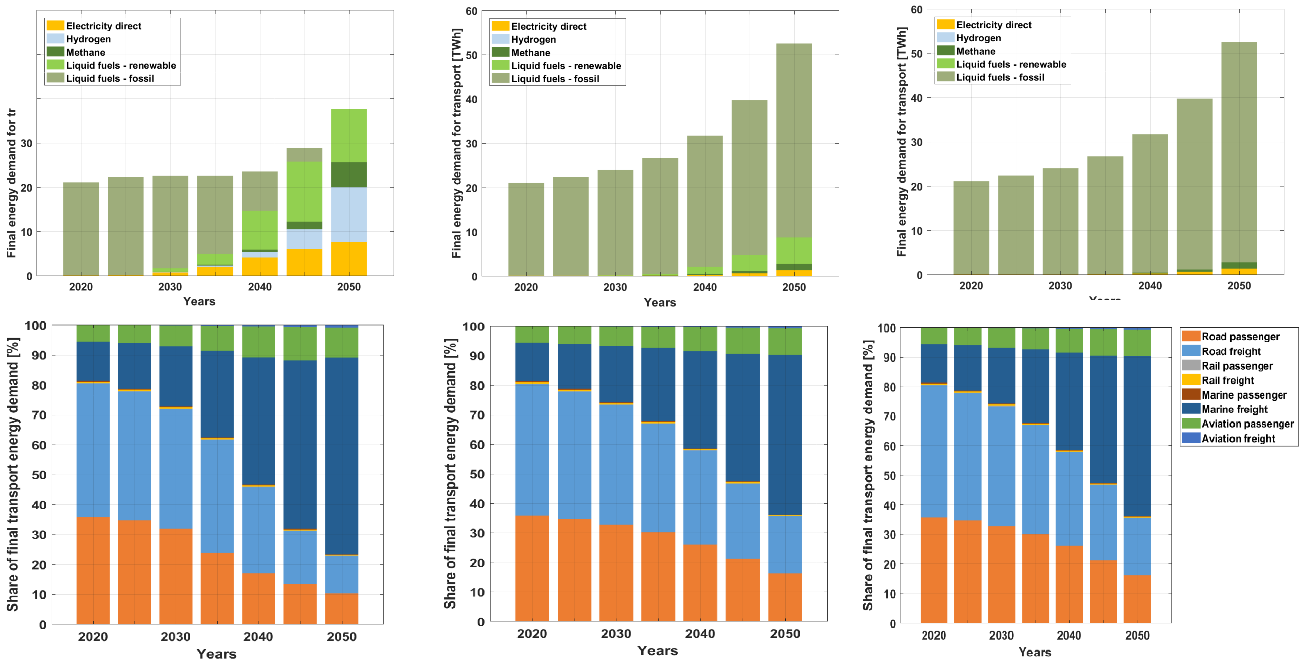

FIGURE 9. Final energy demand for the transport sector by energy sources used (top) and by shares of transportation modes (bottom) for the BPS (left), INDC (centre) and CPS (right).

(bottom), accounting for 66% of the demand in the BPS and 54% in the INDC and the CPS. Absolute values for the transport demand by mode of transport and vehicle type are further displayed in the Supplementary Material (Table S22). In Figure 9 (top), the transport demand is illustrated according to the energy sources used. The final energy demand for the transport sector for the BPS ranges from 21–37 TWh and for the INDC and CPS it ranges from 21–53 TWh. Deployment of battery-electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV) with higher efficiencies contribute to the reduction of the overall transport demand of the road passenger and freight transportation in the BPS by 2050 as compared to the INDC and the CPS which largely depend on internal combustion engines (ICE) with low efficiencies. The defossilisation of the transport sector in the BPS requires direct and indirect electrification from 2030 onwards. In 2050, transport demand accounts for 38% of the TFED in the BPS.

E. FLEXIBILITY COMPONENT IN THE ENERGY SYSTEM

This section analyses various flexibility options such as energy storage, grid transmission and energy system wide integration with sector coupling technologies. As the BPS evolve towards a 100% RE-based system, the technologies within the energy system assume varying roles tailored towards providing flexibility and operational stability of the whole energy system due to high shares of VRE.

1) ELECTRICAL STORAGE

As the share of solar PV generation increases significantly beyond 2030 in the BPS, the role of electricity storage becomes imperative in providing uninterrupted energy supply and enabling system flexibility. The overall electricity storage is entirely battery storage with the storage output by 2050 for the BPS estimated at 23.5 TWh_{el}, equal to 19.6% of total electricity demand, partitioned into battery utility (78%), battery residential (8%), and battery commercial and industry (C&I) (14%) as shown in Figure 11. The INDC and the CPS also display a storage configuration like the BPS with an entire battery storage system. However, the storage outputs in these scenarios are comparatively smaller with respect to the BPS. The total storage output for these two scenarios, evaluated at respectively 1.2 TWh_{el} and 1.1 TWh_{el} for the INDC and the CPS by 2050 are a factor of 16–20 times lower than the storage output in the BPS. This factor illustrates the need for storage technologies due to the inherently variable nature of renewables, particularly solar PV as observed for the case of the Cameroon energy transition. Regional electrical storage capacities and annual storage generation across scenarios in 2050 can be found in the Supplementary Material (Figures S13-S14).

2) HEAT STORAGE

In like manner, the heat storage is indispensable to ensure heat supply in the heat sector mainly domestic hot water and industrial process heat. Gas storage dominates the storage infrastructure in the BPS by 2050 as shown in Figure 12. By 2050, the annual heat storage output in the BPS is 33 TWh_{th} which is mainly from gas storage (hydrogen and synthetic methane) while the INDC and CPS have annual heat storage outputs of 2 TWh_{th} and 0.8 TWh_{th} respectively by 2050 as shown in Figure 13. A transition to a fully renewable energy system

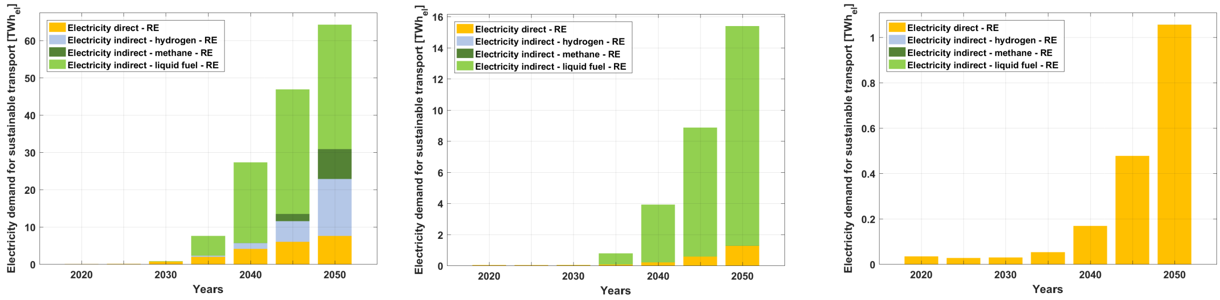

FIGURE 10. Electricity demand for sustainable transportation for the BPS (left), INDC (centre), and CPS (right).

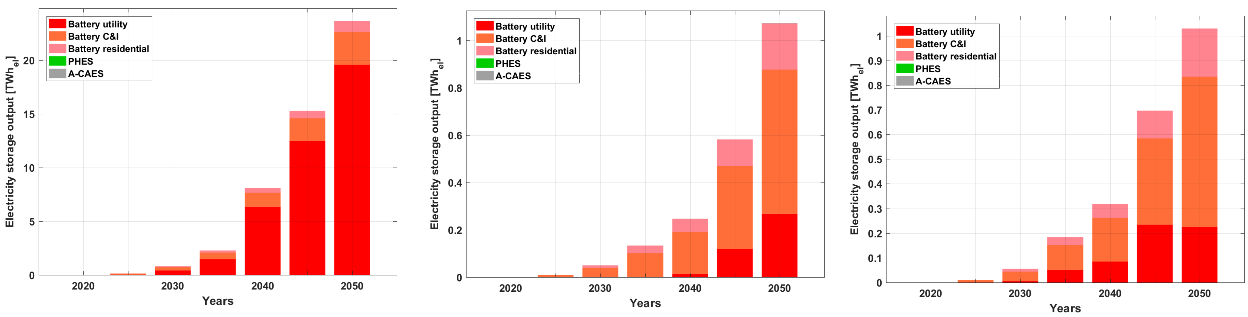

FIGURE 11. Annual electrical storage output for the BPS (left), INDC (centre), and CPS (right).

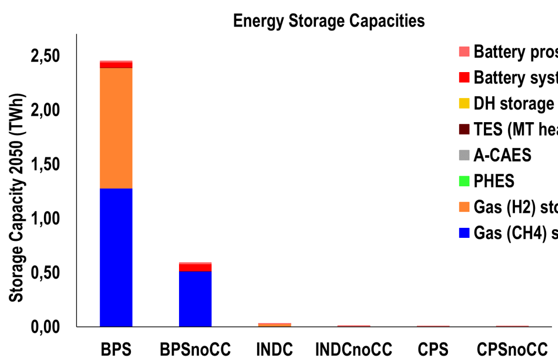

FIGURE 12. Energy storage capacities across scenarios in 2050.

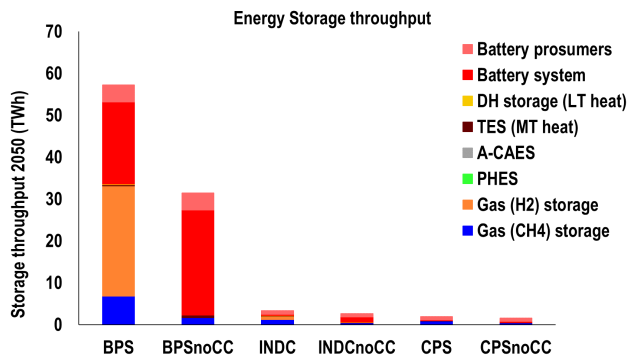

FIGURE 13. Storage output across scenarios in 2050.

in the BPS prompts a need for massive heat storage with an annual output which is 16-40 times higher than in the INDC and the CPS by 2050. The INDC and the CPS have low requirements for heat storage due to the use of fossil fuels in the system. Absolute values for the heat storage as well as the electricity storage capacities across scenarios are included in the Supplementary Material (Tables S23-S28) while the energy to power ratio across scenarios for the storage technologies are included in the Supplementary Material (Table S29). Regional heat storage capacities and throughput across scenarios in 2050 are available in the Supplementary Material (Figures S15-S16).

3) TRANSMISSION REQUIREMENTS

The grid utilization profiles by 2050 for the BPS, the INDC, and the CPS are shown in Figure 14. There is a significant difference in the grid utilization profiles between the BPS on the one hand, and the INDC and CPS on the other hand. In the BPS, high grid utilization is required during the sunny hours of the day to accommodate high electricity generation from grid tied solar PV generation. Due to the high penetration of VRE, grid infrastructure is expected to evolve towards a smart and intelligent distribution system to cater for grid stability. The grid utilization for BPS significantly reduces during the night times. In the INDC and CPS, the grid utilization profiles are on average higher than in the BPS due to a high hydropower system generation that requires a constant grid usage. The net electricity traded between the six regions in Cameroon amounts to 36 TWh in the BPS, 17 TWh in the INDC and 13 TWh for the CPS by 2050. Figure 15 shows the direction and amounts of electricity

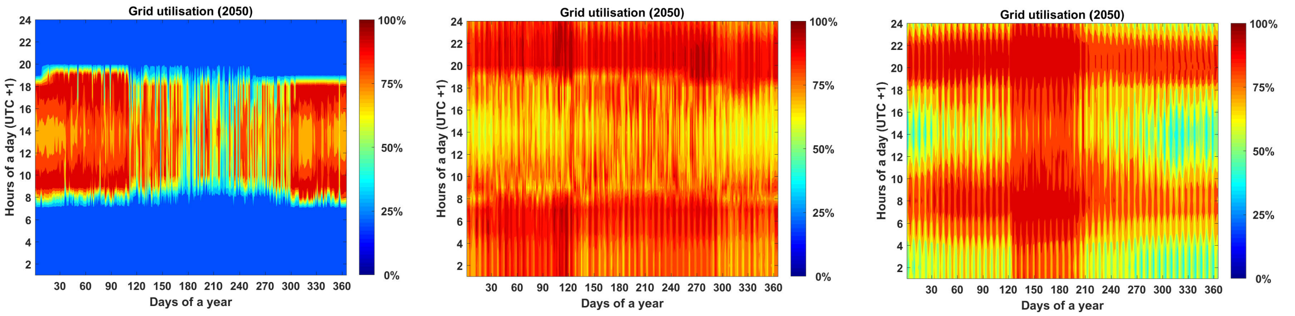

FIGURE 14. Grid utilization profiles for BPS the (left), INDC (centre), and CPS (right) in 2050.

transmitted across the country in the BPS, INDC, and CPS by 2050. In the BPS, CN is the highest electricity exporting region, with exported electricity evaluated at 28 TWh accounting for 78% of total exported electricity. In addition to CN, the NA region also exports 7 TWh accounting for 19% of total exported electricity. These two regions have high single-axis PV generation due to a very good solar resource, large surface area for PV installation and high electricity demand that favours economies of scale in these regions. Most of the exporting electricity in the BPS goes to the LT region (36%), ES region (24%), and NSW (24%). In contrast to the BPS, the LT region is the major electricity exporting region in the INDC due to the large hydropower resource concentrated in this region. The electricity exported from LT is evaluated at 14 TWh accounting for 74% of exported electricity. The highest importer in the INDC is the NSW region, importing 11 TWh accounting for 63% of total imported electricity. The CPS shows similarities to the INDC with the LT region being the major electricity exporter due to the high hydropower resource in this region, exporting 13 TWh (97), while NSW is the main importing region with 11 TWh (73%).

F. THE ROLE OF SYNTHETIC FUEL DURING THE TRANSITION

Transitioning to a fully RE system needs significant synthetic fuels especially for the hard to abate energy services including aviation, marine and industrial processes. The demand for synthetic fuels especially for the transport sector becomes increasingly significant in the BPS beyond 2040. Consequently, the need for appropriate fuel conversion technologies to meet the demand for these fuels increases significantly from 2040 onwards reaching 19 GW by 2050 as depicted in Figure 16. Electrolysers for hydrogen production dominate the fuel conversion capacity beyond 2040 in the BPS, followed by Fischer-Tropsch plants and hydrogen liquefaction plants. The installed capacity for fuel conversion in the INDC is evaluated at 2.6 GW capacity while in the CPS, the 0.17 GW of fuel installed capacity is fully LNG. The CPS shows no need for synthetic fuels throughout the modelling horizon due to large amounts of fossil fuels that continue to dominate the transport sector. Synthetic fuels produced using fuel conversion technologies require storage infrastructures with installed capacities as illustrated in Figure 17. The installed capacity for gas storage by 2050 for the BPS, INDC and the CPS are respectively 2.3 TWh, 0.025 TWh and 0.0007 TWh. The BPS depicts very high gas storage capacities compared to the INDC and the BPS. It is important to note that, by 2050, the gas storage capacity in the BPS of 2.3 TWh is a factor of 92 times higher than the gas storage capacity in the INDC of 0.025 TWh. This factor emphasises the importance of gas storage as an essential technology in a fully sustainable energy system for Cameroon.

G. ENERGY FLOW IN STRONG SECTOR COUPLING

The key to achieving a fully renewable energy system for Cameroon is a high electrification rate of around 83%, which enables sectoral integration and results in significant efficiency gains and cost competitiveness due to access to low-cost renewable electricity and PtX processes. Figure 18 illustrates a strong sectoral integration for the BPS by 2050 which is linked to a strong electricity growth demand and sector bridging technologies, particularly electrolysers for hydrogen production. The future energy system as observed for the case of Cameroon shows a high electrification rate through direct electrification as much as possible and indirect electrification for hard-to-electrify sectors. The energy flow for 2020 and for the INDC and the CPS in 2050 are available in the Supplementary Material (Figures S17-S19).

H. ENERGY COST AND GHG EMISSIONS ANALYSIS DURING THE TRANSITION

The energy cost is crucial in determining the viability of an energy system, scenarios, and transition pathways. Furthermore, the contribution analysis of the elements in the cost structure generates an in-depth understanding of what percentages these cost elements constitute in an energy transition pathway. A crucial question is how much it will cost to fully implement a sustainable energy system for Cameroon. This section therefore answers this question by presenting results of the evolution of the total annual system cost, the cumulative system cost, the levelised cost of energy and the levelised

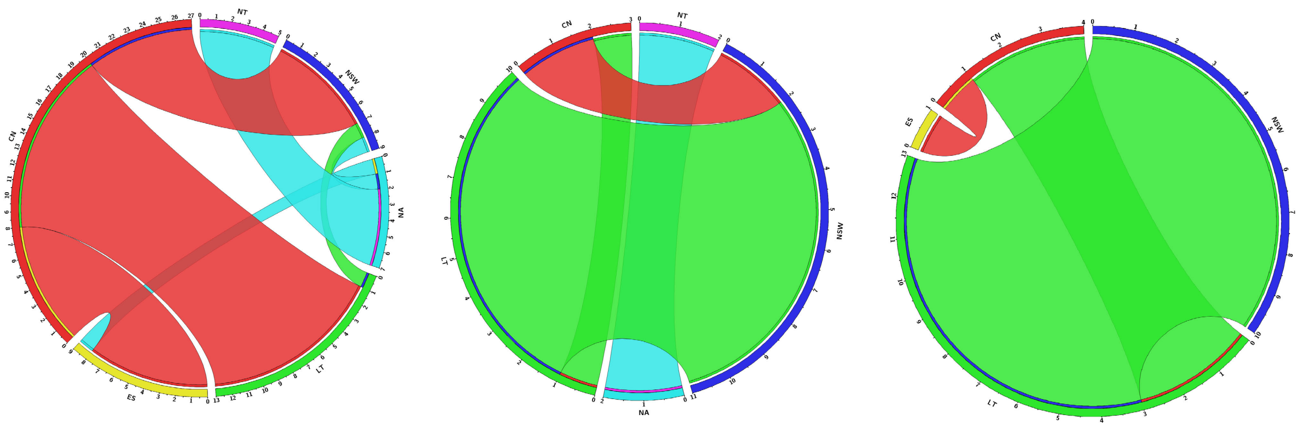

FIGURE 15. Electricity exchange across Cameroon in 2050 for the BPS (left), INDC (centre), and CPS (right).

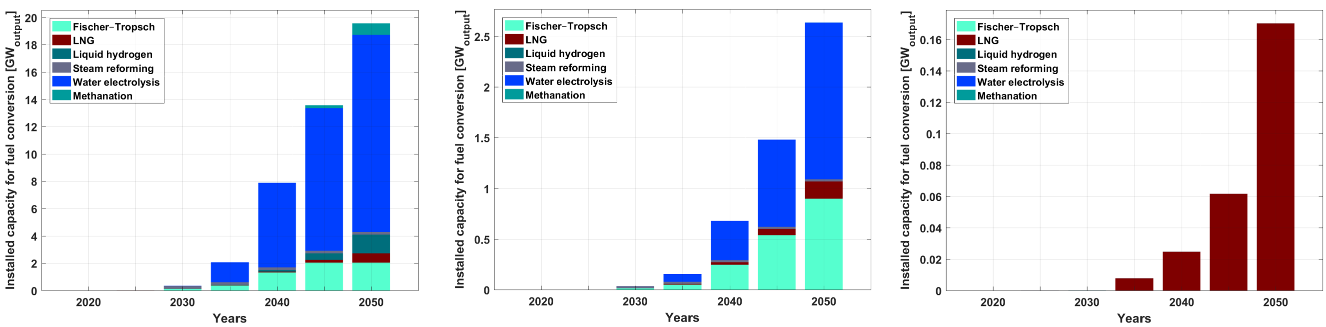

FIGURE 16. Installed capacity for fuel conversion for the BPS (left), INDC (centre), and CPS (right).

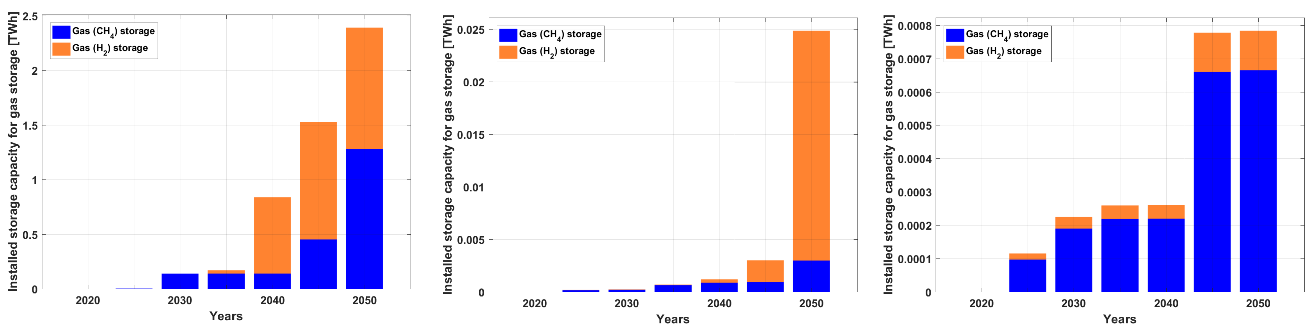

FIGURE 17. Gas storage capacity for methane and hydrogen for the BPS (left), INDC (centre), and CPS (right).

cost of electricity (LCOE) up to 2050 for the BPS, the INDC, and the CPS.

1) TOTAL ANNUAL INVESTMENTS THROUGH THE TRANSITION

The cost structure per energy sector indicates that the transport sector accounts for the largest share of the total annual energy system cost followed by the power sector for both the INDC, and the BPS as shown in Figure 19. The total annual system cost increases progressively for both scenarios starting from a value of 2 billion euros (b€) in 2020 and reaches by 2050 a value of 4.1 b€ for the BPS, 6.7 b€ for the INDC and 8.6 b€ for the CPS. By 2050, the total annual investment of the INDC and the CPS exceeds that of the BPS by 39% and 52%, respectively. In the BPS, capital expenditures (CAPEX) dominate the cost structure from 2040 and beyond, followed by fixed operational expenditures (OPEX). Fuel cost and GHG cost decrease significantly over the transition in the BPS to attain a negligible and zero value respectively by 2050. The INDC and the CPS display an opposing trend to that of the BPS as shown in Figure 20, with significant contribution in the cost structure attributed to fuel cost and GHG

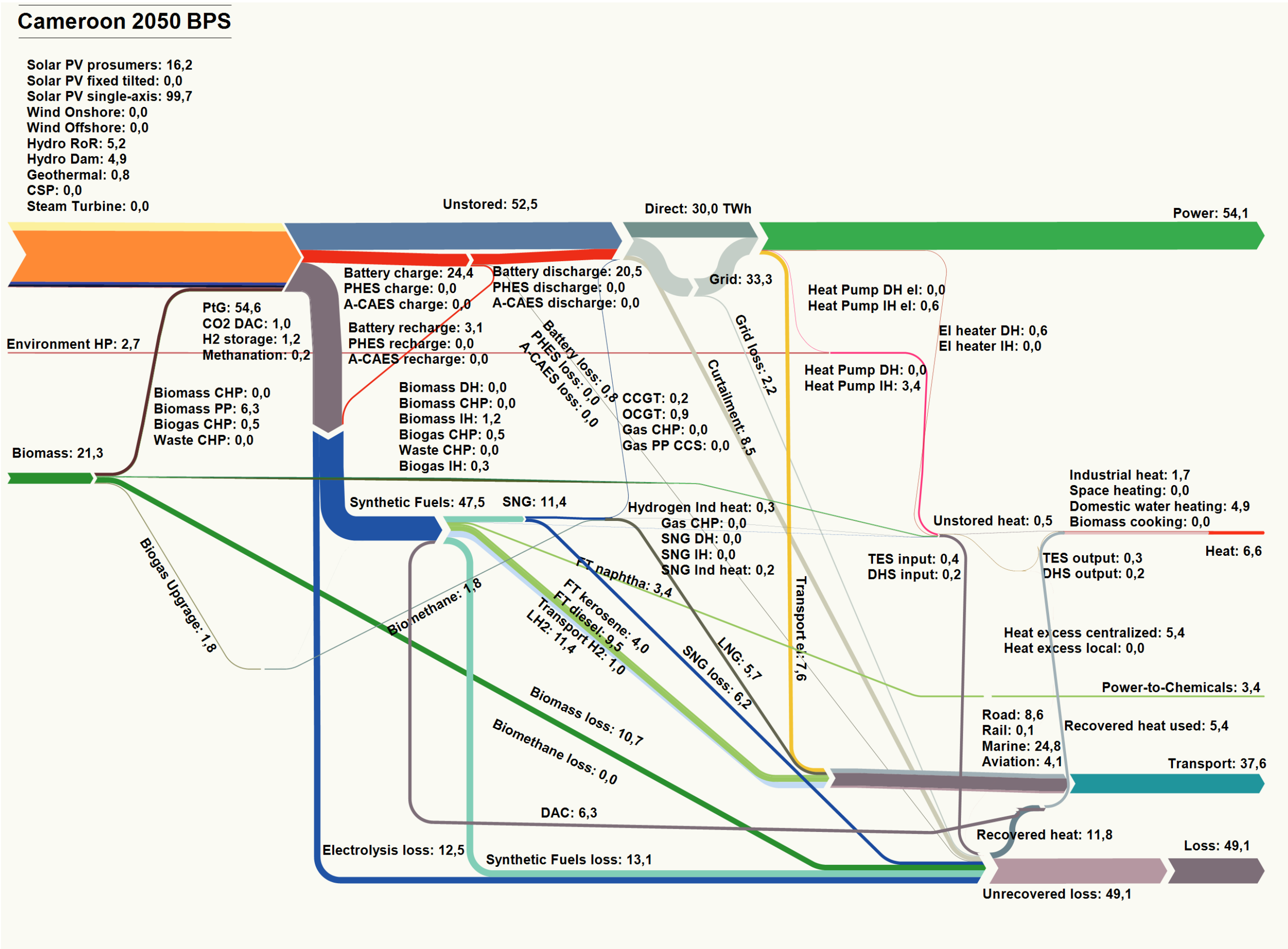

FIGURE 18. Energy flow of the system in 2050 for the BPS.

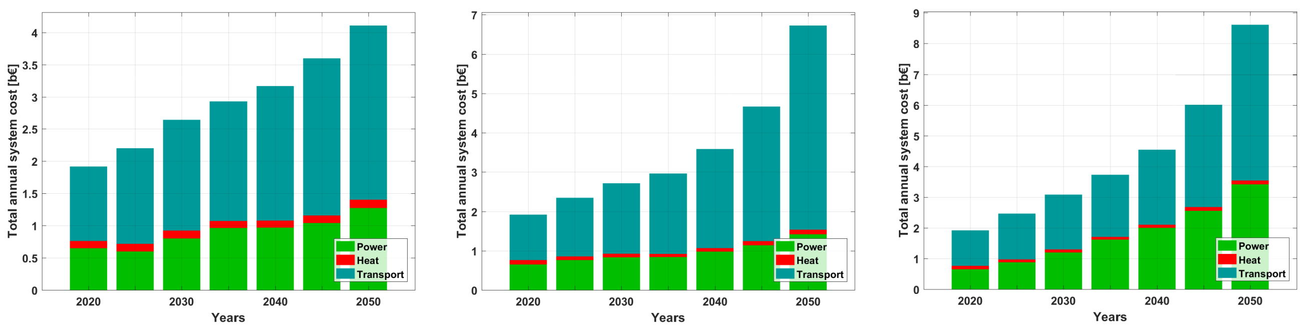

FIGURE 19. Total annual system cost per energy sector for the BPS (left), INDC (centre), and CPS (right).

emissions cost over the transition up to 2050. To answer the question on how much total cost goes into constructing and operating the energy system in Cameroon between 2020 and 2050, it is also analysed the cumulative system cost for both the BPS, the INDC, and the CPS. This cumulative system cost equals 21 b€ for the BPS, 25 b€ for the INDC, and 30 b€ for the CPS. Technology-wise figures for the CAPEX across scenarios are available in the Supplementary Material (Figure S20). Additional transport energy cost figures are displayed in the Supplementary Material (Figures S21-S26).

2) LEVELISED COST OF ENERGY

The levelised cost of energy measures the per unit generation cost of the entire energy system comprising electricity, heat,

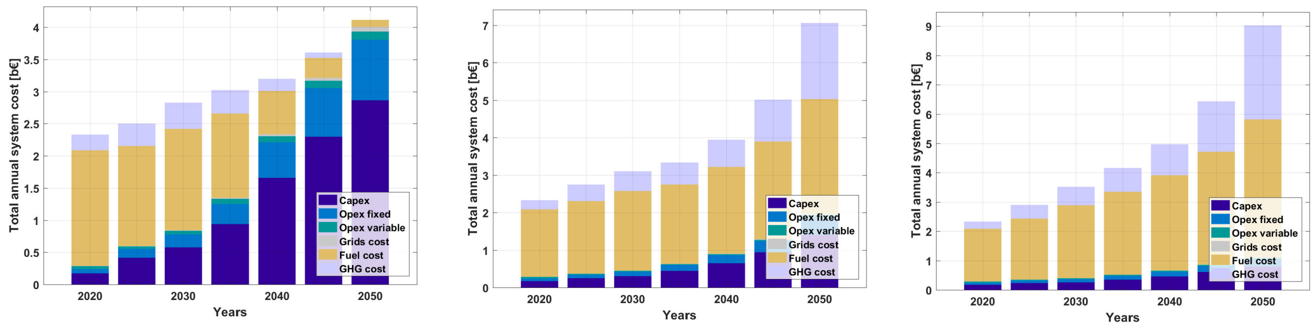

FIGURE 20. Total annual system cost by component for the BPS (left), INDC (centre), and CPS (right).

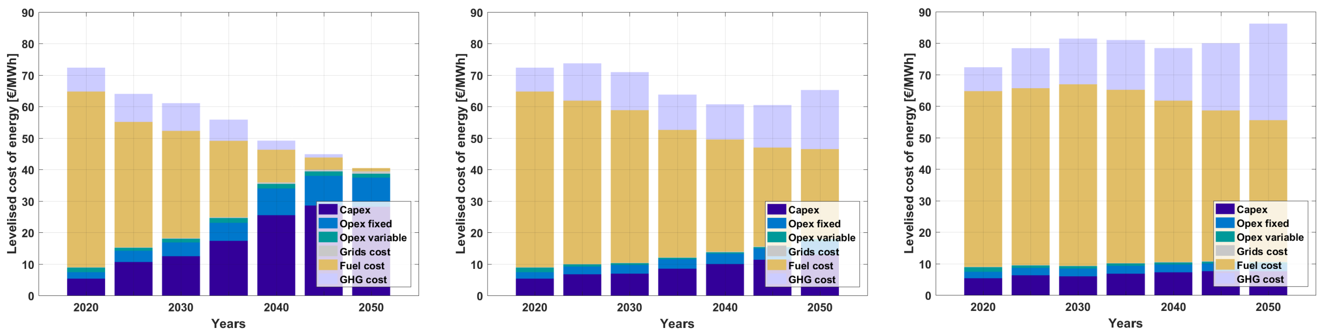

FIGURE 21. Levelised cost of energy for the BPS (left), INDC (centre), and the CPS (right).

and transport sectors. Biomass for cooking is not accounted for in the levelised cost of energy modelled in this study. Figure 21 illustrates the levelised cost of energy for the BPS, the INDC and the CPS. For the BPS, the levelised cost of energy declines from around 72 €/MWh in 2020 to around 49 €/MWh in 2040 and to 41 €/MWh in 2050. Whereas the levelised cost of energy decreases from around 72 €/MWh in 2020 to about 65 €/MWh in INDC and increases to around 86 €/MWh in CPS by 2050. At 41 €/MWh, the BPS is about 38-53% lower than the INDC and CPS by 2050. The cost structure in the INDC and the CPS contains a significant portion spent on fuel and through the transition.

3) LEVELISED COST OF ELECTRICITY (LCOE)

The LCOE measures the per unit generation cost of the power sector using the CAPEX and the OPEX invested in the generation, storage, fuel, curtailment, grid cost, and the cost of GHG emissions. For the BPS, the LCOE progressively reduces over the transition ranging from 71 €/MWh in 2020 to 24 €/MWh in 2050, representing a 66% reduction compared to the 2020 value. The LCOE for the INDC shows a similar trend to that of the BPS reaching a value of 31 €/MWh by 2050 from 71 €/MWh in 2020. As for the CPS, the LCOE fluctuates between 71 €/MWh to 72 €/MWh in 2050, as shown in Figure 22. By 2050, the LCOE of the INDC and the CPS are respectively 1.3 and 3 times higher than that of the BPS. The cost projections show the economic attractiveness of the BPS as compared to the INDC and the CPS. Additional technology-wise splits for the LCOE across scenarios are shown in the Supplementary Material (Figure S27).

4) GHG EMISSIONS

This section presents the GHG emission pathways for the three scenarios in the transition study. Figure 23 illustrates the sector wise GHG emissions for the three scenarios up to 2050. In the BPS, the GHG emissions reduce from 8.8MtCO_{2eq} in 2020 to zero by 2050 characterising a fully defossilised energy system. The GHG emissions increases progressively for both the INDC and the CPS reaching a value of 13.6 MtCO_{2eq} and 21.4 MtCO_{2eq} respectively by 2050. By 2050, the transport sector remains the main driver of GHG emissions in the INDC and the CPS due to its characteristic nature as a hard to abate sector. Additional figures for power and transport sector GHG emissions are displayed in the Supplementary Material (Figures S28-S29).

IV. DISCUSSION

This study presents the evolution of the energy system in Cameroon up to 2050 under defined scenarios. The study is the first to give such comprehensive results of a system-wide energy transition in Cameroon and gears towards setting the pace for such a transition within the Central Africa region. In this section, we draw insights from the results obtained,

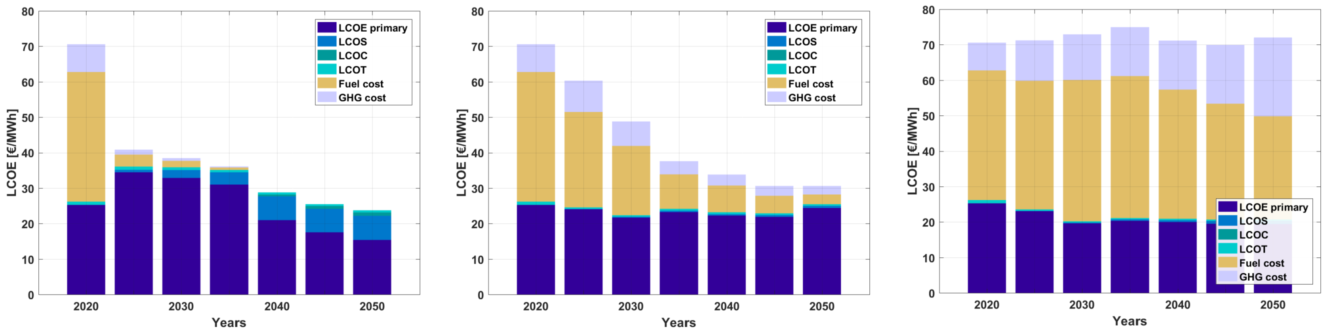

FIGURE 22. LCOE for the BPS (left), INDC (centre), and the CPS (right).

discuss these results, and recommend policy actions based on the results of the modelling process.

A. KEY INSIGHTS FROM RESULTS

Achieving net-zero GHG emissions under the Paris Agreement requires pathways towards a 100% RE-based system. This paper has analysed six different transition scenarios to clearly map out the optimal energy system configuration based on the technical, economic, and environmental aspects for Cameroon. The BPS emerges as the most cost-effective scenario with net-zero GHG emissions by 2050. The modelling results are intended to provide a framework to enlighten and enhance policy decisions in Cameroon and simultaneously provide a reliable reference for similar techno-economic studies within other Central African countries. The results show that transitioning to a RE-based energy system is the least-regret move for Cameroon, which is an important fact for other Central African countries. It therefore only requires a fervent political will and enabling policies to drive this transition into action. The results of the BPS show that the optimal energy generation mix for a least-cost sustainable energy system for Cameroon by 2050 comprises of 86% solar PV, complemented by 8% hydropower and 5% bioenergy. Therefore, the key energy generation technology forming the bulk of the transition in the BPS is solar PV which is representative of sunbelt countries sharing similar climatic conditions to that of Cameroon as shown in similar studies for Africa [5]–[8], [87]. Several related studies for countries belonging to the Global South point to the dominance of solar PV as a driving generating technology for achieving a 100% RE-based energy system both on national and regional regimes, as for the Americas [88]–[91], Middle East [92]–[94], Central Asia [73], [95], and South and Southeast Asia. [96]–[100]. Bioenergy representing 5% of the total generation share also forms a part of the least-cost solution of the energy system in 2050, as shown in detail for Ghana [9]; such a structure in the solution has been also found for the case of Cameroon. As other Central African countries share similar climatic conditions with Cameroon and excellent RE resource conditions, these results for Cameroon therefore provide solid guiderails for energy system planning in other Central African countries. The Central African region has very low electricity access evaluated at 28% [13], which necessitates an energy system to cater for the poor access to clean energy. The solar resource potential for Central Africa is estimated at 50,000 TWh/a [13] which is well sufficient for a solar PV dominated energy system. Results of this research for the INDC are benchmarked with those from the REMP [22] as basis for validating the modelling process. We found results for the INDC which are comparable to those of the REMP. By 2035, the total solar generation of the INDC is estimated at 2 TWh_{el} which is comparable to that of the REMP estimated at 1.5 TWh_{el}. Furthermore, hydropower generation for the INDC scenario is estimated at 18 TWh_{el} which is comparable to 17 TWh_{el} of the REMP. Similar comparative values are observed for the installed generation capacities for the INDC and the REMP. The INDC scenario developed in this study is therefore a good representation of the government's REMP, which in this study creates a solid backbone for comparative analysis with the BPS and the CPS. Results of the BPS show that, by 2050, the total installed electricity generation capacity of 65 GW is 3.8 times higher than that of the INDC and 6.7 times higher than the CPS, while the total annual generation in the BPS of 134 TWh doubles that of the INDC and triples that of the CPS. The dominance of solar PV in the BPS, contributing 86% of total electricity generation by 2050, suggests a paradigm shift of how Cameroon's energy system should be planned. Contrasting with the INDC and the CPS, solar PV generation accounts for only 23% and 13% respectively of total electricity generation by 2050. Further, for the INDC and the CPS, hydropower constitutes a dominant energy source for power generation accounting for 68% and 67% generation shares by 2050 for the respective scenarios. The results of the INDC and the CPS fully reflect the government's ambition to continuously develop the hydropower resources in the country with several hydropower projects either planned or under construction [20]. However, the results of the BPS with solar PV forming the bulk of the total electricity generation by 2050 show that, contrary to continuous investments in developing hydropower which has been the government's focal point [22], [23], solar PV proves to be more attractive than hydropower thereby

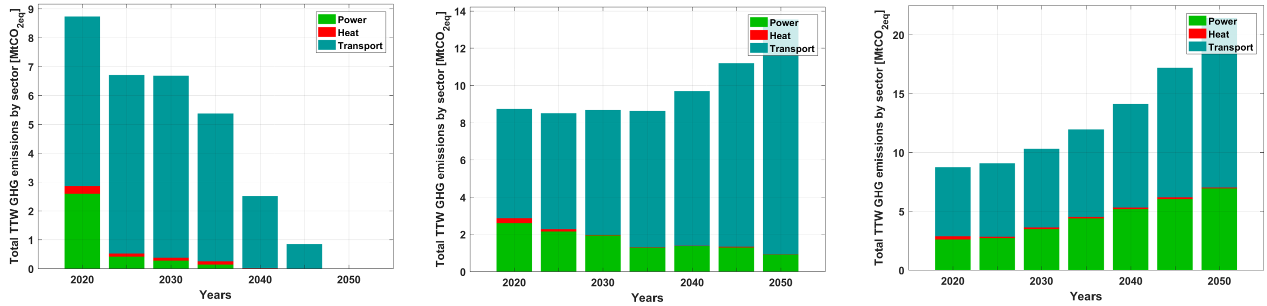

FIGURE 23. GHG emissions per sector for the BPS (left), INDC (centre) and CPS (right).

calling for a strategic reconsideration of existing government plans. Furthermore, hydropower has presented several challenges relating to cost overruns and project schedule extensions [23], [25], [26], [51] and is vulnerable to variabilities in the yearly precipitation patterns. Emodi *et al.* [101] conclude that climate change will have serious impacts on energy systems, which will lead to change in energy demand and supply. According to Emodi *et al.* [101], solar energy is less susceptible than hydropower to climate change, which is an important fact for Cameroon and other Central African countries with top priority for hydropower development. Solar PV systems are more resilient to climate change when compared to other RE sources [101]. Sridharan *et al.* [102] conclude that hydropower plants in Africa may experience a shortfall in generation due to erratic rainfall, and extreme water shortage could leave these assets stranded. The current electricity system in Cameroon dominated by hydropower has suffered from recurrent power outages that significantly impact the economy [28]. It is estimated that these power outages cost Cameroon about 5% of the gross domestic product (GDP) growth per year [28]. As such, planning alternative least-cost energy solutions consisting of solar PV will be a huge success in supplying steady electricity and contributing to economic development. The dominance of solar PV in the BPS in the future energy system has an added advantage as it caters for decentralised consumers. Solar PV generation in 2050 is estimated at 116 TWh which makes up 86% of total generation in the BPS, relatively composed of 16% PV prosumers with an equivalent generation of 18 TWh_{el} and 84% utility-scale PV (98 TWh_{el}). These decentralised and modular PV systems have a high potential to increase access to clean and affordable energy both in urban and remote areas due to rapid decreasing cost. The results of this study are also complemented by the findings of Falama *et al.* [67] who showed that, in Cameroon's northern towns of Maroua, Garoua, and Ngaoundéré, a grid tied PV system with battery storage is an economically viable option in the long-term. They also found out that, such an energy system configuration is a practical and effective solution for problems relating to electrical-load shedding, which adds value to a solar PV dominated energy system as presented in this study. In particular, rural areas can benefit from fast electrification via solar PV based solar home systems, which can be further expanded to local mini-grids [70], also for the case of Cameroon, which may take an intermediate step with diesel generators [103]. Mini-grids and off-grid electrification in Cameroon highly rely on solar PV and battery systems as essential technologies [60]–[62]. A solar PV dominated energy system has a higher potential to drive this rural electrification even further. This is even more the case for the entire Central African region, as electrification rates are lower than in Cameroon. In addition, modular PV systems also experience fewer cost escalations [104] and reduced risk of technical failures and need for maintenance [105] making them practically applicable for decentralised communities. The further outlook on continued cost decline for solar PV and battery storage systems indicates stable cost declines trends [106]. The dominance of solar PV in the BPS triggers a significant need for battery storage. The electrical storage capacity of 23 TWh_{el} in the BPS is approximately 16-20 times higher than the storage capacity in the INDC and CPS. The emergence of solar PV prosumers with battery storage in the future energy system contributes to increasing system flexibility and reducing the high reliance on the grid. As shown in the grid utilization profiles in Figure 14, the reliance on the grid is significantly reduced in the BPS compared to the INDC and the CPS in 2050. This reduction in grid reliance serves several advantages such as reducing long distance grid infrastructure cost and power losses during transmission. The future energy system dominated by decentralised modular systems will be a huge contributing factor to reducing the cost of grid electricity transportation in Cameroon. A similar trend towards PV prosumer self-supply can be expected across entire Central Africa following a global trend [107]. Cameroon's power sector has suffered significantly from grid transmission challenges which prompted the creation of the National Electricity Transmission Company (SONATREL) in 2015 [108], which has committed to construct 460 km of long-distance electricity transmission lines in the coming years. The development of a solar dominated energy system for Cameroon therefore serves multi purposes of distributed generation in prosumers, reduction in grid utilization and a high attractiveness cost wise.

The results of this BPS further give clarity and challenge Cameroon's existing REMP and INDC goals [22]. By 2040, the share of solar PV generation in the total electricity mix

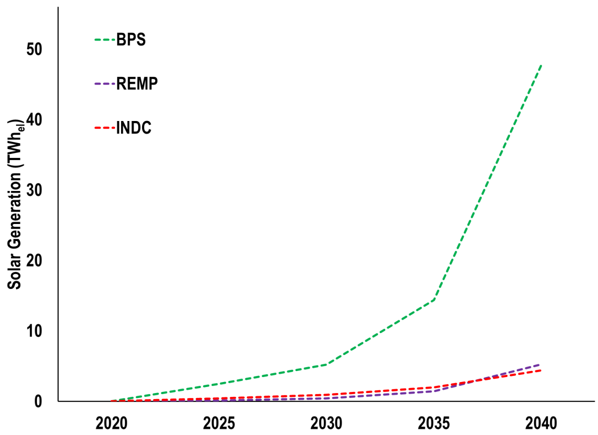

FIGURE 24. Solar generation for the BPS, REMP, and the INDC.

is 69% for the BPS, while the INDC and the REMP both project a share of 16%. In terms of absolute generation values, the INDC and REMP generates only 4.4 TWh and 5.3 TWh by 2040, whereas the BPS generates 48 TWh of solar PV by 2040, 9-10 times higher than the INDC and REMP as shown in Figure 24. The results of the BPS show significant improvement opportunities in the government's existing REMP. A key attribute of the energy system in the BPS is the sector coupling and system flexibility provided by the different conversion technologies to produced renewable electricity-based fuels for the heat and transport sectors. Power-to-X (PtX) technologies become indispensable in the transition beyond 2040 producing synthetic fuels and green hydrogen from renewable based electricity thereby enhancing the flexibility of the energy system. In addition, synthetic fuels and green hydrogen used as fuels for the transport and heat sectors eliminate the reliance on fossil fuels in the BPS. This vital role of PtX technologies is characterised by the increased capacity in the fuel conversion technologies and gas storage capacities beyond 2040 in the BPS. On the contrary, the INDC and the CPS show little or no need for these PtX technologies as there is continuous use of fossil fuels in the system. Further, batteries, heat pumps, and technologies in the value chain for renewable electricity based synthetic fuel production, such as electrolysers enhance flexibility and integration of the energy system. The battery-to-PtG phenomenon [7], [9], [41], [95], [100] is observed in energy systems with very a high share of RE, such as the BPS, as a means of reducing overall system cost. Battery can be used to charge the gas storage via utilisation of electrolysers during off-peak hours, mainly at night and early morning hours. The amount of electricity transferred from battery to PtG is 3.1 TWh in the BPS representing 6% of the total electricity demand, which is more than 10% of battery charging and more than 5% of electricity input of electrolyser. In addition, curtailment, which increases with VRE [109], [110] becomes a vital source of system flexibility in the BPS ranging from 5 TWh$_{el}$ in 2040 to 8.5 TWh$_{el}$ in 2050. In contrast to the BPS, the INDC and the CPS have no curtailment due to the high share of hydropower and fossil fuels in the system. Curtailment, therefore, reduces large investments in grid interconnections and provides and added economic benefit to the system [8], [109]. Curtailment and the ratio of curtailment to electricity generated across scenarios is displayed in the Supplementary Material (Figure S30). Gas engines are valuable and flexible balancing technology in the power system [111]. In addition, the variability of RE supply can be overcome by designing an optimal system as illustrated in the BPS in 2050 as depicted in the Supplementary Material (Figure S31), showing how generation matches demand on hourly resolution during the best week and worst week of solar generation of the year. The supply side flexibility of the power system can be linked to dispatchable renewables such as hydropower, bioenergy, and geothermal. The LCOE for the BPS declines significantly from 71 €/MWh in 2020 to 24 €/MWh by 2050. The LCOE obtained in this research is comparable to the values published for the case of Nigeria [6], West Africa [7], South Africa [5], Ethiopia [8], and Ghana [9]. This LCOE depicts the attractiveness of the transition towards a 100% RE-based system for Cameroon, which is an important fact for Central African countries. The values of the total annual system cost by 2050 is 4.1 b€ in the BPS, 6.7 b€ for the INDC and 8.6 b€ in the CPS, representing respectively 13%, 21%, and 27% of the country's 2019 GDP evaluated at 33 b€ by the World Bank Group [112]. The total annual investment of the INDC and CPS are therefore 31% higher than the BPS by 2050. The CPS and the INDC present higher values of total system cost due to the fuel cost and the GHG emissions cost. The cumulative system cost is 20.5 b€ for the BPS, 25 b€ for the INDC and 30.3 b€ for the CPS. This result show that a fully sustainable energy system for Cameroon benefits from a 17% reduction in the cumulative system cost in the BPS compared to the INDC and a 32% reduction compared to the CPS. Additional capital expenditures incurred in energy system technology development are compensated for by a reduction in the operation and fuel cost in the BPS, rendering it more cost effective than the INDC and the CPS. The BPS shows that a fully sustainable energy system for Cameroon which is least-cost is technically feasible and economically viable. The only challenge is, therefore, the lack of an adequate policy orientation and appropriate government actions to ensure attainment of this transition as stated in [13].

For the GHG emissions, the BPS attains net-zero GHG emissions by 2050, which complies with the Paris Agreement, whereas the INDC and CPS lead to large emissions at 18.5 MtCO$_{2eq}$ and 29.4 MtCO$_{2eq}$ respectively by 2050.

The results of this study point out that the so-called ambitious expectations of the INDC and those of the REMP do not provide a concrete path to a fully sustainable energy system for Cameroon. Not only do they fail to fully defossilise the energy system, but they are also very cost-intensive thereby straining the affordability component of SDG 7. Alternatively, following a new energy system planning pathway dominated by solar PV as illustrated in the BPS gives a feasible

TABLE 2. Comparative summary of key transition results across scenarios in 2050.

		Unit	BPS	BPSnoCC	INDC	INDCnoCC	CPS	CPSnoCC
Financial Parameters	LCOE	[€/MWh$_{el}$]	24	34	31	26	72	49
	Total annual system cost	[b€]	4.1	3.9	6.7	4.6	8.6	5.8
Electricity Parameters	Demand	[TWh$_{el}$]	121	65	66	51	49	49
	Generation	[TWh$_{el}$]	134	76	66	51	49	49
	Installed Capacity	[GW]	65	37	16	12	9	9
Environmental Parameters	GHG	$MtCO_{2eq}$	0	8.5	13.6	15.2	21.4	21.5

and techno-economically viable route to a fully sustainable energy with net-zero GHG emissions, a high attractiveness cost wise and is appropriately decentralised to cater for PV prosumers.

B. COMPARATIVE SUMMARY OF KEY TRANSITION RESULTS

In this section, we present a comparative summary of the results across the six scenarios: the BPS, the BPSnoCC, INDC, INDCnoCC, CPS and the CPSnoCC. The results of this study show that the BPS presents no major technical challenges to a fully sustainable energy system for Cameroon and in addition, it is the most cost attractive option of the different scenarios studied. More so, the BPS calls for a strategic redefinition of the existing government plans including the REMP. The results of the research emphasise the vitality of an electricity based future energy system for Cameroon. Electricity becomes pivotal in the future energy system [113] in the BPS representing about 83% primary energy demand as shown in Figure 25. The ratio of electricity to primary energy demand falls significantly for the INDC, the INDCnoCC, the CPS as well as the CPSnoCC ranging between 23-38% by 2050. High electrification of the BPS allows for a least-cost transition to a fully 100% RE system as opposed to the other scenarios investigated. The evolution of the GHG emissions across scenarios is depicted in Figure 26 with the BPS achieving net-zero GHG emissions by 2050.

A comparative summary of key transition results is shown in Table 2.

C. IMPLICATIONS OF THE TRANSITION SCENARIOS FOR GROWTH AND DEVELOPMENT

The effectiveness of the transition scenarios analysed in this study is measured by its ability to fulfil SDG 7. The current energy situation in Cameroon is challenging with little access to clean, affordable energy throughout the country. According to the International Energy Agency's (IEA) clean cooking database [114], 75% of Cameroonians lack access to clean cooking facilities representing 19 million inhabitants. It is estimated that about 17 million rely on biomass

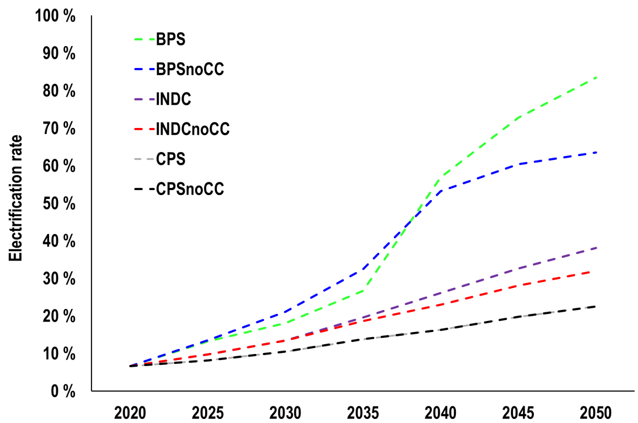

FIGURE 25. Electricity share (%) of primary energy demand across scenarios.

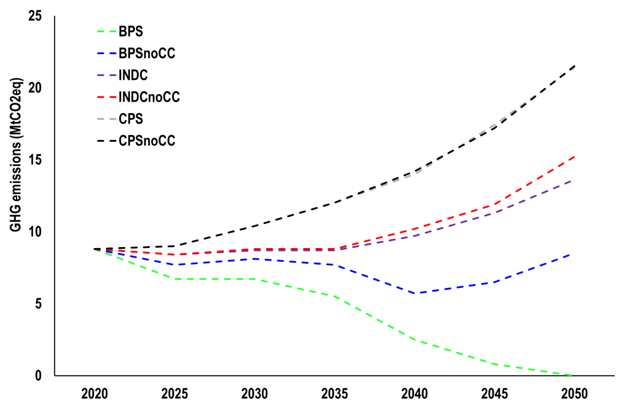

FIGURE 26. GHG emission trajectories across scenarios in $MtCO_{2eq}$.

for cooking [114]. The electricity access rates, especially in rural areas, remain low at 14% [47], while the 68% in urban areas usually experience interrupted power supply. These power interruptions were as high as 35 h/week for industries in 2013 in Cameroon [115]. The need for an energy system that overcomes these hurdles is imperative for the development of Cameroon. This study shows that such an energy system dominated by solar PV complemented by hydropower and bioenergy is technically and economically feasible for Cameroon. The PDSE in parallel with the PDER implemented by the Ministry of Water Resources and Energy (MINEE) and the Rural Electrification Agency (AER) aims at achieving 75% electrification rates by 2030 [116]. The results of this research with a solar PV dominated energy system is practical and timely for rural areas with no access to the grid and are very cost intensive for grid extensions. As Cameroon strategizes to become an emergent economy by 2035 [18], the importance of a steady low-cost energy system with no major technical barriers is imperative as presented in the results of this study. As electricity is a key pillar for education, health, and socio-economic development, access to clean affordable energy is therefore instrumental for eradication of poverty and reduction of social inequality [117]. The BPS presents a convenient projection of the evolution of the energy system for Cameroon fulfilling the necessary criteria upon which Cameroon's economy can pivot for successful growth and development. As the cost of modular PV systems and battery storage continuously decline due to strong technology learning curves [106], they will therefore become more affordable for inhabitants of both urban and rural areas. Sustainable solutions for heat include a phase-out of biomass for cooking which will improve the indoor air pollution and thus increase health conditions, in particular for women and kids. The benefits of a fully sustainable energy system for Cameroon surpasses the investments as depicted in this study.

V. POLICY RECOMMENDATIONS

The solutions of the modelling performed in this study show that a fully sustainable energy system for Cameroon presents no major technical nor economic barriers. However, implementation of these solutions is dependent on enabling policies and a strong will of policy makers. A fully sustainable energy system for Cameroon which is beneficial from all the spheres of sustainability as depicted by the BPS is dominated by solar PV, complemented by hydropower and sustainable bioenergy. Appropriate bridging technologies cater for sector coupling for renewable based synthetic fuels which are vital for the defossilisation of the energy system. Various flexibility options presented in this study enhance a stable and secure energy system. These results provide a robust guidance to how Cameroon's energy system should be planned. As such, a revision of existing government plans (REMP, PDER, RDSE) is therefore recommended from strategic and operational perspectives. This research recommends that policy makers should prioritize solar PV as a core energy technology for Cameroon's future energy system rather than hydropower. Existing institutions such as MINEE, AER, and the Electric Sector Regulation Agency (ARSEL) are therefore advised to incorporate roadmaps to implement low-cost solar PV, battery, and associated sector coupling technologies for a fully sustainable transition in Cameroon. Continuous development of new hydropower plants which has been the case so far requires strategic reconsideration due to the climate vulnerabilities, cost escalations and project schedule extensions which affects this technology. A 100% RE-based energy system for Cameroon by 2050 offers multiple benefits of a highly efficient electricity-based system, with sufficient energy supply to meet the needs of the economy and increase the development of the country. Furthermore, rural electrification which is a serious challenge in the current energy system is taken care of by distributed modular PV-battery systems [70], thereby increasing access to clean, reliable and affordable energy in line with SDG 7 and the AER objectives. In addition to being cost attractive and producing no GHG emissions, a 100% RE-based energy system has the potential to be the most job-rich energy system configuration as in the case of South Africa [5], West Africa [7], Ethiopia [8], and even globally [118]. These advantages therefore make a 100% RE system dominated by solar PV a highly attractive option for Cameroon.

VI. CONCLUSION

This research for the first-time analyses in a comprehensive manner a fully sustainable energy system for Cameroon by 2050. The results show that, there are no major technical nor economic barriers to implement such a system for Cameroon. Of the six different scenarios analysed, the BPS is the best evolutionary pathway towards attaining a least-cost and most environmentally friendly energy system for Cameroon by 2050. Solar PV emerges as the dominant technology in the energy mix by 2050 representing 86% of total annual generation, complemented by hydropower (8%) and sustainable bioenergy (5%). Appropriate bridging technologies cater for sector coupling for renewable electricity based synthetic fuels which are vital for the defossilisation of the energy system. Various flexibility options are presented in this study to enhance a stable and secure energy system. The LCOE for the BPS in 2050 is 24 €/MWh_{el} which is comparatively lower than the LCOE of the INDC and the CPS evaluated at 31 €/MWh_{el} and 72 €/MWh_{el}, respectively. A solar PV dominated energy system provides multiple benefits to the Cameroon's future energy system contrary to hydropower which is liable to high technical and cost challenges and does not appropriately cater for decentralised communities. A fully sustainable energy system for Cameroon is technically feasible and economical viable from the results of this research. Strategic planning and enabling policies are therefore the main constraints for attaining such an energy system configuration.

Extending to other Central African countries, the results of this research provide a reliable reference for guiding policy decisions within these countries as well as highlight interesting opportunities for research towards sustainable energy systems within the Central African region. Aspirations towards a solar driven energy system, complemented by appropriate technologies can be envisaged for the countries within Central Africa. As Central African countries share similar climatic conditions and resource potentials as Cameroon, they can also progressively transition to a fully sustainable energy system by 2050. Research on such a fully sustainable energy system on hourly resolution within Central Africa from a techno-economic perspective is therefore strongly recommended using the results from Cameroon as an initial reference and starting point.

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