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Supply optimization based on society's cost of electricity and a calibrated demand model for future renewable energy transition in Niger

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Abstract

Background: In an attempt to realize the most beneficial and optimal mix of electricity generation in Niger, a society's cost of electricity (SCOE) as the levelized cost of electricity (LCOE) plus the cost of climate change and air pollution is formulated. The SCOE is used as a basis for setting the performance criteria for supply optimization to balance future electricity demand in Niger. The demand projection is derived from a system dynamics model that anticipates future changes based on its influencing factors of population growth, urbanization progress, and industrial development.

Results: Reference case and what-if scenarios are simulated to see the projected electricity demand and possible renewable energy transition pathways. As a result, for example, the annual electricity of 3214 GWh estimated for 2030 might be balanced with about 200 MW, 104 MW, 85 MW, and 63 MW power from hydropower, grid-tied PV, coal, and diesel for SCOE optimized grid. For the same case, a greenhouse gas (GHG) emission reduction of 11.26–15.66% could be achieved when compared to the LCOE-based optimized grid. In addition, the most preferred energy option hydropower will be almost exhausted when the projected electricity demand in 2035 reaches slightly more than double its value in 2025. Thus, Niger should start exploiting its solar as well as conventional sources intensively to balance its future energy demand.

Conclusions: In this work, a mixed energy grid is optimized primarily on affordability while considering its sustainability. The implemented holistic approach lessens the need for energy import in the country and provides relief to energy security issues such as electricity price volatility and supply reliability. Additionally, the proposed strategy helps to guide the renewable energy transition pathway in Niger.

Keywords: Electricity demand projection, Supply optimization, Society's cost of electricity (SCOE), Levelized cost of electricity (LCOE), Renewable energy transition, Niger

Background

The provision of low-cost energy to the rural and peri-urban areas and reliable energy access to the urban and industrial sector are an integral part of Niger's development plan [1]. Nevertheless, the realization of this plan has been hindered by three related challenges. First, the inadequate understanding of the underlying relation

among energy demand and its influencing factors (population growth, industrialization, and urban progress) for balancing supply and demand in developing countries such as Niger [2, 3]. For instance, with Niger's population in 2017 being around 21.48 million [4], the per capita electricity consumption was around 51 kWh, compared to the African average of 780 kWh and West African average of 186 kWh (Fig. 1) [5]. Although the past trend of electricity consumption in Niger has been changing slowly, it is expected to increase significantly

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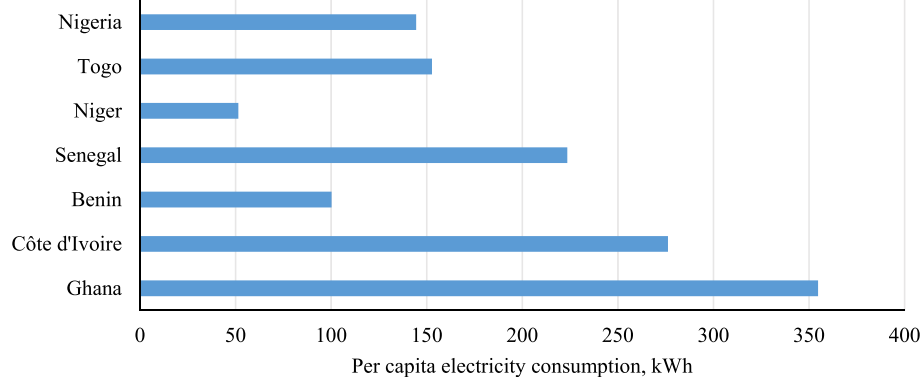


Fig. 1 Per capita electricity consumption of Niger in comparison with selected West African countries in 2017

in the coming years due to a high annual population growth of about 3.3%.

The relationship between economic development and increased energy demand [3, 6–8] as well as the strong correlation between urbanization and enhanced energy utilization [3, 6, 8–11] are clearly observed in the literature. These trends are also accompanied with a relative political stability and large-scale investments in the mining and oil sector of a country, which is also evident in Niger. Often, economic development reciprocates into increased energy consumption by the industrial and urban sectors. Thus, the development of a valid model that translates and anticipates quantitatively these related events would help energy policymakers to realize the development goals.

The second challenge that hinders the provision of low-cost and reliable energy is a heavy reliance on imported electricity from Nigeria, which poses serious energy security issues in Niger [12]. According to Société Nigérienne d'Electricité (NIGELEC, Niger's electricity company), the share of imported energy reached 86.5% in 2017 purchased at about 0.044 \$/kWh and sold at an average price of 0.158 \$/kWh [13]. As can be seen from Fig. 2, the imported electricity from Nigeria has

significantly increased over recent years. Under the existing electricity purchase price, there is hardly any room for renewable energy (RE) participation in the fossil dominated grid. However, this share of cheap imported energy is expected to decrease significantly in the coming years, due to the energy crisis in Nigeria caused by the inability to meet the energy demands of its growing population and economy [14, 15]. This has been a major factor compelling the Nigerian government to launch an electricity market reform resulting in an increased electricity selling price. Moreover, Nigeria's old refineries and inefficient single cycle turbines might have contributed to the reduced availability of power export to Niger [15].

Finally, the absence of an energy mix in the power grid based on the availability and cost of generation (including the cost on the environment), which has led to an inefficient fossil dominated power generation, is another challenge to the provision of low-cost and reliable energy in Niger. Apart from an estimated 2% solar photovoltaic (PV) installation in the telecom and off-grid sectors, power generation in the country still relies entirely on fossil fuels (coal and diesel) [12, 13]. Moreover, many of NIGELEC's diesel power plants are close to the

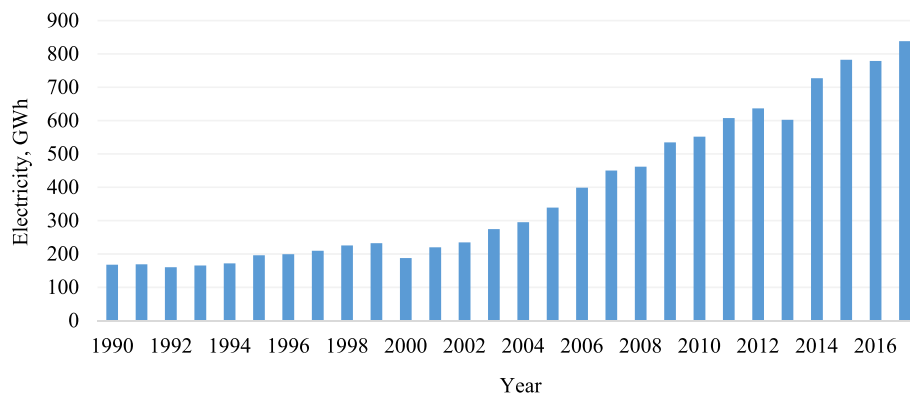


Fig. 2 Electricity import to Niger (based on NIGELEC database) [13]

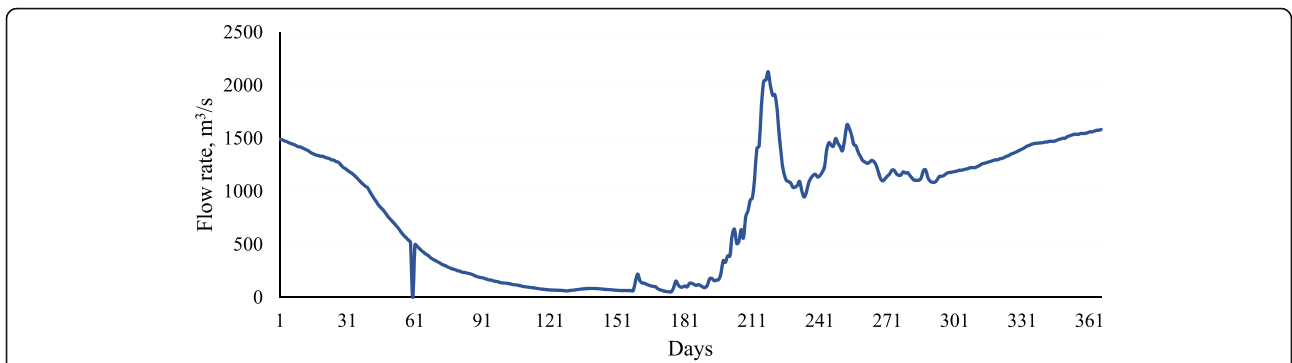


Fig. 3 Flow rate of Niger River in 2015 [16]

decommissioning phase but continue to operate with high generation costs [13].

Against this backdrop, solar PV and hydropower hold the promise of becoming suitable alternative energy sources in Niger. An attractive medium to large hydropower potential in the country is estimated at about 312–450 MW [17, 18]. Until now, only a feasible potential assessment has been carried out for a few sites, such

as Dyodyonga, Gambou, and Kandadji, with an estimated hydroelectric power potential of about 38, 122.5, and 125 MW, respectively [17]. Figure 3 depicts the flow rate of the Niger River in dry and wet seasons measured in Niamey [16]. Some suitable mini-hydropower sites have also been identified along four tributaries of the Niger River, namely Mekrou, Tapoa, Gorouol, and Sirba, amounting to a combined capacity of 3–8 MW [17, 18].

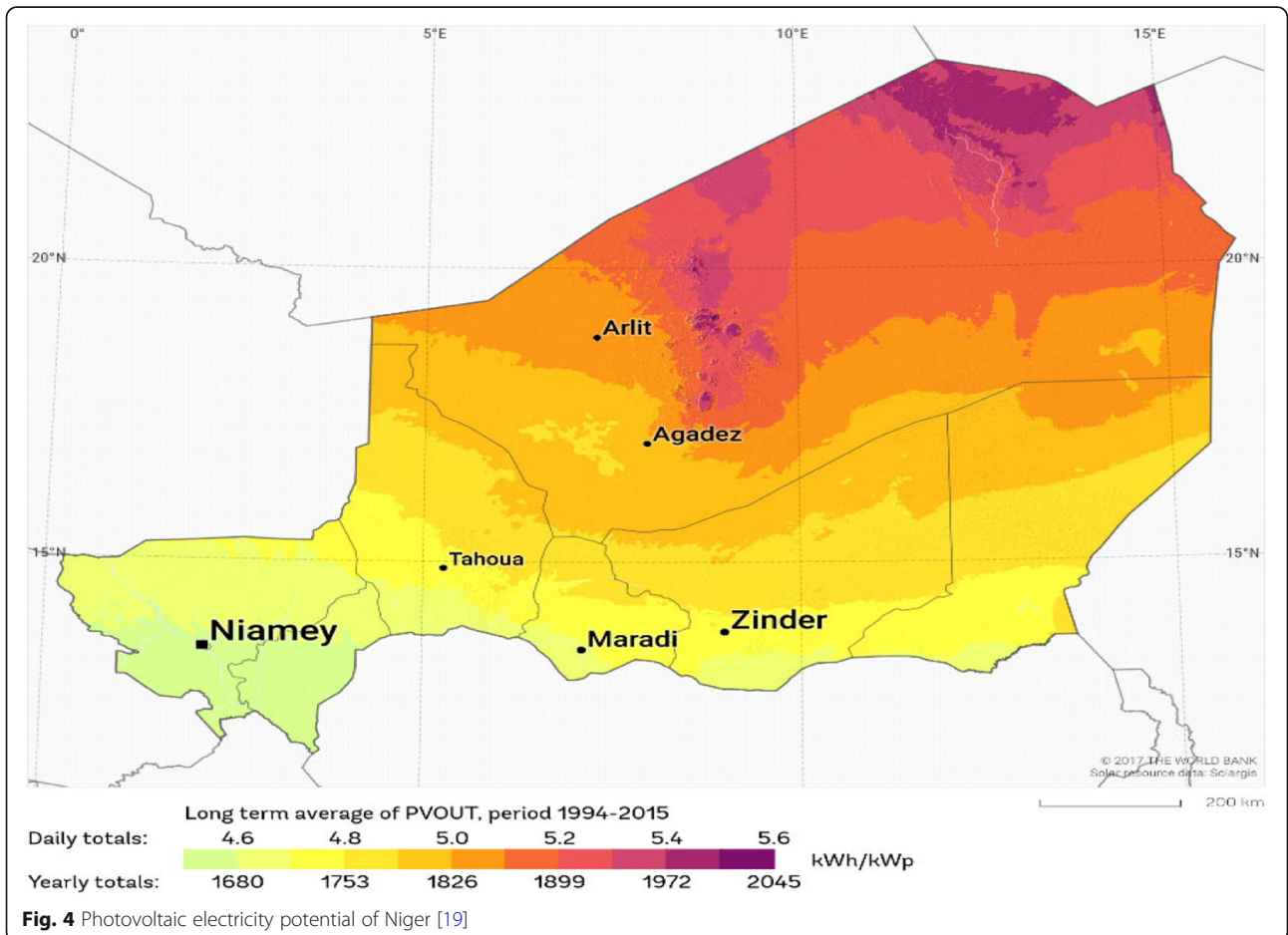
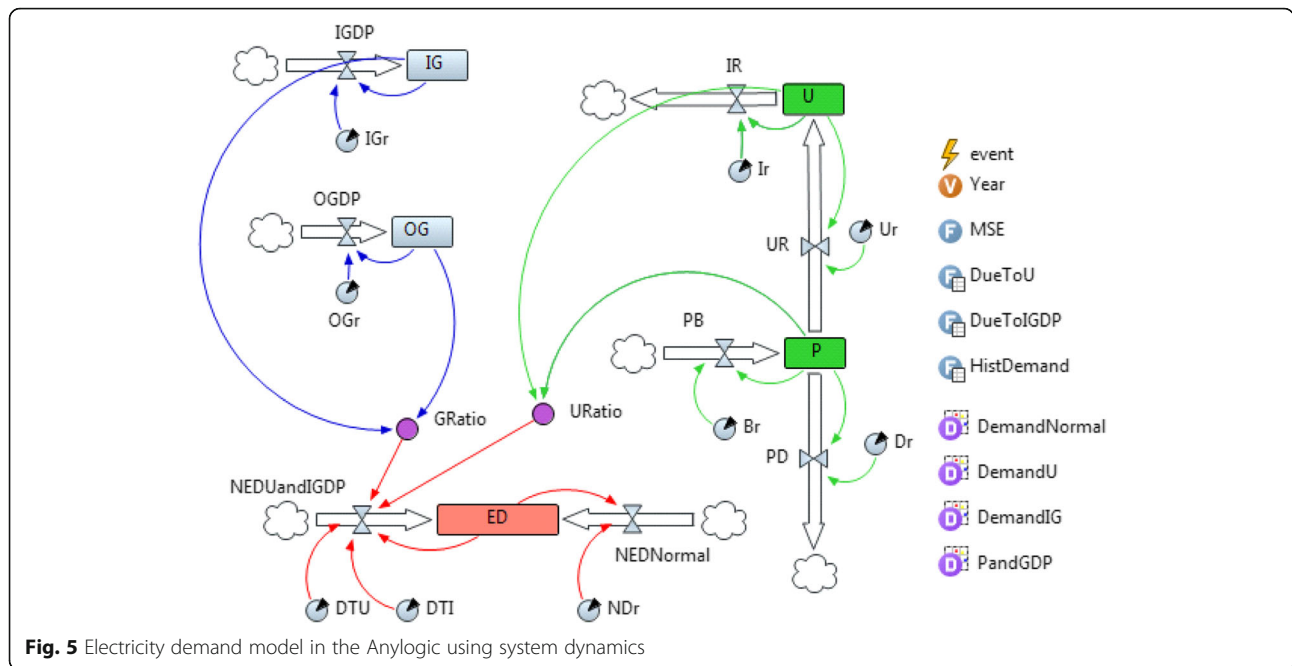


Fig. 4 Photovoltaic electricity potential of Niger [19]



Niger is also endowed with a high solar PV potential. As shown in Fig. 4, almost all regions in the country have a daily average PV potential of over 4.6 kWh/kWp [19]. Thus, if properly designed and operated, power from grid-tied PV systems could provide an efficient method of harvesting the available solar power.

A potential assessment that has been carried out in Niger so far indicates that wind resource is negligible [18]. It also showed that conventional sources of energy such as diesel and coal are abundant in the country [20]. Considering these findings and the aforementioned energy-related issues, a holistic approach for finding an optimal energy mix based on the availability and cost of generation (including the cost to the environment) would be necessary and insightful. Moreover, this

approach should balance the future energy demand and include a strategy to lessen the need for imported energy. Therefore, the optimal energy mix criteria should be based on the following trade-offs:

- The complementary nature of solar and hydropower should be used to compensate for the lower energy output from hydropower during the dry season.
- The high electricity generation cost from solar PV, which has not yet reached a level to be competitive with hydropower, and abundant conventional power sources should be balanced.
- Power from conventional sources should be used to match the future energy demand but lessen their negative impact on climate change and air pollution.

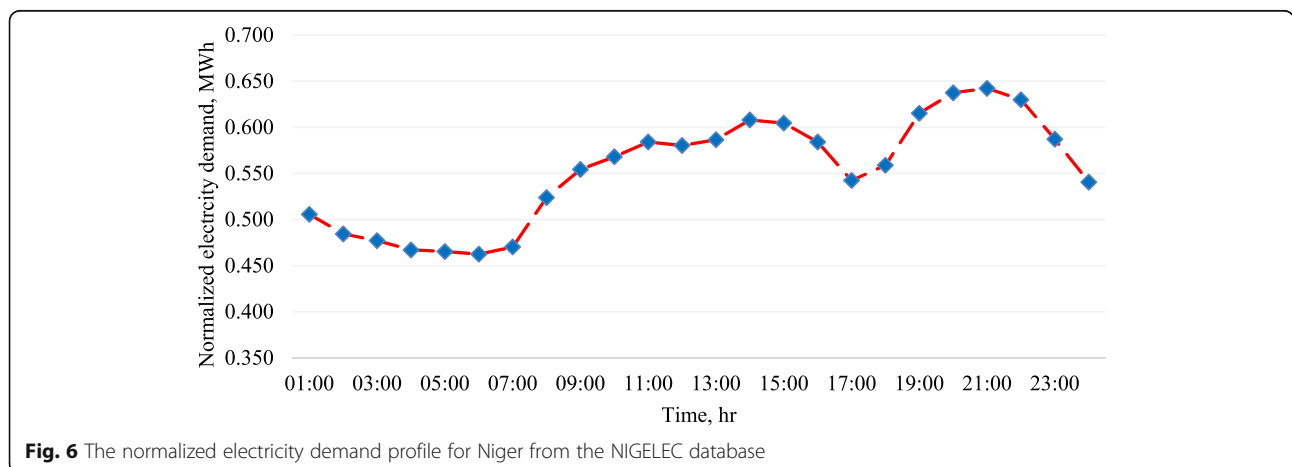


Table 1 Overview of parameter values used to determine the efficiency of a PV system

Parameter	Value	Source
P_p	130 W/m ²	[21]
a	-0.0047 K ⁻¹	[22]
p_0	0.0072	[23]
$\eta_{AC, c}$	99%	[22]
$\eta_{DC, c}$	99%	[22]
η_d	98.5%	[22]
η_{di}	99%	[22]
η_m	98%	[22]

Similarly to the indications given in [24, 25], all future electricity generation schemes should be designed according to the specific context of the country. Considering how poor most developing countries such as Niger are, a policy that ensures a mixed energy grid that is primarily based on affordability and has an eye on sustainability should be the main aim in designing optimal energy supply systems. Therefore, the specific objectives of the study are

- To develop Niger’s future energy demand based on its influencing factors of population growth, industrialization, and urbanization progress.
- To calibrate the model against historical data.
- To formulate and optimize a supply model for an optimal mix of conventional and renewable energy sources based on the LCOE and SCOE.
- To simulate future renewable energy transition scenarios in Niger.

Methods

The model employed in this study consists of three main components: electricity demand projection, supply, and optimization model. The following sections give the details of these components.

Electricity demand model

Several studies were conducted for short or/and long-term electricity demand projection that can be

Table 2 Parameter values used in the supply model and calculation of LCOE for setting the optimization weights [26, 27]

Parameter	Grid-tied PV	Hydropower	Coal	Diesel
Capital cost, \$/kW	2400	2100	1300	1250
Life time, year	20	40	40	20
Capacity factor, %	21	65	70	60
O&M cost, \$/kW/year	24	55	45	10
Fuel cost, \$/Mbtu	-	-	5.1	18.23
Heat rate, btu/KWh	-	-	8937	10,000

Table 3 Greenhouse gas (GHG) emission rates for various power-generation technologies considered [28]

Technology	GHG emissions rates (kg CO ₂ eq/MWh)
Hydroelectric facility	0.5–152
Natural gas-fired power plant	400–500
Oil-fired power plant	790–900
Coal-fired power plant	900–1200

categorized into six types: regression based [29], autoregressive integrated moving average (ARIMA) [30], artificial neural networks [31], fuzzy logic [32], support vector [33], and system dynamics models [34]. The system dynamics approach is able to handle the dynamic evolution of vital energy forecasting variables with feedback loops among each other [35] and allows the incorporation of stochastic behavior [36].

In this work, the inherent relationship between energy demand and economic and social variables is studied using the system dynamics approach. The model anticipates potential electricity demand changes in Niger based on its influencing factors. The following valid assumptions are considered in the system dynamics modeling:

- Due to limited electricity consumption data for Niger (less than a couple of decades), the electricity demand projection is carried out for a short period of up to 2035.
- In Niger’s context, three influencing factors that may strongly affect electricity consumption are included in the model. The first factor is the normal electricity demand due to the change in total population each year. The second influence comes from the effect of urbanization determined from the ratio of the urban population to the total population every year. Lastly, the industrialization change observed each year also influences electricity demand. Electricity demand due to industrialization can be determined from the ratio of other GDPs and industrial GDP in Niger. Other GDPs are defined in this work as GDPs related to service and agricultural economic activities.
- The net change in electricity demand each year from the previous year due to the aforementioned influences can be represented by a linear function [37].

Table 4 Overview of the climate change and air pollution cost used in calculating the SCOE

Cost	Natural gas	Diesel	Coal
COCC, Cents/kWh	0.36	0.49	0.71
COAP, Cents/kWh	0.21	1.3	2.42

Table 5 Calibrated parameter values of the electricity demand model

Calibrated parameters	DTU	DTI	ND _r	a _{1,1}	a _{1,2}	a _{0,1}	a _{0,2}
Value	0.0004	0.0480	4.349E-4	1.1455	-	-	1.5999
					0.0027	1.2352	

Accordingly, each year’s net electricity demand (NED) in Niger can be determined from the rate of change of total electricity demand (ED) as

$$(ED)/dt = NED \tag{1}$$

The NED is the sum of the product of the previous year’s electricity demand by the normal demand rate (ND_r) and the newly added electricity demand rate (AD_r) due to urbanization and industrialization progress calculated by

$$NED = ED \cdot (ND_r + AD_r) \tag{2a}$$

$$AD_r = DTU \cdot UF + DTI \cdot IF \tag{2b}$$

where UF and IF are the urbanization and industrialization factors that affect the net electricity demand due to changes in previous year’s urbanization and industrialization, respectively. DTU and DTI are the urbanization and industrialization coefficients. UF and IF are represented by a functional relation of urban population (U) to the total population (P) ratio and other GDP (OG) to the industrial GDP (IG) ratio as

$$UF = (U/P) \tag{3a}$$

$$IF = (OG/IG) \tag{3b}$$

where *f* is a linear function given by

$$(x) = a_1 + a_0 \cdot i \tag{4}$$

where the coefficients in Eq. (4) are determined from the model calibration experiment based on historical data.

On the other hand, the population and urban dynamics in each year of Eq. (3a) can be represented as

$$(P)/dt = PB - PD \tag{5a}$$

$$(U)/dt = UR - IR \tag{5b}$$

where the total births (PB), total deaths (PD), urbanization rate (UR) and immigration rate (IR) in the current year can be determined as

$$PB = P \cdot B_r \tag{6a}$$

$$PD = P \cdot D_r \tag{6b}$$

$$UR = U \cdot U_r \tag{6c}$$

$$IR = U \cdot I_r \tag{6f}$$

where B_r, D_r, U_r, and I_r are birth rate, death rate, urbanization rate, and immigration rate, respectively.

Similarly, the GDP dynamics can be represented as

$$(IG)/dt = IGDP \tag{7a}$$

$$(OG)/dt = OGDP \tag{7b}$$

where

$$IGDP = IG_r \cdot IG \tag{8a}$$

$$OGDP = OG_r \cdot OG \tag{8b}$$

where OG and IG are industrial and other GDP growth rates in Niger.

The dynamics given in Eqs. (1–8) are based on two sub-dynamics computed from the previous year’s change in model variables. Considering urbanization and industrialization growth rates as negligible, the net electricity demand observed will only be based on the normal population growth in the country. The normal demand rate (ND_r) captures these dynamics. As the urbanization and industrialization growth rates present the change, the net electricity demand will also reflect this change through the UF and IF evolving parameter values. These changes are modeled as a functional value

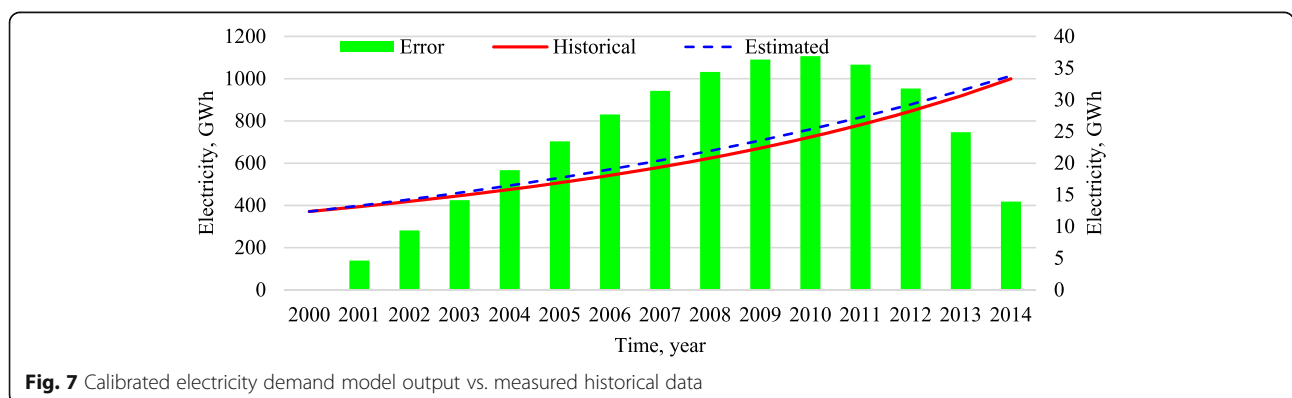


Fig. 7 Calibrated electricity demand model output vs. measured historical data

Table 6 Projected electricity demand in Niger from 2019 to 2050

Year	Electricity demand, GWh	Population, million person	GDP, billion USD
2019	1452.417	22.87	9.42
2020	1560.967	23.59	9.89
2021	1677.672	24.34	10.39
2022	1803.147	25.11	10.92
2023	1938.055	25.90	11.48
2024	2083.108	26.72	12.06
2025	2239.073	27.56	12.67
2026	2406.775	28.43	13.32
2027	2587.102	29.32	13.99
2028	2781.009	30.24	14.70
2029	2989.525	31.18	15.45
2030	3213.755	32.16	16.24
2031	3454.889	33.16	17.07
2032	3714.209	34.19	17.94
2033	3993.094	35.25	18.86
2034	4293.026	36.34	19.82
2035	4615.603	37.46	20.83

of a linear function that takes on the ratios that quantify urbanization (U/P) and industrialization (OG/IG).

The above dynamics given in Eqs. (1–8) is coded into the Anylogic 8.3.2 software resulting in the system dynamics model depicted in Fig. 5. Finally, this model is calibrated against the historical electricity demand data and will be explained in the “Results and discussions” section.

The Anylogic computational platform was chosen because it is an object-oriented modeling framework suitable for system dynamics. Moreover, the Anylogic has a meta-heuristics optimization engine based on the OptQuest package from OptTek Systems that allow parameter variation experiments, calibration of parameters, optimization, and Monte-Carlo runs to be carried out.

Finally, the hourly electricity demand for a given year can be determined from the product of the normalized hourly load profile and annual electricity demand estimate (from the system dynamics model). Figure 6 shows the normalized hourly load profile obtained from the NIGELEC database.

Electricity supply model

Apart from an estimated 2% PV installation in the telecom and off-grid sectors, the power generation in Niger entirely relies on fossil fuels (coal and diesel) [12]. The existing grid capacity is about 173 MW contributed from the five companies NIGELEC, SORAZ, SONICHAR, AGGREKO, and SOMINA. Additionally, there are some

fragmented companies supplying power to mining sites. With a share of about half of the total power production, NIGELEC is the main company responsible for the production, transmission, and distribution of electricity in the country [13]. NIGELEC operates inefficiently and shortly before decommissioning power plants with high operating costs [12], the said inefficient power plants partly contribute to the relatively high electricity selling price (in the range of about 0.16 and 0.22 \$/kWh) despite a very low electricity import price of around 0.044 \$/kWh [13].

In this study, it is assumed that the future electricity supply will be contributed both from RE and conventional sources. Grid-tied PV and hydropower represent the RE generation. Hydropower is a cost-efficient electricity generation technology [38] capable of responding quickly to demand fluctuation [38, 39], and solar PV can complement its seasonal variation [40, 41]. Even though some regions in the northern part of Niger have an average wind speed of over 5 m/s at a 10-m height, the remaining major part experiences a relatively low wind speed of about 4 m/s [12, 18]. Thus, electricity generation from wind is not taken into account in this study. On the other hand, the conventional electricity supply considered is from coal and diesel and not from natural gas since the latter is assumed to be unavailable in Niger [20]. The following section describes the details of the RE and conventional power supply model.

The grid-tied PV system

In order to obtain the specific energy yield of a grid-tied PV system, the approach indicated in [42] is used as follows:

$$P_{PV,s} = \frac{G_t}{1000 \text{ W/m}^2} \cdot P_p \left[+\alpha \left(\frac{G_t}{18 \text{ W/m}^2} + (T_A - 20) \right) \right] \quad (9)$$

where $P_{PV,s}$ denotes the area-specific power of the PV module [W/m^2]; G_t the total radiation on the inclined surface [W/m^2], P_p the peak power of the PV module [W/m^2], and α represents the temperature coefficient and T_A the ambient temperature [$^{\circ}\text{C}$].

The efficiency of the inverter used to convert the DC power to AC power in Eq. (9) can be determined from

$$\eta_i = \frac{p}{p + p_0 + k \cdot p^2} \quad (10)$$

where η_i is the efficiency of the inverter, p_0 denotes the standby losses, k is the rectifier constant, and p is the ratio of the power output of the inverter to its rated power output.

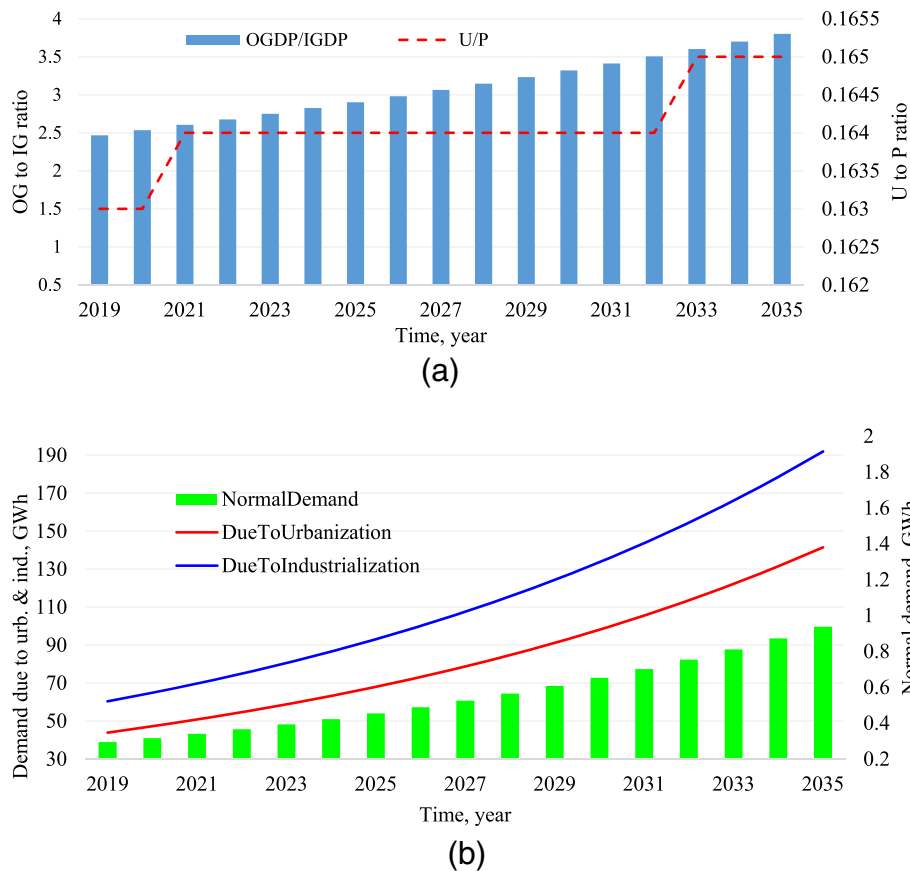


Fig. 8 a Ratio of urbanization to total population as well as other GDPs to industrial GDP and **b** net electricity demand trend contributed from urbanization, industrialization, and population growth (normal demand)

The net power output of a PV system can be calculated by considering the losses in the cables, bypass diodes, and loss due to dust on the PV modules as

$$P_n = P_{PV,s} \cdot \eta_i \cdot \eta_{AC,c} \cdot \eta_{DC,c} \cdot \eta_d \cdot \eta_{di} \cdot \eta_m \tag{11}$$

where $\eta_{AC,c}$, $\eta_{DC,c}$, η_d , η_{di} , η_m are the AC cable loss, the DC cable loss, the efficiency of bypass diodes, and the gross efficiency of the PV module specified by the manufacturer, respectively. Table 1 gives an overview of the coefficients and efficiencies used in the power calculation of the grid-tied PV module.

The PV power calculations based on Eqs. (9–11) were finally coded into the Anylogic. The PV power output is then simulated for a south-facing orientation with a tilt angle equal to the station’s latitude where the solar radiation measurement is collected. The rated power capacity of the PV systems was initially set for 1 kW peak and extrapolated linearly for further output quantities during optimization. It is important to note that the hourly solar radiation data for Niamey are obtained from the Centre National d’Énergie Solaire (CNES) for 2015.

Reservoir hydropower and conventional power plants

The hourly available electrical energy E_h from a given hydropower or conventional power plant can be determined using

$$E_h \leq (P_a + P_i) \cdot C_f \cdot \Delta t \tag{12}$$

where P_i , P_a , C_f and Δt denote the newly added power, the existing installed power, the capacity factor, and simulation time interval, respectively, which is 1 h in this case. The total power capacity is constrained by the maximum value P_m as

$$P_a + P_i \leq P_{h,m} \tag{13}$$

Table 7 Reference and possible scenarios of potential future electricity demand projections

Parameter	Reference	C1	C2
Ur	0.039	0.047	0.039
IGr	0.089	0.089	0.108

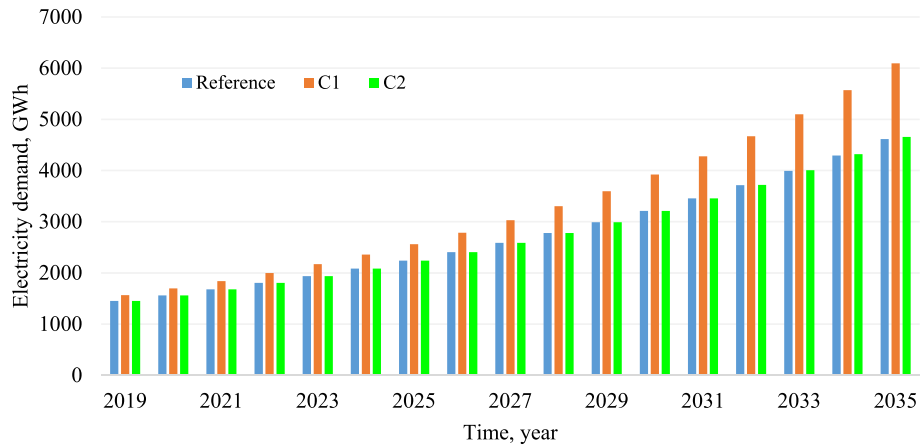


Fig. 9 The effect of urbanization and industrialization growth rate changes on the electricity demand projection

Supply optimization

The optimization problem is formulated based on the minimization of the hourly energy mismatch and the large variation of energy supply from the individual power generation technologies as

$$\Omega = \int_0^T \left[(\alpha(S(t)_t - D_a \cdot L(t))^2 + \sum_{i=1}^{i=n} \beta_i S(t)_i^2) dt \right]^{1/2} \tag{14}$$

where T is the length of the optimization time taken to be 1 year, $S(t)_i$ is the total electricity supply from n renewable and conventional sources $S(t)_i$, D_a is the average hourly load derived from the calibrated demand model, and $L(t)$ is the daily grid power profile normalized to unity taken from NEGELEC main power meter readings. The coefficients α and β 's are the weighting factors that determine the relative share of various power-generation technologies based on LCOE (SCOE) and electricity selling price e_p and can be derived as

$$\alpha = \frac{e_p}{\left[\sum (\text{LCOE}_i)^2 + e_p^2 \right]^{1/2}} \tag{15a}$$

$$\beta_i = \frac{\text{LCOE}_i}{\left[\sum (\text{LCOE}_i)^2 + e_p^2 \right]^{1/2}} \tag{15b}$$

where the LCOE in Eq. (15) is the ratio of total life cycle cost to total lifetime energy production which is calculated as [38]:

$$\text{LCOE} = \frac{I - \sum_{t=1}^T d_t \gamma^t \cdot \alpha + \sum_{t=1}^T C_t \gamma^t \cdot (1-\alpha) - S \gamma^T}{E \cdot \sum_{t=1}^T \gamma^t \cdot x_t} \tag{16}$$

where γ represents the time value of money calculated based on the weighted average cost of capital, r , as $[\gamma =$

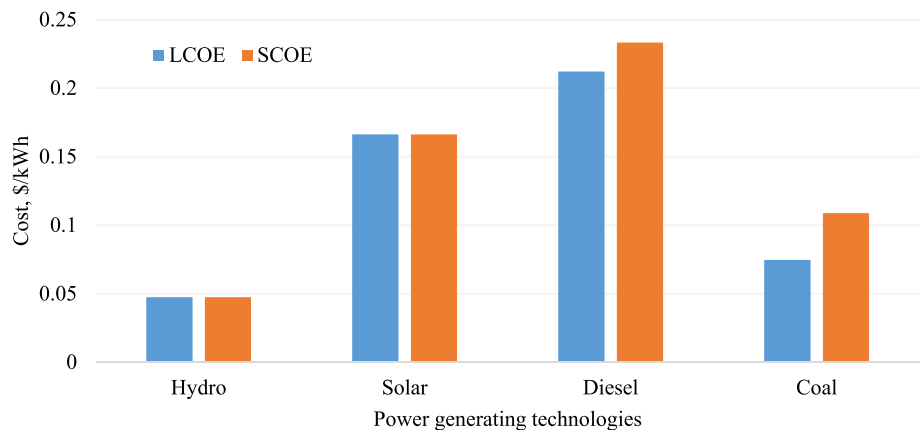
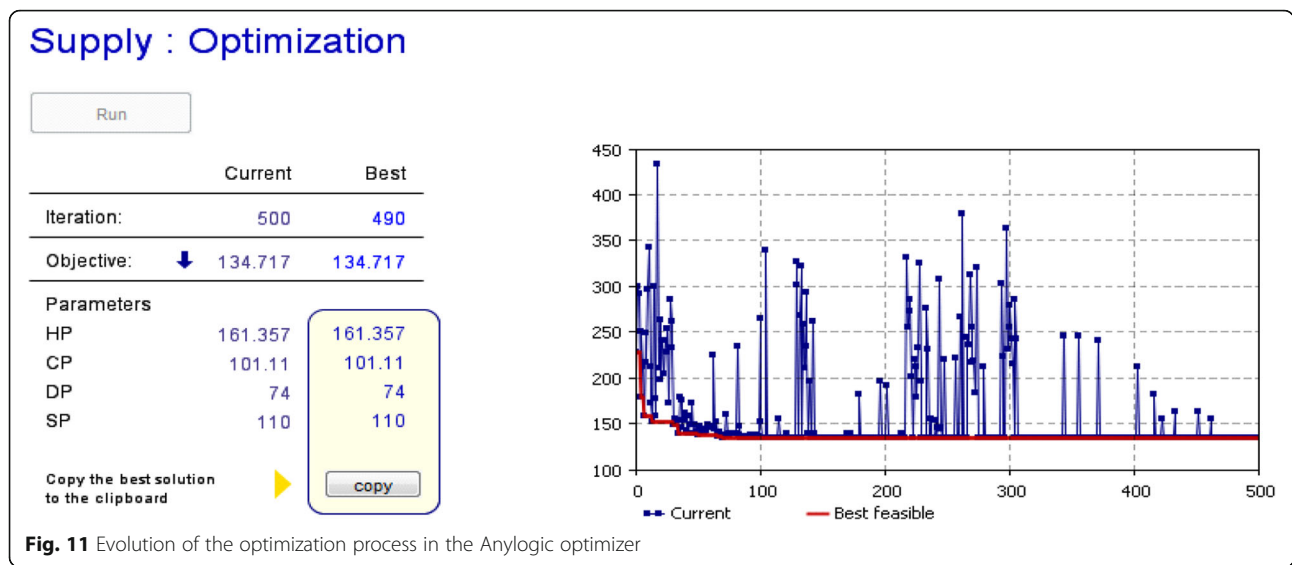


Fig. 10 The LCOE and SCOE for the various power-generating technologies considered



$1/(1 + r)$]. The coefficients $I, S, \alpha, E, T, d_t, C_t,$ and x_t represent the initial investment, the salvage value of the technology at the end of the project, the corporate tax rate, the energy produced, the lifetime of the project, the depreciation rate, the operating cost, and the system degradation in year t , respectively. In the LCOE estimates for this work, the productive capacity remains undiminished for the various power-generation technologies. The weighted average cost of capital and corporate tax rate are also assumed to be 0.08 and 0.0, respectively. The remaining parameter values used in the LCOE calculation are listed in Table 2 [15, 26, 27].

On the other hand, the SCOE, which includes the costs incurred by the society from environmental and social points of view, can be given using [15]

$$SCOE = COCC + COAP \tag{17}$$

where COCC and COAP are costs of climate change and air pollution.

Table 3 illustrates the CO₂ emission rates for the various power-generating technologies considered in this study [28]. Of all technologies, coal-based power generation contributes largely towards global warming emission and air pollution.

The COCC in Eq. (17) is calculated based on a carbon tax that lays a proportional price on fossil fuels

Table 8 Settings for parameter variation experiment

LCOE	Ref.	Min	Max	Step size
Hydro	0.0474	0.02	0.06	0.003
Solar	0.1663	0.1	0.22	0.009
Diesel	0.2121	0.2	0.31	0.008
Coal	0.0746	0.06	0.10	0.003

according to their carbon content. The COAP also varies owing to the presence of different pollutants in fossil fuels. Due to the absence of valid data for hydropower’s emission and air pollution cost, the SCOE is calculated for coal and diesel power generation. Additionally, the solar generation is assumed clean and hence no associated emission and air pollution costs should be considered. Table 4 gives an overview of these costs based on the indications given in [15, 43, 44].

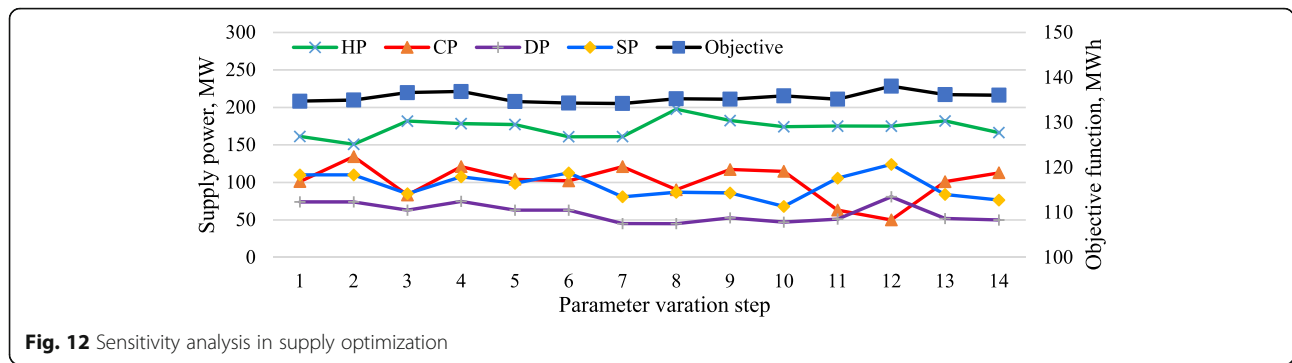
Results and discussions

In the first section, Niger’s future electricity demand estimate derived from the system dynamic model is discussed. This is followed by a second section that depicts the supply optimization process based on LCOE and SCOE. A final section briefly discusses the CO₂ emission reduction potential from the share of RE.

Electricity demand estimate

Niger’s electricity demand for 2019–2035 is forecasted using the proposed electricity demand model that anticipates future changes based on its influencing factors. The trend of the influencing factors, namely GDP, population, urbanization, and industrialization, is explained below.

The annual average industrial and GDP growth rate in Niger from 2000–2017 are taken as 9% and 12%, respectively [4]. However, Niger’s economic growth might increase driven mainly by mining and oil refining activities [1]. As a result, the economic growth rate may vary in the future. This variation is taken into consideration for the projection period from 2019 to 2035. The average birth and mortality rate in the country was about 4.8% and 1% between 2000 and 2017. Although the population growth rate might slightly decrease according



to the observed 7.8% decline in total fertility in Africa from 2005 to 2015 [23], this small change is negligible and it is assumed that the birth and death rate values remain constant for the demand projection period.

Similar to other developing countries, the migration rate from Niger is expected to increase from 0.05% to 0.1% between 2030 and 2050 [45]. The annual average urbanization growth rate amounted to about 3.9% for 2000–2017 [4], and the same rate is assumed for the electricity demand projection period of 2019–2035.

Before simulating the aforementioned scenarios, the electricity demand model needs to be calibrated and validated against the historical trend of electricity consumption in Niger. The procedure aims to minimize the mean square error (MSE) between the simulation output and historical data. Table 5 gives the calibrated variables and their associated values during the calibration process of the electricity demand model that are depicted in Fig. 6.

Figure 7 compares the calibrated electricity demand model output with the historical data and the error between them. As can be seen from Fig. 7, the calibrated model follows the historical trend of electricity demand over the years from 2000 to 2014. The MSE of calibration that is found at 1.66 kWh also validates the capability of the model for estimating the future electricity demand under the given values of the influencing factors.

The projected electricity demand between 2019 and 2035 is illustrated in Table 6. The electricity demand shows an annual average growth rate of 7.5% during this

period. Table 6 also indicates 1.64- and 2.21-fold increases in population and GDP between 2019 and 2035.

Figure 8a shows the relative trend of industrial GDP and urbanization. The contribution towards the total electricity demand because of population growth (normal demand), urbanization, and industrialization is illustrated in Fig. 8b. The ratio of the GDP to the industrial GDP is increasing at a slow pace. This means that Niger’s economy is not dominated by manufacturing and/or processing industries. The small and gradually increasing industrial GDP observed is due to the mining sector that has been in place for a long time. It is possible to see from Fig. 8b that the extent of industrial GDP influence on the electricity demand is much more than the urbanization effect. This is because the urbanization progress is slow (Fig. 8a). It is also important to note that the demand given in Fig. 8b is the net demand for each year based on the change in population, urbanization, and industrialization.

All of the aforementioned factors affecting electricity demand are not fixed and can change following a policy direction from the government. What follows is a scenario of possible anticipated future changes regarding urbanization and industrialization. Two scenarios (C1 and C2) are intended for analyzing their impact on the electricity demand in relation to a reference case presented earlier. The reference and what-if scenarios are given in Table 7.

In Table 7, the urbanization growth rate in C1 and the industrialization in C2 are allowed to vary by 20% from the reference scenario. When considering the electricity demand trend in Fig. 9, it is possible to observe that C2 does not change much compared to the reference scenario, but C1 shows a significant change. A stronger effect of urbanization rate changes on the electricity demand than the industrialization has also been indicated in the literature [3, 6–8].

Supply optimization

The following valid assumptions are taken into consideration for the supply optimization:

Table 9 Optimum values of the various power-generating technologies for the reference and the considered scenarios

Scenario	Reference	C1	C2
Hydropower, MW	161.40	177.43	181.21
Coal power, MW	101.10	129.73	117.54
Diesel power, MW	74.00	74.00	74.04
PV, MW	110.00	112.00	113.05
Average annual demand, GWh	3213.75	3244.79	3719.63

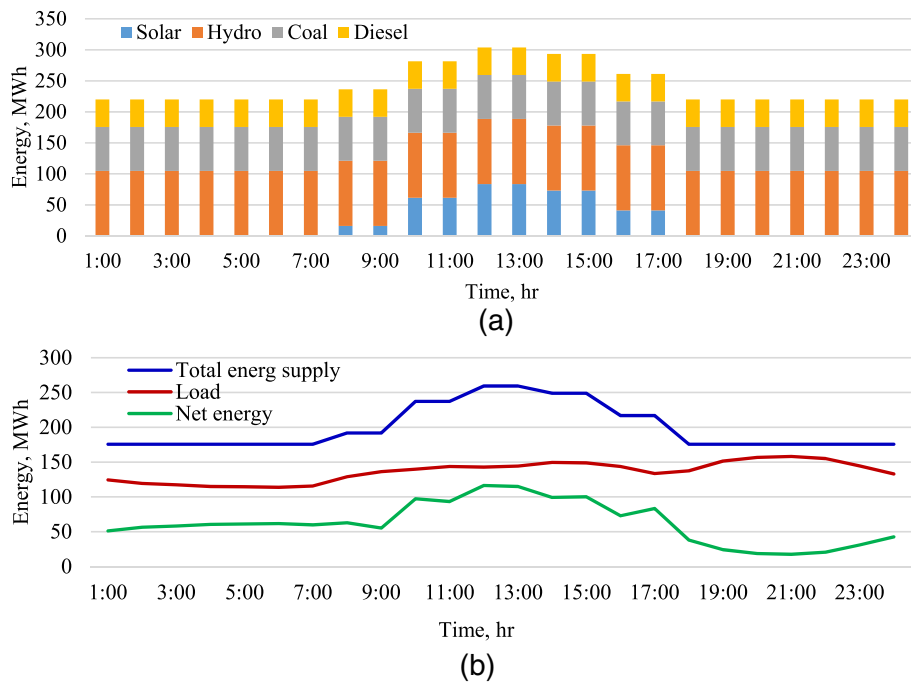


Fig. 13 Simulation of a typical day in the wet season that shows **a** energy supply and **b** demand and supply trend in 2030

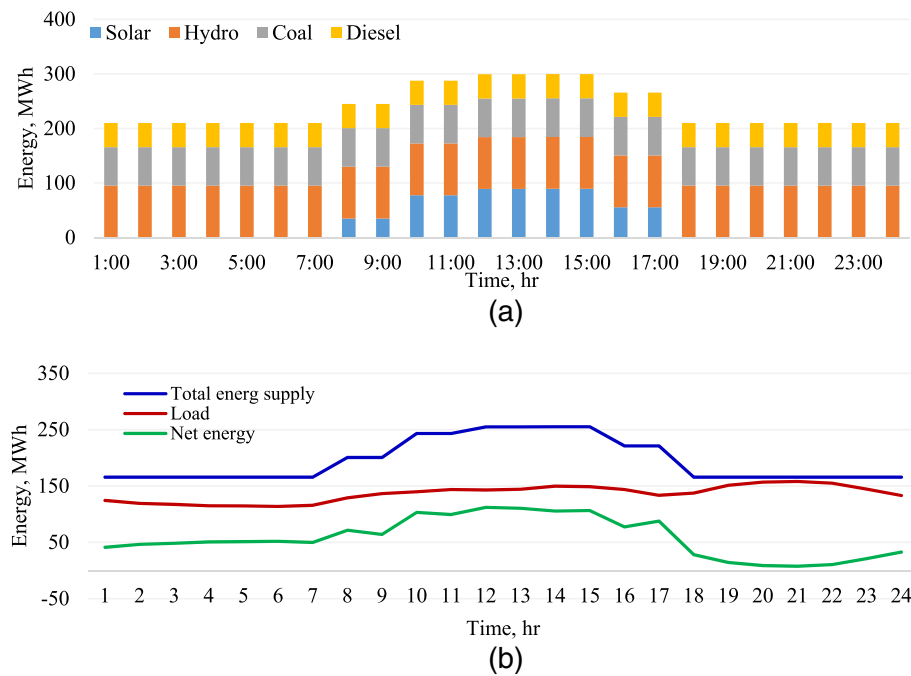


Fig. 14 Simulation of a typical day in the dry season that shows **a** energy supply and **b** demand and supply trend in 2030

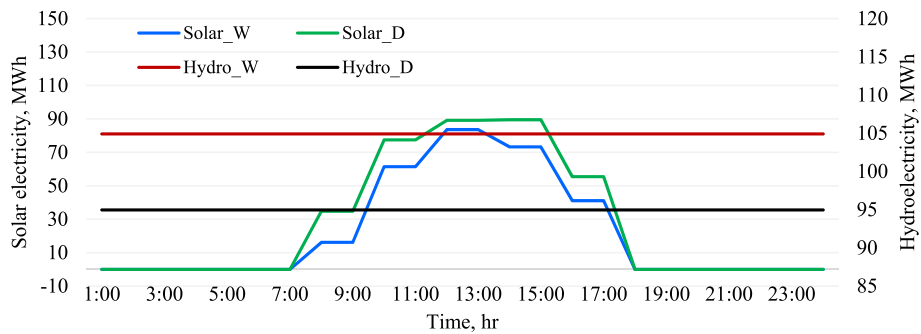


Fig. 15 Dry and wet season complementary nature of solar and hydropower

- As discussed in Section 1, Niger’s heavy reliance on imported electricity from Nigeria stretched to about 86.5% in 2017. Since the average electricity purchase price from Nigeria is cheap at about 0.044 \$/kWh, it is not feasible to completely remove this imported electricity. Instead, a policy should aim at a gradual decrease of this large share to ensure energy security in the country (due to reasons given in the introductory part of this paper). Thus for supply optimization, a 40% decrease in the share of imported electricity is considered.
 - The existing 140 MW from fossil fuels is also included in the supply optimization procedure. The existing and newly introduced power plants constitute an optimal mix of energy supply from conventional and RE sources that will cover the removed imported energy and the added energy demand (due to population, urbanization, and industrialization).
 - The electricity output from hydropower plants in the dry season is allowed to vary from its rated power output by an average value of 28.5%.
 - In the optimization procedure, the total hydropower potential is set to be 400 MW [17, 18], whereas the coal, diesel, and solar power are assumed unlimited to meet the country’s energy demand until 2035.
- The LCOE and SCOE of the various power-generation technologies that are the basis for setting the weighting factor in the objective function of the optimization problem are given in Fig. 10. As for the LCOE, the most economical choices for electricity generation come from hydropower and coal with an LCOE of 0.0474 and 0.0746 \$/kWh, respectively. On the other hand, the SCOE showed that power generation from coal is associated with higher cost from pollution and environment aspects.

Supply : Optimization

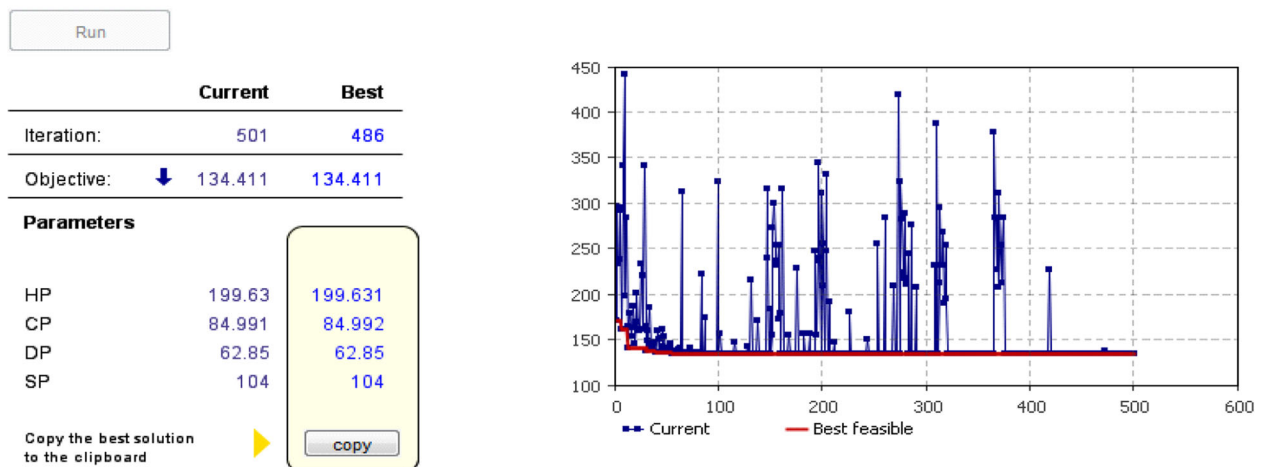


Fig. 16 SCOE-based optimization implementation in the Anylogic optimizer

The supply optimization based on the LCOE is discussed first, and later, this result is compared with the SCOE-based optimization approach.

Figure 11 depicts the states of the objective function and the optimal variables while the simulation is running. The Anylogic optimizer is configured to run for 500 iterations in search of the optimal solution. It gives out the “best feasible” and “current” solutions. The optimizer also keeps a record of the frequency of occurrences of the best optimal solution out of the maximum assigned iteration (490 for the case illustrated in Fig. 11). Finally, the optimizer allows for copying of the best optimal parameter values to transfer them back to the simulation environment for further analysis.

A sensitivity analysis to analyze the effect of variation of the LCOE values on the optimization result based on capacity factor, fuel costs, and projected cost reduction changes is carried out using the experiment setting depicted in Table 8.

The result of the effect of the LCOE variation on the optimal values is illustrated in Fig. 12. There is only a 2.9% change observed in objective function values as the LCOEs vary from the minimum to the maximum values. This is because the weight values of the objective function do not depend on the individual LCOE but on their relative magnitude as given in Eq. (15). For the same reason, it is also possible to notice that there is a relatively high variation in the optimal values for hydro and coal power plants compared to diesel and solar PV.

The LCOE-optimized grid that fulfills the projected demand in 2030 for the reference and the two scenarios C1 and C2 is depicted in Table 9. It is important to note that for C1 and C2, the reference case is used as the starting value during the optimization process. From Table 9, it is evident that the method employed resulted in a 60.78% share of renewable energy sources, including hydropower for the reference case. The PV share in the total RE is about 24.63%. It is also possible to see that the contribution from diesel is the lowest accounting for only 16.57% of the total power. In addition, the diesel contribution remains the same in all the cases due to its relatively high LCOE value. Moreover, this trend of assigning preference based on the LCOE explains the relative variation of optimal values for the various power-generating technologies.

The daily trend of the demand and the supply of energy for the reference case on a typical day in the wet season (August 15 in 2030) is shown in Fig. 13. It is possible to see from Fig. 13 b that the optimal supply guarantees the load constraint placed on the optimization during the whole day.

Similarly, the simulation of the energy output for the various power-generating technologies and a typical dry season (January 15 in 2030) is depicted in Fig. 14. The

solar output is relatively uniform when compared to its yield in the wet season demonstrated in Fig. 13. As indicated in Fig. 14b, the optimal power configuration balances the energy demand despite the observed decrease in hydropower in the dry season.

The complementary nature of solar and hydropower is evident from Fig. 15. In dry seasons, the electricity from hydropower decreases from the wet season value of 104.91 MWh to 94.97 MWh. On the other hand, the solar PV yield increases from its worst day in the wet season from 551.26 MWh to 692.842 MWh for the best day in the dry season.

It is important to note that the actual solar energy supply from the optimized power plant is expected to be higher than that suggested in Fig. 13 and Fig. 14. Due to the absence of measured data, the solar PV output is simulated for Niamey, which receives the lowest solar radiation compared to other regions in Niger, as demonstrated in Fig. 4.

Finally, the consideration of the SCOE as a basis for setting the optimization weights reveals some interesting points. The results given in Fig. 16 show that the contribution from coal and diesel power is negligible in comparison to hydropower and solar power generation. This means that when all costs, including costs borne by the society and environment, are taken into account, a generation from traditional fuels should be avoided. However, given the urgent need for the economic development of Niger, energy affordability should have a priority in designing the optimal mix of energy supply in the grid. As technological advancements make power generation from renewables competitive, the LCOE-based optimal design tends to result in a solution that resembles the SCOE given in Fig. 16.

Another point is that in the years beyond 2030, where the electricity demand is expected to double, the most preferred hydropower will be fully utilized. Thus, Niger should start exploiting its solar as well as conventional sources intensively to balance its long-term energy demand.

Greenhouse gas emissions

The total greenhouse gas (GHG) emission can be calculated by considering the contribution from each energy source to electricity production based on the data given in Table 3 as

$$\text{CO}_{2,T} = \frac{g_1 \cdot E_H + g_2 \cdot E_S + g_3 \cdot E_C + g_4 \cdot E_d}{1000} \quad (17)$$

where $\text{CO}_{2,T}$ is the total annual carbon dioxide generated ($\text{TCO}_{2\text{eq}}$), E_H , E_S , E_C , and E_D are the annual energy yields (MWh) from hydropower, grid-tied PV, and coal and diesel power plants, and g_1 – g_4 are the equivalent

GHG emissions due to the various power generating technologies, as given in Table 3 (kg CO_{2eq}/MWh). Thus, for example, the LCOE-based optimized power supply system in 2030 results in 865,676–1,233,674 TCO_{2eq} emissions. Similarly, the SCOE-based supply optimization reduces the total GHG emission to the range 730,083–1,094,811 TCO_{2eq}.

Conclusions

In this work, efforts have been made to address the future electricity demand and supply in Niger in an integrated and holistic approach. The approach used is a system dynamic model to anticipate future electricity demand changes as a result of population growth, urbanization progress, and industrial development. Reference case and probable scenarios were simulated to obtain the projected electricity demand and their associated renewable energy transition pathways for 2019–2035. Before simulating the aforementioned scenarios, the electricity demand model was calibrated and validated against the historical trend of electricity consumption in the country. The calibration process minimized the MSE between the simulation output and historical data. The MSE of calibration, that is found to be 1.66 kWh, validated the capability of the model in estimating the future electricity demand under the given and assumed influencing factor values. From the calibrated model, it was discovered that a relatively small change in industrialization from the reference case has only a negligible short-term impact. On the other hand, a 20% change in urbanization growth rate will result in a 22% increase of the electricity demand in 2030.

Preceding the electricity demand projection, an optimal energy supply to balance the demand was suggested and implemented. In an attempt to realize the most beneficial optimal mix of electricity generation, an SCOE is formulated as the LCOE plus the cost of climate change and air pollution. The SCOE is then used as a basis for setting the performance criteria of supply optimization. As a result, a power grid contributed from a share of 44.22% hydro, 23.04% grid-tied PV, 18.83% coal, and 13.92% diesel was identified for 2030 according to their relative SCOE values. When compared with the GHG emission, the SCOE-based optimized grid results in 11.26–15.66% less emission than the LCOE-based optimized grid during the same period. Moreover, the optimization highlights the need to intensively use the conventional and solar potential in Niger in the near future to sustain the ever-increasing energy demand. The proposed grid mix also lessens the country's actual electricity import dependency that currently poses serious energy security issues such as electricity price volatility and supply reliability. Likewise, the proposed strategy

helps guide the RE transition pathway in the country with the maximum use of solar PV.

This outcome of the study could help formulate innovative policy pathways for a sustainable energy supply in Niger. There is a growing trend of recognition for developing reliable and adequate electricity supply schemes that can balance the country's future demand. However, a successful realization of the recognition needs an adequate understanding of the underlying relationships among the demand and its influencing factors. A notable requirement is the development of a framework that can link demand and supply. The developed framework needs also to consider the role of an optimized electricity generation mix for the sake of sustainable development (urbanization and industrialization) and climate change goals. Unfortunately, the optimized mix grid, including the alternative energy sources, is not yet considered as a viable energy supply scheme in Niger. This work gives evidence that future RE transition pathways are competitive both from an economical and societal point of view.

Abbreviations

CNES: Centre National d'Énergie Solaire; COAP: Cost of air pollution; COCC: Cost of climate change; GHG: Greenhouse gases; LCOE: Levelized cost of electricity; MSE: Mean square error; NIGELEC: Société Nigérienne d'Électricité; PV: Photovoltaics; RE: Renewable energy; SCOE: Society's cost of electricity

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Authors' contributions

All authors contributed for the modeling and development of the manuscript. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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