



UNIVERSIDADE ESTADUAL PAULISTA
“JÚLIO DE MESQUITA FILHO”
INSTITUTO DE PESQUISA EM
BIOENERGIA



**INTEGRATED PROGRAM (UNESP, USP E UNICAMP) OF POSTGRADUATE
IN BIOENERGY**

**HYBRID BIOMASS, SOLAR, AND WIND ELECTRICITY GENERATION FOR
RURAL ELECTRIFICATION OF MOROCCO**

MEISAM MAHDAVI

Thesis submitted to Bioenergy Research Institute, São Paulo State University UNESP, Rio Claro - SP, Brazil, as part of the requirements for obtaining a Doctor of Science degree.

Advisor: Prof. Dr. Celso Eduardo Tuna

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DEDICATION

This thesis is dedicated to
Marilia, Silvia, Ahmad, and
Fereshteh

RESUMO

A alta dependência do setor de energia de Marrocos em combustíveis fósseis importados e subseqüentes contas caras de importação associadas, bem como acordos globais com redução de emissão de gases de efeito estufa, motivou o Marrocos a utilizar fontes de energia renováveis, como hidrelétrica, eólica e solar para geração de energia. No entanto, nos últimos anos, o uso de energia eólica e solar no Marrocos acelerou mais do que o uso de energia hidrelétrica devido à redução dos níveis de água como resultado da queda das chuvas, aquecimento global e secas naturais. Marrocos tem um grande potencial para geração de eletricidade a partir de energia solar e eólica devido a muitos dias ensolarados, vastas áreas desérticas, longas costas e ventos apropriados. No entanto, as acomodações de unidades de geração eólica e solar em sistemas de energia elétrica são difíceis devido às variações da velocidade do vento, incerteza da irradiação solar e sistemas de armazenamento de energia caros. Em relação às enormes quantidades de resíduos biológicos em Marrocos, a geração de energia a partir da biomassa pode resolver este problema e compensar a diminuição da geração de energia eólica e solar durante momentos nublados, chuvosos e/ou sem vento. Portanto, no presente tese, é avaliada a capacidade de geração de energia elétrica híbrida, usando biomassa, eólica e solar em uma vila marroquina de Tazouta e na área rural da cidade de Fez. O modelo de programação linear inteira mista proposto foi implementado em AMPL (A Mathematical Programming Language) usando um solucionador linear do CPLEX. As usinas de biomassa, solar e eólica são unidades de biogás alimentadas por esterco bovino, módulos fotovoltaicos (PV) de 1 kW e turbinas eólicas de 5,1 kW, respectivamente. A avaliação dos resultados indica que a utilização híbrida de recursos de energia eólica, fotovoltaica e de biomassa é uma forma mais apropriada para geração de eletricidade nas áreas rurais de Tazouta e Fez em comparação com a operação individual de turbinas eólicas e outras combinações de fontes de energia renováveis mencionadas.

Palavras-chave: Eletricidade de Biomassa. Região de Fez-Meknes. Marrocos. Energia solar. Energia Eólica.

ABSTRACT

High dependence of Morocco's energy sector on imported fossil fuels and subsequent associated expensive import bills, as well as global agreements with greenhouse gas emission reduction, has motivated Morocco to utilize renewable energy sources such as hydro, wind, and solar for energy generation. However, in recent years, the use of wind and solar energies in Morocco has accelerated more than hydropower usage because of the reduction in water levels as result of rainfall drop, global warming, and natural droughts. Morocco has a great potential for electricity generation from solar and wind energies because of many sunny days, vast desert areas, long coastlines, and appropriate wind blow. However, accommodations of wind and solar generating units in electric power systems are difficult because of wind speed variations, solar irradiation uncertainty, and costly energy storage systems. Regarding the huge amounts of biowaste in Morocco, power generation from biomass can resolve this problem and compensate for the decrease in wind and solar energy generation during cloudy, rainy, and/or non-windy moments. Therefore, in the present thesis, the capability of hybrid electric energy generation, using biomass, wind, and solar in a Moroccan village of Tazouta and the rural area of Fez city is evaluated. The proposed mixed-integer linear programming model was implemented in AMPL (A Mathematical Programming Language) using a linear solver of CPLEX. The biomass, solar, and wind power plants are biogas units fed by cow manure, 1 kW photovoltaic (PV) modules, and 5.1 kW wind turbines, respectively. The evaluation of the results indicates that hybrid utilization of wind, PV, and biomass energy resources is a more appropriate way for electricity generation in Tazouta and Fez rural areas compared to the individual operation of wind turbines and other combinations of mentioned renewable energy sources.

Keywords: Biomass electricity. Fez-Meknes Region. Morocco. Solar Energy. Wind Energy.

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LIST OF ABBREVIATIONS

Abbreviations

AMPL	A Mathematical Programming Language.
CSP	Concentrated solar power
DNI	Direct normal irradiance
GHI	Global horizontal irradiance
MENA	Middle East and North Africa.

Parameters

A_{pv}	Total area of solar panels (m^2).
A_r	Total area of rotor (m^2).
B	Daily volume of biogas production (m^3/day).
C_p	Performance coefficient of wind turbine (%).
CC_b	Capital cost of a battery (\$/unit).
CC_{bio}	Capital cost of a biomass unit (\$/kW).
CC_c	Capital cost of a converter (\$/kW).
CC_{pv}	Capital cost of a PV module (\$/kW).
CC_w	Capital cost of a wind turbine (\$/kW).
CM_b	Operation and maintenance (O&M) cost of a battery (\$/unit/y).
CM_{bio}	O&M cost of a biomass unit (\$/kWh/y)
CM_{pv}	O&M cost of a PV unit (\$/kWh/y)
CM_w	O&M cost of a wind unit (\$/kWh/y)
d	Interest rate (%).
$D(h)$	Number of days in month h (day/month).
E_b	Capacity of a battery (kW).
F_{bio}	Emission factor of biomass unit (g/kW).
F_{pv}	Emission factor of PV (g/kW).
F_w	Emission factor of wind turbine (g/kW).
$E_{Av}(i)$	Allowable emission in location i (g/kW).
$Ir(i, h)$	Average solar irradiation in month h and location i (kWh/ m^2/d).
LHV	Lower heating value (kWh/ m^3).
L_b	Lifetime of batteries (y).
L_{bio}	Lifetime of biomass units (y).

L_c	Lifetime of converters (y).
L_{pv}	Lifetime of PV modules (y).
L_w	Lifetime of wind turbines (y).
M	Daily dung production per head (kg/head).
N_h	Number of sheep.
N	Number of locations.
$P_c(i)$	Capacity of a converter in location i (kW)
$P_D(i,t)$	Power demand of location i at hour t (kW).
Pg_{bio}	Gross power obtained from biogas (kW).
$Pg_{Tazouta}$	Pg_{bio} in Tazouta (kW).
Pg_{Fez}	Pg_{bio} in Fez (kW).
$P_{pv,max}(i,h)$	Maximum power generation of a PV in location i and month h (kW).
$P_{w,max}(i,h)$	Maximum power generation of a wind unit in location i and month h (kW).
PR	Performance ratio of PV (%).
P_{bio}^o	Capacity of a biomass power plant (kW).
P_{pv}^o	Capacity of a PV unit (kW).
P_w^o	Capacity of a wind turbine (kW).
r	Solar panels reflection factor (%).
TS	Total solids content (%).
VS	Volatile solids (%).
$V(i,h)$	Mean wind speed of location i in month h (m/s).
$W_{max}(i)$	Available water in location i for anaerobic digestion and animal drinking (m^3).
W_{bio}^o	Total water demand of each biogas unit including water needed for anaerobic digestion and animals drinking ($m^3/unit$).
Y_{bio}	Biogas yield of sheep manure
ρ	Air density (kg/m^3).
η_b	Efficiency of batteries (%).
η_g	Efficiency of wind generators (%).
η_{pv}	Efficiency of PV modules (%).
η_r	Efficiency of convertors (%).
η_t	Efficiency of wind turbines (%).

η_{bio} Efficiency of biogas power plant (%).

Variables

$C_{battery}$ Cost of batteries (\$).

$C_{biomass}$ Cost of biomass power plants (\$).

$C_{converter}$ Cost of converters (\$).

C_{pv} Cost of PV modules (\$).

C_T Total cost of the hybrid system (\$).

C_{wind} Cost of wind turbines (\$).

$n_b(i)$ Number of batteries in location i .

$n_{bio}(i)$ Number of biomass power plants in location i .

$n_{pv}(i)$ Number of PV modules in location i .

$n_w(i)$ Number of wind turbines in location i .

$P_{bio}(i,t,h)$ Power generation of a biomass unit in location i , hour t , and month h (kW).

$P_{bio}(i,j,t,h)$ Power generation of location i in hour t and month h which is consumed by load of location j .

$P_{pv}(i,t,h)$ Power generation of a PV module in location i , hour t , and month h (kW).

$P_w(i,t,h)$ Power generation of a wind turbine in location i , hour t , and month h (kW).

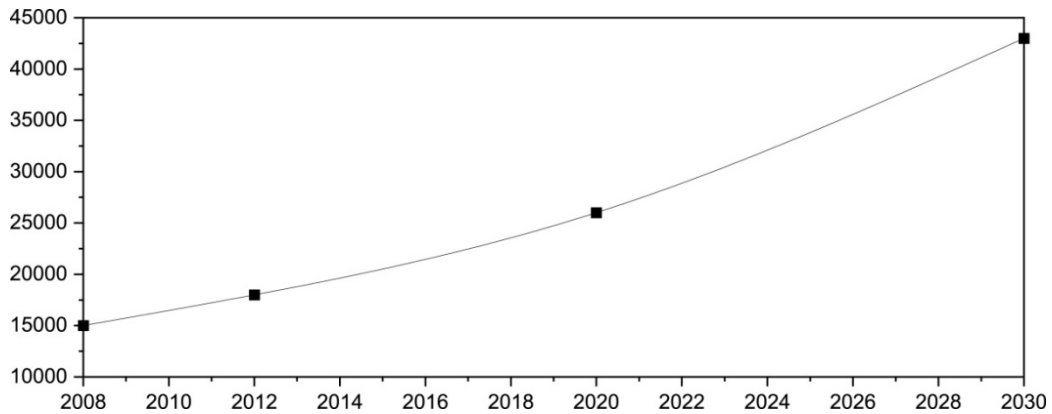
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1 INTRODUCTION

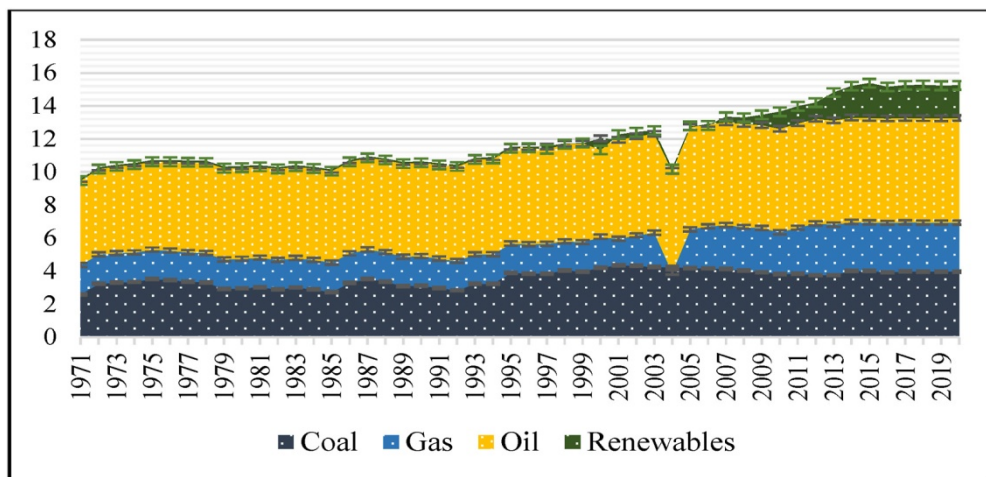
In contrast to some Middle East and North African countries (MENA), Morocco is a net energy importer because of its marginal fossil fuel resources. According to Figure 1, Morocco strongly needs energy import to meet more than 90% of its growing primary energy demand (AGOUZOUL et al., 2021) (e.g. an average rate of 6.5% from 2002 to 2020 annually (KOUSKSOU et al., 2015)), where fossil fuels such as coal, oil, and natural gas provide around 88% of the country's total primary energy needs since 1971, as shown in Figures 2 to 4 (OUAZZANI et al., 2022; BASTIDA-MOLINA et al., 2022).

Figure 1 – The primary energy demand of Morocco in mega tons.



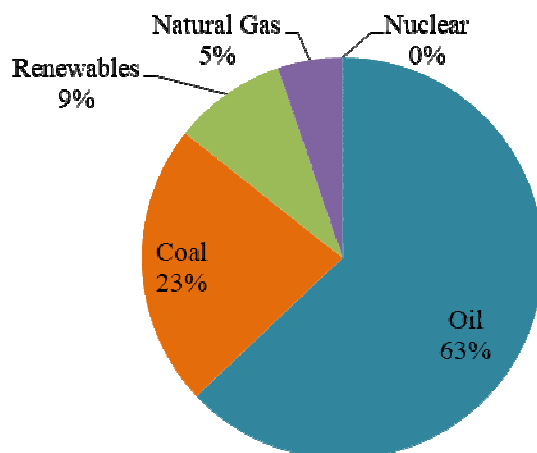
Source: Ouazzani et al. (2022).

Figure 2 – Morocco's different energy production sources in terms of Mtone.



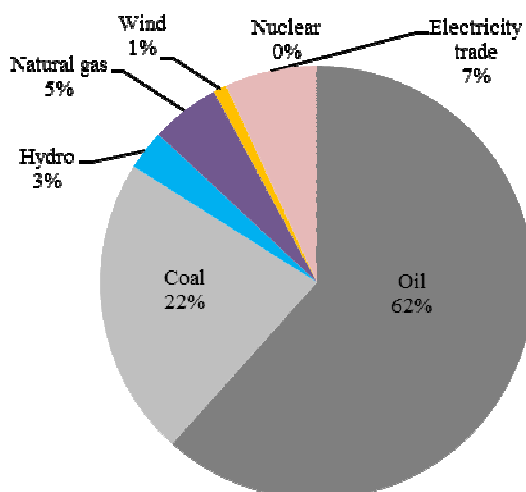
Source: Khan et al. (2022).

Figure 3 – Morocco's energy consumption in 2018.



Source: Bastida-Molina et al. (2022).

Figure 4 – Morocco's energy consumption in 2012.



Source: Kousksou et al. (2015).

Figures 2 to 4 show that renewable energy contribution was increased to 9% in 2018, but the use of oil and coal is still dominating in Morocco's energy matrix. To resolve this problem, Morocco started to increase share of natural gas in its energy matrix to meet power demand of both electrical and industrial sectors, because of shale gas availability and facility of natural gas transactions in current markets due to rising role of liquefied natural gas (LNG) (EL GHARRAS and MENICHETTI, 2018). However, expensive energy import bills, an upward trend of petroleum prices, and growing energy demand due to economic development, industrialization (EL ASRI et

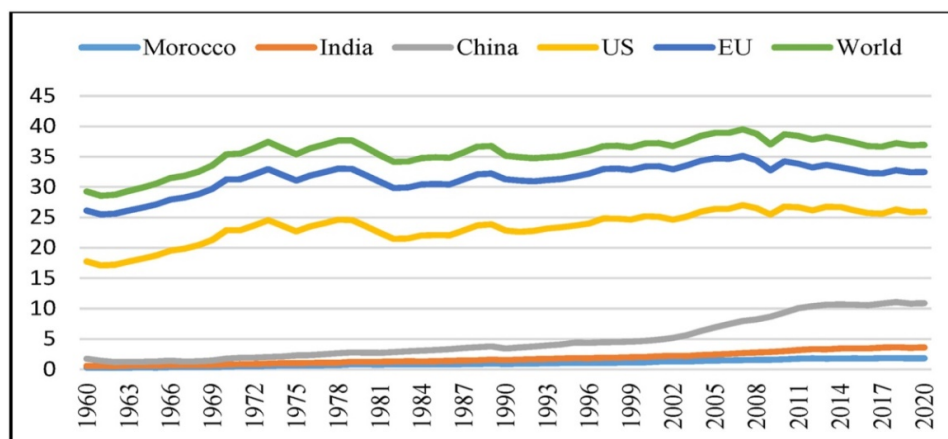
al., 2022), population growth (from 36 million now to 41 million by 2050) (JBAIHI et al., 2022), urbanization (EL IYSAOUY et al., 2019), and improvement of living standards, has pushed Morocco to utilize renewable energies as alternative energy sources (OKPANACHI et al., 2022). In addition to these factors, Paris Climate Change Agreement (KHAN et al., 2022; KHARBACH and CHFADI, 2022), Kyoto Protocol (FRITZSCHE et al., 2011), the country's energy policy, and royal willingness have made Morocco a leader in the use of sustainable energy sources in North Africa.

According to Paris agreement, greenhouse gas (GHG) emission should be reduced using renewable energies to keep the global warming raise below 2°C by 2030 (KHAN et al., 2022). Also, the Kyoto Protocol provided an international agreement for GHG reduction by emission trading based on carbon credit (FRITZSCHE et al., 2011). Global warming causes severe floods, melting glaciers, natural drought, sea levels increase, wildfires, and temperature raise. Also, reduction of GHG emissions leads to economic and social sustainability developments by promoting economic opportunities and facilitating energy technology (ZILLMAN et al., 2028).

With respect to strategic location of Morocco because of the Gibraltar strait, its neighborhood to Europe and Sub-Saharan African countries, and its long coastlines, the country can benefit from free trade and tourism to drive its economic growth if it follows international regulations such as Kyoto protocol and Paris agreement (Michaelowa, 2017).

According to Figure 5, because of the small role of Morocco in carbon emission compared to top carbon dioxide (CO₂) emitters such as Europe, United States, China, and India, using renewable energies can move Morocco to a near net-zero emission country in short-term (BOUYGHRISSE et al., 2021). Whereas investigations by Chishti et al. (2021) prove that the utilization of renewable energy sources in Brazil, Russia, India, China, and South Africa cannot reduce their net carbon emissions to zero in the short run. Therefore, Morocco should urgently increase its sustainable energy utilization, particularly when it is anticipated that the annual temperature in North Africa will increase from 1.5 to 3.5°C by 2060 (MAHDAVI; VERA, 2023).

Figure 5 – Per capita CO₂ emissions of Morocco and other world's top emitters.

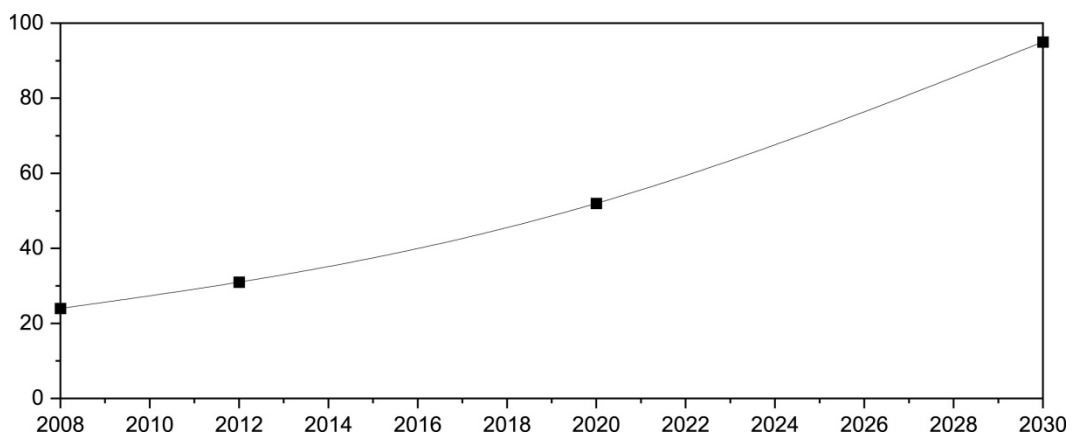


Source: Khan et al. (2022).

In this regard, international organizations suggested that Morocco reforms its clean energy laws to make renewables more attractive for investment. Currently, various institutions such as the National Agency for Electricity and Water (ONEE), the Moroccan Agency for Sustainable Energy (MASEN), the National Agency for Energy Efficiency, the Institute for Research into Solar and Renewable Energies (IRESEN), the National Office of Hydrocarbons and Mines, the Moroccan Limited Company of the Refining Industry (OKPANACHI et al., 2022), and the Moroccan Agency for Promotion of Renewable Energy and Energy Efficiency (ADEREE) (MAHDAVI et al., 2023c) are active in the energy sector of Morocco. Based on suggestions of international organizations, Morocco reformed its national energy regulations and public organizations, created new frameworks for its energy sector, and involved incentives for emissions reduction in governmental policy. For example, the Authority for the Regulation of the Electricity Sector (ANRE) was created parallel with ONEE public utility to regulate electricity market competition, grid access, and energy tariffs. Also, the activities of MASEN were extended from solar projects to the deployment of all renewable energy sources (IEA, 2019b). In addition, Morocco ordained an effective law that allows the connection of small- and medium-sized renewable energy generators as Independent Power Producers (IPPs) to the national network. Moreover, in order to reduce fossil fuel consumption in the agriculture sector, Morocco incentivized a less expensive water irrigation method based on solar pumps to cancel all subsidies on diesel, gasoline, and heavy fuel oil (BEN MEIR et al., 2022).

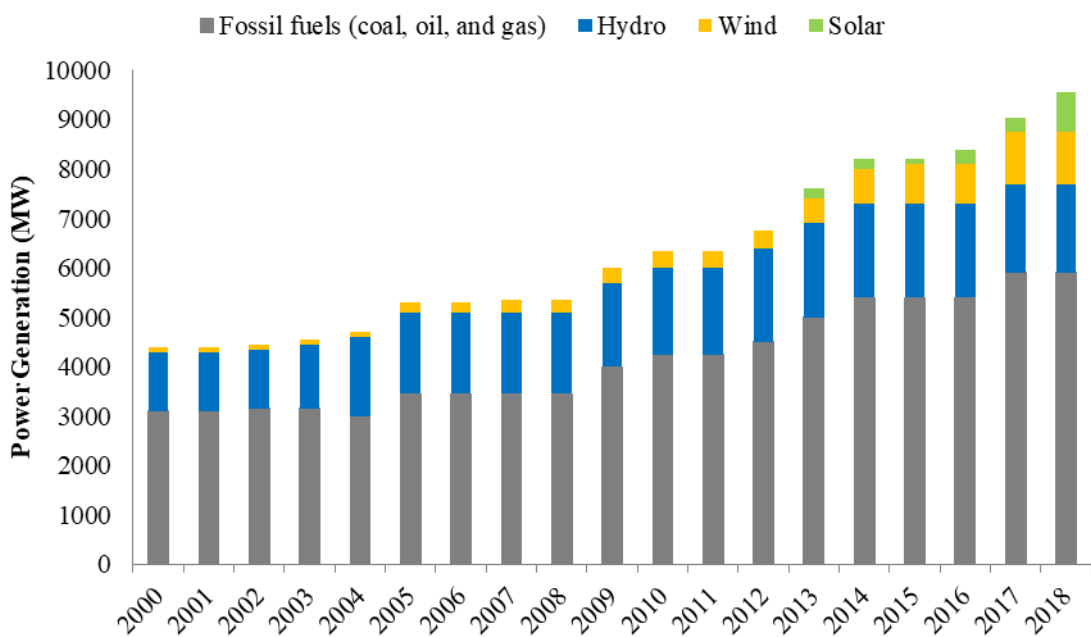
Owing to the faster growth of the need for electric energy (MAHDAVI et al., 2022a) compared to other energy demands and acceleration of rural electrification in order to provide access of all Moroccans to electricity (USMAN and AMEGROUD, 2019), distributed renewable electricity generation (MAHDAVI et al., 2023b) plays important role in Morocco's clean energy production sector (KHAN et al., 2022). From Figure 6, it is expected that electricity consumption increases by 7 to 8.5% per year (KOUSKSOU et al., 2015), while Figure 7 shows the total electric installed capacity (MAHDAVI et al., 2023a) in Morocco from 2000 to 2018 (OME, 2018).

Figure 6 – Morocco's electricity consumption in TWh.



Source: Ouazzani et al. (2022).

Figure 7 – Electric installed capacity in Morocco.



Source: OME (2018).

According to Figure 7, the share of renewable energies in electricity generation, especially wind and solar power has increased from 28% in 2000 to 37% in 2018 and should reach 52% by 2030 (solar: 20% (4560 MW), wind: 20% (4200 MW), and hydropower: 12% (1330 MW)) (IRNA, 2019; IEA, 2019a). Out of the 37% of the country's total renewable electricity generation in 2018, 13.4% was produced by wind, 16.5% by hydropower, 7.03% from solar energy, and the remaining energy was generated by other renewable sources (KONG et al., 2022).

Figure 7 illustrates more growth of wind and solar powers in the Moroccan electricity generation sector compared to hydropower in recent years. According to a comprehensive study on sustainable development in the MENA region by Aghahosseini et al. (2020), it is predicted that from 100% of renewable electricity feasibility by 2030, wind and solar power plants have enough potential to cover more than 90% of generation capacity. However, power generation of a solar and wind unit is very uncertain and this issue reduces the power system stability, in which hybrid utilization of these renewables and certain biomass energy resources can help the system stabilization (MALIK et al. 2021; SINHA et al., 2021).

It should be noted that the energy matrix impacts operational constraints, such as spinning reserves, ancillary services, and system stability. For example, if solar power is paid more attention in energy matrix, spinning reserve increases, but reactive power which is one of important ancillary services does not change. On the other hand, if more contribution is allocated to wind energy generation, the system stability degrades, but reactive power service and spinning reserve capability are enhanced. Also, increasing use of biomass fuels improve power quality, system stability, and spinning reserve. Although, using fossils in countries which are rich in natural energy resources, helps all above targets are achieved, environmental sustainability will be reduced. Whereas, growing use of fossil fuels in Morocco will increase the energy supply insecurity and prices as well as environmental unsustainability (MAHDAVI and VERA, 2023).

2 LITERATURE REVIEW, CONTRIBUTION AND METHODOLOGY

Till now, various energy resources have been utilized in different countries for the hybrid or individual operation of renewable and non-renewable energy technologies. For example, the solar and diesel generating units were employed in Pakistan (ALI et al., 2021) to meet the peak load of the Dera village and satisfy the energy demand of Ethiopian industrial parks (AZEREFEGN et al., 2020), China's Northeast (LI et al., 2019a), Southern Algeria (BERBAOUI et al., 2020), Taiwan's Pratas island (TSAI et al., 2020), and some regions of Iran (GHAFARI and ASKARZADEH, 2020). Also, battery systems were proposed by Javed et al. (2020) to store the additional electric energy generation of large hydropower plants in China.

Ikamran et al. (2019) suggested that the canal between the Ravi and Sutlej rivers in Punjab of Pakistan can be utilized as a micro-hydropower plant. Moreover, the seawater reverse osmosis desalination powered by PV panels and wind turbines was proposed by Delgado-Torres et al. (2020) and Li et al. (2019c) to produce electricity for Australia and England, respectively. Although the results showed the optimality and cost-effectiveness of the PV-diesel system in Pakistan, Ethiopia, Algeria, Iran, and China, the absence of wind power generation in the hybrid energy system is obvious, whereas, Iran, China, and Algeria have a great potential for electricity generation from wind energy (MAHDAVI et al., 2022b). For this reason, Elkadeem et al. (2019), Rinaldi et al. (2021), Ramesh and Saini (2020), Salisu et al. (2019), Diemuodeke et al. (2019), and Wang et al. (2020) combined wind energy resources with PV and diesel (ELKADEEM et al., 2019; RINALDI et al., 2021; SALISU et al., 2019; DIEMUODEKE et al., 2019; WANG et al., 2020) or PV, diesel, and hydropower (RAMESH; SAINI, 2020) generation in Dongola city of Sudan (ELKADEEM et al., 2019), some Peruvian areas (RINALDI et al., 2021), Indian Karnataka state (RAMESH; SAINI, 2020), North and South of Nigeria (SALISU et al., 2019; DIEMUODEKE et al., 2019), and Chines Zhoushan island (WANG et al., 2020). Despite approaching the minimum costs by using PV/wind/diesel or PV/hydro/wind/diesel systems, non-renewable power generation from diesel fuels causes pollutant gas emissions. For this issue, mixed-integer linear programming models were proposed by Alberizzi et al. (2020), Krishan and Suhag (2019), Arabi-Nowdeh et al. (2021), and Mellouk et al. (2019) to find the optimal capacities of PV, wind turbines, and batteries disregarding diesel generators in order to satisfy the

electricity demand of remote mountain lodges in Italy (ALBERIZZI et al., 2020), Yamunanagar district in India (KRISHAN; SUHAG, 2019), the Iranian city of Ardabil (ARABI-NOWDEH et al., 2021), and Laayoune region in Morocco (MELLOUK et al., 2019). However, Alberizzi et al. (2020), Krishan and Suhag (2019), Arabi-Nowdeh et al. (2021), and Mellouk et al. (2019) preferred diesel power generation ignorance rather than using cleaner biomass energy generation.

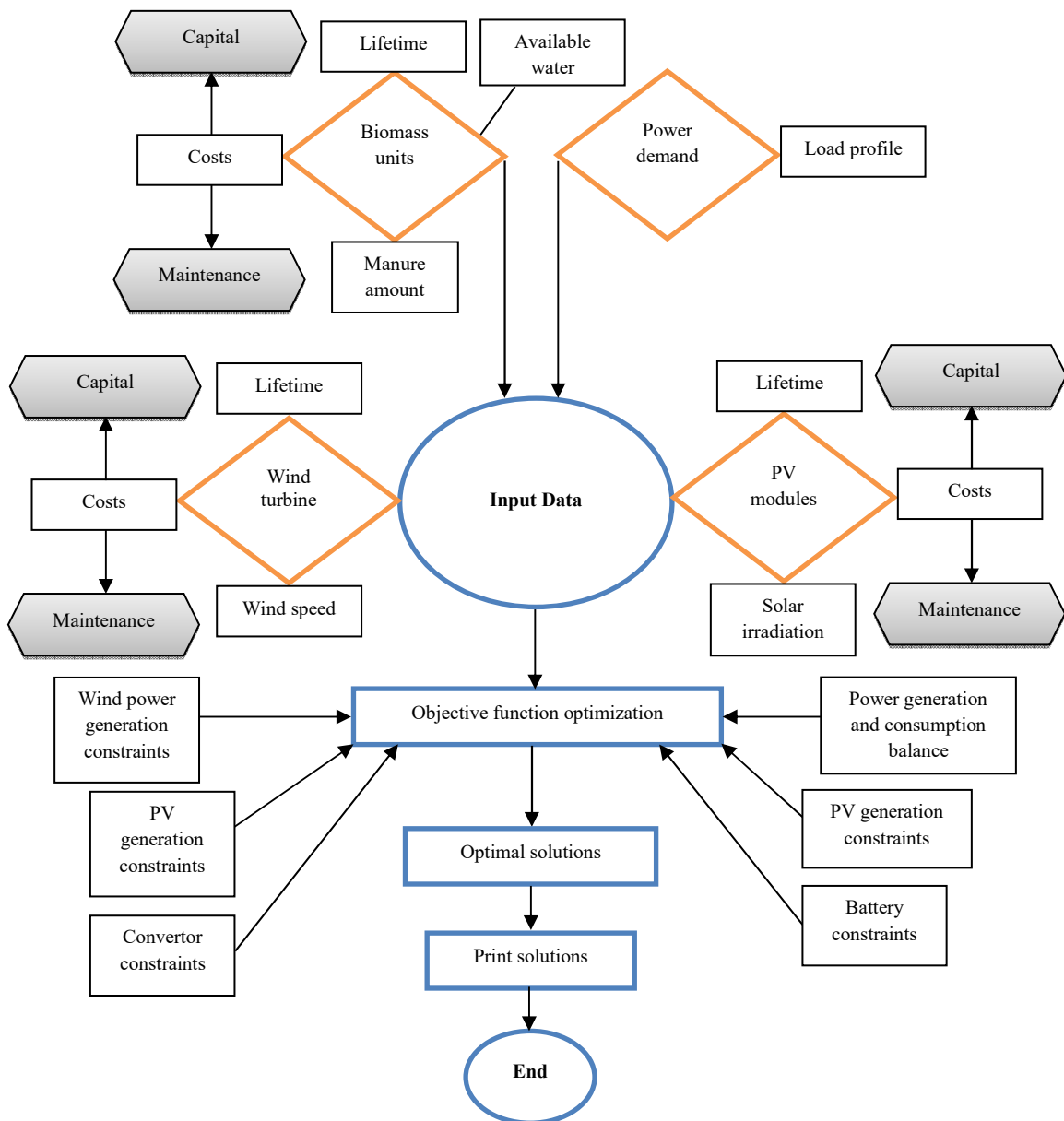
In this regard, Li et al. (2019b) developed a stochastic multi-objective model for optimally designing solar, wind, and biochar generating units in the Carabao Island of Philippines. In addition, Tiwary et al. (2019) proposed hybrid PV and domestic solid biowastes for producing energy and reducing environmental problems raised by the huge volume of household waste accumulation in England and Bulgaria. The analysis of results presented by Li et al. (2019b) and Tiwary et al. (2019) indicates the significant profitability, CO₂ emission reduction, and environmental sustainability of biomass energy.

Consequently, Gado et al. (2022), Vaziri Rad et al. (2020), Baruah et al. (2021), Padrón et al. (2029), Zhang et al. (2019), Akhtari and Baneshi (2019), and Hadidian Moghaddam et al. (2019) combined solar and wind electricity generation with straw biomass in the Egyptian city of Borg El-Arab (GADO et al., 2022), landfilled biogas in Iranian rural areas (VAZIRI RAD et al., 2020), forest biomass in the Indian district of Sikkim (BARUAH et al., 2021), desalination systems in Spanish Lanzarote and Fuerteventura islands (PADRÓN et al., 2029), and hydrogen storage systems in Iranian Province of Khorasan (ZHANG et al., 2019), Iranian cities of Bandar Abbas, Shiraz, Tabriz, Tehran, and Yazd (AKHTARI; BANESHI, 2019), and Northwestern Iran (HADIDIAN MOGHADDAM et al., 2019).

However, electricity generation from animal manure has not been studied in these regions/countries. Accordingly, a hybrid system based on PV and animal dung was proposed by Shahzad et al. (2017) to show the great potential of manure for energy generation in Pakistan. Nevertheless, none of the research reviewed above has evaluated energy production from hybrid utilization of PV, wind, cow manure, and sheep dung energy in rural areas of Morocco with different geographical locations considering water consumption of animals and anaerobic digestion process. Because of variable solar irradiance, wind speed, and animal wastes from one area to another, studying PV-wind-biomass energy generation systems leads to different results in various regions/countries.

Thus, the current study evaluates the hybrid utilization of photovoltaic, wind, and cow manure energy resources to generate electricity in the Moroccan village of Tazouta and the rural area of Fez city. The proposed formulation is a mixed-integer linear programming model that can be optimized by heuristic, metaheuristic, and classic mathematical methods (MAHDAVI et al., 2021b). It should be noted that heuristic and metaheuristic algorithms are not able to guarantee global solutions like classic methods. For this purpose, AMPL (MAHDAVI et al., 2021a) as a powerful classic optimization tool is used to solve the proposed mathematical problem. Figure 8 shows a schematic of the suggested optimization method.

Figure 8 – Schematic of the proposed solution method using AMPL.



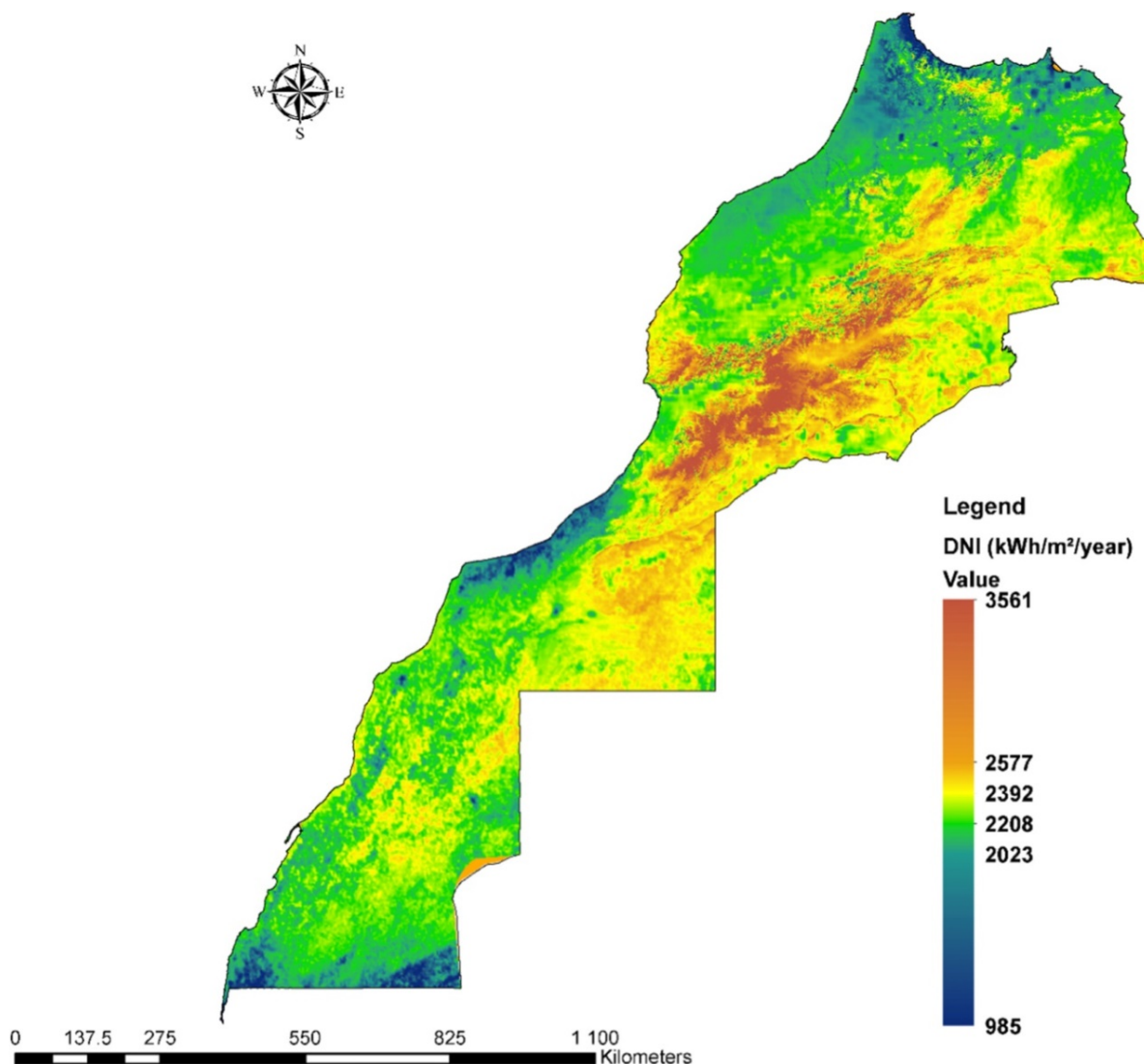
Source: Mahdavi (2023c).

3 POTENTIAL SOURCES FOR POWER GENERATION IN MORROCO

3.1 SOLAR ENERGY

As shown in Figure 9, Morocco has a significant potential for solar power generation because of its high global horizontal irradiance (GHI) with an amount of around 2 MWh/m²/y and its appropriate direct normal irradiance (DNI) with an annual sunny hour of 2700 to 3500 in the North and South, respectively. The DNI is the proper criterion for siting concentrated solar power (CSP) plants, while GHI is an appropriate index for photovoltaic (PV) location assessment (ALAMI MERROUNI et al., 2018b).

Figure 9 – Map of DNI in Morocco.



Source: Ouammi et al. (2012).

In 2009, nine billion dollars were allocated by the government to Moroccan Solar Plan program for installing 2 GW of solar power using PV panels, CSP plants, and hybrid CSP and PV (CSP/PV) systems till 2020 (OUAMMI et al., 2012). According to this project, 3.7 million tons of CO₂ emissions could be annually reduced, particularly when PV module prices have decreased by 90% over the past decade (BRUNET et al., 2022). In PV cells, electric energy is directly produced from solar irradiation, while in CSP system the electricity is obtained from a steam turbine driven by a high-temperature heat. Hybridization of expensive high capable CSP plants and low cost PV systems (CSP/PV) is a good strategy to mitigate unbalances between renewable generation and power demand (VALENZUELA et al., 2017).

In this regard, in 2018, the country constructed 170-MW PV, 200-MW CSP, and 150-MW CSP/PV power plants under PV I phase (Figure 10), NOOR II, and NOOR III projects (BRUNET et al., 2022). Also, Ain Beni Mathar and Sebkhath Tah solar plants with capacities of 400 MW and 500 MW were constructed near Oujda and Sebkhath Tah cities, respectively (KOUSKSOU et al., 2015). In addition, the largest CSP plant and the first advanced hybrid CSP and PV system in the world are accomplished under Noor Ouarzazate and Noor Midelt projects, respectively.

Figure 10 – A Moroccan PV power plant under construction.

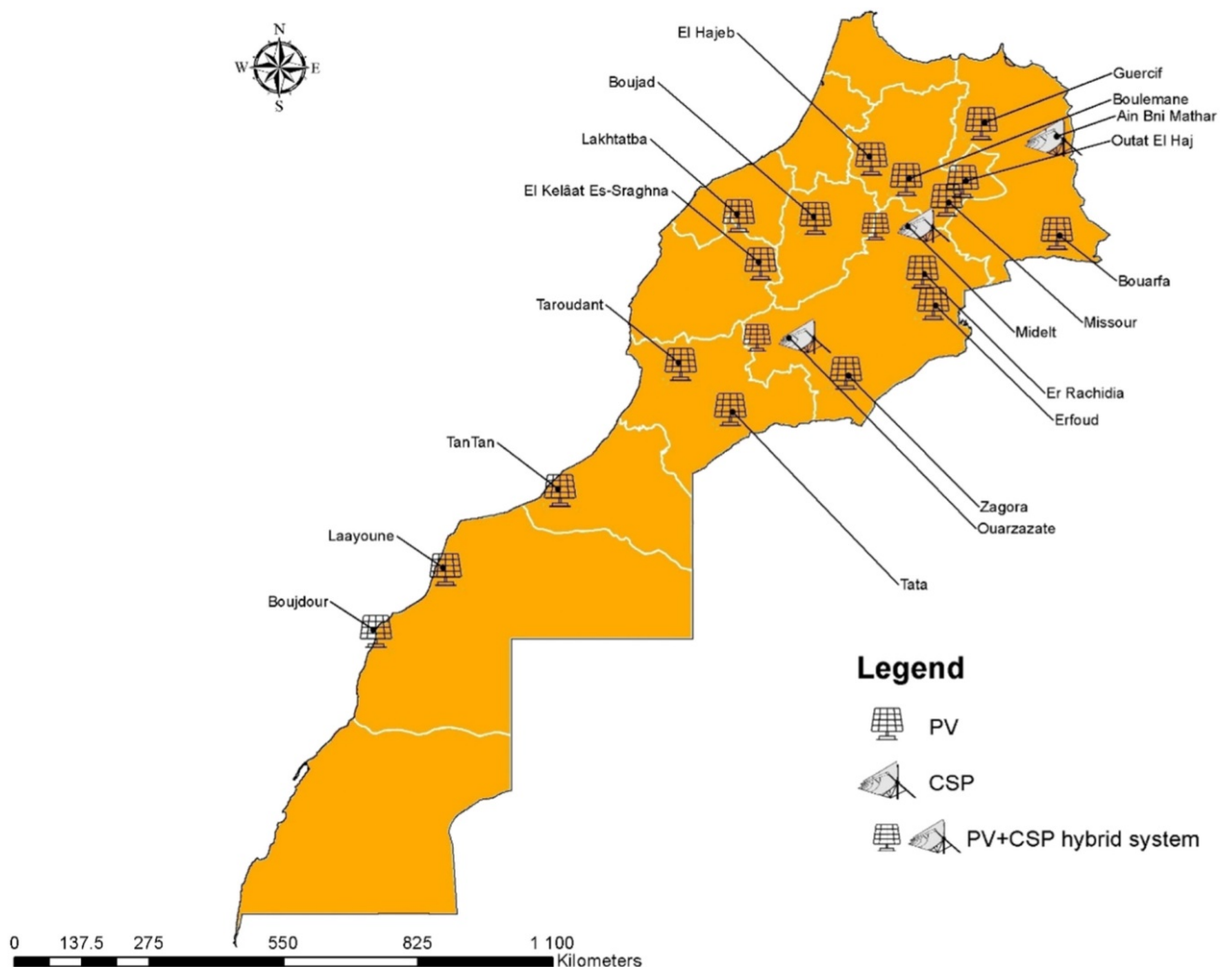


Source: Brunet et al. (2022).

Total capacity of 510 MW was installed in Ouarzazate city through three phases of Noor Ouarzazate project that its first phase (Noor 1) with capacity of 160

MW and 3.5 hours of storage was completed in 2014. The second phase (Noor 2) with capacity of 200 MW and 7 hours of storage was accomplished in 2018 and the third phase (Noor 3) with capacity of 150 MW and 7.5 hours of storage was completed in 2019 (Boretti and Castelletto, 2022). The 240 thousand tons of annual CO₂ emissions are reduced only through the first phase of the Noor Ouarzazate project. Also, the total installed capacity of the Noor Midelt plant located 20 km far from Midelt town in center of Morocco is 1600 MW that its first phase with capacity of 800 MW was completed in 2022. Figure 11 shows large-scale solar projects all over the country. Moreover, two PV power plants of Laayoune and Boujdour, first with capacity of 500 MW and the second with capacity of 100 MW are constructing in Fom El Oued and Boujdour cities, respectively, at the south of Morocco.

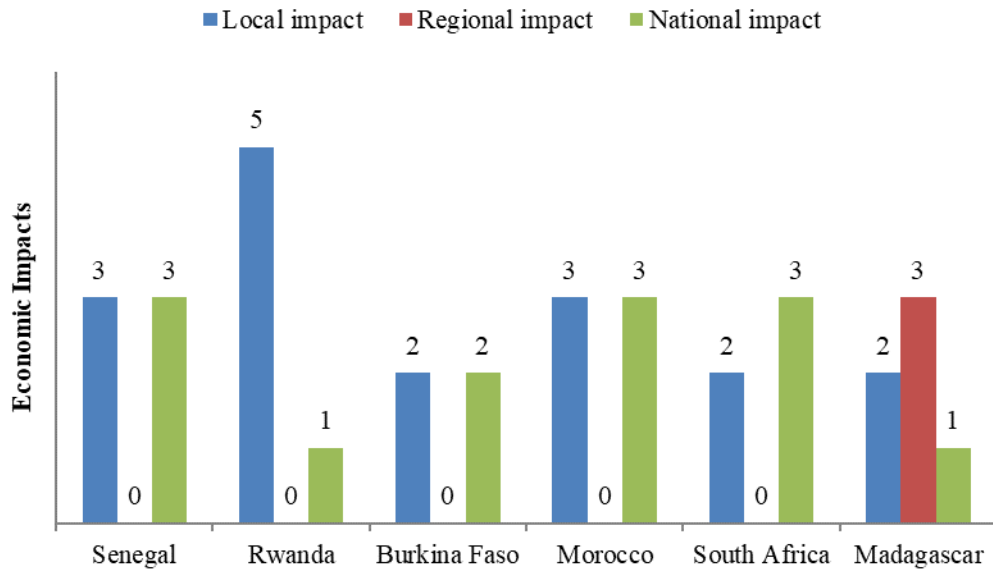
Figure 11 – Map of different solar projects in Morocco



Source: Ouammi et al. (2012).

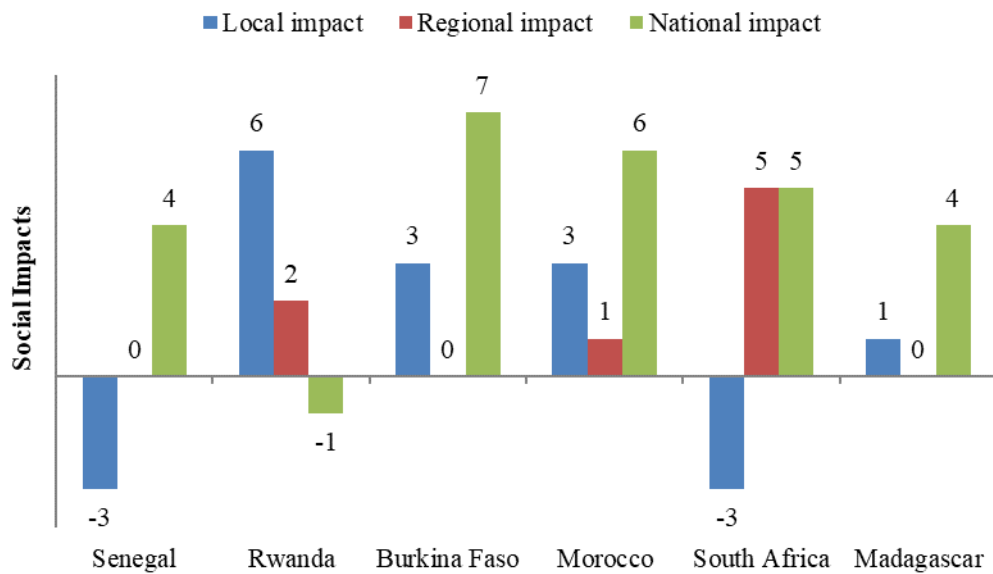
Figures 12 to 14 illustrate economic, social, and environmental impacts of solar power generation in Morocco compared to some other African countries (BRUNET et al., 2022).

Figure 12 – Economic impacts of solar power plants.



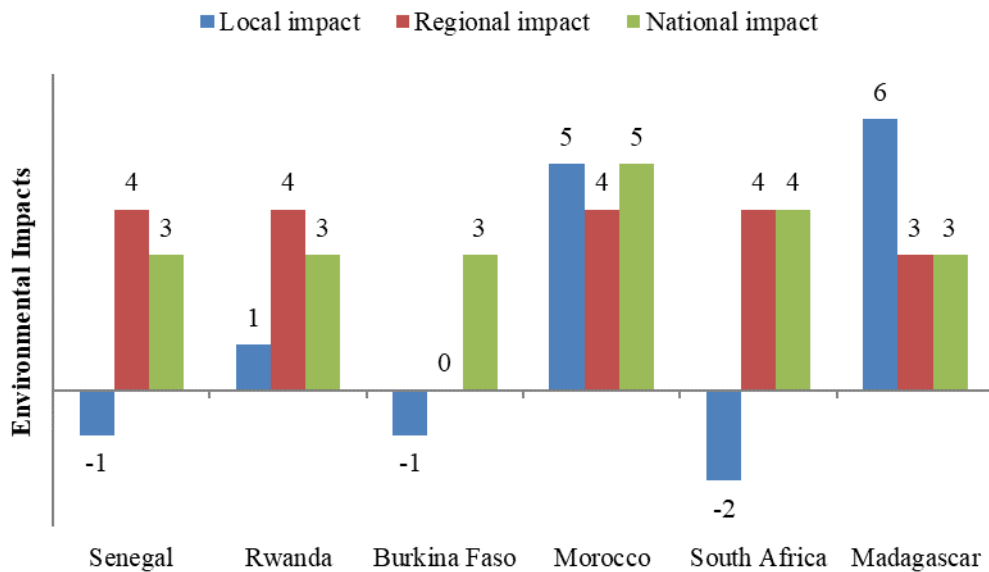
Source: Brunet et al. (2022).

Figure 13 – Social impacts of solar power plants.



Source: Brunet et al. (2022).

Figure 14 – Environmental impacts of the solar power plants.



Source: Brunet et al. (2022).

According to Figure 12, local economic impact of electricity generation from solar power in Morocco, involving income-generating activities and values of lands intended for agriculture or livestock rearing is zero because of PV and CSP installation in desert areas. The regional economic impact including industrial growth and land ownership value in the regions which solar plants are constructed is a few in Morocco. Also, the national economic impact such as decrease in electricity price and the domestic PV industry development does not play a significant role in Morocco, because most of PV parts and facilities are imported except for barriers, maintenance centers, and some ancillary services (MAHDAVI and DAVID, 2023).

From Figure 13, it is observed that local social impacts of solar power generation, such as job creation, free electricity, donations to schools, health center elimination because of PV construction, situation of local residents owing to the lighting of the plant and the road access in village areas, are acceptable in Morocco. However, the regional impact is low because few people are aware of the distant PV and solar power plants. In national level, social acceptability of solar energy is good in Morocco, because of large number of PV and CSP projects in operation (RAZI and DINCER, 2022).

Figure 14 represents good local environmental impacts of solar energy utilization due to significant carbon emissions reduction in Morocco. However, PV fabrication releases considerable GHG emissions and also solar panels installation is one of the deforestation reasons. In addition, the regional impacts such as CO₂ emission and noise pollution reduction, as well as national impacts like participation of solar plants against climate change due to the low emission of CO₂ are notable (MAHDAVI and DAVID, 2023).

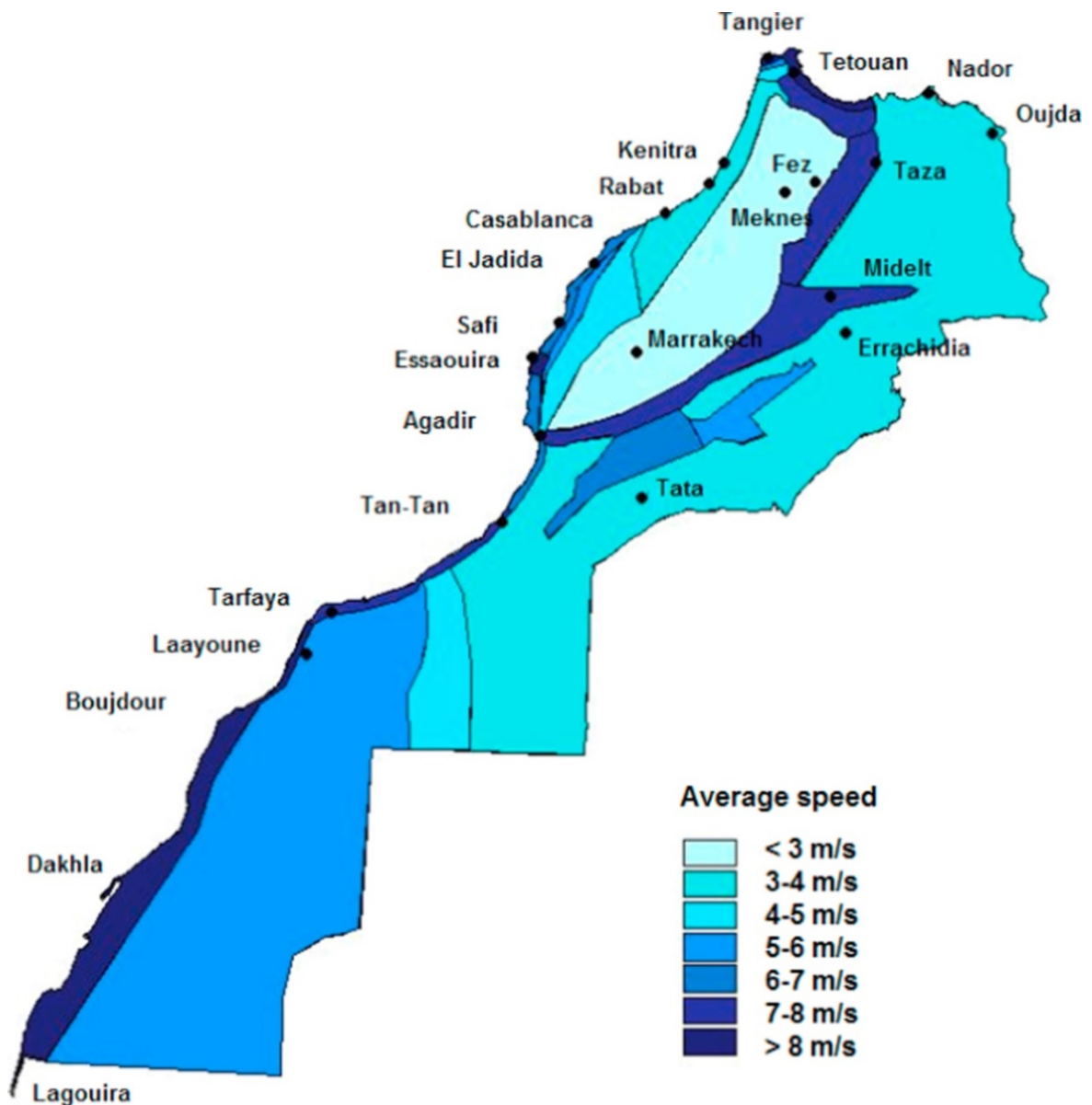
Although PV systems are green electricity generation technologies, the temperature increase inversely affects the PV output. Whereas most appropriate areas for PV installation are sited in deserts because of its high solar irradiation. In such places, the temperature is really high, where optical efficiency of solar plants is considerably reduced by huge amounts of dust and sand (YUSHCHENKO et al., 2018).

In addition, solar irradiation is intermittent and CSP/PV plants need energy storage systems (ESSs) to regulate electricity supply and demand (LIU et al., 2016). Nowadays, the solar electricity generation is possible after the sun sets, during cloudy hours of the day and peak load times because of the thermal energy storage systems (JBAIHI et al., 2022; ALAMI MERROUNI et al., 2018a). However, the thermal ESSs (TESSs) like molten salts- based energy storage systems have many technical problems such as high freezing point of molten salts (GIL et al., 2010), corrosion of the storage tank (GUILLOT et al., 2012), and limited maximum operating temperature (KURAVI et al., 2013). Also, thermal convection of TESSs by means of heat transfer fluids (HTFs) (that are more efficient and low-cost storage materials than molten salts) is reduced by incorporation of solid filler because of HTFs reduction (BROSSEAU et al., 2004). Moreover, despite the good performance of other storage materials such as concrete (LAING et al., 2006), ceramics (ZUNFT et al., 2011), industrial waste (GUTIERREZ et al., 2016), and natural stones (EL ALAMI et al., 2022) in enhancement of the TESSs efficiency, their development costs are high. Usually solar projects life is selected equal to the PV modules lifespan and therefore, the replacement cost of solar panels is taken zero. Also, the annual operating and maintenance costs of PV units are estimated to be 15 \$ in Morocco (EL-HOUARI et al., 2020).

3.2 WIND POWER

Morocco with 3500 km of coastlines and maximum average wind speed of 11 m/s has a great potential for 25 GW of wind power generation, in which 6 GW of that will be implemented by 2030 in areas with maximum mean wind speeds of 9 m/s (OUAMMI et al., 2012). According to Figure 15, the North with annual average wind speed of 8 to 11 m/s, especially in the regions close to Atlantic coasts, and the South with an annual average wind speed of 7 to 8.5 m/s are appropriate locations for wind farms installation.

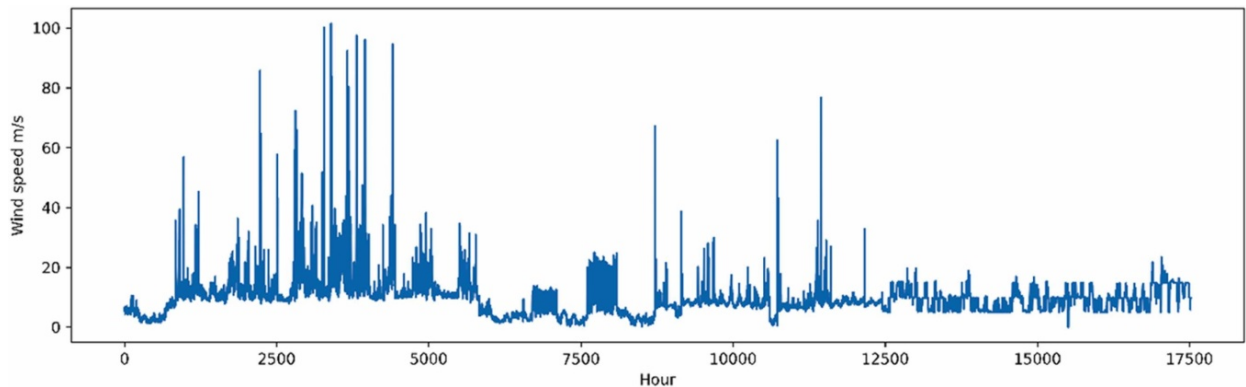
Figure 15 – Map of wind energy in Morocco.



Source: Kousksou et al. (2015).

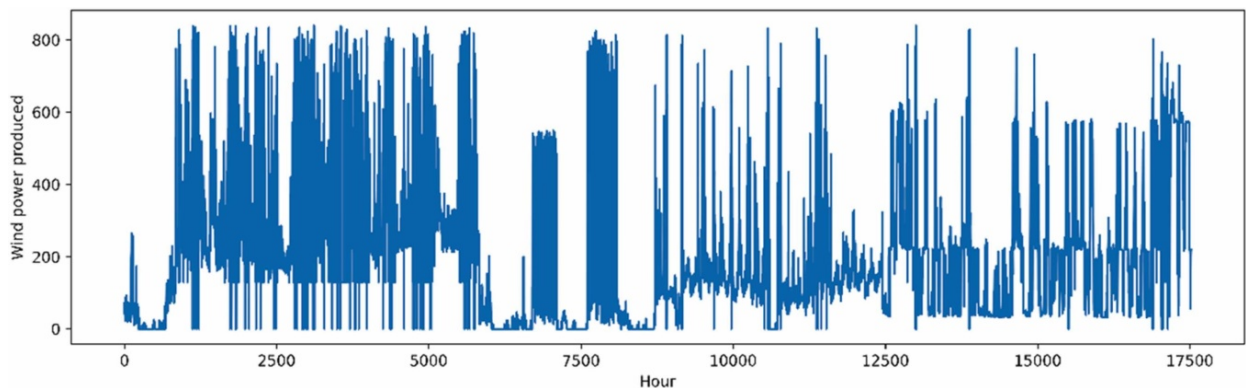
Tetouan city in the north of Morocco with annual wind speed and power generation, shown in Figures 16 and 17, is the best place for wind energy production in Morocco.

Figure 16 – Real time wind speed in Tetouan from July 2013 to June 2015 (m/s).



Source: Gutierrez et al. (2016).

Figure 17 – Real time wind power generation in Tetouan from July 2013 to June 2015 (W).



Source: Gutierrez et al. (2016).

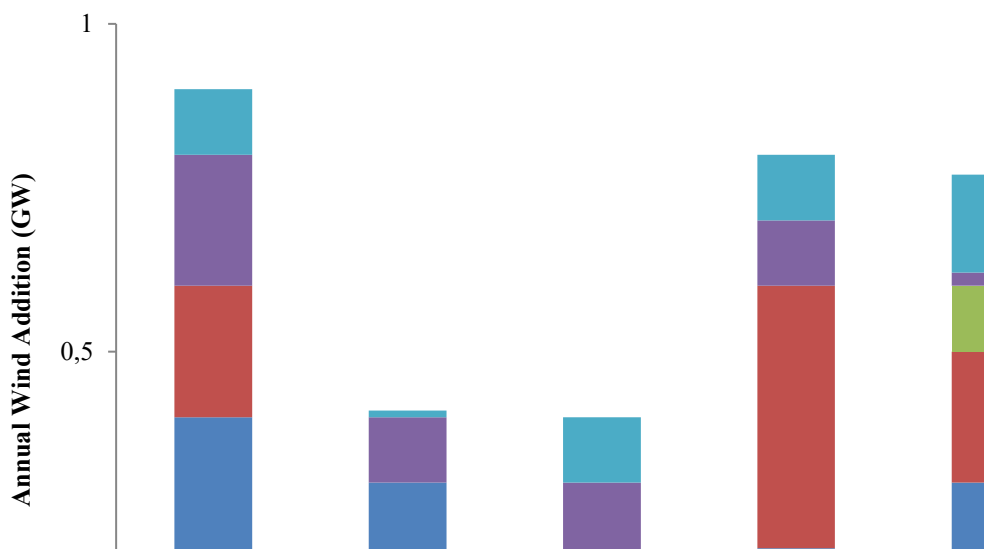
Abdelkhalek Torrès with capacity of 50.4 MW is the first wind park of Morocco that was constructed to satisfy 200 GWh of Tetouan town's energy demand in 2015. Later, more wind farms were constructed in Morocco that most important of them are 140-MW Tangier and 100-MW Touahar-Taza power plants, and Amogdoul wind park near Essaouira province with size of 60 MW. The aim was producing 2 GW of power and 6600 GWh of energy per year from wind with capability of 26% of electricity

generation by 2020 to reduce 5.6 and 1.5 million tons of annual CO₂ emission and fuel consumption, respectively.

To reach this purpose, 850 MW of wind farm was planned to be constructed by ONEE at Tanger II (150 MW), Midelt (100 MW), Jbel Lahdid or Essaouira (200MW), Tiskrad or Laayoune (300 MW), and Boujdour (100 MW) till 2020. Also, turbine of 50-MW Koudiaal-Baida Al II wind farm was developed in such a way that can produce 200 MW of electric power. Moreover, a 150-MW wind farm at Taza in north of Morocco was planned to be constructed by 2020 (KOUSKSOU et al., 2015). Currently, construction of Tarfaya, Boujdour Aftissat, Akhfenir, and Khalladi wind farms with capacities of 301 MW, 201 MW, 200 MW, and 120 MW, respectively, and generation expansion of Midelt power plant to 210 MW are important wind projects of Morocco.

Figure 18 shows the situation of Morocco among other MENA countries from the annual installation progress of wind power plants point of view (RAZI; DINCER, 2022).

Figure 18 – Wind power capacity additions of Morocco compared to other countries of MENA.



Source: Razi and Dincer (2022).

Wind farms investment costs are high, but their operation expenses are low. It is estimated that the maintenance and operating cost of a wind unit be 20 \$ in Morocco. Like PV units, the lifetime of wind turbines is usually the same as wind project life, i.e. 25 years without need for replacement (EL-HOUARI et al., 2020). In

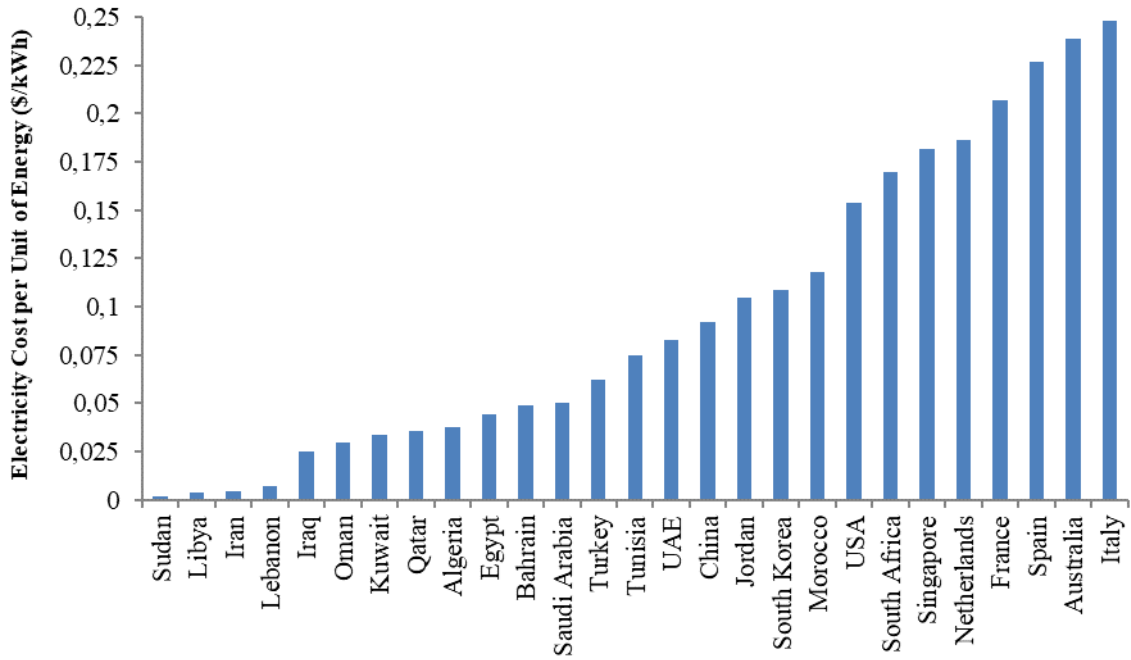
addition, the important points in finding appropriate places for installation of wind farms are wind speed and its duration. The wind speed must be high enough to move the turbine efficiently but should not be over turbine's power because of its danger on the structure integrity. Nevertheless, wind energy is not permanently available because of its dependence on local weather conditions and unpredictable climate changes. Also, wind turbine output varies with random wind speed alterations not only in different days, but also during the day. In this regard, prediction of wind power output is necessary and needs weather data. However, historical wind speed values are time-varying series that most models are not able to capture the long-term correlation between the past wind speed values. This intermittence makes wind turbines accommodation very hard in power system. Moreover, storage and energy management systems are necessary to compensate mismatch between wind energy supply and electricity demand, but they are costly, have their technical problems, and need wind power forecasting. Wind power prediction based on satellite images does not require any historical data; however, needs intensive computations that are not suitable for short-term operations. Also, statistical models consider the linear relationship of time series data, which can limit their capability in long-term operation horizons. Machine learning techniques such as artificial neural networks (ANNs) have strong ability to solve nonlinear problems but need historical climate data and deep learning in time series modeling (EL BOURAKADI et al., 2022).

3.3 BIOMASS ELECTRICITY

As shown in Figure 19, electricity cost in Morocco is average among some important MENA and non-MENA countries. From this figure, it can be realized that the average cost of electricity in MENA countries is below 0.052 \$/kWh which is almost one-fourth of the electricity cost in Australia, France, Spain, and Italy and half of the electricity price in China, South Korea, and USA. Whereas, the average of power generation costs from PV and onshore wind turbines are 0.06 \$/kWh and 0.037 \$/kWh, respectively. Although the wind and solar energy costs have been reduced considerably in the last decade, the little difference between the average electricity cost and solar and wind power prices in MENA region, does not give very attractive cost saving perspective to MENA countries for renewable energy usage. The lowest electricity costs belong to Sudan and Libya with amounts of 0.002 \$/kWh

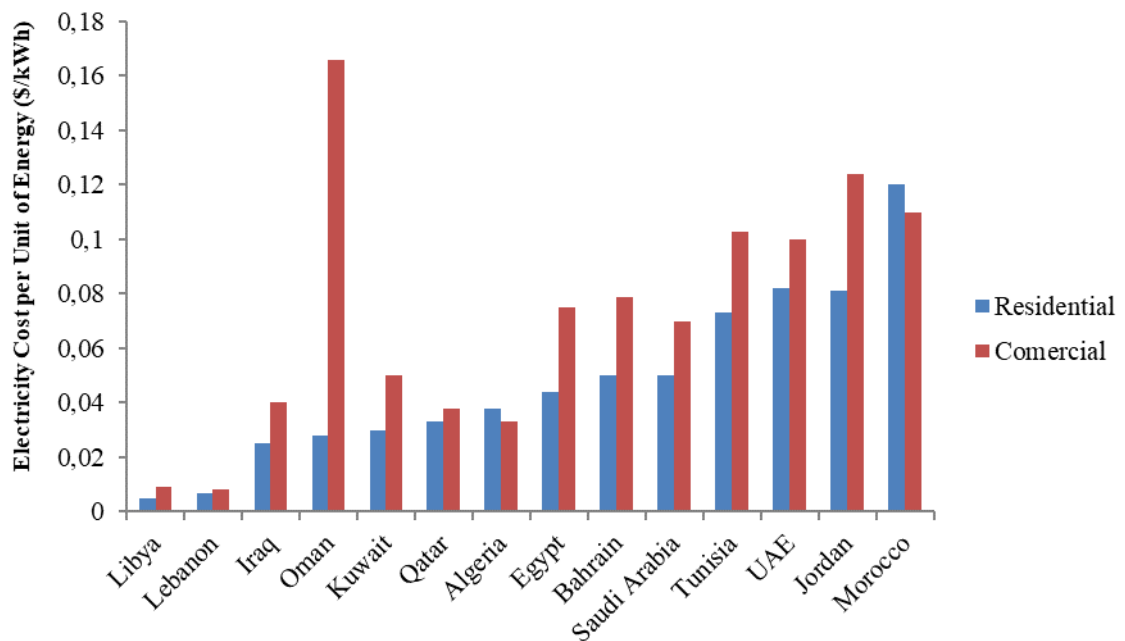
and 0.004 \$/kWh, respectively, while the electricity price in Morocco varies from 0.11 to 0.12 \$/kWh for residential and commercial consumers as shown in Figure 20 (RAZI and DINCER, 2022).

Figure 19 – Electricity cost of Morocco compared to some other countries in 2021.



Source: Razi and Dincer (2022).

Figure 20 – Comparison of electricity cost of Morocco with some MENA countries in 2021.



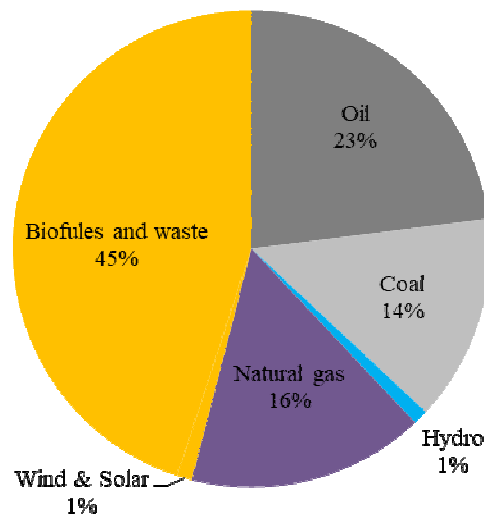
Source: Razi and Dincer (2022).

From Figure 20, the commercial electricity prices are much higher than residential electricity costs in all MENA countries, except for Algeria and Morocco. Therefore, biomass power generation can play important role in moderating commercial electricity prices in MENA and reducing residential electricity bills in Morocco.

All organics derived from photosynthesis process are called biomass which includes non-fossilized and biodegradable organic matters obtained from plants, animals and micro-organisms (KOUSKSOU et al., 2015). Biomass can also be produced from agricultural residues as well as animal, wood, and human wastes and is the fourth largest energy source after oil, coal, and natural gas in the world (ZAFAR; OWAIS, 2006). By using biomass, most of challenges in energy domain will be tackled, such as high energy prices, and costly energy storage and transportation.

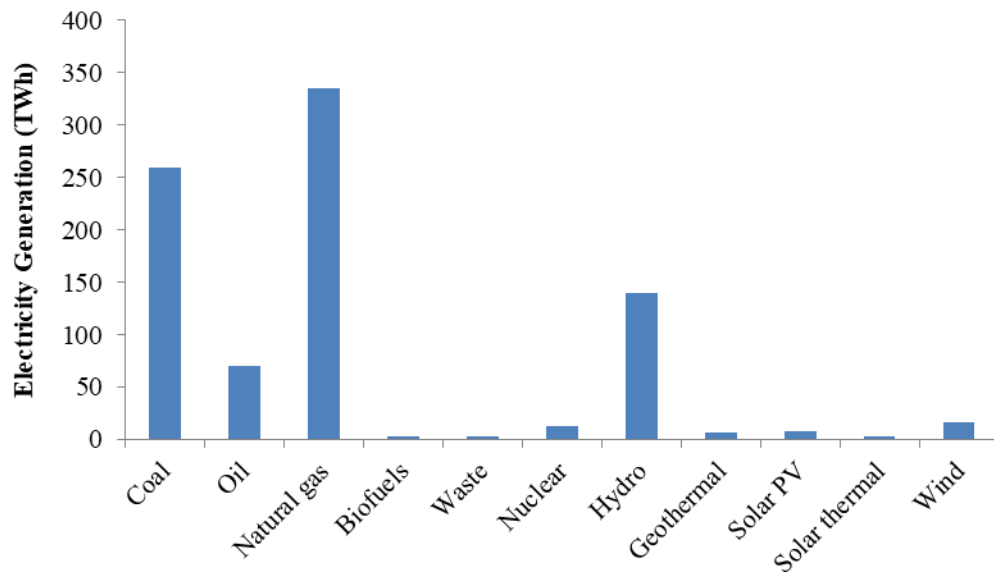
For the case of Morocco, the motivation for using renewable energy is more than other MENA countries. However, renewable power generation is not so cost-effective compared to other energy production technologies due to the longer payback periods for recovering their high initial investments and additional expenses for connecting these intermittent energy sources to stable power systems. Biomass power plants can provide a stable energy for consumers when the wind or sun does not blow or shine. Combining biomass electricity generation with other renewable energy sources is necessary to provide a permanent and uninterruptable electric energy supply, because power quality management is necessary to improve the system efficiency and reliability. Biomass can directly generate electric energy and heat via the common method of combustion or indirectly can be used to produce biofuels using gasification, anaerobic digestion (AD), and fermentation (OUAZZANI et al., 2022). Figure 21 shows high demand for biomass, especially biofuels in Africa; whereas electricity generation by this kind of energy source is still low (see Figure 22) (AYODELE; MUNDA, 2019). Morocco has a good potential for energy production from biomass because of its enormous agricultural, animal and municipal wastes (AFILAL et al., 2013). Table 1 shows potential of Morocco for biomass-based energy production (KOUSKSOU et al., 2015).

Figure 21 – Africa's energy demand.



Source: Ayodele and Munda (2019).

Figure 22 – Share of energy sources in Africa's electricity generation sector.



Source: Ayodele and Munda (2019).

Traditional fuels used for cooking and heating are important uses of biomass in Morocco. From nine million hectares of forested areas, it is estimated that 30 thousand hectares are consumed every year with an energy generation potential of 400 MW. Total annual potentials of energy production from solid biomasses and biofuels including biogases are predicted to be 2568 and 13055 GWh, respectively. Overall potential of installable biogas capacity in the country is 33.8 thousand m² with

annual gas production of 21.6 million m³. According to the project planned by cooperation of the Moroccan agency of ADEREE, German Society for International Cooperation (GIZ), and the Institute of Applied Material Flow Management (IFAS), the province of Essaouira has been recognized as a potent area for biomass energy generation with capability of covering 22% of its own energy need. However, Morocco currently utilizes less than 2% of its huge biomass resources due to the expensive initial investment and insufficient knowledge regarding biomass energy production techniques and processes (KOUSKSOU et al., 2025).

Table 1 – Potential of biomass in Morocco.

Biomass resources	Properties and Potentials
Agricultural residues	Nine million hectares of agricultural area Over half million farms Seven million large livestock places
Residential waste	Five and half million ton/y of residential wastes with annual production potential of 4700 million m ³ of biogas and 4.2 MWh of energy
Wastewater	With annual potential of 230 million m ³ of biogas equivalent to 1.376 million MWh/y
Forest biomass	Moroccan forestry area is almost nine million hectares

Source: Kousksou et al. (2015).

3.4 HYBRID BIOMASS, SOLAR, AND WIND POWER GENERATION

The question is that which strategy is better for electric energy generation? If the question is asked by electricity consumers, the answer is a method that leads to high quality power and cheap energy bills, whereas profit and energy purchases are important for power suppliers. However, if the questioners are system operators, the technical problems like easy accommodation and simple operation are prior. Honestly, we should say that the economic aspect has a great priority to other parts. It means that a low-cost method for providing energy is more important because of the lower energy payments for consumers, operators, and energy suppliers, and the higher profit for energy providers which increase the income of electric utilities.

The hybrid operation of biomass, wind, and solar power plants is unavoidable due to limited access to energy sources in each region. For example, some areas

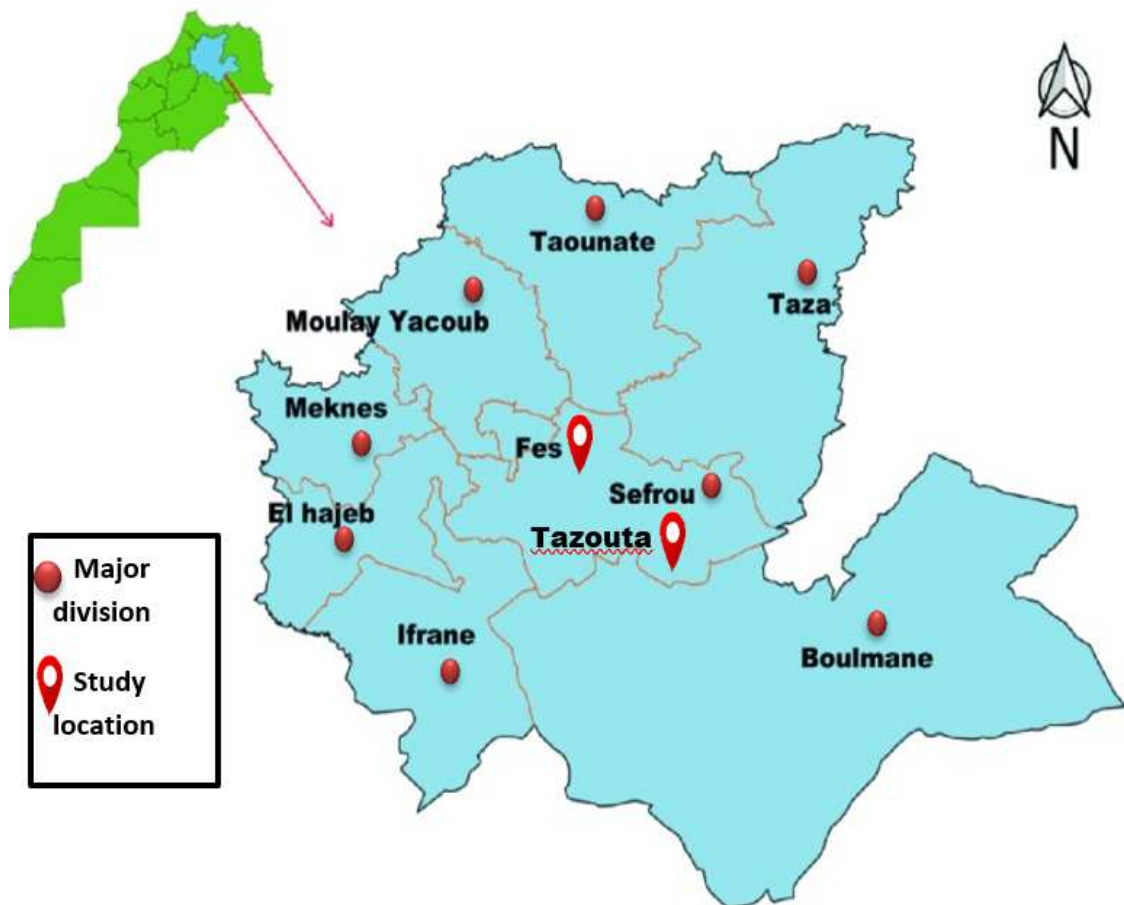
have a great potential for wind power generation, while they are cloudy most of the time as solar irradiation efficiency is low in such places. Whereas, in some sunny areas, the wind is often absent and in some other places like seashores, both wind speed and sunshine are significant. The important question is that if these three energy generation sources are available enough in the same place, which combination of them is more efficient? To address this concern, Tazouta village and Fez rural area in Morocco with great potential for wind, solar, and biomass energy generation are economically studied.

4 CASE STUDIES AND MATHEMATICAL FORMULATION

4.1 CASE STUDIES

Tazouta is a rural village located in the Sefrou zone of the Fez-Meknes region which can be found in the Middle Atlas of Morocco, while Fez is the second largest city in Morocco, serving as the capital of the Fez-Meknes region. Tazouta village has a total land area of about 174 km² and a population of about 5745 inhabitants while Fez has a total land area of 93.91 km² with a total human population of 1.1 million inhabitants (EL-HOUARI 2020). The most important economic activities in Fez are tourism, agriculture, and handicraft. It also serves as the religious and cultural capital of Morocco. Figure 23 is a map of the Fez-Meknes region showing the city of Fez and the rural area of Tazouta.

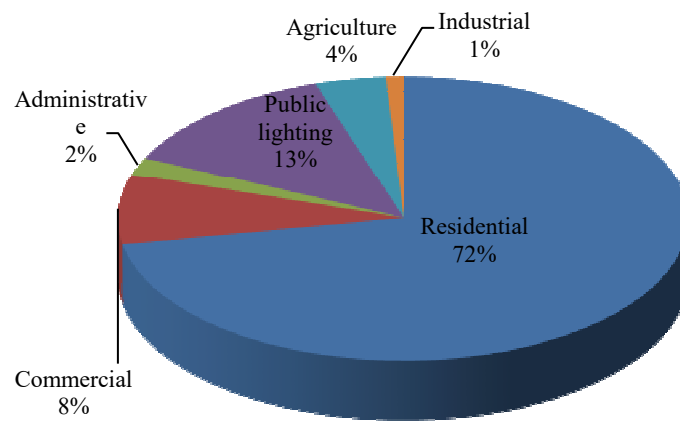
Figure 23 – Administrative map of Fez-Meknes region showing the major division of the region and study locations.



Source: Mahdavi et al. (2023d).

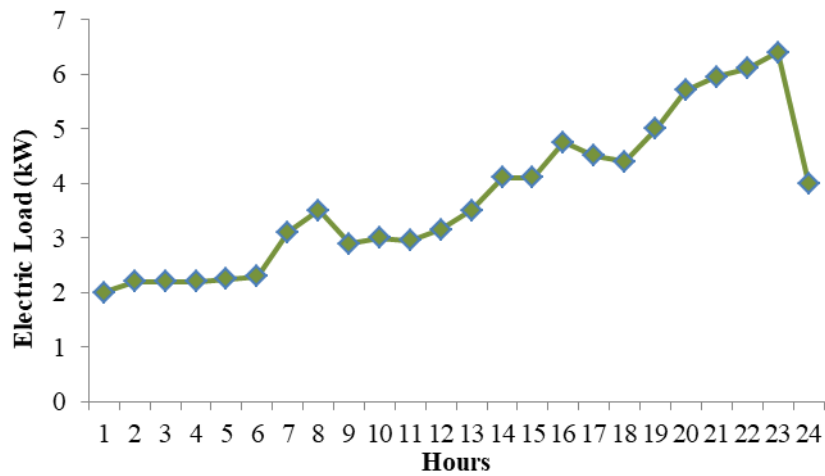
As seen in Figure 24, the majority of electric energy consumers in these rural areas are residential users. For this reason, the typical daily average electric consumption of 10 and 30 houses in Tazouta and Fez rural areas are depicted in Figures 25 and 26, respectively (EL-HOUARI et al., 2020; ALLOUHI et al., 2021).

Figure 24 – Distribution of electricity consumption in the Moroccan village of Tazouta.

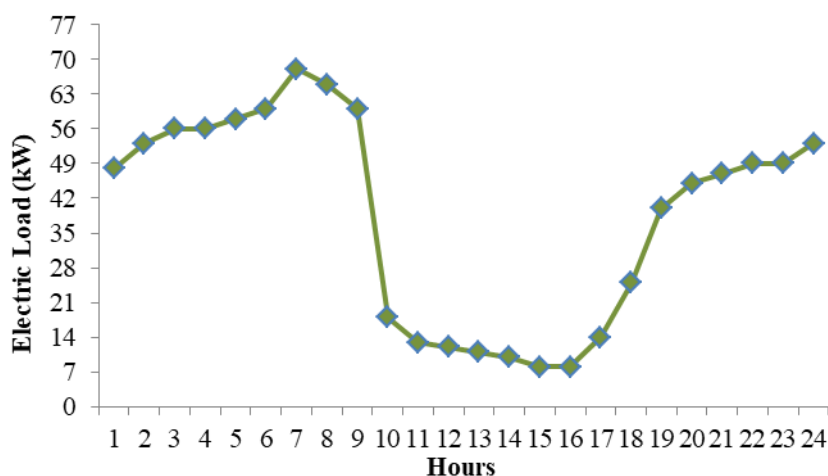


Source: El-Houari et al. (2020).

Figure 25 – Daily average power demand of Tazouta.



Source: El-Houari et al. (2020).

Figure 26 – Daily average power demand of Fez.

Source: Allouhi et al. (2021).

Tazouta village and Fez rural area with an average number of 3 and 7 cows and 10 and 23 sheeps per house have abundant animal biomass resources, respectively (EL-HOUARI et al., 2020; ALLOUHI et al., 2021). By assuming an average amount of 21.865 kg of manure produced by each cow and 1.795 kg of dung produced by each sheep per day (RAMOS-SUAREZ et al., 2019), Tables 2 and 3 show the potential of power generation from 10 and 30 houses' livestock manure based on the anaerobic digestion in Tazouta and Fez regions, respectively. It should be mentioned that the biogas is used to motivate gas turbine for electricity generation. In this case, the cost of fuel is zero due to availability of abundant animal wastes.

Table 2 – Estimated power generation from anaerobic digestion of 30 and 210 cows' manure in Tazouta and Fez.

Regions	Annual manure production (ton)	Matter contents		Biogas		
		Dry	Organic	Amount (m ³ /ton)	Heat energy (kWh/m ³)	Maximum power production (kW/day)
Tazouta	239.42	0.18	0.86	211.84	3.94	9
Fez	1675.9					63

Source: El-Houari et al. (2020); Allouhi et al. (2021).

Table 3 – Dung production and coefficients used for the sheep manure based biogas plant calculations

Areas	Number of sheep	Daily dung production per head (kg/head)	Total solids content (TS) %	Volatile solids (VS) %TS	Biogas yield (L kg/VS)	Biogas methane content (CH ₄) %	Methane lower heating value (kWh/m ³)
Tazouta	100	1.795	30	80	452.4	55	9.96
Fez	690						

Source: Mahdavi et al. (2023); Allouhi et al. (2021).

Regarding Table 3, regional biogas volume produced by sheeps per day can be computed by (1).

$$B = \frac{N \times M \times TS \times VS \times Y_{bio}}{1000} \quad (1)$$

Therefore, the biogas amount in each area is estimated as:

$$B_{Tazouta} = \frac{100 \times 1.795 \times 0.3 \times 0.8 \times 452.4}{1000} = 19.489 \text{ m}^3/\text{day}$$

$$B_{Fez} = \frac{690 \times 1.795 \times 0.3 \times 0.8 \times 452.4}{1000} = 134.48 \text{ m}^3/\text{day}$$

Accordingly, gross power obtained from the biogas of sheep's dung is calculated using (2).

$$Pg_{bio} = \frac{B \times CH_4 \times LHV_{CH_4}}{24} \quad (2)$$

Thus, for each area, we have:

$$Pg_{Tazouta} = \frac{19.489 \times 0.55 \times 9.96}{24} = 4.45 \text{ kW}$$

$$Pg_{Fez} = \frac{134.48 \times 0.55 \times 9.96}{24} = 30.69 \text{ kW}$$

From (2), the total electric power generation of biogas plants by considering 45.5% for their electrical efficiency ($\eta_{bio}=45.5$) is:

$$P_{bio}^o = Pg_{bio} \frac{\eta_{bio}}{100} \quad (3)$$

It means that the maximum biogas electricity generation from sheep dung in Tazouta and Fez areas will be:

$$P_{bio-Tazouta}^o = 4.45 \times \frac{45.5}{100} = 2 \text{ kW}$$

$$P_{bio-Fez}^o = 30.69 \frac{45.5}{100} = 14 \text{ kW}$$

According to the above calculations and considering 2-kW biogas units, the maximum number of installable sheep dung-fueled biogas plants in Tazouta is estimated to be 1 and in Fez is 7.

The manure is mixed with water in preparation tank before entering the digester. Then, wastewater is collected in dewatering system and treated by pressed filtration. Afterward, the liquid is sent to the dilution tank for feeding the reactor. In other words, the water is recycled to dilute the cow manure before feeding the anaerobic digester. About 0.02 m³ of water per kilogram of sheep dung is needed for the reactor to produce biogas sufficient for feeding the 2-kW biogas plant each (BANSAL et al., 2016). The water consumption per annum of one 2-kW biogas unit is estimated to be 1310.3 m³ (100 head×1.795 kg/head.day×365 day×0.02 m³/kg). Also, the water volume needed to be mixed with cow manure in reactor is 19 m³/ton that by considering size of 3 kW for each biomass power plant, the annual water consumption of a biogas unit is estimated to be 1516.3 m³ (239.42ton×19m³/ton÷3kW). In addition, each sheep and cow drinks 1.46 to 5.11 m³ and 4.145 to 41.45 m³ of water per year, respectively, depending on their age, sex, and weight, as well as the environment temperature (Science-based information). With annual average of 23 m³ of water drunk by a cow, 230 m³ of water is required for providing feedstock of a 3-kW biomass power plant by 10 cows. Accordingly, total water demand of each 3-kW biogas plant is 1746.3 m³ (1516.3 m³+230 m³). It is estimated that an annual average of 3.285 m³ of water is needed by one sheep for drinking, while 328.5 m³ of water is necessary for feedstock preparation of a 2-kW biogas plant to be fed by the dung produced by 100 sheeps. This implies the total water required for electricity generation by the 2-kW biogas plant will be 1638.8 m³ (1310.3 m³+328.5 m³).

Meanwhile, each Moroccan has access to 600 m³ of water per year (BELLAOUALI, 2022) that uses 400 m³ of this amount every year (EU, 2023). Considering an average population of six persons per family in Tazouta and Fez, each ten houses in Tazouta has access to 36000 m³ of water that uses 24000 m³ of this amount during the year. Therefore, 12000 m³ of water is available for anaerobic

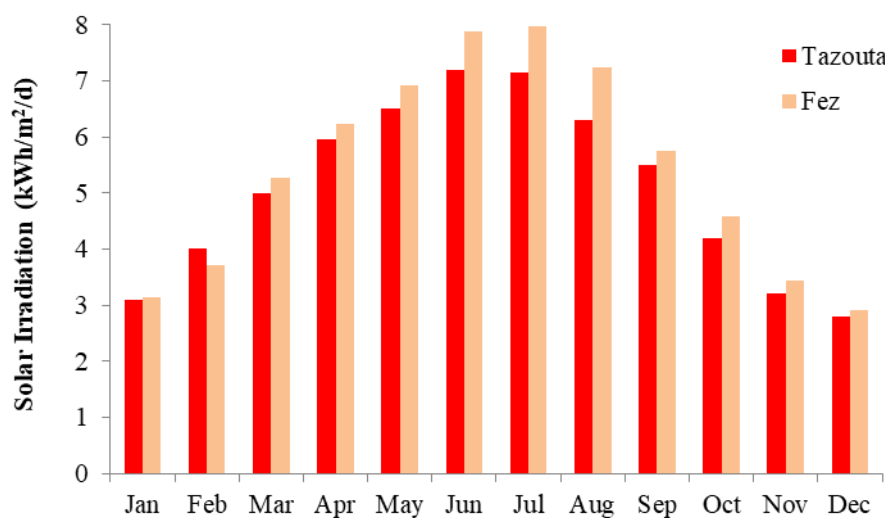
digestion and feeding 30 cows and 100 sheep in Tazouta per year. Accordingly, annual water availability is 36000 m³ for 210 cows and 690 sheep as well as anaerobic digester in 30 houses of Fez rural area.

The investment cost of biomass plant is 1600 \$/kW with the annual operation and maintenance costs of 0.1 \$/kWh, respectively (HEYDARI; ASKARZADEH, 2016). The lifetime of the biogas generator is 2.28 years (EL-HOUARI et al., 2020). In addition, Figures 27 and 28 show monthly average of solar irradiation and wind speed in Tazouta and Fez regions (ALLOUHI; REHMAN, 2023).

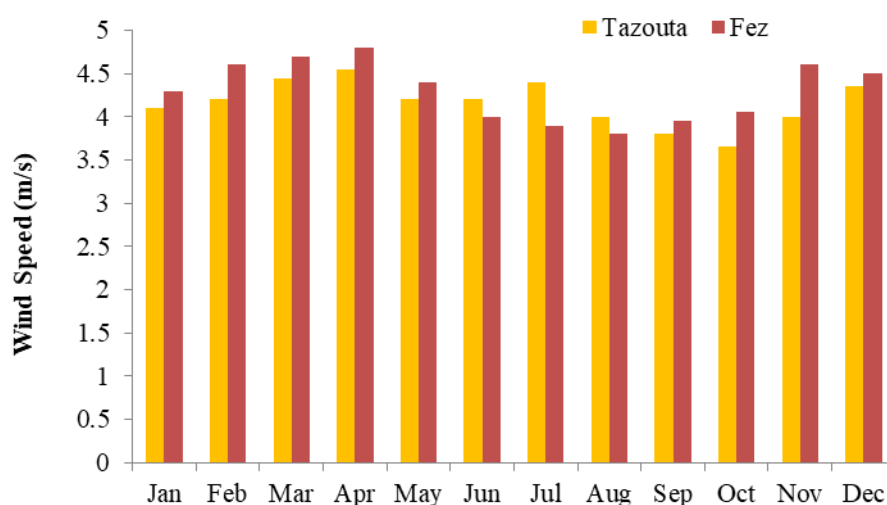
The PV modules are 1 kW-polycrystalline silicon panels with capital cost of 1600 \$/kW and the annual operation and maintenance expenditure of 0.0017 \$/kWh. Also, lifetime, panel yield, performance ratio, solar reflection factor, and total panel area of each 1-kW PV module are 25 years, 28%, 0.75, 0.2, and 7.1 m², respectively. The 5.1-kW wind turbine is a horizontal axis type with the rotor diameter of 5.24 m as well as capital, and yearly operation and maintenance costs of 2155 \$/kW and 0.0023 \$/kWh, respectively.

It should be mentioned that lifetime, performance density, efficiencies of turbine and generator of wind units are 25 years, 0.55, 96%, and 94%, respectively. To provide the connection between PV units and AC network, converters with investment, lifetime, and efficiency of 400 \$/kW, 15 years, and 95% are employed, respectively, without any maintenance and operation costs.

Figure 27 – Monthly solar irradiation.



Source: El-Houari et al. (2020); Allouhi et al. (2021).

Figure 28 – Monthly wind speed.

Source: El-Houari et al. (2020); Allouhi and Rehman (2023).

To store the wind and PV generation surplus, 1 kWh batteries with efficiency, capital cost, annual operation and maintenance expenditure, and usual life of 90%, 330 \$, 10 \$, and 15 years, respectively, are used. The interest rate is 5% in Morocco. The CO₂ emission factors are 16.5 g/kW, 2.686 g/kW, and 16.66 g/kW for a PV, wind turbine, and biomass unit, respectively (ALLOUHI et al., 2019). The technical, economical, and other characteristics of biomass, wind, PV, and battery units, as well as convertor properties are listed in Tables 4-8 (EL-HOUARI et al., 2020; ALLOUHI et al., 2021).

Table 4 – Characteristics of the wind turbine.

Property	Specification
Brand	AWS-HC
Type	Horizontal axis
Nominal power	5.1 kW
Nominal wind speed	11-25 m/s
Number of blades	3
Rotor diameter	5.24 m
Cut in speed	2.7-6 m/s
Capital cost	2155 \$/kW
Annual operation and maintenance cost	0.0023 \$/kWh
Lifetime	25 years
Current type	AC
Performance density	0.55
Turbine efficiency	96%
Generator efficiency	94%
CO ₂ emission factor	2.686 g/kW

Source: El-Houari et al. (2020); Mahdavi et al. (2023c).

Table 5 – Characteristics of the biomass unit.

Property		Specification
Type		Biogas
Nominal power	Cow manure feedstock	3 kW
	Sheep dung feedstock	2 kW
Capital cost		1600 \$/kW
Annual operation and maintenance cost		0.1 \$/kWh
Lifetime		2.28 years
Current type		AC
CO ₂ emission factor		16.66 g/kW
Water consumption	Cow manure based plants	1746.3 m ³
	Sheep dung based plants	1638.8 m ³

Source: El-Houari et al. (2020); Mahdavi et al. (2023c).

Table 6 – Characteristics of the PV.

Property	Specification
Type	Polycrystalline silicon
Nominal power	1 kW
Capital cost	1600 \$/kW
Annual operation and maintenance cost	0.0017 \$/kWh
Lifetime	25 years
Current type	DC
Performance ratio	0.75
Panel yield	28%
Solar reflection factor	0.2
Total panel area	7.1 m ²
CO ₂ emission factor	16.5 g/kW

Source: El-Houari et al. (2020); Mahdavi et al. (2023c).

Table 7 – Characteristics of the battery.

Property	Specification
Nominal voltage	6 V
Nominal capacity	167 Ah
Size	1 kWh
Capital cost	330 \$/unit
Annual operation and maintenance cost	10 \$/unit
Lifetime	15 years
Current type	DC
Maximum charge current	167 A
Maximum discharge current	500 A
Efficiency	90%

Source: El-Houari et al. (2020)

Table 8 – Characteristics of the converter.

Property	Specification
Capital cost	400 \$/kW
Annual operation and maintenance cost	0
Lifetime	15 years
Current type	AC/DC
Efficiency	95%

Source: El-Houari et al. (2020)

Also, the carbon emission limit in Tazouta is 746 g/kW (EL-HOUARI et al., 2020). It should be noted that the maximum carbon emission of Fez is set to be three times bigger than that of Tazouta because of considering 30 houses in Fez for study instead of 10 in Tazouta.

4.2 MATHEMATICAL FORMULATION

In order to evaluate the hybrid electricity generation of biomass, wind, and PV units in the presence of batteries and converters, the proposed problem in different geographical locations can be formulated as follows.

$$\min C_T = C_{pv} + C_{wind} + C_{biomass} + C_{battery} + C_{converter} \quad (4)$$

Where:

$$C_{pv} = CC_{pv} P_{pv}^o \frac{d(1+d)^{L_{pv}}}{(1+d)^{L_{pv}} - 1} \sum_i n_{pv}(i) + 24 CM_{pv} \sum_i \sum_h n_{pv}(i) P_{pv,max}(i, h) D(h) \quad (5)$$

$$C_{wind} = CC_w P_w^o \frac{d(1+d)^{L_w}}{(1+d)^{L_w} - 1} \sum_i n_w(i) + 24 CM_w \sum_i \sum_h n_w(i) P_{w,max}(i, h) D(h) \quad (6)$$

$$C_{biomass} = CC_{bio} P_{bio}^o \frac{d(1+d)^{L_{bio}}}{(1+d)^{L_{bio}} - 1} \sum_i n_{bio}(i) + CM_{bio} \sum_i \sum_t \sum_h P_{bio}(i, t, h) D(h) \quad (7)$$

$$C_{battery} = CC_b \frac{d(1+d)^{L_b}}{(1+d)^{L_b} - 1} \sum_i n_b(i) + CM_b \sum_i n_b(i) \quad (8)$$

$$C_{converter} = CC_c \frac{d(1+d)^{L_c}}{(1+d)^{L_c} - 1} \sum_i P_c(i) \quad (9)$$

$$P_{pv,\max}(i, h) = \frac{1}{24} A_{pv} \eta_{pv} PR(1-r) Ir(i, h) \quad (10)$$

$$P_{w,\max}(i, h) = \frac{1}{2} p A_r C_p \eta_t \eta_g V^3(i, h) 10^{-3} \quad (11)$$

Subject to:

$$P_{bio}(i, t, h) + P_{pv}(i, t, h) + P_w(i, t, h) + \sum_{k=1}^i \sum_{i=k+1}^N P_l(k, i, t, h) - \sum_{i=1}^j \sum_{j=i+1}^N P_l(i, j, t, h) = P_D(i, t) \quad (12)$$

$$\forall t = 1, \dots, 24, \quad h = 1, \dots, 12$$

$$0 \leq P_{bio}(i, t, h) \leq P_{bio}^o n_{bio}(i) \quad \forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N \quad (13)$$

$$0 \leq P_{pv}(i, t, h) \leq P_{pv,\max}(i, h) n_{pv}(i) \quad \forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N \quad (14)$$

$$0 \leq P_w(i, t, h) \leq P_{w,\max}(i, h) n_w(i) \quad \forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N \quad (15)$$

$$0 \leq n_{bio}(i) \leq n_{bio}^{\max}(i) \quad i = 1, \dots, N \quad (16)$$

$$n_{pv}(i) \geq 0 \quad i = 1, \dots, N \quad (17)$$

$$n_w(i) \geq 0 \quad i = 1, \dots, N \quad (18)$$

$$P_b(i, t, h) = (P_{pv,\max}(i, h) n_{pv}(i) - P_{pv}(i, t, h)) \eta_b + (P_{w,\max}(i, h) n_w(i) - P_w(i, t, h)) \eta_b \eta_r \quad (19)$$

$$\forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N$$

$$E_b n_b(i) \geq \sum_t P_b(i, t, h) \quad \forall h = 1, \dots, 12, \quad i = 1, \dots, N \quad (20)$$

$$n_b(i) \geq 0 \quad i = 1, \dots, N \quad (21)$$

$$P_c(i) \geq P_{w,\max}(i, h) n_w(i) - P_w(i, t, h) \quad \forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N \quad (22)$$

$$P_c(i) \geq P_{pv}(i, t, h) \quad \forall t = 1, \dots, 24, \quad h = 1, \dots, 12, \quad i = 1, \dots, N \quad (23)$$

$$F_{pv} n_{pv}(i) P_{pv}^o + F_w n_w(i) P_w^o + F_{bio} n_{bio}(i) P_{bio}^o \leq E_{Av}(i) \quad i = 1, \dots, N \quad (24)$$

$$n_{bio}(i) W_{bio}^o \leq W_{\max}(i) \quad i = 1, \dots, N \quad (25)$$

Objective function (4) represents total cost of the hybrid system (C_T), including costs of PV modules (C_{pv}), wind turbines (C_{wind}), biomass power plants ($C_{biomass}$), batteries ($C_{battery}$), and converters ($C_{converter}$). The first term of Eq. (5) describes the annual investment cost of PV modules that is obtained through multiplication of total number of installed PV in each region (summation of $n_{pv}(i)$), each PV size (P^o_{pv}) and capital cost (CC_{pv}) annualized according to panels lifetime (L_{pv}). Also, the second term of this equation shows operating and maintenance costs of PV modules per year which is estimated by multiplying number of installed modules in both regions (summation of $n_{pv}(i)$) by each PV annual maintenance cost (CM_{pv}), hourly solar power generation of a month in region i ($P_{pv,max}(i,h)$), number of corresponding month days ($D(h)$), and daily hours (24 h). According to (10), $P_{pv,max}(i,h)$ depends on daily average solar irradiation of each month ($Ir(i,h)$), PV performance ratio (PR), PV efficiency (η_{pv}), panels area (A_{pv}), and module's absorption factor of solar irradiation ($1-r$). The first term of Eq. (6) indicates the capital cost of wind units, consisting of wind turbine numbers in each region ($n_w(i)$) as well as a turbine's power generation capacity (P^o_w) and capital cost (CC_w) annualized respect to its lifetime (L_w). Its second term denotes that annual operation and maintenance costs of wind units are obtained from multiplying number of installed turbines ($n_w(i)$) by each turbine's yearly maintenance cost (CM_w), hourly regional wind electricity generation of a month ($P_{w,max}(i,h)$) and number of days in that month ($D(h)$). From Eq. (11), $P_{w,max}(i,h)$ is proportional to mean wind speed of each month ($V(i,h)$), air density (ρ), total area of rotor (A_r), wind turbine's performance coefficient (C_p), efficiency (η_t), and generator yield (η_g). Also, first and second terms of Eq. (7) represent capital costs and operation and maintenance expenses of biomass units, respectively. The biomass investment can be calculated by multiplying construction cost of each biomass plant (CC_{bio}) annualized based on plant lifespan (L_{bio}) by number of generating units (n_{bio}) and their capacity (P^o_{bio}). The maintenance and operation cost of biomass power plants is obtained by multiplying the maintenance cost of each unit by total power generation of all biomass plants.

The first terms of Eqs. (8) and (9) represent capital costs of batteries and converters, while the second term of Eq. (8) denotes operation and maintenance cost of batteries. The batteries' investment cost is calculated based on annualized price of one battery (CC_b) according to its lifetime (L_b) and number of installed batteries

$(n_b(i))$. Also, the batteries' maintenance expenditure is equal to annual maintenance cost (CM_b) of $n_b(i)$ batteries.

Equation (12) explains that the total hourly power generation is equal to the total hourly electricity demand in each month. Constraints (13) to (15) indicate power generation limits of biomass, PV, and wind units in each hour, month, and location, respectively. Constraint (16) denotes that number of installable biogas units in each region is limited by the maximum manure production of that place. According to Tables 2 and 3, up to 3 and 21 of 3-kW and 1 and 7 of 2-kW units can be installed in Tazouta and Fez areas, respectively. Equation (19) denotes that the surplus of PV and wind power generation is stored in batteries, while Eq. (20) exhibits the number of batteries required for storage of excess generation of PV and wind units. In addition, (22) and (23) indicate that the rated power of converters that connect AC and DC systems should be bigger than wind generation surplus and the PV's output. Constraints (24) and (25) respectively describe the limits of air emission and the maximum number of installable biomass units in each region regarding water availability.

5 SIMULATION RESULTS

The proposed mathematical formulation is a mixed-integer linear programming problem with integer variables $n_{pv}(i)$, $n_w(i)$, $n_{bio}(i)$, and $n_b(i)$, real variables $P_{pv}(i,t,h)$, $P_w(i,t,h)$, $P_{bio}(i,t,h)$, and $P_l(i,j,t,h)$, objective function (4), equations (5) to (11), and constraints (12) to (25) that can be computed by linear solvers. Therefore, CPLEX in AMPL was used to solve the proposed optimization problem. Tables 9-18 present simulation results for different generation technologies.

Table 9 – Simulation results after operation of wind turbines for simultaneously satisfying the power demand of both regions.

Item	Value		
	Tazouta	Fez	Total
Capacity of each wind turbine (kW)	5.1	5.1	-
Number of wind turbines	54	135	189
Annual electricity generation of wind turbines (kWh)	226066.4	626176.7	852240
Portion of annual wind electricity generation of each region in satisfying the total demand (kWh)	177151.3	194634.1	371790
Annual electricity demand (kWh)	33795.3	337990	371790
Unmet energy demand (kWh)	0	0	0
Excess energy generation (kWh)	41822.4	368968.9	410790
Annual emission (g)	739.8	1849.5	2589.3
Number of 1-kWh batteries	164	1654	1818
Capacity of converter (kW)	22.4	79.1	101.6
Annualized capital cost of wind turbines (\$)	42109.4	105273.4	147380
Annual operation and maintenance costs of wind turbines (\$)	516.1	1429.6	1945.8
Annualized capital cost of batteries (\$)	5214	52585.5	57800
Annual operation and maintenance costs of batteries (\$)	1640	16540	18180
Annualized capital cost of converters (\$)	865.3	3049.1	3914.5
Total cost (\$)	50345	178880	229225

Source: Mahdavi et al. (2023c).

Table 10 – Simulation results after operation of wind turbines for individually satisfying the power demand of each region.

Item	Value		
	Tazouta	Fez	Total
Capacity of each wind turbine (kW)	5.1	5.1	-
Number of wind turbines	20	190	210
Annual electricity generation of wind turbines (kWh)	83728.3	881285.71	965010
Annual electricity demand (kWh)	33795.35	337990	371790
Unmet energy demand (kWh)	0	0	0
Excess energy generation (kWh)	49933	543300	593233
Annual emission (g)	274	2603	2877
Number of 1-kWh batteries	173	2035	2208
Capacity of converter (kW)	8.69	110.94	119.63
Annualized capital cost of wind turbines (\$)	15596.06	148162.57	163760
Annual operation and maintenance costs of wind turbines (\$)	191.16	2012.07	2203.2
Annualized capital cost of batteries (\$)	5500.18	64698.66	70199
Annual operation and maintenance costs of batteries (\$)	1730	20350	22080
Annualized capital cost of converters (\$)	335.068	4275.21	4610.3
Total cost (\$)	23352	239500	262852

Source: Mahdavi et al. (2023d).

Table 11 – Simulation results after operation of PV units.

Item	Value		
	Tazouta	Fez	Total
Capacity of each PV module (kW)	1	1	-
Number of PV units	45	269	314
Annual electricity generation of PV units (kWh)	99385.94	636029.47	735420
Annual electricity demand (kWh)	33795.35	337990	371790
Unmet energy demand (kWh)	1439.1	115030	116470
Excess energy generation (kWh)	67030	413070	480100
Annual emission (g)	742.5	4438.5	5181
Number of 1-kWh batteries	326	1812	2138
Capacity of converter (kW)	6.2	67.52	73.72
Annualized capital cost of PV units (\$)	5108.58	30537.94	35647
Annual operation and maintenance costs of PV modules (\$)	170.18	1089.09	1259.3
Annualized capital cost of batteries (\$)	10364.5	57608.83	67973
Annual operation and maintenance costs of batteries (\$)	3260	18120	21380
Annualized capital cost of converters (\$)	235.78	2601.9	2837.7
Total cost (\$)	19139	109960	129099

Source: Mahdavi et al. (2023d).

Table 12 – Simulation results after operation of sheep biomass power plants.

Item	Value		
	Tazouta	Fez	Total
Capacity of each biogas plant (kW)	2	2	-
Number of biogas plants	1	7	8
Annual biogas electricity generation (kWh)	17520	122640	140160
Annual electricity demand (kWh)	33795.35	337990	371790
Unmet energy demand (kWh)	16275	215350	231625
Excess energy generation (kWh)	0	0	0
Generation deficiency	16275	215350	231625
Annual emission (g)	33.3	233.1	266.4
Annual water consumption (m ³)	1638.8	11471.6	13110
Number of 1-kWh batteries	0	0	0
Capacity of converter (kW)	0	0	0
Annualized capital cost of biogas units (\$)	1519.79	10638.56	12158
Annual operation and maintenance costs of biogas units (\$)	1752	12264	14016
Annualized capital cost of batteries (\$)	0	0	0
Annual operation and maintenance costs of batteries (\$)	0	0	0
Annualized capital cost of converters (\$)	0	0	0
Total cost (\$)	3271.8	22903	26175

Source: Mahdavi et al. (2023d).

Table 13 – Simulation results after hybrid operation of PV and wind.

Item	Tazouta		Fez		Total	
	PV	Wind	PV	Wind	PV	Wind
Capacity of each unit (kW)	1	5.1	1	5.1	-	-
Number of units	37	9	36	120	73	129
Annual electricity generation of units (kWh)	81717.3	37677.7	85119.2	556601.5	166840	594280
Portion of annual electricity generation of each region in satisfying the total demand (kWh)	48538.5	16520.4	25779.6	280946.8	74318	297470
Annual emission (g)	610.5	123.3	594	1644	1204.5	1767.3
Annualized capital cost of units (\$)	4200.4	7018.2	4086.9	93576.4	8287.3	100590
Annual operation and maintenance costs of units (\$)	139.9	86	145.7	1270.8	285.6	1356.8
Annualized capital cost of batteries (\$)	5309.4		41998.5		47308	
Annual operation and maintenance costs of batteries (\$)	1670		13210		14880	
Annualized capital cost of converters (\$)	435		2904.8		3339.8	
Annual electricity demand (kWh)	33795.3		337990		371790	
Unmet energy demand (kWh)	0		0		0	
Number of 1-kWh batteries	167		1321		1488	
Capacity of converter (kW)	11.3		75.4		86.7	
Excess energy generation (kWh)	47950.4		289090.4		337040	
Total cost (\$)	18859		157190		176050	

Source: Mahdavi et al. (2023c).

Table 14 – Simulation results after hybrid operation of biomass and wind.

Item	Tazouta		Fez		Total	
	Bio	Wind	Bio	Wind	Bio	Wind
Capacity of each unit (kW)	3	5.1	3	5.1	-	-
Number of units	3	1	20	5	23	6
Annual electricity generation of units (kWh)	5369.2	4186.4	339038	23191.7	344410	27378
Portion of annual electricity generation of each region in satisfying the total demand (kWh)	5369.2	4186.4	339038	23191.7	344410	27378
Annual emission (g)	5238.9	13.7	34926	68.5	40165	82.2
Annualized capital cost of units (\$)	6839.1	779.8	45593.8	3899	52433	4678.8
Annual operation and maintenance costs of units (\$)	536.9	9.6	33903.8	52.9	34441	62.5
Annual water consumption (m ³)	5238.9	0	34926	0	40165	
Annualized capital cost of batteries (\$)	0		0		0	
Annual operation and maintenance costs of batteries (\$)	0		0		0	
Annualized capital cost of converters (\$)	0		0		0	
Annual electricity demand (kWh)	33795.3		337990		371790	
Unmet energy demand (kWh)	0		0		0	
Number of 1-kWh batteries	0		0		0	
Capacity of converter (kW)	0		0		0	
Excess energy generation (kWh)	0		0		0	
Total cost (\$)	8165.4		83450		91615	

Source: Mahdavi et al. (2023c).

Table 15 – Simulation results after hybrid operation of PV and biomass.

Item	Tazouta		Fez		Total	
	Bio	PV	Bio	PV	Bio	PV
Capacity of each unit (kW)	3	1	3	1	-	-
Number of units	0	41	20	39		
Annual electricity generation of units (kWh)	0	90551.6	207353	92212.4	207353	182764
Portion of annual electricity generation of each region in satisfying the total demand (kWh)	0	88590.1	207353	75842.2	207353	164430
Annual emission (g)	0	676.5	34926	643.5	34926	1320
Annualized capital cost of units (\$)	0	4654.5	45593.8	4427.4	45593.8	9081.9
Annual operation and maintenance costs of units (\$)	0	155	20735.3	157.9	20735.3	312.9
Annual water consumption (m ³)	0	0	34926	0	34926	
Annualized capital cost of batteries (\$)		349.7		3751.6		4101.3
Annual operation and maintenance costs of batteries (\$)		110		1180		1290
Annualized capital cost of converters (\$)		563.8		595.1		1158.9
Annual electricity demand (kWh)		33795.3		337990		371790
Unmet energy demand (kWh)		0		0		0
Number of 1-kWh batteries		11		118		129
Capacity of converter (kW)		14.6		15.4		30
Excess energy generation (kWh)		1961.5		16370.2		18332
Total cost (\$)		5833		76441		82274

Source: Mahdavi et al. (2023c).

Table 16 – Simulation results after hybrid operation of cow biomass, PV, and wind units.

Item	Tazouta			Fez			Total
	Bio	PV	Wind	Bio	PV	Wind	
Capacity of each unit (kW)	3	1	5.1	3	1	5.1	-
Number of units	3	7	1	16	84	1	-
Annual electricity generation of units (kWh)	5854.9	15460	4186.4	173458.7	198611.4	4638.3	402210
Portion of annual electricity generation of each region in satisfying the total demand (kWh)	5854.9	13120.5	3360.6	173458.7	172522.5	3468.1	371790
Annual emission (g)	150	115.5	13.7	800	1386	13.7	2478.9
Annualized capital cost of units (\$)	6839.1	794.7	779.8	36475.1	9536	779.8	55205
Annual operation and maintenance costs of units (\$)	585.5	26.5	9.6	17345.9	340.1	10.6	18318
Annual water consumption (m ³)	5238.9	0	0	27940.8	0	0	33180
Annualized capital cost of batteries (\$)		731.2			4292		5023.2
Annual operation and maintenance costs of batteries (\$)		230			1350		1580
Annualized capital cost of converters (\$)		96.3			1281.7		1378
Annual electricity demand (kWh)		33795.3			337990		371790
Unmet energy demand (kWh)		0			0		0
Number of 1-kWh batteries		23			135		158
Capacity of converter (kW)		2.5			33.3		35.8
Excess energy generation (kWh)		2811.6			24480.6		27292
Total cost (\$)		10093			71411		81504

Source: Mahdavi et al. (2023c).

Table 17 – Simulation results after hybrid operation of sheep biomass, PV, and wind units in Tazouta.

Item	Value			
	Bio	PV	Wind	Total
Capacity of each unit (kW)	2	1	5.1	-
Number of units	1	15	5	-
Annual electricity generation of units (kWh)	1043.27	33128.65	20932.07	55103.99
Annual electricity demand (kWh)	1043.27	23462.21	9289.86	33795.34
Unmet energy demand (kWh)	0	0	0	0
Excess energy generation (kWh)	0	9666.4	11642	21308.4
Annual emission (g)	33.3	247.5	68.5	349.30
Annual water consumption (m ³)	1638.8	0	0	1638.8
Annualized capital cost of units (\$)	1519.79	1702.86	3899.01	7121.66
Annual operation and maintenance costs of units (\$)	104.33	56.72	47.79	208.84
Annualized capital cost of batteries (\$)	2861.37			2861.37
Annual operation and maintenance costs of batteries (\$)	900			900
Annualized capital cost of converters (\$)	140.57			140.57
Number of 1-kWh batteries	90			90
Capacity of converter (kW)	3.65			3.65
Total cost (\$)	7382.6	1759.58	3946.2	13088.38

Source: Mahdavi et al. (2023d).

Table 18 – Simulation results after hybrid operation of sheep biomass, PV, and wind units in Fez.

Item	Value			
	Bio	PV	Wind	Total
Capacity of each unit (kW)	2	1	5.1	-
Number of units	7	179	50	-
Annual electricity generation of units (kWh)	3064.92	423231.51	231917.29	658213.72
Annual electricity demand (kWh)	3064.92	217968.98	116956.11	337990.01
Unmet energy demand (kWh)	0	0	0	0
Excess energy generation (kWh)	0	205260	114960	320220
Annual emission (g)	233.1	2953.5	685	3871.6
Annual water consumption (m ³)	11471.6	0	0	11471.6
Annualized capital cost of units (\$)	10638.56	20320.78	38,990.15	69949.49
Annual operation and maintenance costs of units (\$)	306.49	724.71	529.49	1560.69
Annualized capital cost of batteries (\$)				35417.35
Annual operation and maintenance costs of batteries (\$)	11140			11140
Annualized capital cost of converters (\$)	1851.54			1851.54
Number of 1-kWh batteries	1114			1114
Capacity of converter (kW)	48.05			48.05
Total cost (\$)	119920	21045.49	4428.64	145394.13

Source: Mahdavi et al. (2023d).

Comparing Table 9 with Table 10 and also Table 16 with Tables 17 and 18 shows that operation of wind turbines or hybrid system for simultaneous providing the energy requirements of both regions (on-grid operation) is less expensive than satisfying the electricity demand of each individual area (off-grid utilization) because of need for fewer number of wind turbines and batteries, smaller convertor capacity, and therefore lower capital and operational expenses in on-grid power operation compared to when the load is met as off-grid.

Tables 11 and 12 show that the operation of either only PV modules or biomass power plants cannot supply 100% of the electricity demand of each rural community due to carbon emission limits, water availability restrictions, and limited access to animal biomass feedstock, respectively. Nevertheless, Tables 9 and 10 denote that utilization of wind turbines without the participation of biomass and PV units is possible due to the lower emissions and also independent of water resources in wind power generation as compared to solar and biomass electricity production, respectively. For instance, Table 12 indicates that a total volume of 1638.8 m³ and 11471.6 m³ of water will be required for generating 17520 kWh and 122640 kWh for Tazouta and Fez respectively per annum through AD of sheep dung. This power is unable to satisfy the entire load of each study location, which is contrary to the case of the wind power generation (see Table 10). Table 10 indicates that the utilization of only wind turbines can supply all the power demand of each community under the lower emission and water resources constraints as compared to the situation of solar and biogas electricity generation but at a high cost. However, using only wind to supply power cannot guarantee power supply security, and this can be addressed by hybrid power generation. For this, results presented in Table 13 show that, the operation of PV units besides wind turbines reduces the total cost of the system considerably because of the cheaper capital and operation costs of PV modules and the fewer batteries and smaller converter capacity requirements, owing to the lower excess generation compared to when only wind turbines are operated.

A similar study by Miller et al. (2018) found that the use of PV and wind for power generation will emit less than 25% of GHG as compared to the use of fossils for power generation. In contrast to the finding of this study where the PV modules emitted the highest amount of carbons among the renewable sources considered, their study found PV modules to emit a negligible amount of carbon dioxide in the generation stage with the majority of the emissions coming from PV modules

production stage (GARCIA and OLIVA, 2023). The highest cost of wind power investment has always contributed to low penetration of wind power generation. From Table 10 it can be found that total cost associated with the wind generation is very high as compared to that of PV only and biogas only generation.

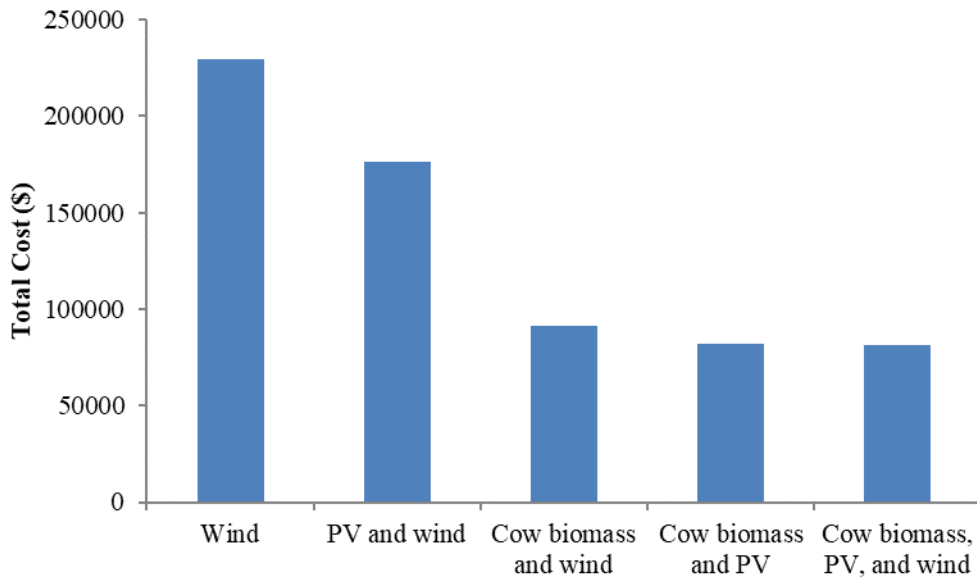
Also, comparing Table 12 with Table 10 shows that the utilization of only biogas power is less expensive than wind generation but the standalone biogas power plant cannot supply the entire load demand of the two study locations due to insufficient sheep's dung supply. Table 14 shows that the utilization of biomass power plants instead of solar panels besides wind turbines is less expensive than hybrid PV and wind power generation since there is no need for battery and converter installation because of zero excess generation.

In addition, comparing Table 17 with Table 18 and Table 14 with Tables 9 and 13 denote that the construction of biomass power plants reduces the number of wind turbines and subsequently the costly installation of wind units. Moreover, less amount of carbon is emitted in the case of sheep dung biogas energy production as compared to photovoltaic and wind electricity generation. This implies that in areas where there is sufficient feedstock for biogas power generation, standalone sheep dung biogas power generation will be the most ideal since it is less expensive and also emits less amount of carbon dioxide. However, a considerable amount of water is consumed by the anaerobic digestion as well as sheeps for bioelectricity generation and therefore in water-stressed areas, biogas power generation might become a bit problematic even when there is sufficient feedstock for the anaerobic digestion process. In addition, a higher amount of carbon is emitted in biomass energy production from cow manure compared to photovoltaic and wind electricity generation.

Table 15 indicates that the hybrid utilization of cow biomass and solar energy resources is more economical than the individual or combined operation of wind turbines with PV or biomass units, because of cheaper solar electricity generation and lower excess biomass power. In addition, the hybrid operation of biomass and PV units leads to lower water consumption, but higher air pollution compared to the case of hybrid biomass and wind energy generation. Furthermore, Table 16 shows that hybrid utilization of cow manure biomass, PV, and wind units is more cost-effective compared to the other generation scenarios and leads to lower water consumption and carbon emission compared to when biomass electricity is

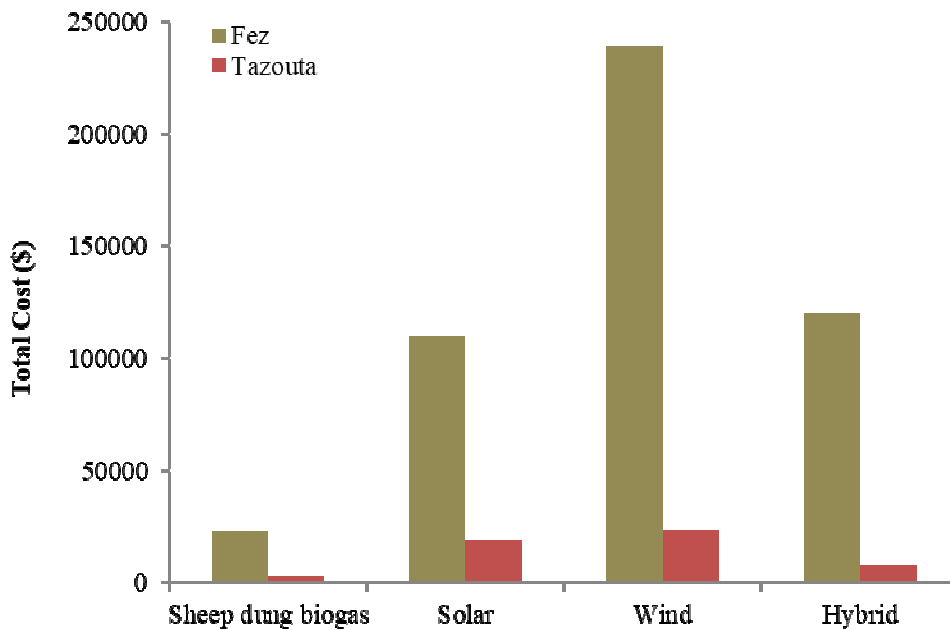
generated at the same time with solar or wind electric energies. Figures 29 and 30 compare the total costs of different electricity generation methods, while Figures 31 and 32 show the water need of each method. Furthermore, Figures 33 and 34 exhibit the amount of CO₂ emission for all energy generation technologies.

Figure 29 – Total cost of different generation technologies for both regions.



Source: Mahdavi et al. (2023c).

Figure 30 – Total cost of different generation technologies for each region.

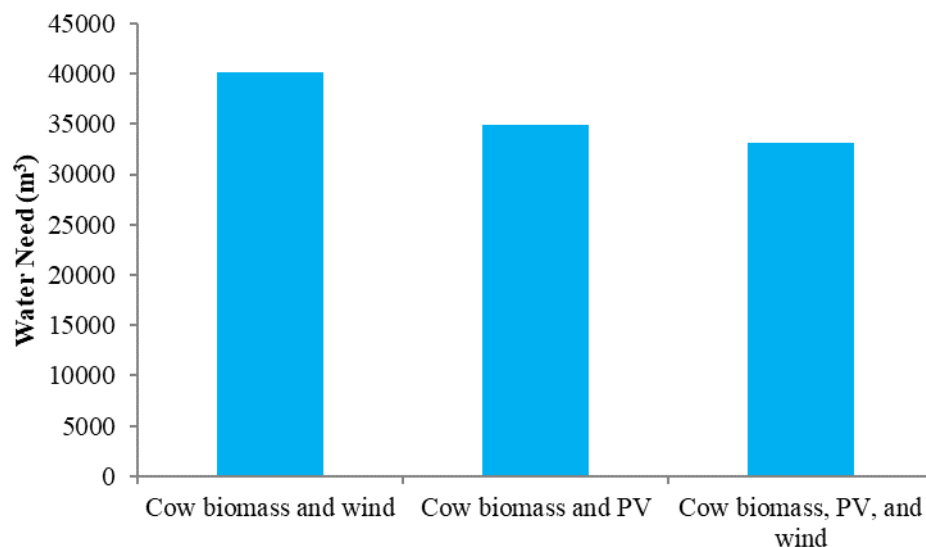


Source: Mahdavi et al. (2023d).

Figure 30 shows that the use of only biogas power plants for power generation is more economical as compared to other generation methods like wind, PV, or hybrid operation. Nevertheless, the sole utilization of biogas or solar energy makes it impossible to meet the entire energy demand of all the users. The wind or hybrid operation of wind, solar, and biogas can meet all the domestic loads demand considered in the study. Even though the study shows that both the wind and the hybrid power operations are capable of meeting the entire load demand, it is worth knowing that, the hybrid system is cheaper than only the wind power generation system.

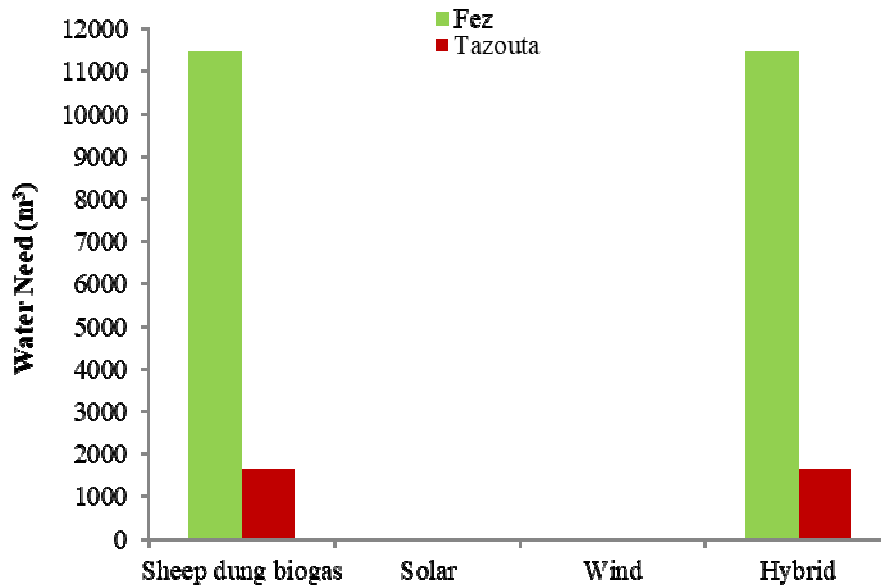
In addition, in Figure 29, it can be observed that employing cow manure based biomass power plants beside other kinds of renewable energy technologies for electricity generation is more economic than utilization of only wind turbines or hybrid PV and wind units. The reason is that biomass unit commitment does not need batteries and converters, whereas wind and PV utilization require both of them. To store AC wind electricity surplus in batteries, rectifiers are essential, while for satisfying AC loads using DC power of PV modules, inverters are necessary. Nevertheless, the hybrid operation of biomass, PV, and wind is a less expensive feasible option for electricity generation, because biomass makes a balance between cheaper electricity production of PV and variable solar and wind power outputs.

Figure 31 – Water needs of different feasible generation methods including cow biomass.



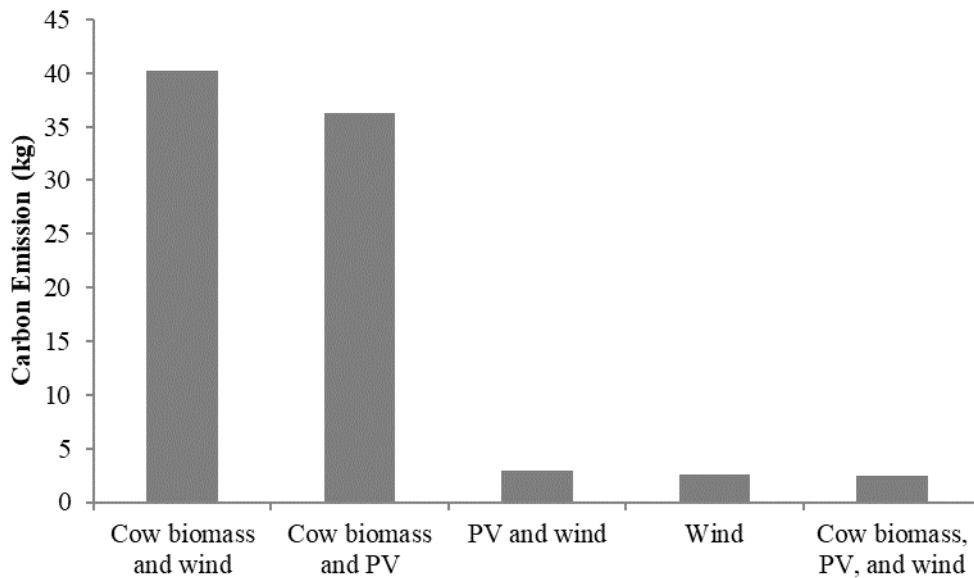
Source: Mahdavi et al. (2023c).

Figure 32 – Water needs of different generation methods including sheep biomass.



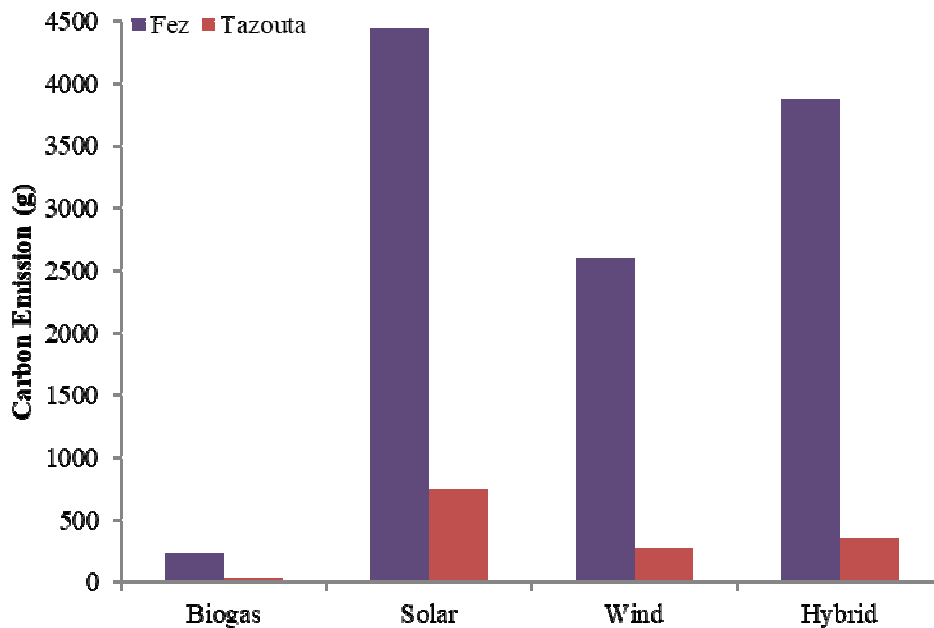
Source: Mahdavi et al. (2023d).

Figure 33 – Carbon emission of all feasible generation methods including cow biomass.



Source: Mahdavi et al. (2023c).

Figure 34 – CO₂ emission of all generation methods including sheep biomass.



Source: Mahdavi et al. (2023d).

Figure 32 indicates that the water consumption of the hybrid generation and the biogas electricity generation are the same, while wind and PV do not need access to water resources. However, hybrid electricity generation is cheaper than wind and can afford the whole electric load of both regions, opposite to the situation of the biogas and solar plants. Also, Figure 31 represents that water consumption of hybrid cow biomass, solar, and wind electricity generation are less than other hybrid energy production methods involving biomass.

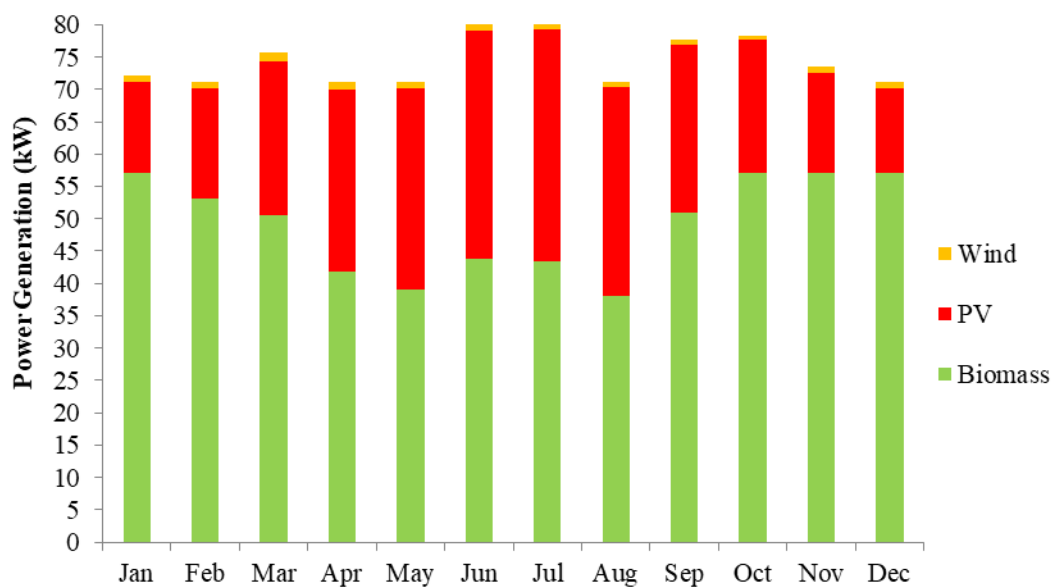
Figure 34 shows that bioelectricity generation has the lowest carbon emission potential followed by wind power, hybrid power generation, and the solar system being the 2nd, 3rd, and 4th respectively in terms of their environmental friendliness. But the biogas plant has generation capacity limitations hence unable to meet all the energy demands of the consumers due to the limited sheep dung availability. The wind and hybrid systems are not subjected to this limitation, hence do not have any unmet load, but with high carbon emissions. However, Figure 33 indicates that carbon emission of hybrid biomass, wind, and solar system is lower than all other hybrid electricity generation technologies. Similarly, the study by Sanni et al. (2021) on the use of PV/diesel/biogas as a backup solution for unreliable grid electricity at an abattoir also found the hybrid operation of grid/PV/biogas to reduce CO₂ emission

by up to 61% as compared to the operation of grid/PV/diesel while providing the least cost of energy.

Therefore, if the goal is achieving only the cheapest and cleanest energy generation without taking into consideration the unmet demand of consumers, bioelectricity will be the most ideal option. However, if the objective is to produce electricity that does not require water usage without regarding generation cost, wind power should be the preferred alternative. Moreover, if the aim is to generate less expensive electricity without considering carbon emissions and the unmet load of consumers, then solar power should be the best option. Meanwhile, if the goal is achieving the most cost-effective and clean energy generation method with reasonable water consumption that can meet the entire energy demand of the region, hybrid biomass, solar, and wind energy is a good solution. However, if the goal is to find an economic system with zero wastewater and low carbon emission, hybrid wind and solar energy employment is an appropriate way.

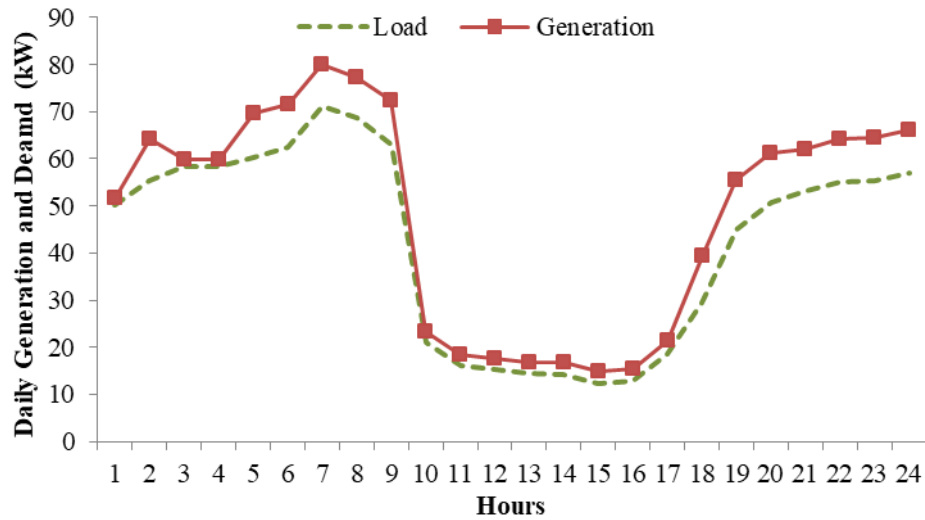
Figure 35 indicates the share of each electricity generation technology in satisfying the load of both regions when cow biomass, PV, and wind units are operated simultaneously. Also, Figure 36 shows graphically how the proposed system is meeting the total daily load demand.

Figure 35 – Electric power generation during the year.



Source: Mahdavi et al. (2023c).

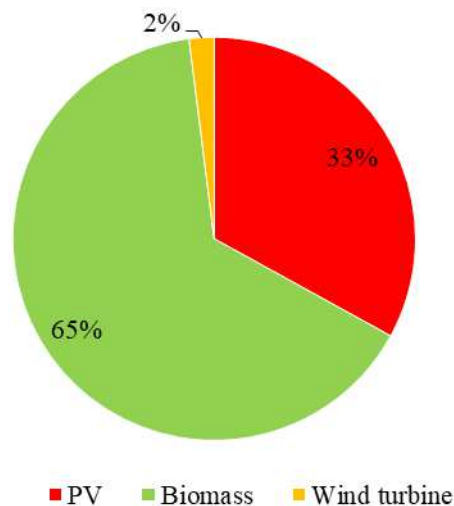
Figure 36 – Daily generation profile versus total daily load demand.



Source: Mahdavi et al. (2023c).

As observed in Figure 35, the electricity generated by the biomass meets the majority of monthly power demands. The reason is that the wind power generation strongly depends on wind speed that is so variable parameter not only throughout the year, but during the month, week, and even day. Also, PV power generation experiences a slight decrease in rainy seasons such as January, February, November, and December due to low solar irradiation because of rainy and cloudy conditions. Therefore, as seen in Figure 37, contribution of biomass power plant in load satisfaction is more than PV modules and wind turbines, respectively.

Figure 37 – Share of different generation technologies from annual electric consumption.



Source: Mahdavi et al. (2023c).

6 CONCLUSION

Morocco has a great potential to utilize renewable energy sources for tackling problems raised by high energy import bills, air pollutants emission, and increasing energy demand. Wind power with 14% of electricity demand supply is the most important renewable energy source in Morocco after hydropower. However, investment costs of wind farms are high and wind energy is not permanently available because of its dependence on local weather conditions and unpredictable climate changes. This intermittence makes wind turbines accommodation very hard in electric power systems. For these reasons, many PV projects are completed throughout Morocco because of the country's significant potential in solar power generation. However, temperature increment inversely affects the PV modules output. Also, optical efficiency of solar plants is considerably reduced by amounts of dust and sand on panels. In this situation, hybrid energy generation of biomass, wind, and PV can tackle most of challenges in the energy domain such as high investment costs of wind power plants and costly energy storage of wind and solar energy generation. Morocco with large number of livestock places has a great potential to use the huge quantity of biomasses produced by animals for electric energy generation. Therefore, in the present research, the capability of electric energy produced by biogas obtained from cow manure as well as wind and solar electricity generation were studied.

The analysis showed that, in terms of standalone power generation, the biogas electricity generation is the most economical method; nevertheless, the usage of biogas for power generation is not able to meet all the energy demands in any of the two study areas considered in the analysis due to the feedstock supply challenge. Therefore, the hybrid utilization of biomass power plants, wind turbines, and PV units in the Moroccan village of Tazouta and Fez rural area is considered to be the most ideal generation option in terms of cost if all the energy demand of the study location must be satisfied since this has the least cost, while the wind is the most suitable generation for meeting all the load demand of the locations in terms of carbon emission. This implies, if the objective is to reduce cost at high supply security, then the hybrid operation of solar PV, wind, and biogas power generation is the best option, but if the objective is to meet all load demand at the least emissions level, without considering cost and supply security, then the standalone wind generation is

the most ideal. Also, if the objective is just to have the lowest cost without considering unmet load, biogas power generation is the best option. However, to produce energy from animal manure a significant amount of water is necessary, which is a very important issue to be considered before the utilization of biomass power plants for electricity generation. Furthermore, in hybrid operation, constant biomass power can mitigate variable PV and wind generation that highly depends on solar irradiance and wind speed variations. On the other hand, cheaper capital and operation costs of PV modules compared to wind and biomass units cause more economic plans in the hybrid operation. Therefore, the construction of biomass power plants and PV modules reduced the number of expensive wind turbines in the hybrid case. For these reasons, biomass could satisfy almost two-third of total power demand of Tazouta and Fez regions compared to 33% and 2% of PV and wind generation, respectively. Biomass power plants can provide stable energy for consumers during the year and the moments without sunshine and wind blow. The operation of biomass plants with wind and solar units is necessary to provide a permanent and uninterrupted electric energy supply.

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