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Grid-connected renewable energy systems flexibility in Norway islands' Decarbonization

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ABSTRACT

In recent decades, investing in renewable and eco-friendly energy technologies, such as replacing clean energy systems instead of traditional ones and equipment management, is an interesting and practical topic in all sectors. This research analyzes the optimization of a hydro plant, wind turbines, and photovoltaic (PV) panels with a careful examination of three scenarios in the Hinnoya region, Norway. Three consumption scenarios—including an industrial/domestic load scenario, transportation load, and household load alone—for this region are considered. HOMER software is used to simulate and analyze the techno-economic performance of solar panels/wind turbines/grid/batteries and converters. The results of this research show that using renewable and eco-friendly systems in accordance with the region's potential leads to a lower cost of electricity generation. The COE production is at least 50% less than the normal sales price of the electricity grid. The use of electric grid exchanges results in energy modification at night. The potential for the use of onshore wind turbines is more than offshore turbines. The results also indicate that using renewable systems in the household field can reduce the COE by nearly 70% (0.0296 €/kWh), and in other energy fields (transportation and industrial) can diminish the COE by nearly 50% (0.055 €/kWh). Thus, increasing the percentage of employing renewable and eco-friendly energy systems leads to reduce greenhouse gas (GHG) emissions (particularly carbon dioxide).

1. Introduction

Islands, as remote and isolated places, are in demand for becoming self-reliant in terms of energy. Particular attention has been given to this subject matter over the past few decades, and an adequate number of ongoing studies are seeking to provide effective and practical strategies [1,2]. Different solutions have been offered to address self-sufficiency, green-energy dependency, and carbon mitigation in remote and isolated locations. Fortunately, renewable energy sources (RESs), such as solar, wind, and geothermal, are the remedy to this issue. However, employing these eco-clean energies has to be technically, environmentally, and economically sound [3].

All different RESs are converted into either electrical or thermal energy. Various system arrangements can be devised depending on which type of energy is available. In the first case, the foremost intention is to supply electricity for lighting, heating, cooling, freshwater, and even transportation [4]. However, heat-driven systems can produce heating, cooling, and potable water via thermal energy. On the other hand, the intermittent nature of RESs (e.g., wind and solar) makes using energy storage systems (ESSs) necessary [5]. Hydrogen energy storage, as a chemical ESS, is an enabling technology for electricity generation in different sectors [6,7]. Burning hydrogen in fuel cell systems also provides heat to drive other systems for heating, cooling, and freshwater production [8].

Shahverdian et al. [9] presented 3E analysis in a hybrid system including photovoltaic (PV), Electrolyze, and polymer electrolyte membrane fuel cells to provide electricity in an off-grid application. Their findings show the levelized COE was improved to 0.29 $/kWh, and the system's energy production was increased by 18.32%.

Technical and economic indicators give a various range of options to design and develop different multi-generation systems. Yet, determining the most thermodynamically efficient and cost-effective system cannot be effortlessly obtained [10]. Multi-objective optimization (MOO) is one of the interesting methods to consider energy-exergy efficiency in

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renewable and eco-friendly energy systems. The effect of the innovation dimension on exergy, energy, and environment, plus the economy was considered by Sohani et al. [11]. They used the MOO for analyzing the annual yield (AYI) and annual CO_2 saving (ACDS). Their findings show that the annual average exegertic efficiency (AEXEF), AYI, and ACDS were respectively enhanced about 5.56%, 28.01%, 28.01% via applying the MOO. Mahmoudan et al. [12] indicate the maximum exergy and minimum energy price in the proposed system containing geothermal and solar with a thermoelectric generator, showing that the exergy efficiency can reach 35.2% by applying the MOO.

Launching the smart monitoring system can help increase efficiency and reduce energy production costs in the region. Renewable energy production systems have been used in recent years in providing energy for distant and isolated areas, islands, and so on. The techno-economic feasibility study of the hybrid, integrated renewable energy connected to the electricity grid has been one of the favorite issues for researchers today. These types of feasibility studies are based on different simulators to determine the amount of energy requirement and balance [13–16]. EnergyPlus and TRNSYS are the most exciting software for designing renewable systems and optimizing them in buildings and power plants. They are also very useful tools to design net-zero buildings and energy systems [17,18].

Modeling and numerical simulations have been done to find the best performance of wind turbines and PV panels in recent years, so that good progress has been made [19–21]. Today, the design of intelligent energy systems is essential especially for a city and determining the amount of the required panel in terms of the region's potential. These systems reduce energy costs and are helpful for energy optimization and management [22].

The simulation results of artificial intelligence (AI) on a PV/wind/fuel cell/hydrogen storage system demonstrate that particle swarm optimization (PSO) is a good algorithm for sizing hydrogen storage system than other algorithms such as simulated annealing (SA), tabu search (TS), and harmony search (HS). Although PSO has the most robustness [23,24], for the system included PV/wind/battery, artificial bee swarm optimization (ABSO) is a practical algorithm in comparison to PSO, TS, and HS [25].

Energy systems can reduce pollution and energy consumption when they combine with various renewable resources (e.g., wind, solar, geothermal) and energy storage systems (e.g., batteries, hydrogen tanks, and the compressed air storage systems). The use of batteries and hydrogen tanks can help energy balance during courier and non-courier hours [26,27]. The effects of decarbonization in the production process were compared in three different scenarios of carbon reduction plus static scenario, and the results showed that the houses in the past have a high potential to deal with global warming potential, up to 70% compared to static scenario [28].

Solar PV systems connected to the power grid in various countries are investigated, and the simulation results obtained from MATLAB show that the connection of the PV power plant to the electricity grid can cause grid stability [29]. These studies show that by optimizing the purchase and sale of electricity from the power grid, it can be used up to 64% more than the region's energy potential, resulting in reducing 35% of carbon dioxide content [30].

Finding the best solar panels' installation angle and determining the yield coefficient of PV panels in renewable systems is essential. Past studies show that increasing reflective conductivity can increase up to 30% of the panel efficiency [31,32]. The economic analysis of the construction of solar power plants, such as the net present value (NPV) in terms of the project's lifetime, has been considered by a number of researchers [15,33,34], They have examined the COE, and the return on investment (ROI) in various scenarios [35], and compared the economic indicators with one another, and selected the best scenario in terms of energy production and energy prices. Dehghani-Sanij et al. [36–38] predicted the potential of using wind energy in Canada by 2040. They found a relation between the wind power capacity factor and levelized cost of energy (LCOE) based on different forecasting scenarios. They also showedthat the most regions of Canada have a highly promising potential to utilize wind energy.

The ROI for a 5-kW power plant of rooftop in Turkey is about 14 years, with an internal return rate of almost 2.01 over the project's lifetime [39]. An investigation in Australia indicate that although the use of grid/battery/solar panels and converter can reduce 95% of carbon dioxide and 90% of the payment costs, using solar PV panels independently to supply electricity is not still logical [40]. Results of research in Catalonia, Spain, show that roof potential for electricity generation by PVs could provide the municipalities 8–30% of residential electricity demand, although energy demand of dwellings depends on the characteristics of the buildings [41]. The use of hybrid systems has expanded in many European countries, such as Norway and Italy. European countries have optimized power-generating systems for the implementation of climate change [42,43]. The feasibility of combined wind turbines and solar PV panels in each region is carried out based on wind beam and wind speed in that region [44–46].

Optimizing and analyzing the sensitivity of renewable energy systems have been done in many papers using MATLAB and HOMER software. The sensitivity of the systems and scenarios considered for any region can directly indicate the amount of energy production and its surplus, in addition to estimating the amount of income and profit from energy sales to the electricity grid [47,48]. Although the simulation of hybrid systems may be technically justified, it cannot always be justified economically; for example, the simulation with MATLAB combines wave and PV systems in three coastal points in Iran, showing that energy production on the Caspian sea coast reaches 4.83 USD/kWh; thus, this system is not cost-effective in Iran [49]. The importance of using a renewable energy system instead of a traditional one is undeniable. Most researchers believe solar energy is a reliable and accessible source that could provide electricity and thermal energy. Investigations on using solar collectors in different climates of Iran show that Mediterranean climate has the highest thermal efficiency (71.97%), humid continental climate has the highest exergy efficiency (22.01%) in compression with other climates [50]. The use of renewable hybrid systems to meet the energy needs of the areas that are not connected to the power grid is an effective approach. The selection of the best equipment and power generator in accordance with the capacity of the area plays significant role in reducing the COE production—usually in areas that are not linked to the grid, such as the islands and forest areas—or the cost of the electricity grid development to these areas, but not cost savings [13, 51–53].

According to the reviews conducted in literature, there is a gap in renewable energy research to cover a comprehensive economic and technical analysis in the grid-connected system with multilateral sensitivity analysis. This research combines several renewable systems (PV, wind turbine, hydro-turbine, battery, and power grid) in Hinnoya city, Norway. Three different scenarios have been selected due to the various loads of the region, and sensitivity analyses in the supply of three scenarios (household demand, transportation demand, demand of industry and household together) have been done. Given that hydro-turbine is the basis of the simulation in each plan, all scenarios have been considered the hydro-turbine. In this study, the consumption of this region (i.e., Hinnoya, Norway) has been stimulated with the real and existing data of the city for the first time.

Considering the current state of knowledge in this area, a Systematic Literature Review (SLR) like procedure was conducted to not only find the research gap but also to highlight the potential novelty of the current work. In order to do this by exploring the scientific database of Web of science through SLR protocol, authors tried to find works related to grid-connected systems flexibility and optimization through the following query code in WoS platform:

ALL=((grid-connected) AND (Energy Systems) AND (optimization) AND (Flexibility))

Then, the results were filtered only to research articles not earlier than 2019. It showed more than 150 papers within the last 5 years in the selected area. Within the normal steps of SLR according to the latest standard of PRISMA, using the relevancy check the numbers dropped to 49 to be considered for a deep analysis. These papers then were subjected to filtration according to the selection criteria (in Fig. 1). The final selection of the papers consists of 28 papers for further analyses. Taking a deeper look at these papers, it revealed that this topic has been increasingly mentioned in the paper where papers in 2023 even now (before the end of August) is more than before (Fig. 2).

In the realm of scholarly exploration, it is of paramount importance to delve into the intricacies that underlie the research landscape. In this context, the endeavor to illuminate the research gap takes center stage, serving as a crucial foundation upon which the edifice of knowledge is constructed. Concurrently, directing our gaze towards the novelty inherent in a particular scholarly undertaking not only augments the intellectual discourse but also serves as a catalyst for intellectual advancement. To traverse this intellectual terrain, a comprehensive analysis was undertaken, meticulously scrutinizing the final subset of research papers. This analytical expedition yielded a tangible outcome, manifested in the form of a succinct yet illuminating tableau, designated as "Table 1." The contents of this tableau stand as a testament to the multifaceted nature of the scholarly realm, encapsulating within its confines the essence of research gaps and the vibrant novelty that various scholarly contributions bring to the fore. By engaging in this analytical pursuit, we aim not only to spotlight the gaps in the current tapestry of knowledge but also to underscore the innovative spirit that propels researchers towards uncharted domains. Thus, the creation of "Table 1" emerges not merely as a static representation but as a dynamic embodiment of the scholarly journey, beckoning us to unravel its layers and glean insights that extend beyond the surface, thereby enriching our understanding of the intellectual pursuit at hand.

As it is shown in Table 1, the novelty of this research is the examination of different scenarios (industrial, household, and transportation) separately, plus the effect of each consumption scenario on determining the capacity and the cost of the renewable system. Separate and independent examination of each scenario will reduce the interference of peak hours and have an optimal effect on the investment cost. This research explicitly examines the importance of each plan by focusing on meeting the energy demand in that scenario. This study answers the question of which plan imposes a less electrical load on the power grid as well as helps the power grid. One of the benefits and innovations of this study can be the proposed analysis in each scenario that can have a policy for the construction of different power plants in areas with similar potential and resources, and it can be predicted that how increasing the amount of benefit from renewable systems can reduce energy prices.

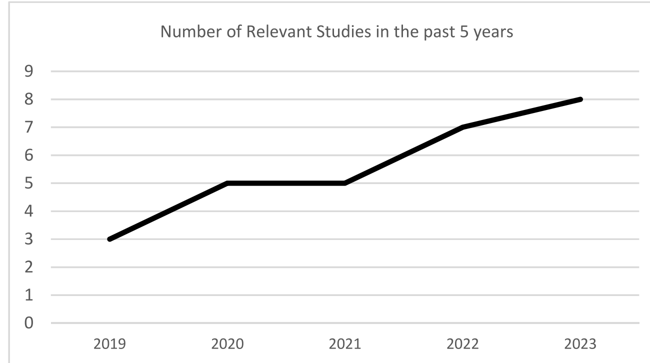


Fig. 2. Average energy load during a day.

It is worth mentioning that the development of the integrated structures for RES is also one important aspect to be considered [82] along with the decision making support techno-economic analyses [83–86].

2. Design and simulation

Simulation of a renewable system to produce clean energy and reduce pollution is of high importance in Norway. In this research, Hinnoya city has been selected with the geographical coordinates 68°19.4′ N and 15° 24.2′ E. The amount of energy demand in this city is shown in Fig. 4. The household and industrial consumptions are approximately calculated to be 60 kWh/day and 6000 kWh/day, respectively, and the amount of transport consumption at the peak hours

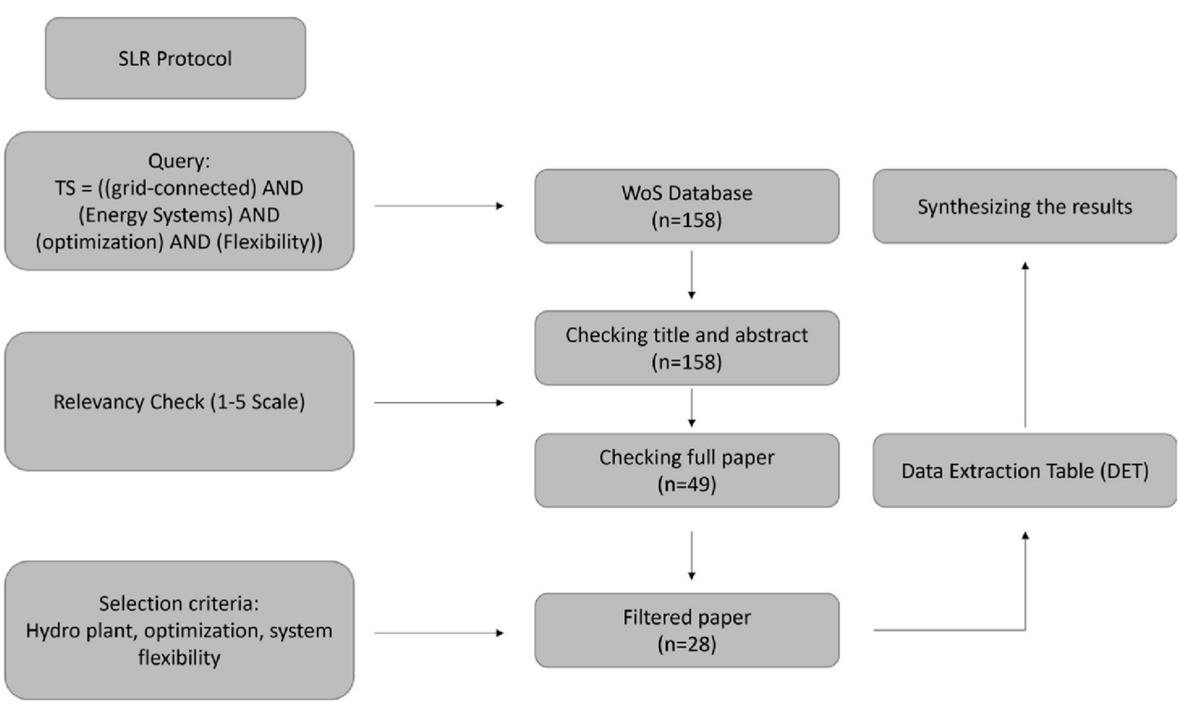


Fig. 1. the workflow of SLR procedure.

Table 1
Chronological analysis of the literature.

Authors	Year	Uncertainty consideration	System capacity	System cost	Case Study	Region
Li Z et al. [54]	2019		x	x	x	China
Shabani M et al. [55]		x	–	x	x	Sweden
Shah P, and Mehita B [56]			x	x	–	–
Allani M Y et al. [57]	2020		x	x	x	Tunisia
Khdhairi S et at [58]		x	x	–	–	–
XiaoWei Z et al. [59]		x	x	x	–	–
Kokkonda K and Kulkarni P [60]		–	x	–	–	–
Hoseinzadeh S and Astiaso Garcia D [61]			x	x	x	Italy
Zhou Y and Cao S [62]	2021		x		x	Hong Kong
Remache S et al. [63]		–	x	–	–	–
Fei Y et al. [64]		–	x	–	–	–
Sayeed F et al. [65]			x	x	–	–
Che Q et al. [66]			x	x	–	–
Essayeh C and Morstyn T [67]	2022	–	–	x	x	UK
Dong J et al. [68]		–	x	–	–	–
Elsir M et al. [69]			x	x	–	–
Emara D et al. [70]		–	x	–	–	–
Vakilifard N et al. [71]		x	–	x	x	Australia
Yu W et al. [72]		–	x	x	–	–
Hovsapian R et al. [73]		–	x	–	–	–
Guo B et al. [74]	2023	–	x	–	–	–
Peng Y et al. [75]		–	x	–	–	–
Ahmadi M et al. [76]		–	x	–	x	Iran
Perez R et al. [77]		–	–	x	x	USA
Rezende GMD et al. [78]		–	x	–	–	–
Magni CA et al. [79]		x	–	x	x	Italy
Yang L et al. [80]			x	x	–	–
Ge X et al. [81]			x	–	–	–
Current study		x	x	x	x	Norway

of consumption (from 9 p.m. to 5 a.m.) is 2000 kW, and the rest is the 500 kW.

2.1. Scenarios description

For simulating the system, the wind turbine, PV panel, batteries, and a convertor are combined to help the production of a hydro-turbine for household, industry, transportation demands. Accordingly, an economic, technical, and environmental analysis is performed using HOMER software.

In this regard, it is important to discuss how search space has been defined. The search space in the context of HOMER refers to the range of possible values and configurations that the optimization algorithm explores to find the "best" alternative for a given renewable energy system design. In HOMER, the search space is defined by specifying the ranges or constraints for various parameters and components of the system. For wind Turbine it could include a range of different wind turbine models with varying capacities, costs, and lifetimes. These parameters help HOMER explore different possibilities of wind turbine configurations to find the most cost-effective option. For run-of-river Hydro Turbine, it involves different options for capacity, cost, and efficiency, which HOMER analyzes to determine the optimal configuration. For photovoltaic (PV) Panels it includes different configurations of panel capacity and cost. The search space for the battery involves different battery types, sizes, and costs. Finally, the search space for the converter includes different options with varying costs and efficiencies. HOMER evaluates these options to determine the most suitable converter for the system.

The basis of all scenarios is shown in Fig. 3. In addition, it should be noted that the limitations in HOMER simulation can be pointed to the lack of separation of simulation in terms of technical and economic studies so that the software optimizes and estimates renewable systems according to the lowest cost, while with the application of technical indicators in cases of the economic justification is not acceptable.

According to the data received from NTNU (Norwegian University of Science and Technology), the industrial and household energy consumption of the Hinnoya are used for the simulation due to three scenarios as follows:

Scenario 1: Simulations based on household consumption,

Scenario 2: Simulations based on household and industrial consumption,

Scenario 3: Simulations based on transportation consumption.

2.1.1. Components of scenarios

According to scenarios 1, 2, and 3, and studies performed on the available initial information, the proposed system for optimizing the run-of-river hydropower plants is shown in Fig. 5. This system includes solar panels, batteries, a converter, and two types of turbines (onshore and offshore). The consumption load has been considered for household, industrial, and total forms.

2.2. Conditions of design

2.2.1. Resources data of the region

Figs. 6–8 show the changes in wind speed, river water flow, and solar irradiation based on the submitted local data and the downloaded meteorological data. As shown in Fig. 4, the amount of radiation in January and December is almost zero, and no energy is expected to be generated by the solar panels.

As illustrated in Fig. 7, the area has a good potential for using wind turbines. The wind speed in January and December is the maximum, so choosing a wind turbine complementing a solar panel does make sense.

The wind speed is obtained at the height of 10 m of the area [87].

Fig. 8 shows the flow rate of the river for different months. As shown in this figure, the choice of water turbine is in the category of micro-turbine systems, based on the data obtained from NTNU.

2.2.2. Economic characteristics

The amount of inflation and discount rates in Norway is assumed to be 2.17% and 1%, respectively [88].

2.2.2.1. Wind turbine. Two wind turbine models are considered: an offshore wind turbine model and an onshore wind turbine model. The

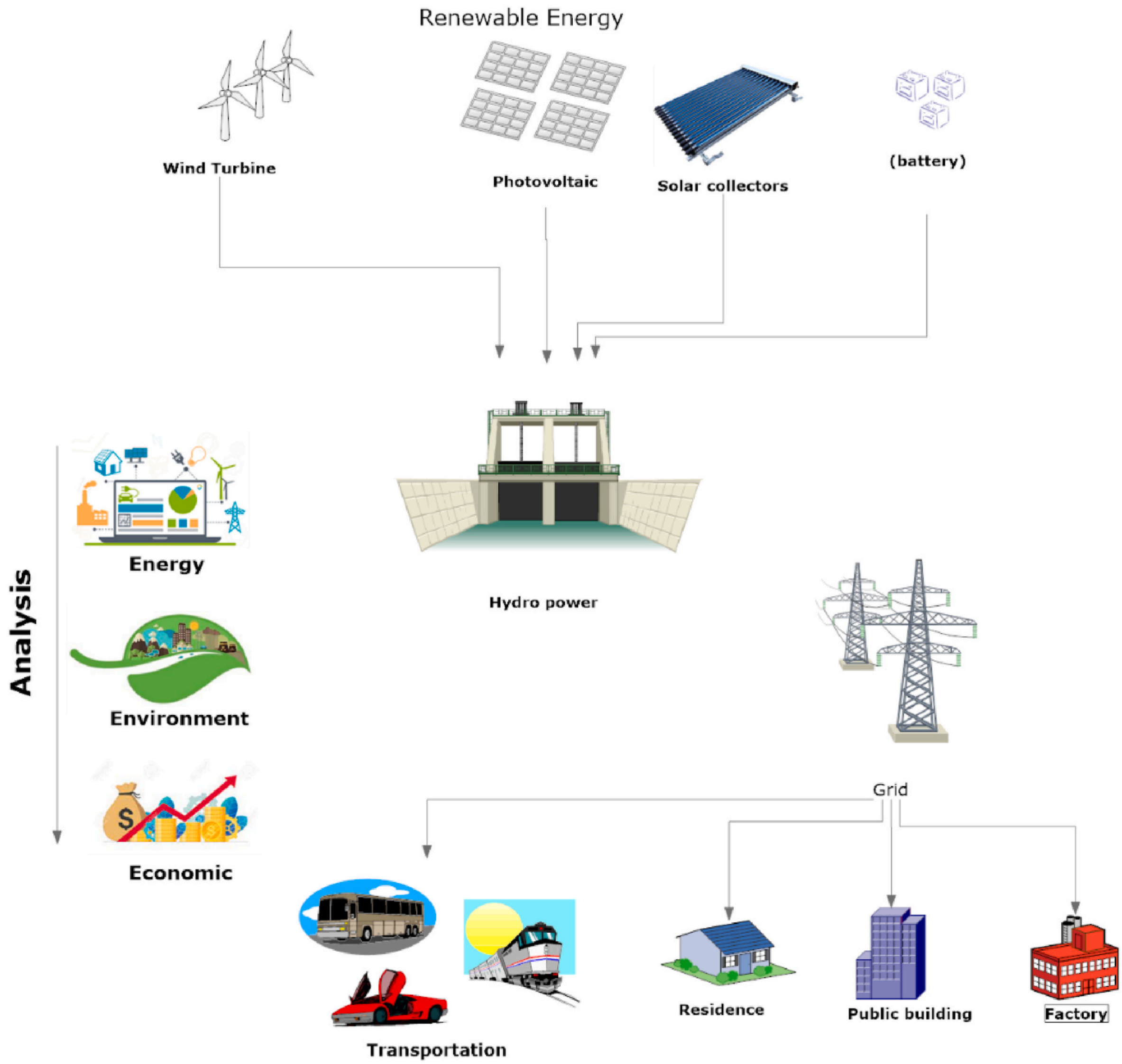


Fig. 3. Fundamental scenarios considered in this research.

specifications of the selected turbines with the economic information are shown in Table 2.

2.2.2.2. Run-of-river hydro turbine. Due to the intensity of streamflow in the river, a 5-kW hydro-turbine is considered with the specifications shown in Tables 3 and 4.

2.2.2.3. Photovoltaic (PV) panels. According to the past studies, the cost of operating a solar power plant in Norway is equal to 2.79 Euros per watt. After accounting for the 26% Federal Investment Tax Credit (ITC) and other state and local solar incentives, the net price that needs to pay for a solar system can fall by thousands of dollars [89]. The amount of cost determined for 1 kW panel with a deduction of 26% ITC is equal to Table 5.

2.2.2.4. Battery. In order to adjust the energy during the day and night and the energy balance during high and low consumption hours, a battery bank is considered. Table 6 shows the economic information of the considered batteries.

2.2.2.5. Grid. Table 7 shows the assumed price for buying and selling energy to the electricity grid.

2.2.2.6. Converter. A converter is used to convert AC to DC and vice versa for the energy stored in the battery as well as the energy produced in the solar panels. Table 8 displays the economic information of the converter used.

2.2.3. Sensitivity variables

A sensitivity analysis is performed in the following sections to investigate the critical points and estimate economic indicators. Table 9 illustrates the sensitivity variable and inputs.

3. Theory and methodology

3.1. Energy charge calculation

HOMER calculates the total annual energy charge by using the following equation [90]:

$$C_{grid\ .\ energy} = \sum_{i}^{rates} \sum_{j}^{12} E_{grid\ .purchases.i.j} C_{power.i} - \sum_{i}^{rates} \sum_{j}^{12} E_{grid\ .sales.i.j} C_{sellback.i} \quad (1)$$

where:

$E_{grid\text{-}purchases,i,j}$ = The amount of energy purchased from the grid in month j during the time that rate i applies [kWh].

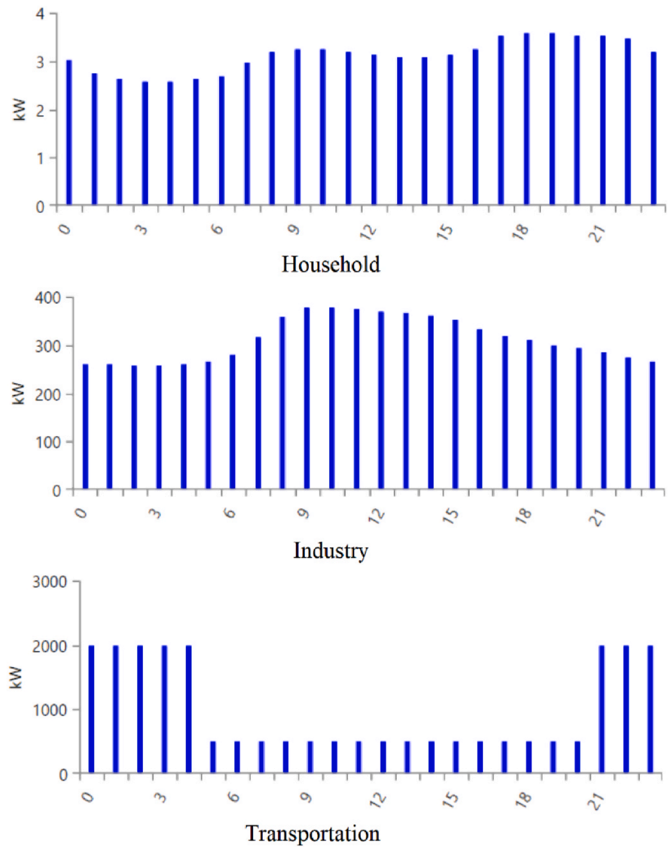


Fig. 4. Average energy load during a day.

$c_{power,i}$ = The grid power price for rate i [$/kWh].

$E_{grid\text{-}sales,i,j}$ = The amount of energy sold to the grid in month j during the time that rate i applies [kWh].

$c_{sellback,i}$ = The sellback rate for rate i [$/kWh].

If net metering applies and net generation is calculated monthly, HOMER determines the total annual energy charge through the equation below [57]:

$$C_{grid\ .\ energy} = \sum_{i}^{rates} \sum_{j}^{12} \left\{ \begin{array}{ll} E_{netgrid\ .purchases.i.j} C_{power.i} & if\ E_{netgrid\ .purchases.i.j} \geq 0 \\ E_{netgrid\ .purchases.i.j} C_{sellback.i} & if\ E_{netgrid\ .purchases.i.j} < 0 \end{array} \right\} \tag{2}$$

where.

$E_{net\text{-}grid\text{-}purchases,i,j}$ = The net grid purchases (grid purchases minus grid sales) in month j during the time that rate i applies [kWh].

$c_{power,i}$ = The grid power price for rate i [$/kWh].

If net metering applies and net generation is calculated annually, HOMER calculates the total annual energy charge by using the following equation [57]:

$$C_{grid\ .\ energy} = \sum_{i}^{rates} \left\{ \begin{array}{ll} E_{netgrid\ .purchases.i.j} C_{power.i} & if\ E_{netgrid\ .purchases.i.j} \geq 0 \\ E_{netgrid\ .purchases.i.j} C_{sellback.i} & if\ E_{netgrid\ .purchases.i.j} < 0 \end{array} \right\} \tag{3}$$

where.

$E_{netgridpurchases,i}$ = The annual net grid purchases (grid purchases minus grid sales) during the time that rate i applies [kWh].

$c_{power,i}$ = The grid power price for rate i [$/kWh].

3.2. Demand charge

HOMER calculates the total annual (listed after December) grid demand charge by using the equation below [57]:

$$C_{grid\ .\ energy} = \sum_{i}^{rates} \sum_{j}^{12} P_{grid.peak.i.j} C_{demand.\ i} \tag{4}$$

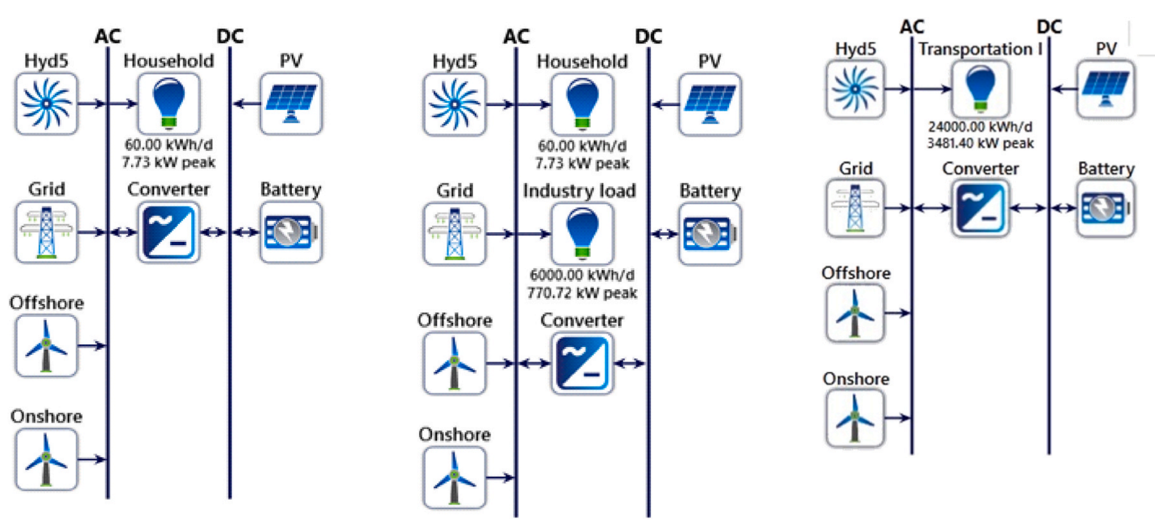
where.

$P_{grid,\ peak,i,j}$ = The peak hourly grid demand in month j during the time that rate i applies [kWh].

$c_{demand,i}$ = The grid demand rate for rate i [$/kW/month].

3.3. Maximum battery discharge power calculation

In each time step, HOMER calculates the maximum amount of power



a) Household load

b) Total load (household + industry load)

c) Transportation simulation

Fig. 5. Schematic plan for simulation.

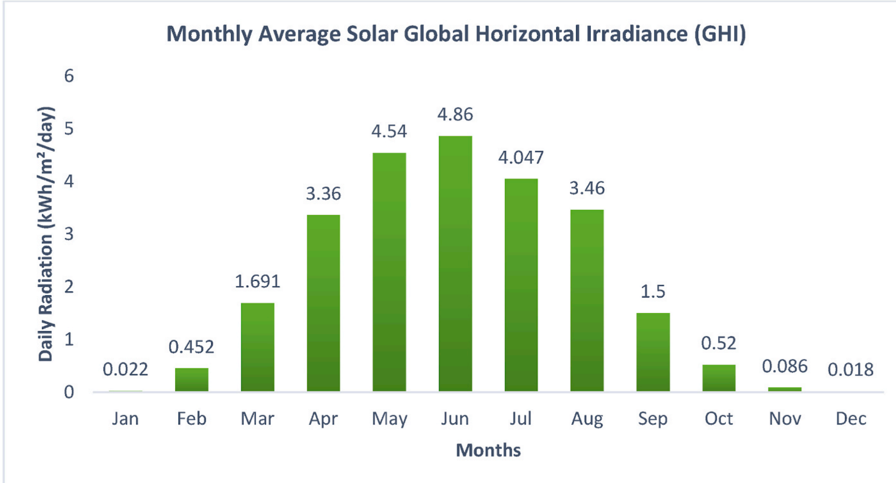


Fig. 6. Average solar irradiation and clearness diagrams for each month of the year.

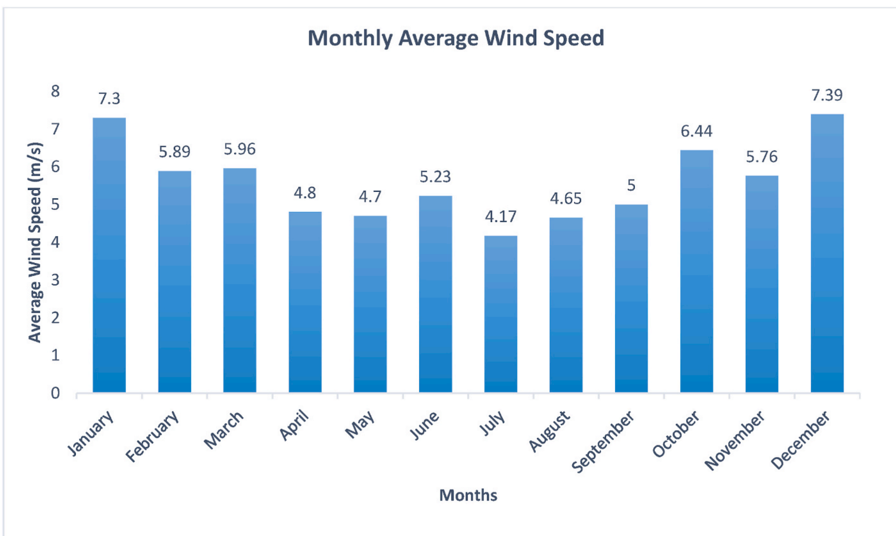


Fig. 7. The average wind speed for each month of the year.

that the storage bank can discharge. It uses this “maximum discharge power” when making decisions such as whether the storage component can serve the load on its own. The maximum discharge power varies from one-time step to the next according to its state of charge and its recent charge and discharge history, as determined by the kinetic storage model.

As described in the kinetic storage model section of the software help, the maximum amount of power that the storage bank can discharge over a specific length of time is given by Ref. [57]:

$$P_{batt.\ dmax.kbm} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(-k\Delta t - 1 + e^{-k\Delta t})} \tag{5}$$

where:

Q_1 = The available energy [kWh] in the storage component at the beginning of the time step.

Q = The total amount of energy [kWh] in the storage component at the beginning of the time step.

Q_{max} = The total capacity [kWh] of the storage bank

c = The storage capacity ratio [unitless].

k = The storage rate constant [h-1].

Δt = The length of the time step [h].

HOMER assumes that the discharging losses occur after the energy leaves the two-tank system; hence, the storage bank’s maximum discharge power is given by Ref. [57]:

$$P_{batt.dmax} = \eta_{batt.d} P_{batt.dmax.kbm} \tag{6}$$

where $\eta_{batt,d}$ is the storage discharge efficiency.

4. Results and discussion

According to the simulations in HOMER, from one million simulations performed in terms of the sensitivity analysis to find the most economical design to supply the energy needs of the region for home, household and industrial models and transportation as determined in Table 10. The capacity designated in terms of the lowest and the most optimal system for each model is selected in the geographic coordinates.

According to the region’s energy needs in all three models, the amount of power generation estimation of each component is displayed in Table 11; the systems are connected to the power grid in all three simulation models, and if necessary, electricity during courier hours automatically supplies its power supply. The amount of power provided from electricity in all three models has not exceeded 25%, and the lowest

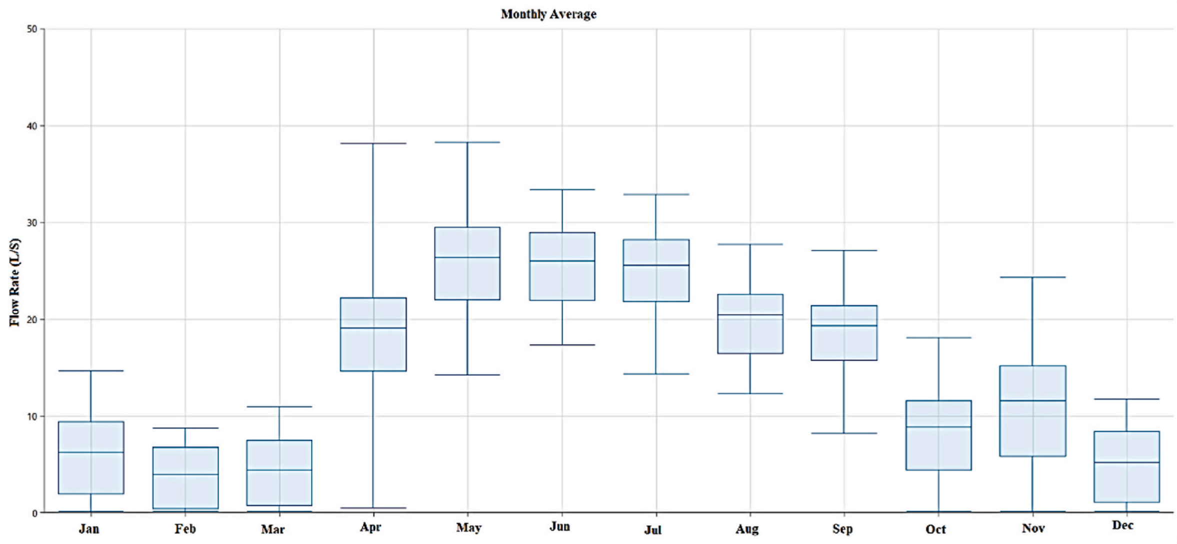


Fig. 8. Streamflow rate of the river in different months.

Table 2
Wind turbines' economic information.

	Quantity	Investment cost €	Replacement €	O&M €/y	Lifetime y
Offshore wind turbine (1 kW)	0,400,600,800, 1000,1500	1500	1500	10	30
Onshore wind turbine (1 kW)	0,400,600,800, 1200,1500	1100	1100	10	30

Table 3
Run-of-river hydro-turbine's economic information.

	Quantity	Investment cost €	Replacement €	O&M €/y	Lifetime y
Hydro turbine (5 kW)	1	6500	2000	120	40

Table 4
Run-of-river hydro-turbine's specifications information.

Available head (m)	Design flow rate (L/s)	Minimum flow ratio (%)	Maximum flow ratio (%)	Efficiency (%)
20	25	20	150	50

amount of household power supply system alone is less than 1%.

Table 12 shows the power consumption in different sectors, given that simulated systems are connected to the electricity grid in all three models (household, household and industrial, and transportation). When the power consumption of the region is less than production, it sells its surplus to the electricity grid and exchange. This will make the energy balance in the region minimize the percentage of shortage.

The exchanges between simulated systems with electricity grids in different months of the year are depicted in Table 13. According to this table, the highest sales rate and the lowest purchases of the electricity grid are related to the home simulated model, with a purchase ratio of less than 0.04%. The highest purchase rate is sold to the household and industrial model, accounting for 50%.

Production costs, production capacity factors based on regional potential, as well as working hours of each constituent, can be seen in Table 14. Most of the work hours are related to wind turbines, and the lowest cost is related to the water-turbine.

The amount of energy production and consumption in terms of the scenarios determined are shown in Figs. 9, 10, and 11.

4.1. Scenarios

The most important part of each design and simulation is the sensitivity analysis. With the sensitivity analysis, the effect of changes in the designed system can be considered and also obtained possible results in different conditions. In this research, a sensitivity analysis was conducted based on climate change, so the impacts of effective changes in solar radiation, wind speed, and river flow rate have been studied. The rate of these impacts is considered to be 50% growth and decrease, and

Table 5
Economic information for photovoltaic (PV) panels.

	Quantity	Investment cost €	Replacement €	O&M €/y	Lifetime y
Photovoltaic (1 kW)	0,400,800,1200, 1500,2000	2000	2000	10	25

Table 6
Economic information of battery.

	Quantity	Investment cost €	Replacement €	O&M €/year	Lifetime year
Battery (1 kWh)	0,500,1000,1500	550	550	10	15

Table 7
Grid power and sell back prices.

Grid power price (€/kWh)	Grid sell back price (€/kWh)
0.106	0.06

in cases where the sensitivity of the subject is very high, the amount of changes to nearly 100% reduction or increase is considered.

- Scenario 1: Household and industry

As is shown in Fig. 12, the sensitivity analysis of the renewable system designed for the household and industrial model is distinct, with different colors. According to Fig. 12, it can be concluded that if the wind speed is less than 4.6 m/s, the use of wind turbines is not affordable, and if the solar irradiation is less than the value of 2 kWh/m^2.day, the use of solar panels are not cost-effective. This conclusion is based on the assessment of the cost of implementing a particular energy source (wind or solar) is within a justifiable budget taking into account factors such as initial installation costs, maintenance expenses, expected energy production, and potential returns on investment over the project's lifetime. Also by checking the benefits gained from utilizing the studied energy source in the form of comparing the cost per unit of energy generated to the prevailing energy market prices.

In cases where the solar irradiation is higher than 2.06 kWh/m^2.day but the wind speed is less than 4.6 m/s, a combination of the PVs/grid/hydro is affordable.

- Scenario 2: Household

Fig. 13 shows the sensitivity of the household model. As illustrated in this figure, due to the low electrical demand in the domain of household as well as the potential of the area, there is no economic justification for PV panels because of their high costs, and hydro and wind turbines are affordable for this scenario.

- Scenario 3: Transportation

In Fig. 14, according to the selected system and the size and power of the selected components, it is used to meet the need for electric transport systems from wind turbine and hydro. Due to the sensitivity analysis of this model, it can be seen that a combination of wind/hydro/battery are more valuable than the system compound with solar panels, because the peak load of transportation systems is at night, and PV panels are not reachable for meet this demand.

4.2. Economic analysis

Evaluation of each layout, although it may be technically justified, an economic justification is of great importance. An effective research is

Table 9
Sensitivity variable and inputs.

Variables	Sensitivity input
Maximum annual capacity shortage	0
Wind: Scaled annual average (m/s)	4,4.5,5,5.61,6,6.5,7,7.5
Solar: Scaled annual average (kWh/m^2/Day)	0,0.5,1,1.5,2.06,2.5,3,3.5,4
River Steam flow: Scaled annual average (L/s)	5,10,14.71,15,20

justified both economically and technically. In this section, the cost of each model to separation of components of each system is provided.

The salvage value of a component is directly proportional to its remaining life. It is also assumed that the salvage value depends on the replacement cost rather than the capital cost [57]. Salvage value is calculated by:

$$S = C_{rep} \frac{R_{rem}}{R_{Comp}} \tag{7}$$

R_{rem} is the remaining life of the component at the end of the project lifetime, which is given by:

$$R_{rem} = R_{comp} - \left(R_{Proj} - R_{rep}\right) \tag{8}$$

R_{rep} is the replacement cost duration, which is determined by:

$$R_{rep} = R_{comp}\ INT\ \frac{R_{proj}}{R_{comp}} \tag{9}$$

where C_{rep}, R_{comp}, and R_{proj} are the replacement cost (€), component lifetime (year), and project lifetime (year), respectively. *INT* is a function that returns the integer amount of an actual number. The net present cost (NPC) of scenario 1 is shown in Table 15.

As can be seen in Table 15, small costs related to capital and maintenance for each component are formed. In the grid area, as can be seen, negative values are written, which represents the high sales of electricity costs. The NPC of scenarios 2 and 3 is shown in Tables 16 and 17.

The summary of the NPC for each scenario in each section is shown in Table 18. According to this table, the home supply system model has the lowest energy price and the highest efficiency and return on capital.

Given that the amount of the COE is less than the number of energy prices, the benefit of reducing the cost and sales price to the consumer is equal to Table 19.

The "Household Scenario" has the lowest cost of energy at €0.0296/kWh, while the "Household and Industry Scenario" has the highest at €0.0598/kWh. The "Transportation Scenario" falls in between with €0.0557/kWh. The "Transportation Scenario" stands out as the most profitable, generating €240,607/yr in profit from electricity sales, primarily due to the significant amount of electricity sold (4,717,793 kWh/yr). On the other hand, the "Household and Industry Scenario" generates €64,334/yr, and the "Household Scenario" generates €1606/yr. All scenarios have the same energy price of €0.106/kWh. The "Household Scenario" has the highest difference between the COE and EP at €0.077/kWh, indicating a higher potential for profit compared to the other

Table 8
Economic information of converter.

	Design capacity kW	Investment cost €	Replacement €	O&M €/year	Lifetime year
Converter	0,500,1000,2000	550	550	10	15

Table 10
Simulated models in three predicted scenarios.

Type	Name	Size			Unit
		Household & industry	Household	transportation	
PV	flat plate PV	400	400	2000	kW
Wind turbine #1	Offshore wind turbine	400	200	2000	kW
Wind turbine #2	Onshore wind turbine	1500	800	6000	kW
System converter	System Converter	1000	500	2000	kW
Hydroelectric	5 kW	2.45	2.45	2.45	kW

Table 11
Estimated production capacity in all three predicted scenarios.

Component	Household & industry		Household		Transportation	
	Production (kWh/yr)	Percent	Production (kWh/yr)	Percent	Production (kWh/yr)	Percent
flat plate PV	283,361	7.35	283,361	16.4	1,416,807	8.38
Offshore wind turbine	572,333	14.8	286,167	16.6	2,861,667	16.9
Onshore wind turbine	2,146,250	55.7	1,144,667	66.3	8,585,001	50.7
Hydro	11,132	0.289	11,132	0.645	11,132	0.0658
Grid Purchases	843,088	21.9	781	0.0453	4,042,207	23.9
Total	3,856,165	100	1,726,108	100	16,916,814	100

Table 12
Estimation of energy consumption in all three predicted scenarios.

Component	Household & Industry		Household		Transportation	
	Consumption (kWh/yr)	Percent	Consumption (kWh/yr)	Percent	Consumption (kWh/yr)	Percent
AC Primary Load	2,211,900	57.6	21,900	1.28	8,760,000	52.0
Grid Sales	1,630,097	42.4	1,690,040	98.7	8,085,974	48.0
Total	3,841,997	100	21,900	1.28	16,845,974	100

Table 13
Annual average energy exchanges with electricity grid in different months in three predicted scenarios.

Month	Household & Industry		Household		Transportation	
	Energy Purchased (kWh)	Energy Sold (kWh)	Energy Purchased (kWh)	Energy Sold (kWh)	Energy Purchased (kWh)	Energy Sold (kWh)
January	74,928	226,439	42.9	218,349	199,866	1,225,038
February	108,714	95,378	176	118,545	282,330	565,505
March	98,840	105,136	167	153,869	312,865	698,562
April	88,415	61,367	34.6	104,979	398,998	395,133
May	59,737	70,954	7.27	103,699	389,340	366,421
June	43,555	162,752	0	150,461	339,010	694,262
July	48,266	47,102	0.172	75,411	466,467	231,297
August	58,386	129,144	5.70	126,369	429,440	557,811
September	50,135	112,221	9.99	109,212	388,258	482,443
October	57,472	217,762	75.0	178,810	311,340	972,792
November	91,567	74,056	72.2	98,245	312,439	399,609
December	63,073	327,786	190	252,090	211,854	1,497,101
Annual	843,088	1,630,097	781	1,690,040	4,042,207	8,085,974

scenarios. the "Transportation Scenario" appears to be the most financially rewarding due to its higher electricity sales and associated profits. However, the "Household Scenario" demonstrates a notable difference between the cost of energy and energy price, suggesting potential for significant savings. The "Household and Industry Scenario" shows a moderate level of profitability and cost, likely due to a combination of industrial and residential energy consumption.

4.3. *Environment analysis*

According to Table 20, the results of emission reduction in the present study show that each upload increases the percentage of renewable energy in energy production is, directly reduced the production of carbon dioxide production and reduces the amount of alignment CO_2 emitted.

The "Household Scenario" stands out as the most environmentally

Table 14
Capacity factors and levelized cost of each component.

Component	Capacity Factor %	Hours of Operation (Hours)	Levelized Cost €/kWh
flat plate PV	8.09	4249	0.203
Offshore wind turbine	16.3	7350	0.0694
Onshore wind turbine	16.3	7350	0.0527
Hydro	51.8	70,92	0.0448

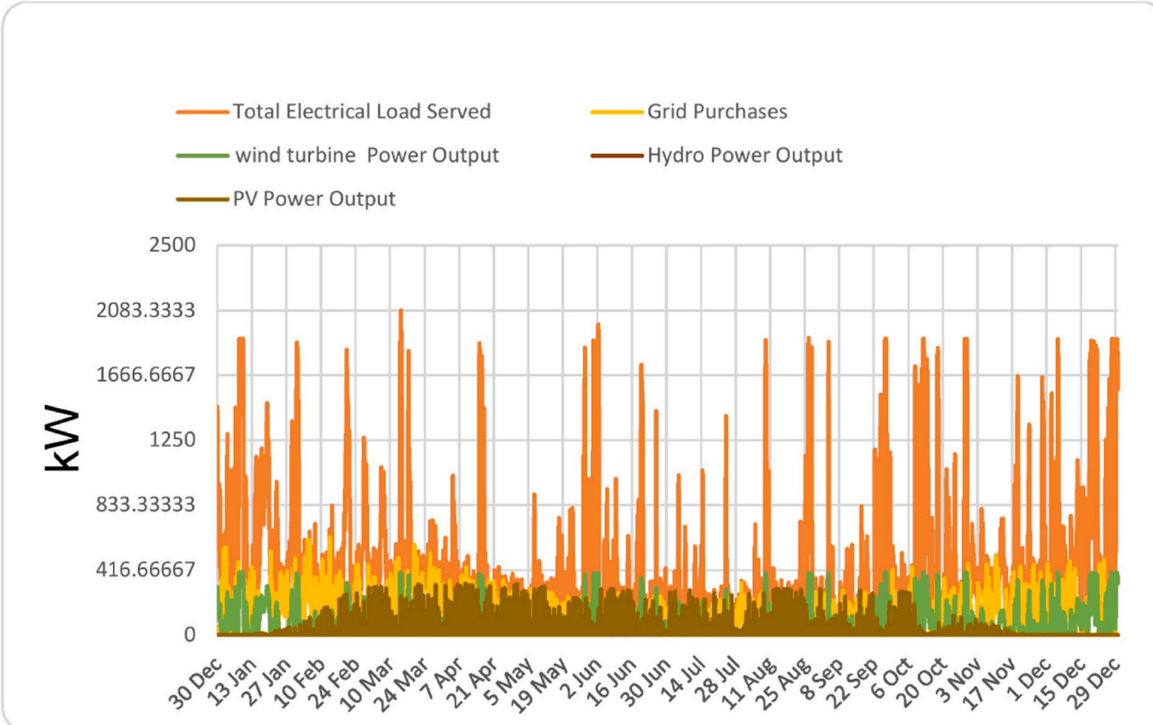


Fig. 9. Comparison of energy output and consumption for scenario 1 (industrial and household).

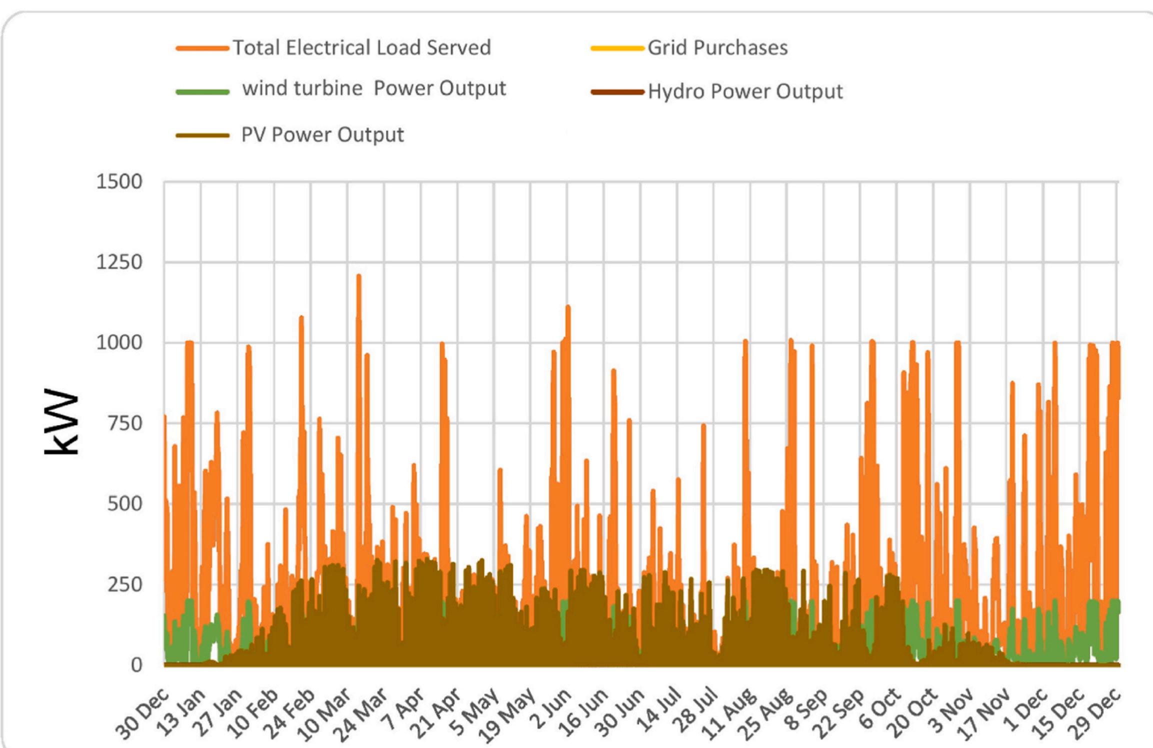


Fig. 10. Comparison of energy output and consumption for scenario 2 (household).

friendly, emitting the lowest amount of CO2 at 494 kg/yr. In contrast, the "Transportation Scenario" emits the highest amount at 2,554,675 kg/yr due to its higher energy consumption and associated emissions. The "Household Scenario" also shines in terms of renewable contribution, with 99% of its energy generation coming from renewable sources. The "Household and Industry Scenario" follows with 78.4%, and the "Transportation Scenario" lags with 76.1%. gain, the "Household Scenario" demonstrates its eco-friendliness by emitting only 0.28 g CO2 per kWh, while the "Transportation Scenario" emits the highest at 151 g CO2 per kWh. The "Household and Industry Scenario" falls in between. the

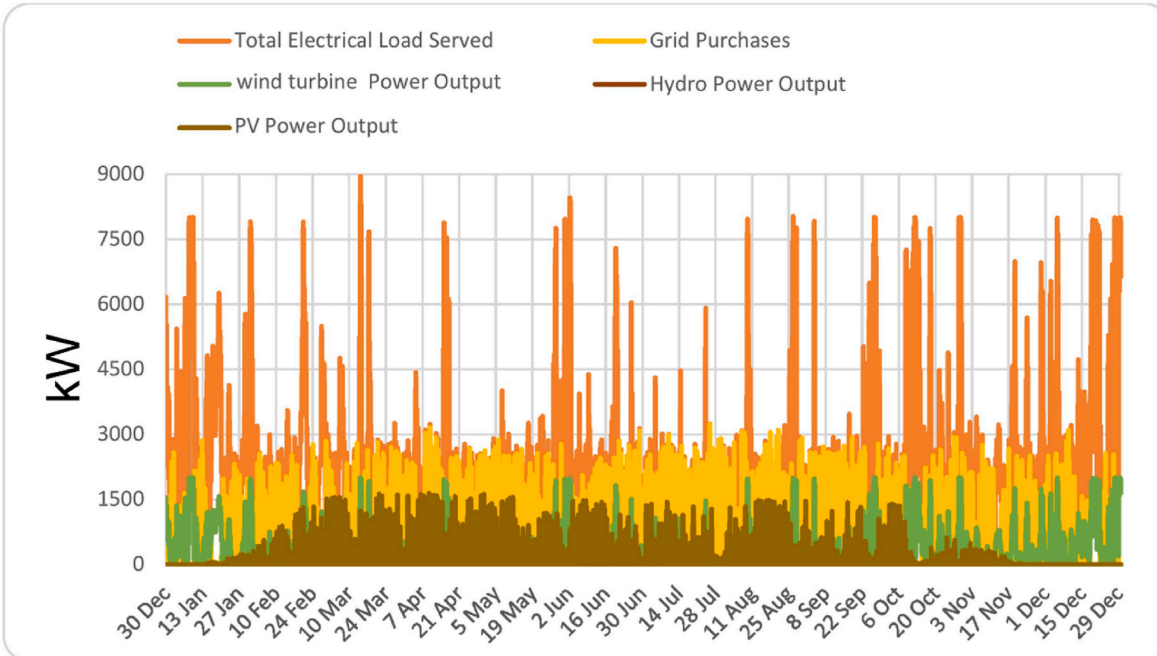


Fig. 11. Comparison of energy output and consumption for scenario 3 (transportation).

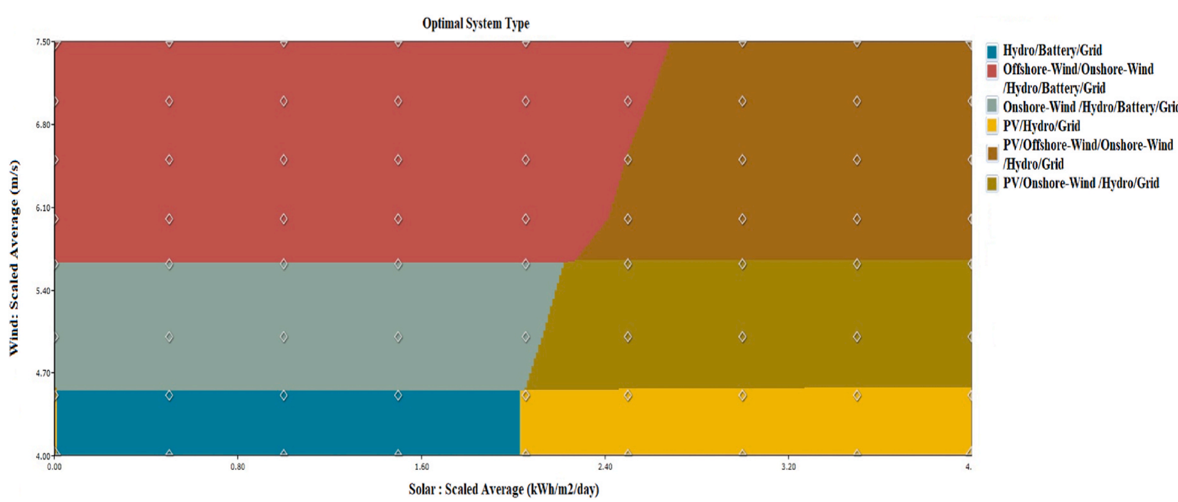


Fig. 12. Sensibility analysis of scenario 1 (household and industry).

"Household Scenario" clearly demonstrates the most environmentally responsible approach with minimal CO2 emissions, a high proportion of renewable energy, and extremely low CO2 emissions per kWh. The "Transportation Scenario" presents the greatest environmental challenge due to its higher emissions and lower renewable energy contribution. The "Household and Industry Scenario" strikes a balance between these factors.

5. Conclusions

In this research, the potential for the optimization of the run-of-river power plant in the Hinnoya region, Norway, was investigated. The simulation conducted by HOMER uses PVs/onshore and offshore wind turbines/batteries/convertor/hydroelectric turbine. Based on energy consumption scenarios that were selected for household, household with industrial, and transportation, three separate simulations were performed, and the results were examined. The main results can be concluded as follows:

- The onshore wind turbines have the highest production capacity. However, the most production capacity in PV panels is in June, while the most production capacity in wind turbines is in December and January.
- Although the cost of setting up a renewable power plant may be very high at first glance for transportation (€14.2 M), it can be noted that the production price is 0.055 €/kWh and less than the general price in Norway (0.106 €/kWh). As a result, € 400,000 will be returned by selling energy every year.
- Although the lowest cost is for the household scenario (€0.0296/ kWh), the load of the region is not high to have benefited from this point.
- The results show that the use of renewable systems in the household field could reduce the COE by nearly 70% (0.0296 €/kWh) and in

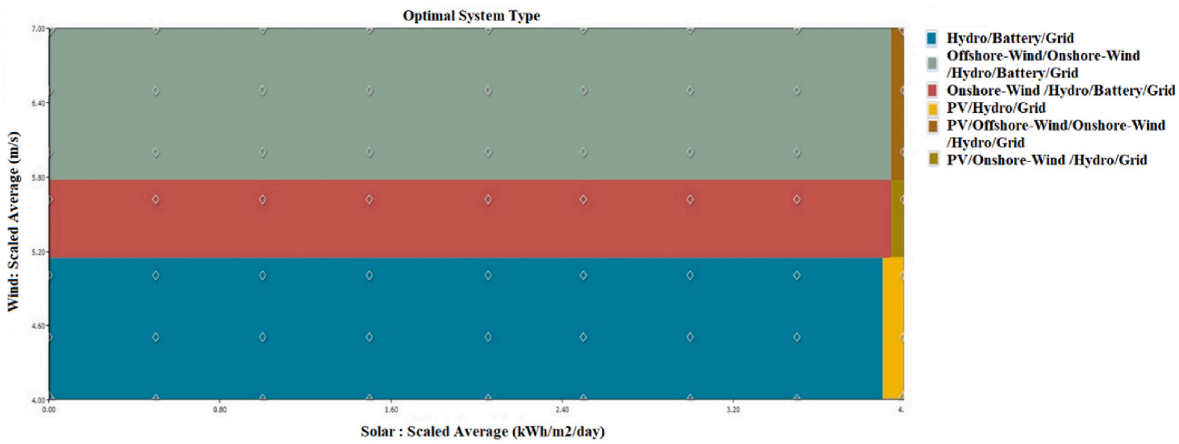


Fig. 13. Sensibility analysis of scenario 2 (household).

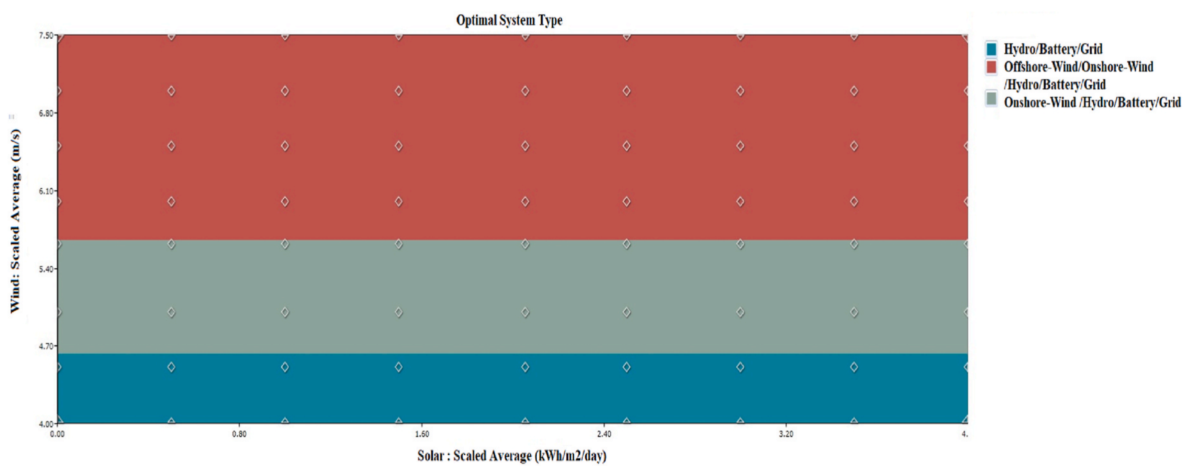


Fig. 14. Sensibility analysis of scenario 3 (transportation).

Table 15
Net present costs of scenario 1 for industrial and household.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Hydro	€6500	€2016	€0.00	-€143.94	€0.00	€8372
PV	€800,000	€67,212	€283,423	-€184,244	€0.00	€966,391
Grid	€0.00	-€141,793	€0.00	€0.00	€0.00	-€141,793
Offshore Wind Turbine	€600,000	€67,212	€0.00	€0.00	€0.00	€667,212
Onshore Wind Turbine	€1.65 M	€252,046	€0.00	€0.00	€0.00	€1.90 M
System Converter	€300,000	€0.00	€160,964	€0.00	€0.00	€460,964
System	€3.36 M	€246,694	€444,386	-€184,388	€0.00	€3.86 M

Table 16
Net present costs of scenario 2 for household.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Hydro	€6500	€2016	€0.00	-€143.94	€0.00	€8372
PV	€800,000	€67,212	€283,423	-€184,244	€0.00	€966,391
Grid	€0.00	-€1.70 M	€0.00	€0.00	€0.00	-€1.70 M
Offshore Wind Turbine	€300,000	€33,606	€0.00	€0.00	€0.00	€333,606
Onshore Wind Turbine	€880,000	€134,424	€0.00	€0.00	€0.00	€1.01 M
System Converter	€150,000	€0.00	€80,482	€0.00	€0.00	€230,482
System	€2.14 M	-€1.47 M	€363,905	-€184,388	€0.00	€850,798

other energy fields (transportation and industrial) diminish the COE by nearly 50% (0.055 €/kWh).

Finally, the key message of this study is that the optimization of a run-of-river hydropower system, combined with wind turbines, solar panels, and other components, offers a promising approach to meeting energy demands in different scenarios (household, household and industry, and transportation). The study emphasizes the importance of

Table 17
Net present costs of scenario 3 transportation.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Hydro	€6500	€2016	€0.00	-€143.94	€0.00	€8372
PV	€4.00 M	€336,061	€1.42 M	-€921,220	€0.00	€4.83 M
Grid	€0.00	-€952,471	€0.00	€0.00	€0.00	-€952,471
Offshore Wind Turbine	€3.00 M	€336,061	€0.00	€0.00	€0.00	€3.34 M
Onshore Wind Turbine	€6.60 M	€1.01 M	€0.00	€0.00	€0.00	€7.61 M
System Converter	€600,000	€0.00	€321,927	€0.00	€0.00	€921,927
System	€14.2 M	€729,849	€1.74 M	-€921,364	€0.00	€15.8 M

Table 18
Summary of the net present cost (NPC) for the three scenarios.

	Household and Industry	Household	Transportation
Capital	€3.36 M	€2.14 M	€14.2 M
Operating	€246,694	-€1.47 M	€729,849
Replacement	€444,386	€363,905	€1.74 M
Salvage	-€184,388	-€184,388	-€921,364
Total	€3.86 M	€850,798	€15.8 M
Cost of Energy	€0.0598/kWh	€0.0296/kWh	€0.0557/kWh

Table 19
Benefit of selling the energy to the region in each scenario.

	Household and Industry	Household	Transportation
Cost of energy	€0.0598/kWh	€0.0296/kWh	€0.0557/kWh
Energy price	€0.106/kWh	€0.106/kWh	€0.106/kWh
Defference of the COE and EP	€0.047/kWh	€0.077/kWh	€0.051/kWh
The amount of electricity sold to the area	1368812 kWh/yr	21119 kWh/y	4717793 kWh/yr
Profit from electricity sold to area	64334€/yr	1606 €/yr	240607€/yr

Table 20
Summary of the emission for three scenarios.

	Household and Industry	Household	Transportation
CO_2 Emitted (kg/yr)	532,832	494	2,554,675
Total renewable production divided by generation	78.4%	99%	76.1%
Co2 emitted (g/kWh)	138	0.28	151

integrating multiple renewable energy sources to achieve energy sustainability and reduce reliance on conventional energy sources. Here are the implications for different stakeholders. Policymakers can recognize the potential of integrated renewable energy systems in diverse scenarios. They should consider supporting policies that encourage the adoption of such systems to reduce carbon emissions and enhance energy security. Policies that incentivize the adoption of renewable energy technologies, provide financial support, and streamline regulatory processes can be instrumental in promoting the widespread implementation of these systems. End-users, such as households and industries, can benefit from adopting integrated renewable energy systems by reducing their energy costs and environmental impact.

The study suggests that adopting a combination of renewable energy sources, such as wind, solar, and hydropower, can help ensure a reliable and consistent energy supply while taking advantage of local resources. Prosumers (Energy Producers and Consumers) can play an active role in producing and consuming renewable energy. By generating surplus energy from their integrated systems, they can contribute to the local energy grid and earn revenue through selling excess energy. The study encourages prosumers to consider the cost-effectiveness of different renewable energy technologies and combinations, such as wind turbines, solar panels, and hydropower, to maximize their benefits and returns on investment. The study underscores the positive environmental impact of integrating renewable energy sources. By reducing carbon emissions and promoting cleaner energy production, integrated systems contribute to combating climate change and achieving sustainability goals. Further research and development efforts can focus on optimizing the design and performance of integrated renewable energy systems. This includes improving energy storage technologies, enhancing system efficiency, and developing innovative ways to manage energy production and consumption.

In summary, the study suggests that the integration of multiple renewable energy sources, such as wind, solar, and hydropower, can provide economically viable and environmentally sustainable solutions to meet energy demands in various scenarios. This approach has the potential to benefit policymakers, end-users, prosumers, and the environment, contributing to a more sustainable energy future.

At the end it should be noted that the results and methods of this study can be generalized to other locations with some considerations and adaptations considering resource availability assessment, component specifications, energy demand and consumption patterns, economic and policy factors as well as environmental consideration for each specific region.

Credit author statement

Siamak Hoseinzadeh: Term, Conceptualization, Formal Analysis, Methodology, Software, Investigation, Validation, Data Curation, Resources, Writing-Original draft, Visualization, Project administration, Writing-Original draft, Writing - review & editing. **Davide Astiaso Garcia**: Term, Methodology, Formal Analysis, Investigation, Writing-Original draft, Visualization, Project administration, Data Curation, Resources, Writing - review & editing, Supervision. **Lizhen Huang:** Data Curation, Resources, Visualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113658.

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