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Sustainability assessment of energy supply scenarios: case study of Mali

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Abstract

Mali is endowed with significant untapped renewable energy potentials paradoxically the country is identified as an energy-poor nation characterized by very high dependency on imports of petroleum products and heavy reliance on biomass (wood-fuel and charcoal). Access to electricity remains very low, with significant disparities across urban and rural remote areas. The gap between the electricity demand and supply keeps increasing yearly, and power shortages get frequent and longer, especially during dry periods from March to June. The energy demand increase, due to of population grow and rapid urbanization (causing more use of fossil fuels resources in the energy mix) bears the unsustainability of the country's current energy supply. The challenge for the country is then to meet this growing energy demand with a sustainable energy supply system. In the present work, Analytical Hierarchy Process technique is applied to perform Multicriteria Decision Making analysis to identify and assess the most sustainable long-term energy supply options in Mali considering technical, environmental, social, and economic dimensions. The current situation and five alternatives of energy supply based on the country's current and future energy supply and climate change policies are proposed for assessment. Results show that the highest priority indicators by stakeholders' survey are under economical dimension followed by the technical ones. The best scenario considers deploying renewable energy to up to 42% of the energy mix as the sustainable option for energy supply. Adopting such scenario requires measures as a strong political will to subsidize renewable energy equipment in order to make them affordable and also policies that encourage the use of renewable energy (such as lower taxes and duties). The suggested framework gives decision-makers, authorities, practitioners, and researches an effective tool for the country future energy planning.

1. Introduction

The world's major interest is in reaching sustainable energy, avoiding both the negative effects of global warming and significant economic problems linked to fossil fuel reserves deflating (Zolfani and Saparauskas 2013). Mali, a developing country is facing an increasing demand of energy as result of its growing population and economy. The energy supply systems in the country rely heavily on traditional biomass (firewood and charcoal) accounted for about 78% of national energy consumption. The fossil fuel and the hydropower represent respectively 16% and 3% in the energy mix while the share of the renewable energy is only about 1% (AfDB 2015, SE4ALL 2019). Residential energy demand grows by 14% per year over the last decade (SE4ALL 2019). Thus, the excessive use of traditional biomass for domestic energy contribute to a fast deforestation in Mali with about 500,000 ha of forest

lost per year (CPDN 2016). Almost all household's energy needs met by forest resources (firewood and charcoal) are causing health problems and overexploitation of the forest resources translating to deforestation (Fronteras 2016) and an excessive greenhouse emission increasing from 3434 kT-eq CO₂ to 5268 kT-eq CO₂, with an average annual increase of 6.44% from 2007 to 2014 (CPDN 2016). The energy demand increase (exacerbated by population and economic growth and rapid urbanization) causing more use of fossil fuels resources in the energy mix, and the increasing greenhouse gas from the energy generation and consumption bear the unsustainability of countries current energy supply. The challenge for the country is therefore to meet its growing energy demand with a sustainable energy supply system. Indeed, accessible, available, and affordable energy supply systems are key aspects of socioeconomic development for the country. According to SE4ALL (2019) the electrification rate in Mali is still very low, although the share of population with access to power has nearly doubled over the past decade (50% in 2019 compared to 22.3% in 2010). Despite that improvement, electricity access in the country remains lower than that of other low-income countries on the continent. The situation in rural areas is particularly challenging with 21.12% access rate in 2019 (SE4ALL 2019). Moreover, most rural households meet their electricity needs using kerosene and batteries, those products are expensive, unreliable, and sources of greenhouse gas emission into the atmosphere.

Currently, the country's energy transitions and supply security faces major challenges: poor diversification of the production sources, poor accessibility and poor reliability of energy systems, and lately climate change, reflecting in sum the poor sustainability of the Malian energy supply system (Fock *et al* 2012). According to Third National Communication of Mali in 2018, designing sustainable energy supply systems for Mali is tedious considering the country's heavy reliance on fossil fuel, natural resources such as biomass, and energy import exposing it to climate change, fossil price volatility, etc (TNC 2018). Investigations have highlighted that the Malian energy system is characterized by its very high dependency on energy imports (oil sub-sector which represented 26% of all imports in 2010 and 22% in 2015) (SE4ALL 2019). Also, the non-diversification of the electricity production resources concentrated on hydropower leave the country's energy system facing unstable electricity distribution (PANER 2015). Furthermore, the country is exposed to climate change, land degradation, and natural resource depletion, hence the current energy supply systems based on firewood resources and hydropower cannot adequately respond to growing energy needs.

Therefore, a certain number of policies and strategies have been adopted by the government to identify country priority sectors and key actions to achieve sustainable energy for all in the country (PANER 2015, Fronteras 2016, SE4ALL 2019). Hence, those energy policies and strategies target to promote sustainable energy which constitutes a guarantee for economic growth, energy supply security, and mitigation of climate change effects (PANER 2015, PANEE 2015, AfDB 2015, CPDN 2016). The National Energy Policy (NEP) was the first set of national strategy initiatives and development prospects in the energy sector. Established in 2006, NEP indicates the rural sector as the driving force of the national economy, and proposes strengthening the energy infrastructure including expansion, diversification, and extension of the energy system to the sector (NEP 2006). Thus, six (6) sub-sectors namely traditional energies, hydrocarbons, electricity, renewable energies, nuclear energy, and energy conservation, were targeted by the authorities for development based on the strengthening and diversification of the energy supply systems to satisfy a predominantly residential energy demand (SE4ALL 2019). The national policy NEP aimed to promote the wide use of Renewable Energies (RE) technologies to increase the share of RE in national electricity production from less than 1% in 2004 to 6% in 2010, and 10% in 2015 (NEP 2006). So, the priorities of the country were to secure and increase the power grid coverage from 14% in 2004 to 45% in 2010, and 55% in 2015; and increase the rural electrification rate from 1% in 2005 to 12% in 2010, and 55% in 2015 (NEP 2006, SE4ALL 2019). Moreover, the National Action Plan for renewable energy (PANER), for energy efficiency (PANEE) both adopted in 2015, sought to increase by 2033 the share of renewables sources in the national energy balance by 10% and in the electricity production by 25% (PANER 2015, PANEE 2015, CPDN 2016). Another important aspect of the Malian energy planning strategies and energy policy includes the West African Power Pool (WAPP) which includes a policy of energy sharing between countries facilitated by the interconnectors installed in those countries.

Thus, developing a sustainable energy supply strategy for Mali required multidimensional aspects taking into account the existing resources and the country policies and targets. So, the future energy supply needs to consider sustainability criteria on the pathways of the country's energy transition and decarbonization such as those pursued by the Nationally Determined Contributions (NDC). Hence the goal of the present study is to assess the country's present and future energy supply options using sustainability assessment tools based on Multi-criteria Decision Making (MDCM). Specifically, the objectives are to (a) evaluate the current national energy situation; (b) develop and select scenarios and indicators that sought to evaluate the energy supply options, (c) and evaluate the sustainability of the future energy supply options.

2. Overview of energy sustainability assessment tools

Sustainability development is defined as ‘the development that meets the needs of the present generation without compromising the ability of the future generation to meet their own needs’ (Wang *et al* 2009, Demirtas 2013, Mortey *et al* 2019). Sustainability issues and human activities are closely related to energy use. The goal of sustainable energy systems is to deliver affordable energy services, raise living standards to the global population by increasing energy efficiency and deployment of renewable energy (RE) resources (for which the Levelized Cost has substantially dropped and their cost-effectiveness in terms of electricity price is now lower than that of fossil fuels (Sawadogo *et al* 2019)).

Sustainability of energy supply options should be assessed with respect to various dimensions since energy systems are key factors in achieving country sustainable development by improving social and economic well-being and human welfare (Demirtas 2013, Rösch *et al* 2017). The basic dimensions for energy sustainability analysis include environmental, technical, economic, and social aspects (Demirtas 2013). Therefore, MCDM constitutes an ideal tool to assess the sustainability of energy supply options. MCDM is a renowned decision-making method that uses analytical approaches to make proper decisions by finding distinct alternatives from a set of proposed options (Zolfani and Saparuskas 2013, Kumar *et al* 2020). Since in the 1980s growing global environmental analyses shifted from single parameter assessment toward MCDM techniques (Wang *et al* 2009). The MCDM approach is used to assess the sustainability of the country’s long-term energy supply under different scenarios by scoring different alternatives/options according to the country’s selected sustainability criteria and energy situation. Therefore, the present study considers sustainability dimensions as environmental, technical, social, and economic, and the weight of each dimension is determined depending on the resources potential and the country policies and targets considered to assess the sustainability of energy systems comprehensively.

Various MCDMs techniques have been used in energy systems planning as decision support framework to choose the most sustainable system. They include Weighted Sum Method (WSM), Weighted Product Method (WPM), Analytic Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Multi-Objective Optimization by Ratio Analysis (MULTIMOORA), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), Elimination and choice translating reality (ELECTRE), etc In this study, AHP approach is considered to perform the MCDM analysis in determining the most sustainable energy supply scenario for Mali. AHP is one of the most popular tools in multi-criteria decision-making (MCDM) (Solangi *et al* 2019). A major strength of AHP is the pair-wise comparison, where the influence of the elements of a particular level over those of a lower level is measured (Nigim *et al* 2004). However, the main disadvantage of AHP is the large number of pairwise comparisons, which can certainly cause errors to arise. Nevertheless, consistency indices are developed for identifying and minimizing errors likely to occur with AHP (Pant *et al* 2022). Alternatively, TOPSIS and PROMETHEE could be used because of their accuracy and ability to handle large number of criteria (Widiarta *et al* 2018).

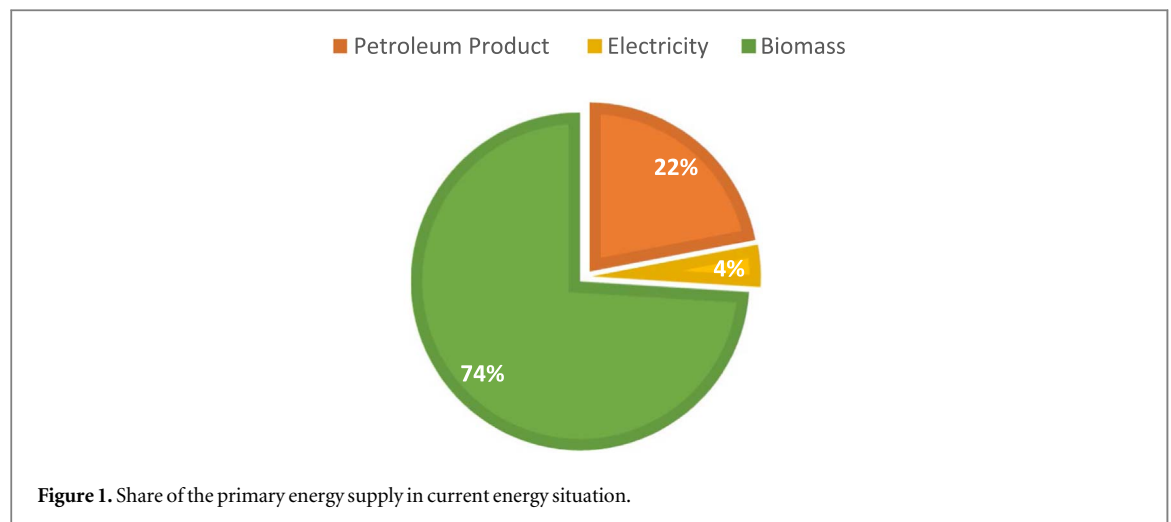
3. Methodology for the development of energy supply scenarios

3.1. Current situation of energy supply in Mali

Currently, the country’s national primary energy and electricity systems are dominated by biomass and hydropower with 78% and 50% respectively (AfDB 2015, SE4ALL 2019). Such dependency would become a particular problem in light of climate impact on energy resources. Biomass, 78% of the total share of the primary energy supply, and electricity production based on thermal and hydropower, are revealing a heavy dependency on energy import and hydro energy resources (figure 1). Energy import in the country represents 22% exclusively petroleum products since the country doesn’t have proven fossil fuel resources. It imports all the petroleum products for its needs and that excludes the import of electricity from the neighboring countries. In the year 2016, the import from Cote d’Ivoire increased from 30 MW in 2012 to 50 MW representing 17.3% of the total electricity supply (SE4ALL 2019).

3.2. Definition of energy supply scenarios for mali

To evaluate the energy situation in Mali, scenarios are considered. The development of these has consisted of two stages: first a literature consideration and second energy expansion plans based on Mali national energy policies (‘la politique des énergies au Mali’). Based on the above, six (6) different energy supply mix options (scenario) for the horizon of 2050 were defined. The assumptions considered the overall objective of the National Energy Policy (PEN) which has been lightened in the energy situation of the country stated above. Future energy planning that may or may not happen and provide answers to ‘what if’ types of questions is assessed using scenario analysis to assess alternative Malian energy futures and assess the sustainability implications. The



development of scenarios for consideration in any study will depend on many different factors, including policy and socio-economic drivers such as economic growth, security of supply, and mitigation of climate change as well as the anticipated technological development in the future (Santoyo-castelazo and Azapagic 2014). These will also determine the time horizon to be considered in scenario analysis; typically, the period of analysis covers the period from 2020 up to 2050. The technologies and proven resources and the ones accessible to the country are integrated to form the energy mix for the different scenarios.

The present exercise focuses on the present energy supply path and the assumption of the options to be evaluated (table 1). The scenarios reflect the aspirations of the Malian government to transform the country's energy systems along with increasing energy efficiency of the systems, increasing the share of renewable and decreasing the dependency of the supply on traditional biomass and were constructed considering the structure recommended by (PANEE 2015, PANER 2015, SE4ALL 2019). The perspective of oil and Hydrogen exploitations and nuclear energy are foreseen by the report but the present study considers these options unsustainable considering that Mali doesn't have the technological expertise in place, the study considers that this field will be socially and economically burdens to be integrated into the national energy supply. A brief description of the scenarios follows, and table 1 lists the specific parameter-characterized scenarios. The (6) scenarios focus on the targeted domain of intervention depicted in the national policy documents and energy strategies:

- Reducing the consumption of biomass used for cooking, through the wider dissemination of efficient improved stoves;
- Development of renewable energies
- Improving access to electricity and efficiency in the supply

The scenarios were developed based on the projection from the year 2018 which is the reference basis of the Malian energy supply and the base scenario considered here as BAU to the year 2050. The scenarios were developed to explore and investigate key features of possible technological (energy resources and energy technologies) developments. To make all the options comparable, the assumptions in scenario 0: BAU of the annual energy demand growth rate of 10%, increasing from the current (AfDB 2015) assumed to be constant on the period of analysis. As shown in figure 1, the scenarios adopt more or less an increase or decrease in the proportion of production sources between 2020 and 2050. The percentage of the technology's dependent on the nature of the scenario. The corresponding energy mix then prioritizes the production sources that the scenario represents.

3.3. Multi-criteria decision-making applied to the malian energy system

To propose a sustainable energy system considering the country's (Mali) energy policies and development plans, a Multi-Criteria Decision-making approach was applied. Twenty (20) indicators based on four (4) sustainability dimensions were selected after extensive literature reviews to be the base of the systems assessment. Data availability has been the major factor in this selection. Indicators are strongly dependent on the type of system they monitor. The selection of indicators has prioritized aspirations and strategies towards the socio-economic

Table 1. Detailed Scenario of energy supply in Mali to 2050.

S0	Scenario 0: BAU	The current energy trend is based on the heavy reliance on biomass (fuel wood and charcoal) 74% and the dependence on fossil fuel importation 22%; with a small share of electricity production 4%, biomass 74%, petroleum products 22%, hydro 50.7%, solar 2.4%, wind 0%, thermal 46.9%, import 17% of electricity.	The business-as-usual (BAU), where no action is taken and the current energy situation is projected as the same to 2050. This is the basic scenario, in which current trends persist without the necessary corrections to meet the SDGs.
S1	Scenario 1: increases the share of renewable energy and reduction of the share of traditional biomass	Energy policy supporting development strategies that support the decrease of energy consumption pressure on the forest reserves by decreasing the share of traditional biomass in the energy mix: electricity 17%, biomass 50%, modern biomass 10%, petroleum product 23%, hydro 20%, solar 28%, wind 2%, thermal 30%, import 17%, bioenergy 3%	Scenario 1 assumes a slow and steady transition from this resource to introduced modern biomass in the form of briquettes, which denotes the reduced access to energy supply and the low level of electrification in the country. Hydropower is the main source of electricity generation followed by thermal production together with minor contributions from minor share producers from solar energy.
S2	Scenario 2: increases the share of renewable energy and reduction of the import	Energy policy supports diversification of electricity supply and encourages investment in low-carbon options with emphasis on renewable energies. Favor strategy that supports the increase of renewable energy share in the mix energy: electricity 17%, biomass 40%, modern Biomass 20% natural gas 3%, petroleum products 20%, hydropower 30%, solar 30%, wind 10%, thermal 15%, import 0% of electricity, bioenergy 15%.	This option proposes to steadily decrease the use of traditional biomass and introduce the modern biomass (charcoal produced by efficient carbonization). Increase the production of electricity to improve the rate of electricity access and diversify the production resources to increase renewable energy sources in the generation and induce reliability of the systems.
S3	Scenario 3: increases the share of electricity access and energy diversification	An energy development strategy that supports the deployment and energy diversification of renewable energy: electricity 40, biomass 27%, modern biomass 10%, natural gas 3%, petroleum product 20%, hydro 25%, solar 30%, wind 10%, thermal 15%, import 5%, bioenergy 15%	This scenario focuses on the deployment of renewable energy resources. It takes account of all renewable energy resources available in the country, and the highlights the reduction of the country dependence on hydropower production.
S4	Scenario 4: decrease CO ₂ emission, prioritizing renewable in the energy mix.	An Energy development strategy that supports the decarbonization of the energy systems and the adaptation and mitigation of climate change: electricity 70%, biomass 10%, modern biomass 5%, natural gas 5%, petroleum product 10%, hydro 25%, solar 35%, wind 10%, thermal 0%, import 5% of electricity, bioenergy 25%	This scenario focuses on making the most use of local resources to meet long-term demand, diversification of energy supplies, finding new and renewable energy sources, introducing energy efficiency measures, and minimizing losses in energy production, transmission, distribution, and consumption.
S5	Scenario 5: increase the electricity importation	Energy development strategy, the increase electricity access at the national level and with strong support for electricity import from Neighboring countries: electricity 70%, biomass 10% modern biomass 5%, natural gas 5%, petroleum product 10%, hydro 18.4%, solar 22%, wind 0% thermal 38.1, import, 41.3% of electricity, bioenergy 0%,	The scenario 5 focuses on the dependence of the country on hydropower as well as the advantage of the interconnectors between the countries for electricity sharing buy importing significant share off its electricity through these systems.

development of Mali, where income creation is identified as the most important aspect hence the choice of consideration.

The survey was conducted to prioritize dimensions and associated criteria to be used. Thus, a questionnaire (see Annex) was submitted to key energy institution actors and other energy stakeholders and the responses of 80 respondents (table 2) are used to prioritize the dimension and criteria to be applied in the evaluation of the sustainability of Mali's energy supply systems. The survey was structured around attributing notes to the selected four (4) dimensions and 20 criteria in table 3 considering the importance of those in achieving sustainable energy

Table 2. National institutions involved in the survey and the number of respondents.

National institutions involved in the survey		Number of respondents
DNE	The national direction of energy	6
AMADER	Malian Agency Domestic and Rural Energy	10
AER	Agency for renewable energy	6
ANADEB	National Agency for biofuel development	2
GIZ MALI	German Society for International Cooperation	5
EDM-SA	Malian Electricity Company	30
ACCESS	Private Company for rural electrification	1
USTTB	The University of Science, Technique, and Technology	20
TOTAL		80

Table 3. List of evaluation criteria for Malian energy supply.

Dimensions	Indicators	Unit	Nature	
Technical	TCH1: Production Efficiency	(%)	Positive	(IAEA 2007)
	TCH2: Capacity Factor	(%)	Positive	(EIA 2021)
	TCH3: Resources potential	(MW)	Positive	(Fang <i>et al</i> 2018)
	TCH4: Reliability of the system	Qualitative	Positive	
	TCH5: Resources availability	(Toe)	Positive	
Economical	ECO1: net import dependency	(%)	Negative	(Wang <i>et al</i> 2009)
	ECO2: Fuel cost	\$ / MMBtu	Negative	(Stein 2013)
	ECO3: Levelized cost of electricity	\$ / kWh	Negative	(Brand and Missaoui 2014)
	ECO4: Investment cost	\$/kW	Negative	
	ECO5: Payback period.	years	Negative	
Social	ECO6: Government support	Qualitative	positive	
	SCO1: Energy acceptability	Qualitative	Positive	(Banacloche <i>et al</i> 2020)
	SCO2: Energy accessibility	Qualitative	Positive	(Siksnylyte-Butkiene <i>et al</i> 2020)
	SCO3: Job creation	prs. /MW	Positive	
	SCO4: energy Affordability	Qualitative	Positive	
Environment	SCO5: People displacement	Qualitative	Negative	
	ENV1: Energy diversification	%	Positive	
	ENV2: Fraction of renewable energy	%	Positive	
	ENV3: Land demand/ Rate of deforestation	m2/MWh/km2	Negative	
	ENV4: Emission and Global warming potential	gCO2e/kWh	Negative	

supply in the country's energy mix. We employed both quantitative and qualitative data to estimate the most dimension (technical, social, economic, and environmental) indicator values.

3.3.1. Description of sustainability indicators and dimensions

Defining indicators is a major step in energy systems sustainability assessment. The choice of indicators (table 3) is driven by the country energy development and poverty alleviation policies (published in SEforALL-Mali) that presents the action agenda for energy efficacy, renewable energy, and sustainable energy for all (SE4ALL 2019). Indicators are used to investigate the technical, economic, social, and environmental sustainability of energy systems. For instance, the price of Malian electricity, although relatively high, is nevertheless insufficient to cover the production costs of the energy systems which makes the integration of these four (4) dimensions particularly important into the sustainability assessment for the energy planning (Afgan and Carvalho 2004). The effective indicators have to meet characteristics reflecting a problem and criteria to be considered by showing how well the system is working. These indicators are necessary to reflect various aspects of the energy system for the country's future energy scenario.

• Technical Dimension

The technical indicators for this study are selected in such a way they reflect the impact of this on energy supply technical performances. The production efficiency defined as the ratio between the useful output of an energy conversion system and the input, is adapted by several studies as a sustainability indicator (Afgan and Carvalho 2004, IAE 2007, Stein 2013, Liu 2014). The various options under consideration being composed of different energy mixes are bound to have different technical performances. for the present study, the technical dimension is composed of indicators, namely: TCH1: production efficiency, TCH2: capacity factor, TCH3: RP (resources potential), TCH4: reliability of the system, TCH5: resources availability (toe). They refer to the

efficiency of energy conversion and distribution, including fossil fuel efficiency for electricity generation, the efficiency of oil refining and losses occurring during electricity transmission and distribution.

- **Social Dimension**

The energy system interacting with the surroundings, need to reflect social aspect of the country (Afgan and Carvalho 2004). That interaction can be positive and/or adverse hence the great interest to investigate the social aspect of the options under consideration. Hence, the importance of the social dimension aspect in assessing energy system sustainability. The effective assessment of the social contribution in energy planning considers some social indicators. Availability of energy resources for a greener and diversified energy generation is important. Creating jobs and generating income for energy to be affordable to the population although a high share of renewable energy in the mix might hinder the reliability of the systems due to the intermittent character of these energy sources (Santoyo-Castelazo and Azapagic 2014). Hence the following indicators are selected to assess the social impact of the Malian energy systems: SOC1 energy acceptability, SCO2 energy accessibility, SOC job creation, SCO4 energy affordability, SCO5 people displacement.

- **Economical Dimension**

The economic aspect has also been identified by various studies (Afgan and Carvalho 2004, IAEA 2007, Dombi *et al* 2014, Liu 2014, Santoyo-castelazo and Azapagic 2014, IEA 2021) as a very important aspect in assessing long-term energy sustainability planning. It is also considered an essential dimension in Malian energy planning by the country's Third National Communication Mali (Mali NC 2018). Economic indicators are used to assess the economic impact on the evaluation of energy systems which are very important in the decision-making of energy supply systems. Costs and return analysis, and payback period are used frequently, with a focus on the following indicators: ECO1: net import dependency (%), ECO2: fuel cost (\$/GJ), ECO3: LVC USD/ KWH, ECO4: investment cost (€/KW), ECO5: payback period (year), ECO6: government support.

- **Environmental Dimension**

Environmental indicators are selected to reflect the impacts of an energy supply system on environmental sustainability hence mitigating climate change and helping the country fulfill the NDCs (Liu 2014). CO₂ emission has been defined by several studies to be a significant indicator for the sustainability assessment of an energy system along with Renewable energy fraction, energy efficiency (Afgan and Carvalho 2004, IAEA 2007, Dombi *et al* 2014, Liu 2014, Santoyo-castelazo and Azapagic 2014). The following indicators are used to assess the environmental sustainability of the energy systems: ENV1 Energy diversification, ENV2 Fraction of renewable energy, ENV3 Land demand/Rate of deforestation, ENV4 Emission and Global warming potential.

3.3.2. AHP

This study applied AHP comprising three steps approach, problem decomposition, pairwise comparison, and synthesizing as done by Bhandari *et al* (2021) to rank the different alternatives. The data were aggregated into a decision matrix. The principle is to compare different alternatives by identifying a set of evaluation criteria applicable to all of the alternatives. The values of these criteria are then normalized, and their weights are determined according to the relative importance of the criteria (Wang *et al* 2009).

Step 1: Decomposing the problem

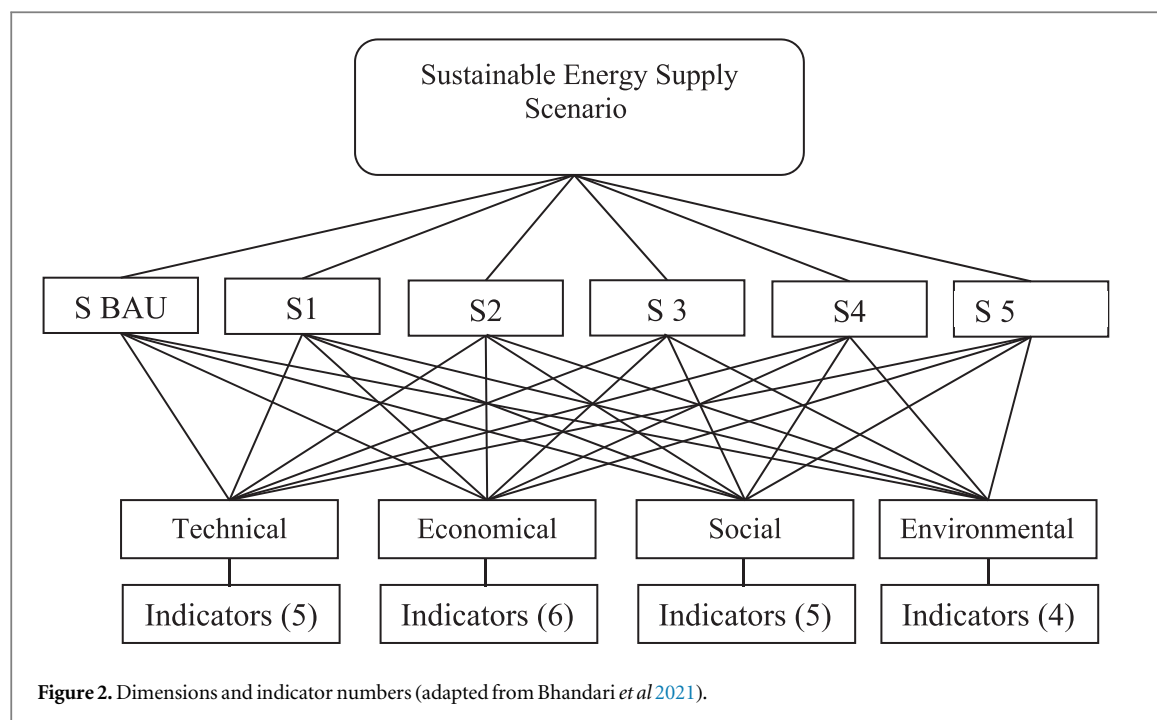
The following flowchart (figure 2) depicts the Decomposing problem considered in the energy situation of Mali.

Step 2: Pairwise comparisons

Weights and ranks of selected criteria are determined by pairwise comparison. The sub-criteria are compared concerning the corresponding main dimension, and the different scenarios are compared with respect to each sub-criterion to determine the weights and rank the different sub-criteria and alternatives (Mastrocinque *et al* 2020). During this step, the pairwise comparisons are organized into an $n \times n$ matrix.

3.3.2.1. Assumptions and data sources

All the initial indicator values for individual technology (Diakoulaki and Karangelis 2007, Stein 2013, Troldborg *et al* 2014, Bhandari *et al* 2021) were taken from the literature. All the initial indicator values per scenario are obtained from processing the following formula. The obtained values are then considered as the initial indicator values per scenario.



$$X_{ij} = \frac{\sum_i Id_i * Perc}{\sum_i Perc} \frac{Id_{ij}}{Id_i} \quad (1)$$

i : scenrio, j : indicator, X_{ij} : initial value of the indicator per scenario, $Perc$: percentage per the scenario, Id_{ij} : initial value of the indicator.

3.3.2.2. Normalization

To evaluate the equivalence, the indicators have to be brought to a common scale through normalization. By normalization, a direct comparison is achieved because each indicator is dimensionless, with values between 0 and 1. The normalization processes were achieved through linear normalization (Vafaei *et al* 2016) as follows:

- Normalization equation of positive-type indicators (beneficial criteria):

$$\bar{X}_{ij} = \frac{X_{ij}}{X_{jMax}} \quad (2)$$

- Normalization equation of negative-type indicators (non-beneficial criteria)

$$\bar{X}_{ij} = 1 - \frac{X_{ij}}{X_{jMax}} \quad (3)$$

$\bar{X}_{ij}$: the normalized value of the indicator, X_{ij} : initial indicator value

Step 3: Synthesis

To ensure the statistical consistency of the pairwise comparison, the consistency ratio needs to be calculated (Bhandari *et al* 2021) in which the value should be less than 0.10 to show a statistical consistency (for consistency ratio for N greater than 15) (Alonso and Lamata 2006).

4. Results and discussion

4.1. Analysis of energy supply scenarios and projection to 2050

Table 4 shows the current energy situation considered as the basic scenario (BAU) which does not target reduction of the share of traditional biomass which is the highest Malian energy supply component, based on traditional cooking fuels. While BAU consists mainly of traditional biomass, petroleum product, thermal energy and hydropower, the alternative scenarios (S1, S2, S3, S4 and S5) include in addition, renewable energy components and natural gas which have a huge potentiality in the country. The energy demand of Mali growth

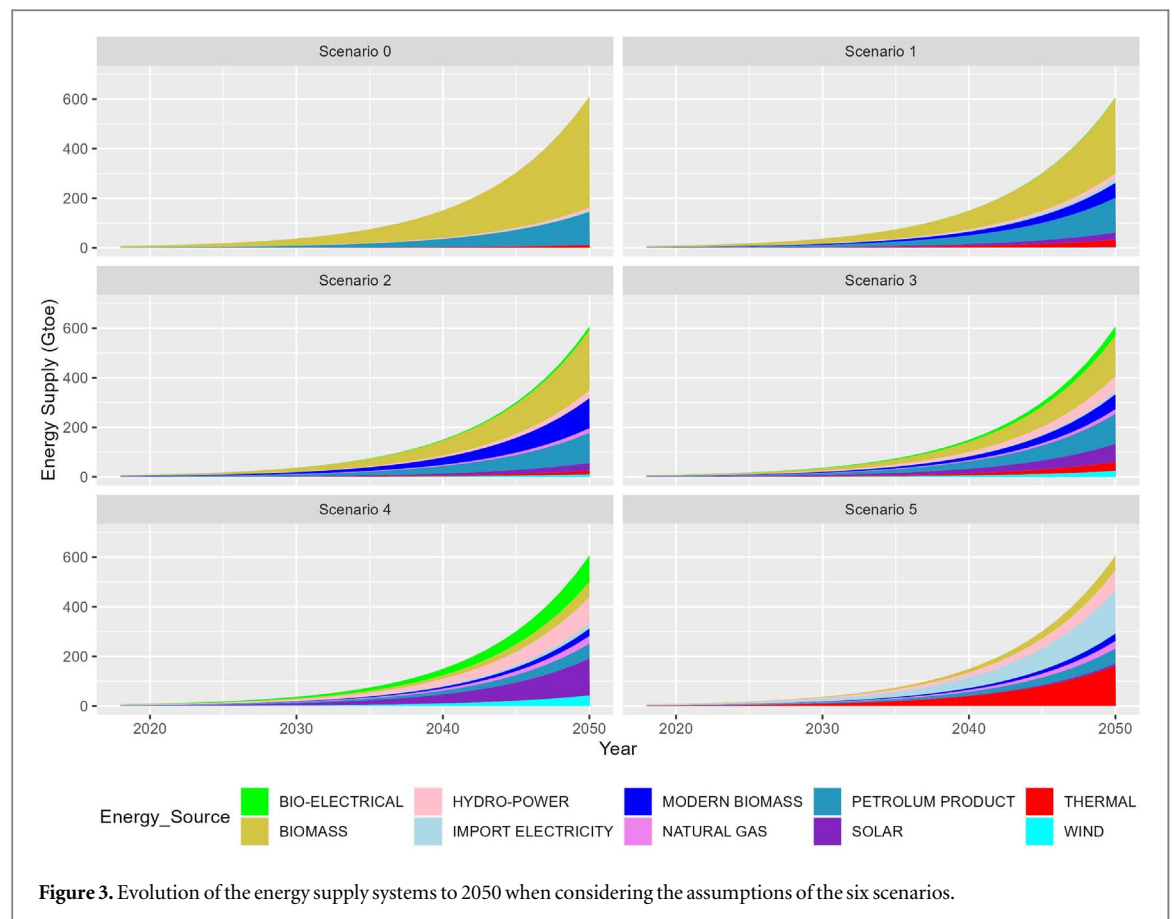


Table 4. Detailed share of energy sources for different alternatives of energy supply in Mali.

Energy technology share (%)	S0 (BAU)	S1	S2	S3	S4	S5
Biomass (Traditional)	74	50	40	27	10	10
Biomass (Modern)	—	10	20	10	5	5
Petroleum Product	22	23	20	20	10	10
Natural Gas	—	—	3	3	5	5
Electricity supply	4	17	17	40	70	70
Hydro*	(50.7)	(20)	(30)	(25)	(25)	(18.4)
Thermal*	(46.9)	(30)	(15)	(15)	(0)	(38.1)
Bioenergy	—	(3)	(15)	(15)	(25)	(0)
Solar*	(2.4)	(28)	(30)	(30)	(35)	(22)
Wind*	(0)	(2)	(10)	(10)	(10)	(0)
Import*	(17)	(17)	(0)	(5)	(5)	(41.3)

*Share (%) in electricity production

annually with a rate of 10% (AfDB 2015), this rate is maintained constant to assess the future evolution of the energy supply systems on the period of analysis. The evolution of each share from 2018 to 2050 is presented in figure 3.

Figure 3 give a details representation of each energy supply scenario. It appears that the scenario BAU is the less diversified energy supply option based essential on the use of traditional biomass (charcoal and firewood) which amount increase to 500 Gtoe in 2050 (figure 3, scenario 0). The forests of Mali will not be able to support such a production of firewood and charcoal which, moreover, already suffer from the combined effects of overexploitation and desertification (CPDN 2016). Scenarios 2, 3, 4 and 5 are all consisted by well diversified sources of energy supply. The share of forest biomass is still significant in scenario 1 and 2 while scenario 5 supports the excessive use of thermal plants and the import electricity both projected to 150 Gtoe in 2050. Energy supply sources are better balanced in scenario 3, unlike scenario 4 which calls for intensive use of renewable sources up to around 150 Gtoe in 2050.

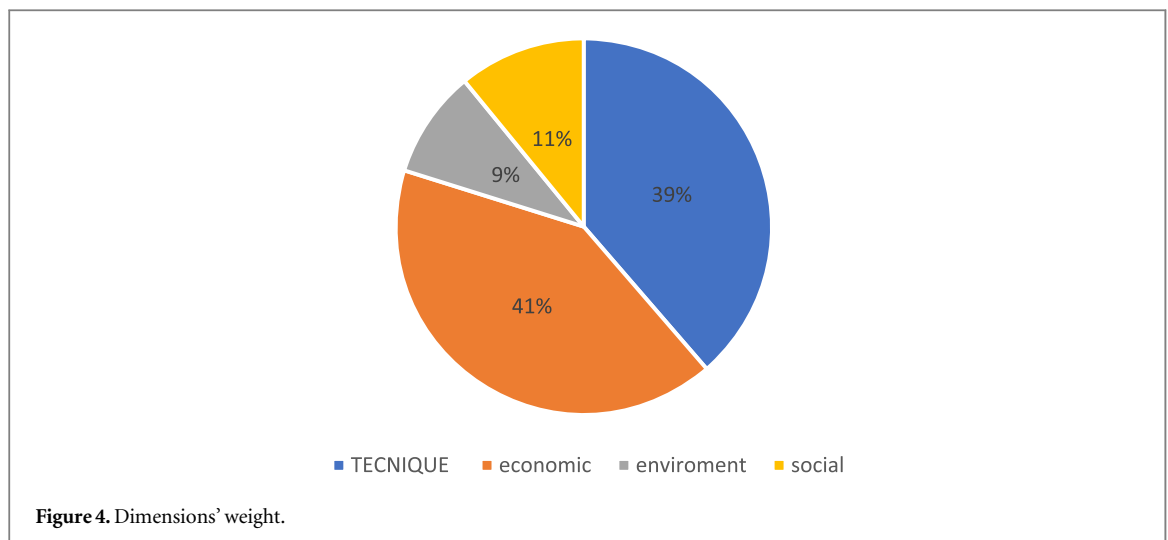


Figure 4. Dimensions' weight.

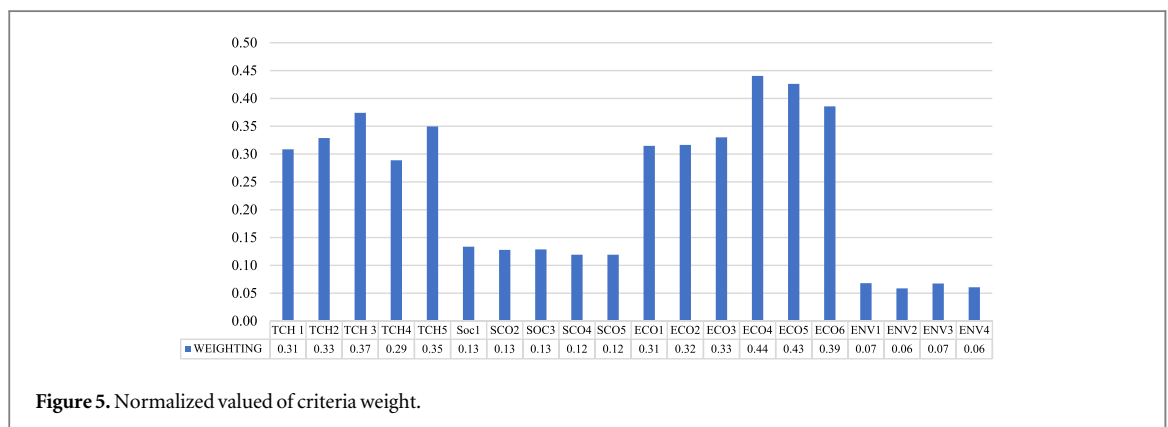


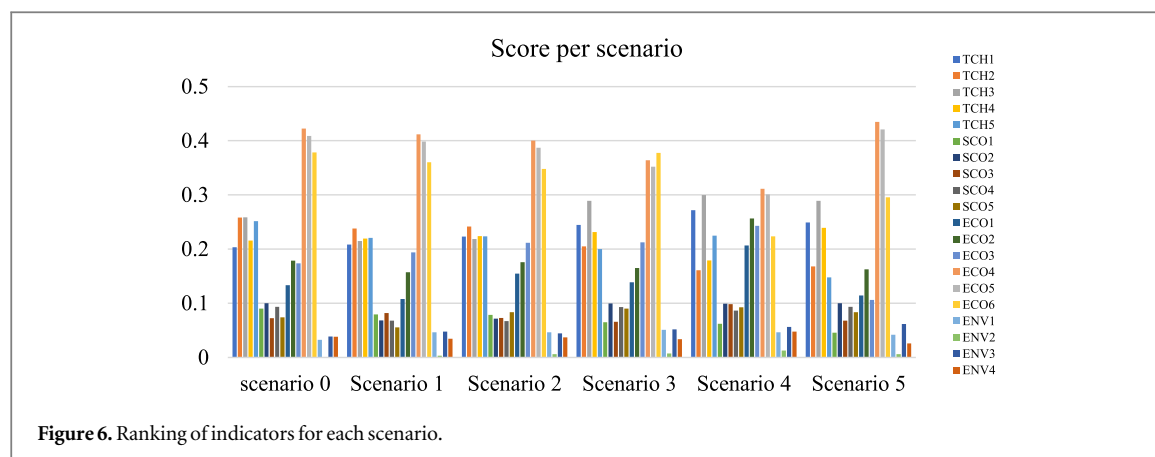
Figure 5. Normalized valued of criteria weight.

4.2. Weighting coefficient for dimensions and indicators

In this section, weighting coefficients of the four dimensions as well as for each of the 20 sustainability indicators were analyzed with respect to the current energy situation of the country and priority defined by stakeholders' survey. Then, the six defined scenario are examined under each of the four dimensions. The weighting coefficients in figure 4 reveal that the prioritization of energy stakeholders has shown a preference for the economic and technical dimensions with respectively 41% and 39% of the average weights for sustainable energy planning in Mali. Then, the social and environmental dimensions have been given the least important weight with 11% and 9% respectively. The normalized mean values are used as the basis to estimate the weight coefficient of indicators (figure 5). It also gives an idea of the importance of each indicator considering a common scale, thus allowing the comparison of the alternatives. The three highest priority indicators by stakeholders are all under economical dimension (ECO4: Investment cost ECO5: Payback period and ECO6: Government support). Then comes the indicator TCH3: the resources potential under the technical dimension. The energy stakeholders' choices of priorities are in favor of the economic and technical indicators for the energy sustainable supply assessment; which is deplorable since the environmental indicators are important aspects of the sustainability of the energy supply system considering they reflect the impacts of an energy supply system on environmental sustainability hence mitigating climate change (Liu 2014).

4.3. Ranking of scenario under each dimension

The representation below (figure 6) depicts the ranking of the various criteria of each scenario for the MCDM evaluation. Based on the fact that criteria don't have the same importance, the scenarios also will have criteria with different importance. The ranking of all criteria for each scenario are highlighted (figure 6). The indicator with the highest ranking is ECO4 followed by ECO5 in all scenarios, except the scenario 3 where ECO6 is the most performing. For Scenario BAU, criteria ECO4, ECO5 et ECO6 are the most performing and the environmental indicators own the smallest ranking. Scenario 1, 2, 3 and 5 exhibit similar pattern as BAU with high preference to economic indicators while the environmental indicators are least performing. For scenario 4,



the economic indicators are more or less balanced by the technical factors and the small scores are observed for environmental indicators.

4.3.1. Technical dimension

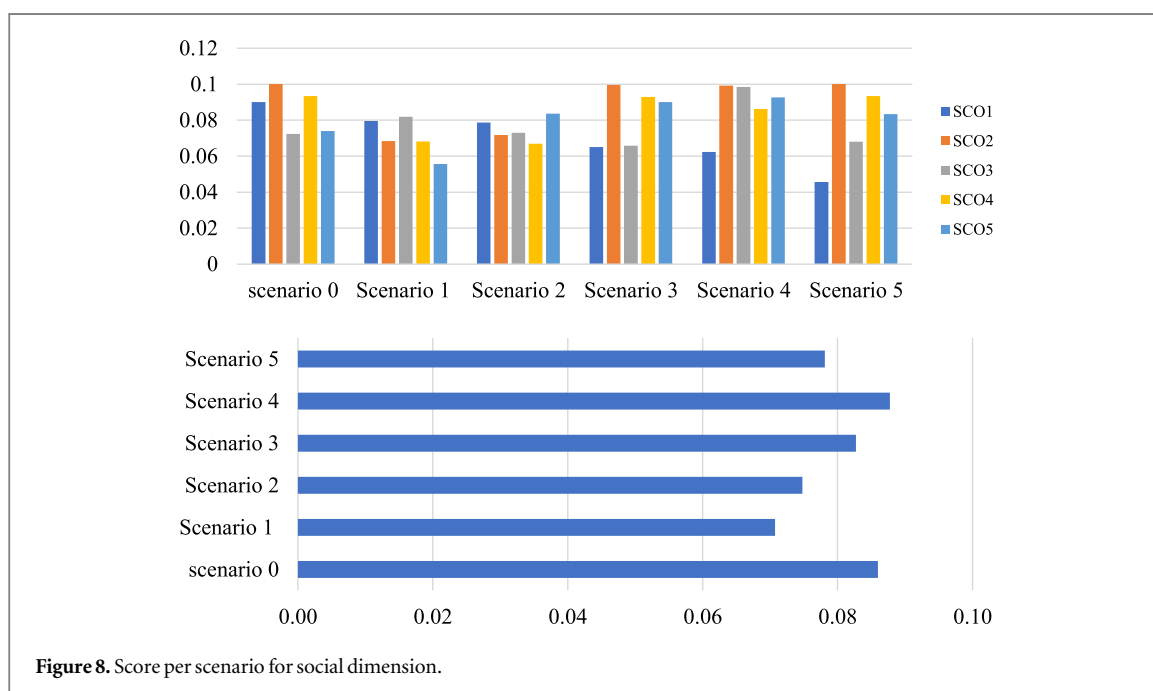
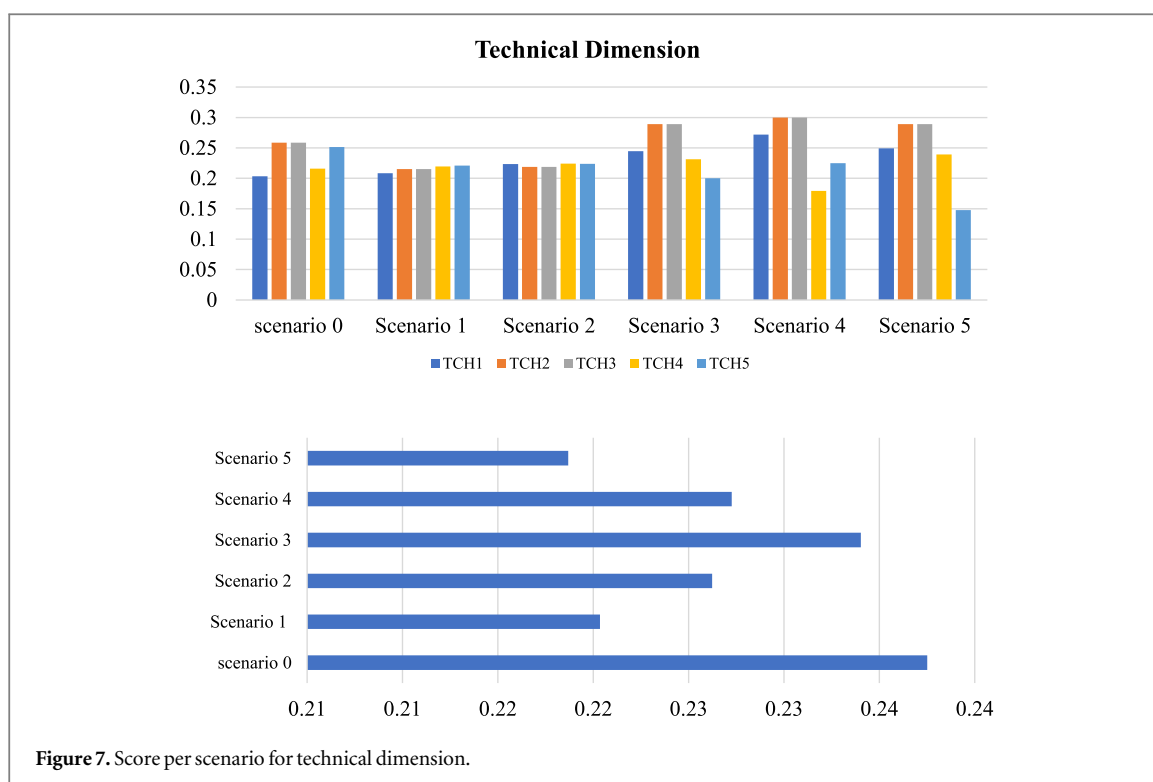
The evaluation of the six proposed energy supply alternatives including the Business as usual according to the technical dimension is here presented. The dimensions TCH1: production efficiency, TCH2: capacity factor, TCH3: RP (resources potential, toe), TCH4: reliability of the system, TCH5: resources availability (toe) having different weights are used for the assessment. It resulted that the scenario BAU showed the best performance and obtained by far the highest overall score followed by scenario 3 (figure 7). This finding is in confirmation of several studies demonstrating that scenario-driven fossil fuels together with hydropower scores better results under technical dimension attributed to those technologies' stability, reliability, and maturity (Afgan and Carvalho 2004, Bhandari *et al* 2021). Scenarios 1, 5, 2 and 4 obtained the least score in that dimension. This could be explained by the high share of renewable energy in Scenario 4 and the important energy import contribution in Scenario 5 evidence of generation stability and high dependency on weather conditions of those energy resources.

4.3.2. Social dimension

In the present study, social dimension was given 11% of weight importance (figure 4). Under this Dimension, different selected alternatives are evaluated with respect to indicators SCO1: Energy Acceptance, SCO2: Energy Accessibility, SCO3: Job creation (Job./Mw), SCO4: Energy Affordability, and SCO5: People Displacement. Considering the scenario performance by criterion, Energy Accessibility presents the highest ranking for all scenarios. Scenario 4 scores the best performance and exhibits high rank for indicator SCO3 which favors job creation. Scenarios 3 and 5 come closer to BAU considering the criterion SCO4, energy affordability. Indeed, BAU is the most affordable (figure 8) since it is based on the use of biomass (74% share in the mix) from the country's forest reserves, which is due to the low cost of purchasing. Charcoal and wood fuel (in this scenario) are the most socially accepted and affordable technologies in Mali like in other developing countries (Bhandari *et al* 2021). The overall performance of Scenario 4 compared to others can be explained by the fact that renewable energy responds better to social criteria than fossil energy, and it has the worst performance when it comes to the evaluation criteria SCO5 favoring limiting people displacement. Thus, Scenario S4 becomes the one to be considered for socially sustainable energy planning for sustainable energy supply in Mali.

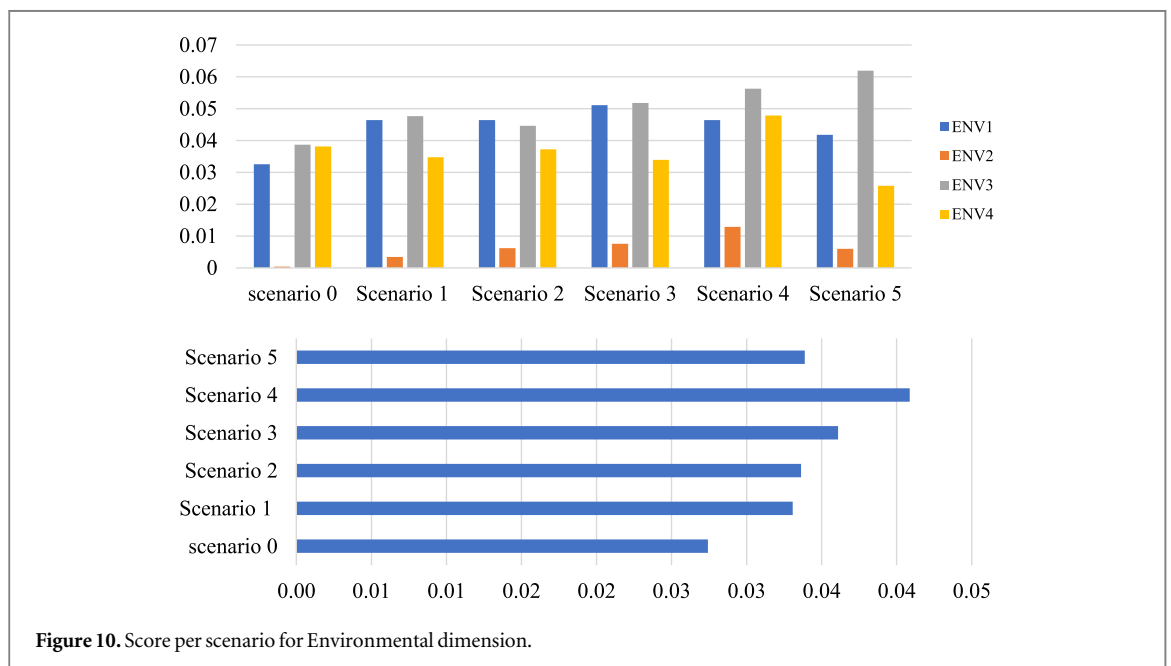
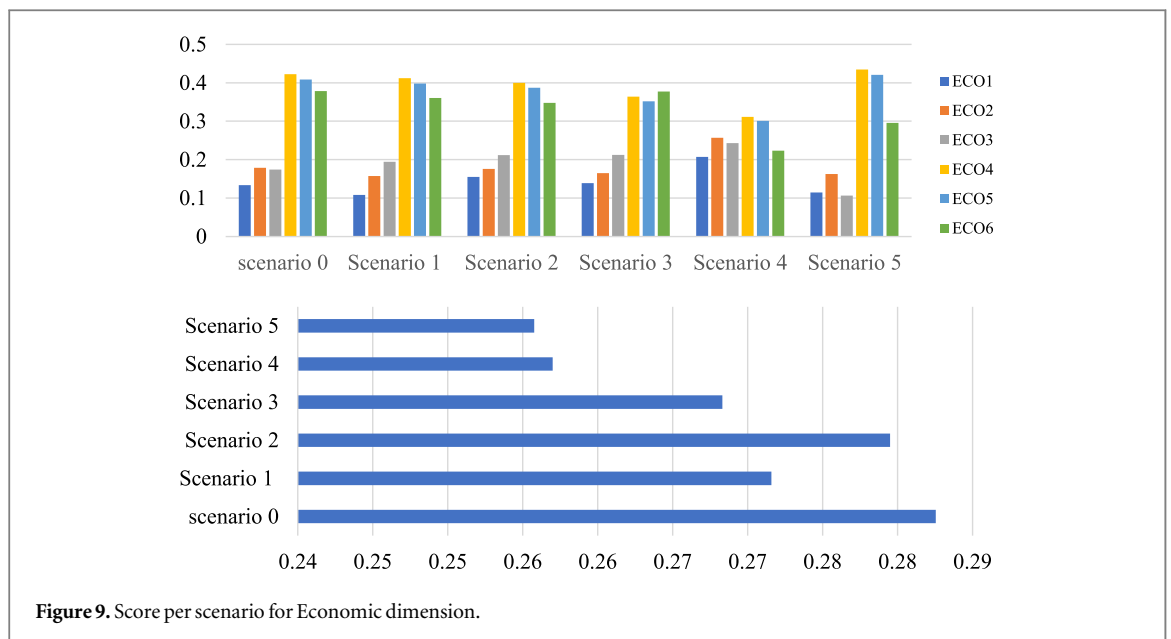
4.3.3. Economic dimension

Assessing of economic impact of energy supply options, the following indicators have been used ECO1: energy dependency (%), ECO2: net import dependency (%), ECO3: fuel cost (\$/GJ), ECO4: LVC USD/ KWH, ECO5: investment cost (€/KW), ECO6: payback period (YEAR), ECO7: government grant/support, which has critical weight consideration for the assessment. The result in Figure 9 shows that scenario BAU was the most sustainable economically. The economic affordability of BAU scenario could be explained by the low fuel cost, low investment cost, and most importantly the low energy dependency on this scenario's resources. Alternatively, to BAU, scenario 2 is the most performing for sustainable energy supply. With 34% of renewable energy, scenario 2 is based on the economic advantage offering renewable energies. Which have become more cost-effective than most fossil fuel technologies in recent years (Shaaban *et al* 2018).



4.3.4. Environmental dimension

The selection of potential sustainable energy mix supply options for this study gives particular attention to the environment considering indicators (figure 10); ENV1: Energy Diversification, ENV2 Fraction of Renewable Energy, ENV3: Land Use and Rate of Deforestation (M2/Mwh), ENV4: Emission (Gco2e/Kwh) criteria for the assessment. In all scenario, the indicator ENV3 ranks the greatest scores (figure 10) with its highest value being in scenario 5 which favor energy import. Thus, land deforestation is a priority indicator for all supply energy options. Scenario 4 presents the best energy supply options by considering the environmental dimension with more priority given to indicators related to land use and deforestation (ENV3) and the potential for global warming due to CO₂ emissions (ENV4). Indeed, the carbon intensity of energy production, supply, and consumption is the principal driver of energy-related environmental issues. So, besides the advantage of



reducing the emission and global warming potential of the systems, renewable energy systems can be high land demand (their low intensity) and cause deforestation for the country (Afgan and Carvalho 2004, Akan *et al* 2015), particularly the photovoltaic technology which represents the heightened renewable energy potential in Mali. Impacts could be variability of rainfalls and deforestation which could be particularly harmful to the Malian energy systems based on biomass and hydropower. The high score of energy diversification indicator (ENV1) for all energy supply alternative to BAU attests the importance of environmental benefits as it prevents relying on fossil fuel that is harmful to the environment.

4.4. Overall scores of scenarios

The BAU and the five alternatives' scenarios are given an overall score, and the highest value is then presented as the sustainable option for Malian's energy path. After aggregating the indicator, it was discovered that scenario BAU performs the best, with a normalized score of 0.68, followed by scenarios 3, 2, 4, 0, 0, 1, and 5, with scores of 0.66, 0.66, 0.65, 0.64, and 0.63, respectively (figure 11). Although scenario BAU initially performed well based on the aggregated score of the evaluation, the energy imports of 17% have not been taken into account for this scenario, which is why it has emerged as the best Scenario. Therefore, Scenario 3 (Petroleum product: 29%, Renewable energy: 42%, Biomass: 27%, and Energy Import: 2%), which is based on a shift in the country's

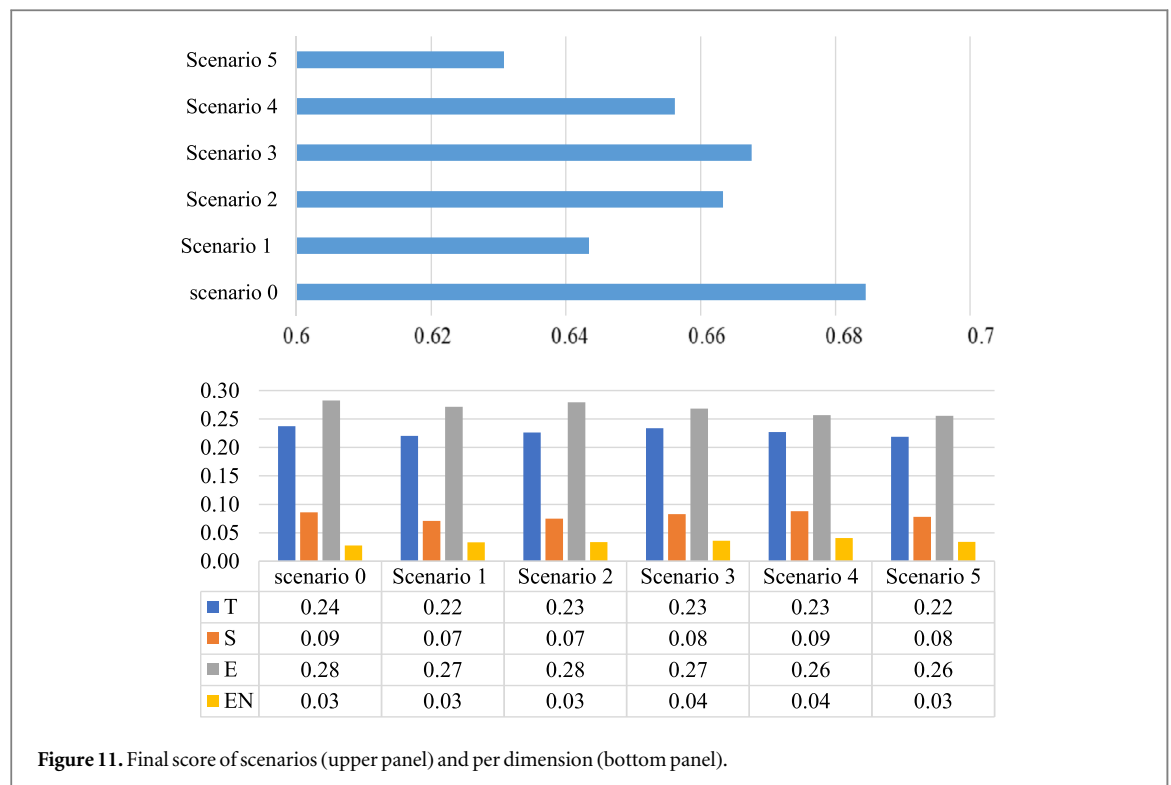


Figure 11. Final score of scenarios (upper panel) and per dimension (bottom panel).

energy system towards the development of renewable energy, is actually the most sustainable energy supply scenario to take into account for the Malian energy planning.

In comparison to hydropower and electricity produced from fossil fuels, renewable energy is a clean technology with a great potential for the country, high levels of public acceptance, and low greenhouse gas emissions. The deployment of renewable technology has a number of drawbacks, including high investment costs, production dependence on weather, and relatively low efficient conversion (Bhandari *et al* 2021). Such problems can be overcome by the adoption of certain measures such as a strong political will that leads the authorities to invest in subsidizing all the equipment of renewable energy technologies in order to make the cost more affordable and also policies that encourage the population to use renewable energy (such as lower taxes and duties). In addition, problems related to intermittency and production inefficiency can be mitigated by interacting with the energy storage options.

Nevertheless, findings regarding the sustainability of renewable sources of energy supplying are in line with previous investigations revealing huge potential of renewable energy, especially solar PV as better option for power supply in Mali (Diarra and Akuffo 2002, Sessa *et al* 2021). Results further converge toward the ensemble of energy supply policies and strategies in Mali as well as international pledges (sustainable development goals and Paris Agreement) all promote the introduction of clean, affordable renewable energy in the country system to limit the CO₂ level in the atmosphere. In addition, sustainable long-term energy planning should focus on the development of renewable energy (Zelt *et al* 2019). Hence, the transition towards renewable energy technologies (Scenario 3) is the most sustainable, since there is evidence that renewable energy adoption and development is driving economic growth, and decreasing environmental impact through the reduction of emission of greenhouse gas (Quadrat-Ullah and Nevo 2021). These results also support the country's NDC which targets to reduce the GHG emissions from energy sources by 31% in 2030 (NDC 2021).

5. Conclusion

In this study, the multi-criteria decision-Making approach is used to evaluate the sustainability of the long-term Malian energy supply, and five different energy supply alternatives and the BAU developed above were submitted to the assessment. The approach presented in this article aims to support long-term energy planning decision-making, especially in the context of climate change. A sustainability assessment technique for the energy system was developed, including 20 indicators distributed among the four dimensions: technical (5), social (5), economic (6), and environmental (4). Based on energy stakeholders' survey, the priority choice of energy stakeholders has shown a preference for the economic and technical dimensions with respectively 41%

and 39% of the average weights for sustainable energy planning in Mali. Thus, the social and environmental dimensions have been given less weight with 11% and 9% respectively.

Scenario 3, the transition towards renewable energy technologies (petroleum product: 29%, renewable energy: 42%, biomass: 27%, and energy import: 2%), ranks as the best option for sustainable energy supply in Mali. This scenario considering the input of Malian energy stakeholders, favor economic and technical aspects in the planning of sustainable energy supply. The identified supply alternative constitutes the most diversified with a significant share of renewable energy. The least sustainability score is found for scenario 5 (petroleum products: 40%, renewable energy: 33%, biomass: 10%, and energy imports: 17%) which raises the problem of energy supply dependency on a high share of petroleum products and the energy import.

The approach for sustainable energy planning put forward in this paper aids in educating decision-makers on numerous options for defining and shaping national energy strategies that fulfil important commitments of Mali. The current work updates the lists of literature on the assessment of the Mali energy supply systems (Gazull *et al* 2019, Sessa *et al* 2021) and presents literature on the use of the MCDM method of assessment, which gives to energy stakeholders a tool to make more accurate decisions about the future energy supply for the subregion.

The paper's findings offer the Malian government tools to establish new energy policies and guidelines and adjust old policies and strategies in order to help the country to meet its NDCs and achieve the Sustainable Development Goals (SDGs 7) ensuring access to clean and affordable energy for all. Additionally, the outputs of this study are expected to be helpful for other developing and developed countries, proving a consistent pathway for sustainable energy planning.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Annex

5.1. Form used in stakeholder Survey for weighting dimensions and indicators

- a. Assign percentages to these dimensions (sum should be 100%) based on priority for sustainable supply of energy in Mali

Dimension	percentage
Technical aspect	
Economic aspect	
Social aspect	
Environmental aspect	

- b. Give a score over 10 to indicators of the technical dimension based on priority for sustainable supply of energy in Mali

Technical Indicators	score
TCH1: Production Efficiency (%)	
TCH2: Capacity Factor (%)	
TCH3: Resources potential (MW)	
TCH4: Reliability of the system (Qualitative)	
TCH5: Resources availability (Toe)	

c. Give a score over 10 to indicators of the economic dimension based on priority for sustainable supply of energy in Mali

Economical Indicators	score
ECO1: net import dependency	
ECO2: Fuel cost	
ECO3: Levelized cost of electricity	
ECO4: Investment cost	
ECO5: Payback period.	
ECO6: Government support	

d. Give a score over 10 to factors of the social dimension based on priority for sustainable supply of energy in Mali

Social Indicators	score
SCO1: Energy acceptability	
SCO2: Energy accessibility	
SCO3: Job creation	
SCO4: Energy Affordability	
SCO5: People displacement	

e. Give a score over 10 to the factors of the environmental dimension based on priority for sustainable supply of energy in Mali

Environmental Indicators	score
ENV1: Energy diversification	
ENV2: Fraction of renewable energy	
ENV3: Land demand/ Rate of deforestation	
ENV4: Emission and Global warming potential	

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