Check for updates

RESEARCH ARTICLE

Linear programming-based optimization of renewable energy systems for island decarbonization: The case of Borkum, Germany

[version 1; peer review: 2 not approved]

Alfredo GONZALEZ NARANJO, RAFAEL MARTIN SALINAS

Universidad de Sevilla Escuela Tecnica Superior de Ingenieria de Sevilla, Seville, Andalusia, Spain

v1 **First published:** 10 Dec 2025, **5**:377
https://doi.org/10.12688/openreseurope.21399.1
Latest published: 10 Dec 2025, **5**:377
https://doi.org/10.12688/openreseurope.21399.1

Abstract

Background

Islands face unique challenges in achieving decarbonized energy systems due to their geographic isolation, reliance on imported fossil fuels, and limited infrastructure. Renewable energy sources such as wind and solar represent viable alternatives, but their variability and spatial constraints difficult reliable system design. A systematic approach is required to align local demand, renewable generation, and storage capacity in a cost-effective way.

Methods

This study applies a linear programming optimization framework to determine the optimal configuration of distributed energy resources for the island of Borkum (Germany). The model integrates multiple technologies, including photovoltaic systems, wind turbines, lithium-ion batteries, hydrogen storage, and electric vehicle charging infrastructure. Techno-economic input data such as capital and operational costs, resource availability, and load profiles were used to simulate ten scenarios, each reflecting different technology mixes and investment assumptions.

Results

The baseline scenario shows high dependence on mainland imports to cover annual electricity demand. Scenarios with expanded photovoltaic and wind capacity significantly reduce import

Open Peer Review

Approval Status ✗ ✗

	1	2
version 1 10 Dec 2025	✗ view	✗ view

1. **Erfan Babaee Tirkolaee**, Istinye University, Istanbul, Turkey

2. **Sayeed Hasan**, Tallinn University of Technology, Tallinn, Estonia

Any reports and responses or comments on the article can be found at the end of the article.

requirements, while the addition of battery storage enhances temporal alignment between renewable production and demand. However, storage deployment is only economically viable under reduced cost assumptions. The most effective configuration, combining solar, wind, and storage, achieves substantial reductions in imported energy while maintaining a balanced cost-performance profile. The analysis highlights the importance of diversified technology portfolios and cost-efficient storage solutions for advancing local energy autonomy.

Conclusions

The optimization framework demonstrates strong potential as a decision-support tool for island energy planners. By quantifying trade-offs between cost, energy independence, and system reliability, it provides a structured basis for designing decarbonization pathways tailored to insular contexts. The findings support evidence-based planning for Borkum (Germany) and offer replicable insights for other islands pursuing the transition toward renewable and sustainable energy systems.

Plain Language Summary

The decarbonization of island energy systems is a key objective aligned with the European 2050 long-term climate strategy, which aims for a climate-neutral economy by 2050. This strategy envisions an economy with net-zero greenhouse gas emissions, requiring all sectors — power, industry, mobility, buildings, agriculture, and forestry — to play a role in achieving full decarbonization. In this context, optimizing the energy infrastructure of islands is essential to achieve sustainable and cost-effective decarbonization. Islands present unique challenges due to their geographic isolation, dependence on fossil fuels, and limited energy storage capacity. Efficiently sizing Distributed Energy Resources (DER) and Hybrid Energy Storage (HES) systems through optimization models ensures a balanced integration of renewable sources while minimizing costs and space constraints. By leveraging advanced optimization techniques, this study contributes to the design of an efficient, resilient, and fully decarbonized energy system for islands. The demonstration pilot will be the island of Borkum, in Germany.

Keywords

Island decarbonization; Linear programming; Renewable Energy Systems (RES); Distributed Energy Resources (DER); Hybrid Energy Storage (HES); Photovoltaics (PV); Wind turbines; Battery Energy Storage Systems (BESS); Hydrogen storage; Electric Vehicle (EV) charging; Techno-economic optimization; Borkum

H2020 This article is included in the Horizon 2020 gateway.

Corresponding authors: Alfredo GONZALEZ NARANJO (agnaranjo@ayesa.com), RAFAEL MARTIN SALINAS (rmartin@ayesa.com)

Author roles: GONZALEZ NARANJO A: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration; **MARTIN SALINAS R**: Conceptualization, Formal Analysis, Investigation

Competing interests: No competing interests were disclosed.

Grant information: This research received funding from the project "ISLANDER", funded from the European Union's Horizon 2020 research and innovation program under grant agreement n° 957669.
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Copyright: © 2025 GONZALEZ NARANJO A and MARTIN SALINAS R. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: GONZALEZ NARANJO A and MARTIN SALINAS R. **Linear programming-based optimization of renewable energy systems for island decarbonization: The case of Borkum, Germany [version 1; peer review: 2 not approved]** Open Research Europe 2025, **5**:377 https://doi.org/10.12688/openreseurope.21399.1

First published: 10 Dec 2025, **5**:377 https://doi.org/10.12688/openreseurope.21399.1

Motivation

Islands exhibit distinct structural and operational constraints in their transition towards decarbonized energy systems. Their geographic isolation often necessitates a high dependency on imported fossil fuels, resulting in elevated energy costs, heightened vulnerability to supply disruptions, and increased greenhouse gas (GHG) emissions. Although renewable energy sources (RES), particularly wind and solar, represent viable and sustainable alternatives, their deployment in insular environments is hindered by constraints such as limited land availability, pronounced variability in generation profiles, and the absence of extensive energy infrastructure typically available in continental systems. Moreover, the inherently intermittent nature of RES poses significant challenges for maintaining grid reliability and operational stability in the absence of advanced energy storage and management frameworks. Therefore, achieving complete decarbonization mandates not only the substitution of conventional generation assets with renewables but also the holistic optimization of system architecture — encompassing accurate sizing of infrastructure components — to effectively align energy demand, storage capabilities, and renewable generation potential.

Objectives

To address the aforementioned challenges, this study employs a linear programming–based optimization framework to determine the optimal configuration of Distributed Energy Resources (DER) and Renewable Energy Systems (RES). The design of an efficient and sustainable energy infrastructure constitutes a high-dimensional and multi-criteria problem, requiring the simultaneous consideration of interrelated variables such as capital and operational expenditures, spatial constraints, resource availability, load profiles, and technical limitations. The inherent complexity and interdependence of these factors render manual evaluation approaches infeasible, thereby necessitating the application of advanced mathematical modeling and computational optimization techniques to derive cost-effective and technically viable solutions. The proposed optimization methodology is subsequently applied to a set of case studies, with a particular focus on the island of Borkum (Germany). Through the simulation and comparative analysis of multiple deployment scenarios, the study generates quantitative evidence and strategic insights regarding the integration of RES in insular contexts. The results aim to validate the effectiveness of the proposed approach and to inform decision-making processes related to the design, scalability, and long-term sustainability of decarbonized energy systems for island communities.

Literature review

The optimization of renewable energy resource deployment has become a pivotal area of research, particularly within islanded energy systems where supply security, reliability, and cost-effectiveness are significantly constrained. This literature review provides a structured synthesis of the most influential contributions in the domain, with an emphasis on linear programming–based optimization approaches, the design and operational control of microgrids, integration strategies for energy storage systems, and empirical case studies that illustrate the technical and economic feasibility of achieving high renewable energy penetration in insular contexts.

Optimization for renewable energy allocation

1 establishes a significant precedent in “Optimization for Renewable Energy Resource Allocation Using Linear Programming: A Case Study”, where linear programming techniques are applied to optimize the allocation of a limited budget (500.000€) across various renewable energy projects. The study “Optimizing Design and Dispatch of a Renewable Energy System”[2] advances methodological complexity by presenting a mixed-integer programming model that prescribes optimal combinations of renewable technologies, conventional generation, and storage systems, including combined heat and power systems. This model prioritizes the minimization of fixed and operational costs while ensuring system interoperability and reliability[2].

Applications in Island environments

The research “Renewable Energy Communities in Islands: A Maltese Case Study” offers a valuable perspective on the implementation of renewable energy communities (RECs) in Malta’s low-voltage distribution network. This study, through the analysis of five cases, demonstrates how centralized community storage can significantly improve self-sufficiency, reduce peak electricity demand, and minimize reverse power flows into the utility grid[3].

The work “Linear Programming Approach Based Demand Response to Support Intermittent and Non-Dispatchable Renewable Energies Penetration in Nusa Penida Iconic Island” evaluates the potential penetration of renewable sources in the Cyclades, a complex of Greek islands. This study highlights the importance of hydrogen as an energy vector to increase the participation of renewable and intermittent sources in the energy supply, suggesting the possibility of achieving 100% renewable supply for island communities[4].

The research "Research on Energy Storage Optimization Operation Schedule in an Islanded Power System with High Renewable Energy Penetration" focuses on Taiwan's Kinmen Island, studying scheduling systems for renewable energy penetration with the aim of reducing accidents in the electrical system. The study emphasizes the importance of full participation of power system stabilizers in reserve scheduling to handle unexpected situations and load changes[5].

Case study design

Problem description

The primary objective of the sizing algorithm is to identify the optimal configuration of energy generation and storage assets that satisfies the projected energy demand of a given site, while minimizing the total system cost, including both capital and operational expenditures. The algorithm operates on a predefined set of candidate technologies, provided as input parameters, which encompass onshore and offshore wind turbines, photovoltaic (PV) installations, prosumer systems (capable of both energy generation and storage), lithium-ion and hydrogen-based energy storage systems, interconnection capacities, and electric vehicle (EV) charging infrastructure.

Mathematical model

The algorithm is formulated as a modular optimization model based on Linear Programming (LP). The dimensionality of the model—i.e., the number of decision variables and constraints—adapts dynamically according to the set of technologies selected for deployment. Its modular architecture allows for the selective activation or deactivation of entire technology blocks (modules), enabling flexible configuration beyond simple parameter tuning. Each module encapsulates its own constraints and cost formulations, contributing to the overall objective function and system behaviour. The LP-based model is applied to key infrastructure components such as wind turbines (onshore and offshore), energy storage systems (lithium-ion and hydrogen), electrical interconnections, prosumer units, and photovoltaic systems. A separate optimization module is used for electric vehicle (EV) infrastructure, and its resulting outputs—primarily cost metrics—are integrated into the cost function of the main model to ensure holistic system-level optimization.

Cost expressions (Cost function) are very typical of LP optimization, used in many problems in which expenses are being minimized, including energy hubs models[6,7].

The installation costs multiply the sizing variables, whereas the O&M costs multiply the sum of all the energy either generated or flowing through the module.

This formula is structured as follows:

$$\sum_{modules} c_{inst} \cdot P + \sum_{modules} (c_{O\&M} \cdot P) \tag{1}$$

Where P is the sizing variable of each installation (generally a power value [kW]).

In addition to the cost function, there is a similar approach for a constraint at a general level (for all the modules): there is an expression that is the difference between the expected consumption and the sum of the total installed power between all the elements. The objective of the restriction is to reduce this difference to 0.

$$C = C - \sum_{modules} P_{installed} < 10^{-3} \tag{2}$$

where

$C \rightarrow$ Consumption expression

$P_{installed} \rightarrow$ Installed power

All the modules have information about costs and space limitations that are used in the model constraints. For example, in the case of the onshore turbines: The installed power, that is computed through the product of a generation coefficient and the wind speed, should be greater than what exists initially:

$$P_{0_{onshore}} \leq P_{onshore} \tag{3}$$

The space occupied by turbines should be lower than available:

$$S_{onshore} \cdot \left(P_{onshore} - P_{0_{onshore}} \right) \leq S_{T_{onshore}} \tag{4}$$

$S_{onshore} \rightarrow$ Onshore installation space

$S_{T_{onshore}} \rightarrow$ Total onshore space

$P_{onshore} \rightarrow$ Onshore installed power

$P_{0_{onshore}} \rightarrow$ Initial onshore installed power

In the case of the solar parks, the generation is calculated using the irradiance and the guaranteed minimum performance. The space limitation, like in the case of the turbines, is related to the initial installed power in the lower bound and to the available space in the upper. The prosumers, in addition to the space limitations, include other restrictions like the battery capacity:

$$E_{battery} \geq E_{0_{prosumer}} - \epsilon_{prosumer} \cdot \sum_{0}^{t+1} E_{prosumer}[t] \tag{5}$$

$E_{battery} \rightarrow$ Battery capacity

$E_{0_{prosumer}} \rightarrow$ Prosumer initial stored energy

$\epsilon_{prosumer} \rightarrow$ Battery prosumer efficiency

$E_{prosumer} \rightarrow$ Prosumer net energy

Or the energy flow (the energy leaving should be less than that entering):

$$\epsilon_{prosumer} \cdot E_{prosumer}[t] \leq E_{0_{prosumer}} - \epsilon_{prosumer} \cdot \sum_{0}^{t+1} E_{prosumer}[t] \tag{6}$$

Similar expressions appear for lithium batteries, regarding the battery capacity:

$$E_{lithium_{cap}} \geq E_{0_{lithium}} - \epsilon_{lithium} \cdot \sum_{0}^{t+1} E_{lithium}[t] \tag{7}$$

$E_{lithium_{cap}} \rightarrow$ Lithium battery capacity

$E_{0_{lithium}} \rightarrow$ Lithium initial stored energy

$\epsilon_{lithium} \rightarrow$ Lithium battery efficiency

$E_{lithium} \rightarrow$ Lithium battery net energy

The charging and discharging power limits:

$$P_{min_{lithium}} < E_{lithium}[t] / h_p_t < P_{max_{lithium}} \tag{8}$$

Or the energy flow:

$$\epsilon_{lithium} \cdot E_{lithium}[t] \leq E_{0_{lithium}} - \epsilon_{lithium} \cdot \sum_{0}^{t} E_{lithium}[t] \tag{9}$$

Hydrogen batteries have very similar expressions, also regarding space constraints, battery capacity and charging limits.

Interconnexions are part of the complete installation, and there are two different modules for them: the existing ones, that have power limitation

$$-S_{e_{cable}} < E_{e_{conn}}[t]/h_p_t < S_{e_{cable}} \tag{10}$$

$S_{e_{cable}} \rightarrow$ Size of existing cable

$E_{e_{conn}} \rightarrow$ Energy net of existing connection

and the new ones, for which there are also power restrictions:

Upper bound:

$$E_{new}[t]/h_p_t \leq S_{n_{cable}} \cdot I_n \tag{11}$$

$E_{new} \rightarrow$ New interconnection net energy

$S_{n_{cable}} \rightarrow$ Size of new cable

$I_n \rightarrow$ New installed interconnections

Lower bound:

$$E_{new}[t]/h_p_t \geq -S_{n_{cable}} \cdot I_n \tag{12}$$

As commented before, there is an additional module that computes the costs and contributions to the consumption expression from the electrical vehicles. The restrictions related to this part of the installation are the following: The number of charging vehicles is lower than the number of slow and fast charging stations:

$$cper_{tour}[t] \cdot veh_{tour}[t] + cper_{urban}[t] \cdot veh_{urban}[t] + cper_{inhab}[t] \cdot cper_{veh} \cdot veh_{inhab}[t] \leq cs_{slow_{active}}[t] + cs_{fast_{total}}[t] \tag{13}$$

$cper_{tour} \rightarrow ev_tourists_charging_percentage$

$veh_{tour} \rightarrow ev_tourists_vehicles$

$cper_{urban} \rightarrow ev_urban_services_charging_percentage$

$veh_{urban} \rightarrow ev_urban_services_vehicles$

$cper_{tour} \rightarrow ev_tourists_charging_percentage$

$cper_{inhab} \rightarrow ev_inhabitants_charging_percentage$

$cper_{veh} \rightarrow ev_tourists_charging_percentage$

$veh_{inhab} \rightarrow ev_urban_services_vehicles$

The number of slow and fast charging stations Is lower than the total of each kind:

$$cs_{slow_{active}}[t] \leq cs_{slow_{total}} \tag{14}$$

$cs_{slow_{active}} \rightarrow ev_active_slow_charge_stations$

$cs_{slow_{total}} \rightarrow ev_total_slow_charge_stations$

$$cs_{fast_{active}}[t] \leq cs_{fast_{total}} \tag{15}$$

$cs_{fast_{active}} \rightarrow ev_active_fast_charge_stations$

$cs_{fast_{total}} \rightarrow ev_total_fast_charge_stations$

Space limitation for charging stations:

$$cs_{slow_{total}} \cdot cs_{slow_{space}} + cs_{fast_{total}} \cdot cs_{fast_{space}} <= cs_{total_{space}} \quad (16)$$

$cs_{slow_{space}} \rightarrow ev_slow_charge_station_installation_space$

$cs_{fast_{space}} \rightarrow ev_fast_charge_station_installation_space$

$cs_{total_{space}} \rightarrow ev_total_charging_station_space$

The number of charging stations installed should be greater than the initial number:

$$P_{slow_{installed}} \leq cs_{slow_{total}} \quad (17)$$

$P_{slow_{installed}} \rightarrow ev_already_installed_slow_charge_power$

$$P_{fast_{installed}} \leq cs_{fast_{total}} \quad (18)$$

$P_{fast_{installed}} \rightarrow ev_already_installed_fast_charge_power$

The sum of the objective function corresponding to electric vehicles considers the installation and maintenance cost of the slow and fast charging stations:

$$IC_{slow} \cdot \left(cs_{slow_{total}} - P_{slow_{installed}}\right) + IC_{fast} \cdot \left(cs_{fast_{total}} - P_{fast_{installed}}\right) + MC_{slow} \cdot P_{max_{slow}} \cdot \sum cs_{slow_{active}} + MC_{fast} \cdot P_{max_{fast}} \cdot \sum cs_{fast_{active}} \quad (19)$$

$IC_{slow} \rightarrow$ Slow charge station installation cost

$IC_{fast} \rightarrow$ Fast charge station installation cost

$MC_{slow} \rightarrow$ Slow charge station maintenance cost

$MC_{fast} \rightarrow$ Fast charge station maintenance cost

Data

Environmental variables such as ambient temperature, solar irradiance, and wind speed constitute key input parameters for estimating the energy output of the various generation technologies integrated into the system. In parallel, energy demand profiles are incorporated as critical boundary conditions within the optimization framework, influencing the sizing and dispatch strategy of installed capacity[8].

Each technological component within the system requires detailed techno-economic data, including capital expenditure (CAPEX), operational and maintenance costs (OPEX), spatial footprint per unit, and constraints related to the total area available for deployment.

Furthermore, the electric vehicle (EV) infrastructure module integrates additional socioeconomic and behavioural parameters, such as local population density, fleet size of urban service vehicles, and the proportion of time these vehicles are operated under active charging conditions. These variables collectively inform the estimation of EV-related energy demand and infrastructure requirements within the overall system model.

Results and discussion

his section aims to assess the performance and applicability of the proposed linear programming–based optimization algorithm for the design of an energy infrastructure tailored to insular environments. The specific characteristics of the selected use case—namely, limited land availability and strategic commitment to renewable

energy integration—position the island as an optimal testbed for evaluating advanced energy system design methodologies. The following subsections outline the scenario definition, including the technical assumptions, boundary conditions, and input parameters used for modelling the case of Borkum Island. Results are then presented and discussed, covering the evaluated deployment scenarios, key performance indicators (KPIs), and the broader implications for the island's energy transition pathway. This case study focuses on Borkum, the westernmost and largest of Germany's East Frisian Islands, encompassing approximately 31 km^2. Located roughly 20 miles off the German mainland, Borkum represents the country's northwesternmost territory and serves as a representative example of a geographically constrained yet strategically positioned energy system[8].

Borkum has a resident population of approximately 5,500 inhabitants, primarily concentrated in its sole urban settlement, also named Borkum. However, during peak tourist seasons, the island's population increases significantly, exceeding 25,000 individuals. The island's climate is predominantly influenced by the North Atlantic polar front throughout the year, resulting in variable and frequently overcast weather conditions. Summer temperatures tend to be lower than continental averages due to the moderating effect of oceanic currents, while winters are comparatively mild, though often accompanied by strong winds and persistent cloud cover. Climatic data for the year 2019—including ambient temperature, solar irradiance, and wind speed—has been used as the basis for energy generation modelling. In that same year, the island's total annual electricity demand was 30.6 GWh. The installed generation capacity on Borkum produced a total of 14.74 GWh annually. Of this, approximately 10.6 GWh was generated by two wind turbines rated at 1.8 MW each, while a 1.4 MW central photovoltaic (PV) installation contributed 1.24 GWh, and distributed rooftop PV systems—primarily deployed under the NETfficient project—generated an additional 0.27 GWh. Supplementary electricity generation is provided by a gas-fired Combined Heat and Power (CHP) plant, supplying over 2.9 GWh per year. Regarding thermal energy, annual heating demand is estimated at approximately 130 GWh, currently met through a combination of the gas CHP system and individual natural gas boilers. Due to the deficit between local generation and consumption, the island imports approximately 17.06 GWh of electricity annually from the mainland. Interestingly, despite the negative net balance, approximately 1.2 GWh is exported back to the mainland. This is attributed to the temporal mismatch between renewable energy production and local consumption—specifically, surplus generation during peak production periods that exceeds local demand is fed into the external grid.

Assumptions

A total of ten (10) scenarios were developed for Borkum using different facilities and comparing with the facilities already installed in Borkum (base example). Some assumptions were considered in advance prior to generating each scenario.

Assumption 1. Price-related assumptions

Table 1 provides the cost ratios related to the different facilities and energy parameters that have been considered in the examples developed:

The cost ratios of H2 storage facilities (Electrolyzer and Fuel Cell) described in Table 2 have been obtained from the literature where Levelized Cost of Storage (LCOS) for a hydrogen system is analyzed and researched.

Table 1. Facilities and energy cost ratios.

Cost Ratio	*Value*
Energy from mainland	100 €/MWh
PV facilities supply and installation	600 €/kWp
Batteries supply and installation	300 €/kWh
Wind turbine	1200 €/kW
Hydrogen storage	700 €/kWh
Electrolyzer	650 €/kW
Fuel cell	1700 €/kW

Table 2. Equipments cost ratios.

Equipment	*Ratio*		*Size*			*Cost*		
			min	**max**	**units**	**min**	**max**	**units**
Electrolyzer	650	€/kW	5	15	kW	3250	9750	€
Fuel cell	1700	€/kW	5	15	kW	8500	25500	€
Battery Buffer	300	€/kWh	5	10	kWh	1500	3000	€
TOTAL						13250	38250	€

The cost ratio of Hydrogen Storage has been obtained based on the costs included in the Grant Agreement subtracting the prices of electrolyzer, Fuel Cell and Buffer Battery.

Considering the price of the H2 storage system considered (495.000,00 €) and the size range of the H2 storage tank, the price range for the storage results as describe in Table 3:

A 700,00 €/kWh ratio has been considered for the H2 storage tank.

No Maintenance nor operation costs have been considered for any renewable technology. In addition, no monetary compensation is obtained for the energy fed into the grid.

Assumption 2. Return of Investment Assumptions
Another assumption considered is the Return of Investment (ROI) period. There has been considered a period of 10 years, and has been considered by dividing the costs of supply and installation of the facilities stated previously by 10. Consumption, temperature and wind speed data have been provided by NBG partner and included in data.csv input file.

Irradiance data has been obtained from PVGIS for a horizontal plane and a typical year[9].

No limitations of space have been considered.

Assumption 3. Efficiencies assumptions
The following efficiencies have been considered:

- PV plant and Prosumers:
  - Performance Ratio: 75%
- Batteries:
  - Efficiency: 100%
- Wind Turbines:
  - Minimum Wind: 5,0 m/s
  - Optimal Wind: 18,9 m/s
  - Maximum Wind: 34,0 m/s
- H2 Storage:
  - Electrolyzer efficiency: 45%
  - Fuel Cell efficiency: 65%

Table 3. H2 storage tank price.

Equipment	*Price (€)*		*Size (kg)*		*Cost (€/kWh)*	
	min	**max**	**min**	**max**	**min**	**max**
H2 storage tank	456.750	481.750	5	20	685,19	2.890,79

4. Total Energy Consumption Assumptions

A total of 32,62 GWh consumption will be considered for all scenarios.

Results comparison between configurations

Scenario 1: Consider just the facilities already installed in Borkum:

- One PV Plant of 1,4 MWp.
- One set of prosumers with an installed power of 0,27 MWp.
- Two wind turbines of 1,8 MW each.

The objective function reflects the cost of energy from the mainland.

Scenario 2: PV optimization has been calculated with the base example data and optimizing the use of PV plants

Scenario 3: Wind Turbine Optimization. Using data considered and optimizing the use of Wind Turbines.

Scenario 4: Batteries Optimization. First trial with the pieces of the batteries initially considered has been performed, returning no battery should be installed that means the benefits of the battery (less energy from and to mainland) do not compensate the cost of the battery.

Scenario 5: Batteries Optimization. Second trial with the pieces of the same batteries as scenario 4 but with one tenth of the initial cost for the batteries (30 €/kWh).

Scenario 6: H2 storage optimization. First trial with the pieces of H2 initially considered has been calculated, returning no equipment should be installed to optimize the function cost, similar to scenario 4.

Scenario 7: Second H2 storage optimization with also one tenth of the initial cost of H2 storage has also been calculated, but it also does not propose the installation of any equipment.

Scenario 8: PV optimization with batteries: PV plant optimized combined with Battery Optimization. One tenth of the initial cost for the batteries has been considered.

Scenario 9: Wind Turbine Optimization, also with batteries consideration (one tenth of battery costs).

Scenario 10: PV and Wind Turbine Optimization, with also usage of batteries (Considered one tenth of the initial cost of the batteries.

Table 4 summarizes scenarios results:

The application of the linear programming–based optimization algorithm across multiple deployment scenarios yields valuable insights into the most cost-effective and technically viable configurations for energy generation, with a particular focus on maximizing renewable energy integration and minimizing dependence on external supply. The baseline scenario, which reflects the existing infrastructure on Borkum, exhibits a higher dependency on electricity imports from the mainland, resulting in elevated operational costs. Scenarios

Table 4. Scenarios results summary.

Scenarios		Energy (GWh)				Cost (k€)				
		Import	Export	PV, prosumers	Wind Turbines	Import	PV, prosumers	Wind Turbines	Batteries	Total
1	Base	23,04	0,14	1,54	8,18	2303	-	-	-	2303
2	PV of 7747 kWp	16,62	0,85	8,67	8,18	1662	465	-	-	2127
3	3 Wind Turbines 1800 kW each	16,19	3	1,54	17,9	1619	-	513	-	2131
4	No equipment	-	-	-	-	-	-	-	-	-
5	Batteries of 1323 kWh	22,09	0,08	1,54	8,18	2299	-	-	4	2302
6	No equipment	-	-	-	-	-	-	-	-	-
7	No equipment	-	-	-	-	-	-	-	-	-
8	PV plant of 14.826 KWp Batteries of 27.311 kWh	10,16	0,91	15,18	8,18	1016	890	-	82	1988
9	3 additional Wind Turbines 1.800 kW each Batteries of 10.284 kWh	14,56	3,25	1,54	19,77	1456	-	640	31	2127
10	2 additional Wind Turbines 1.800 kW each PV plant of 12.667 kWp Batteries of 29.467 kWh	8,56	1,72	13,2	12,58	856	760	233	88	1937

incorporating additional renewable energy sources (RES) demonstrate a significant reduction in import requirements and, in some cases, a net energy export, thereby enhancing local energy autonomy. The degree of cost reduction is strongly influenced by the specific mix and installed capacity of the selected technologies. Scenarios integrating photovoltaic (PV) systems and wind turbines exhibit a pronounced shift toward local generation, contributing to both increased self-sufficiency and decreased levelized energy costs. Notably, scenario 3, which includes the deployment of additional wind turbines, further mitigates external energy reliance. The inclusion of battery energy storage systems (BESS) enhances the temporal alignment between renewable generation and demand, improving grid stability and the overall utilization of locally produced energy. While scenarios that integrate storage solutions exhibit further reductions in energy imports, the economic viability is highly sensitive to the high capital expenditures associated with battery systems. The cost-effectiveness of such investments must be justified by the corresponding reduction in imported energy volumes and peak shaving benefits.

Among the configurations evaluated, scenario 10—characterized by the simultaneous deployment of utility-scale PV, additional wind turbines, and battery storage—achieves the highest reduction in dependency on mainland imports while maintaining a balanced cost-performance profile. The results suggest that the optimal trade-off between energy independence and investment cost is attained through a diversified portfolio of renewable generation technologies complemented by storage capacity.

Ethics and consent

Ethical approval and consent were not required

Contribution

The proposed solution is intended to serve as a pre-sizing and decision-support tool for follower islands seeking to evaluate and adapt energy system configurations aligned with the ISLANDER framework. The tool enables users to perform techno-economic optimization analyses, the outputs of which provide a foundational design reference for the tailored deployment of energy technologies in diverse insular contexts. Users are required to supply a structured input dataset representative of a full typical meteorological year (TMY), including all relevant techno-environmental and demand-side parameters associated with the candidate technologies to be considered in the optimization process. Furthermore, users must define and parameterize the specific characteristics (e.g., technical performance, costs, spatial constraints) of each technology selected for inclusion in the analysis. By executing multiple simulation scenarios, the tool allows comparative assessments of alternative technology mixes and system configurations. This facilitates the identification of optimal solutions in terms of cost efficiency, energy autonomy, and environmental performance, thereby supporting evidence-based decision-making for the energy transition of follower islands.

Conclusions

This article presents the implementation and application of a linear programming–based software tool developed for the optimal sizing of energy systems, with a focus on scenario-based analysis and interpretation of the resulting outputs. The tool is designed to support energy system planners and decision-makers in identifying the most cost-effective technological configurations for the decarbonization of islanded or geographically isolated energy systems. It accounts for both capital investment and operation and maintenance (O&M) costs, thereby facilitating informed decision-making during the early-stage design and planning phases. By simulating and analyzing multiple deployment scenarios, the tool generates quantitative insights that are critical for the techno-economic optimization of distributed energy systems in insular contexts. Key conclusions derived from the scenario analyses include:

1. **Enhanced Energy Autonomy Through Technology Diversification:** Systems integrating a broader portfolio of renewable energy technologies—each with distinct generation profiles—exhibit increased resilience and reduced dependency on external grid connections.

2. **Synergistic Role of Energy Storage Systems (ESS):** The coupling of variable renewable energy sources with appropriately sized energy storage significantly enhances system performance. Storage integration enables both the temporal balancing of generation and demand and the economic viability of higher renewable penetration levels.

3. **Economic Constraints of Grid Disconnection:** The analysis underscores the critical role of affordable and efficient energy storage technologies in achieving grid-independence. Current cost structures for advanced storage solutions remain a limiting factor, highlighting the need for further innovation and cost reductions to enable fully autonomous island energy systems.

Overall, the tool provides a robust analytical framework for exploring decarbonization pathways in isolated energy systems, offering a data-driven foundation for strategic infrastructure planning and investment.

Limitations and future work

While the current version of the software fulfills the core functional requirements, there are several opportunities for enhancement that could be incorporated into future iterations to improve analytical depth, user experience, and decision-support capabilities for energy system planners.

From a usability standpoint, improvements to the graphical user interface (GUI) could enhance interaction efficiency and accessibility. Minor interface refinements, such as the integration of a target Return on Investment (ROI) parameter within both the computational model and the visualization layer, would increase transparency

and facilitate financial assessment. Furthermore, the current version lacks the capability to simulate the full duration of the ROI period—a critical feature that could be implemented to support long-term investment evaluation. Enhanced output visualizations, such as detailed energy production profiles, cumulative performance indicators (e.g., totalized energy flows), and a comprehensive energy dashboard, would offer greater insight beyond system sizing metrics. Additional temporal analysis functionalities, including disaggregation of results by month or intraday intervals, as well as scenario comparison tools, would significantly broaden the scope of strategic analysis.

In terms of system modelling, several functional extensions are proposed. These include the incorporation of thermal energy generation systems, the enforcement of energy storage boundary conditions (e.g., ensuring battery and hydrogen tank state of charge (SOC) equivalence at the start and end of simulation periods), and the inclusion of SOC degradation dynamics over time. Moreover, the optimization framework could be expanded to accommodate energy export transactions, thereby introducing a revenue stream component and enhancing the financial realism of the simulations. Cost modelling could also be refined by incorporating dynamic grid electricity pricing and energy export tariffs. Maintenance cost estimation could be improved by introducing a more granular methodology that accounts not only for energy throughput but also for system capacity and operational cycles. Furthermore, the adoption of advanced financial metrics—such as Levelized Cost of Ownership (LCO)—would enable a more comprehensive assessment of system lifecycle economics, facilitating robust techno-economic comparisons across alternative configurations.

Data availability

The datasets generated and analysed in this study are openly available in DOI: https://doi.org/10.23728/b2share.4a96fdc741d54ea285eda021df413933[8].

The repository includes:

- Input datasets used for the linear programming optimization (typical meteorological year data, load profiles, and techno-economic parameters for photovoltaic, wind, storage, and electric vehicle infrastructure).
- Scenario configuration files and model parameters used to reproduce the results.
- Output data generated by the simulations, including energy balances, cost calculations, and performance indicators.

No restrictions apply to the use of these data.

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

References

1. Ghabban MO, Marzouq AH, Alsughayyir YA, *et al.*: **Optimization for renewable energy resource allocation using linear programming (a case study).** *Academic Journal of Research and Scientific Publishing.* 2024; 18.
Publisher Full Text
2. Ogunmodede O, Anderson K, Cutler D, *et al.*: **Optimizing design and dispatch of a renewable energy system.** *Appl Energy.* 2021; **287**: 116527.
Publisher Full Text
3. Micallef A, Staines CS, Licari J: **Renewable energy communities in Islands: a maltese case study.** *Energies.* 2022; **15**(24): 9518.
Publisher Full Text
4. Nurhayati G, Sasmono S, Hariyanto N: **Linear programming approach based demand response to support intermittent and non-disptachable renewable energies penetration in Nusa Penida Iconic Island.** 2023; 648–653.
Publisher Full Text
5. Chen YT, Kuo CC, Jhan JZ: **Research on energy storage optimization operation schedule in an Island system.** *Appl Sci.* 2011.
6. Geidl M, Andersson G: **Optimal coupling of energy infrastructures.** IEEE, 2007.
Publisher Full Text
7. del Real AJ, Arce A: **Optimization strategy for element sizing in hybrid power systems.** *Journal of Power Sources.* 2008.
8. González Naranjo A: **Borkum Island environmental and energy input data.** s.l.: -EUDAT-, 2024.
http://www.doi.org/10.23728/b2share.4a96fdc741d54ea285eda021df413933
9. European Comission: **Photovoltaic geographical information system.** 2024.
Reference Source

Open Peer Review

Current Peer Review Status: ✗ ✗

Version 1

Reviewer Report 04 February 2026

https://doi.org/10.21956/openreseurope.23147.r68860

© **2026 Hasan S.** This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

✗

Sayeed Hasan
Tallinn University of Technology, Tallinn, Estonia

Beyond optimizing a few scenarios under a predefined cost constraint, the objectives of the study are unclear. The manuscript lacks clarity and coherence, making it difficult for the reader to fully comprehend the proposed work. Overall, the paper does not demonstrate clear or substantial contributions. While the study appears to involve linear-programming-based optimization of an energy system, it lacks clear motivation, well-defined constraints, and strong technical justification.

The literature review is inadequate and does not clearly establish how the proposed work advances beyond existing studies. There is no explicit discussion of the novelty or contribution of the paper relative to the reviewed literature.

Several assumptions in the results section are unrealistic. For example, batteries are implicitly treated as nearly 100% efficient, without accounting for round-trip efficiency, converter losses, or other practical inefficiencies. These assumptions should be revised to reflect realistic operational values.

Furthermore, the assumptions made for each system component are poorly explained. The methodology used to derive these assumptions, as well as their underlying motivation, is unclear. For technologies such as PV, wind turbines, battery energy storage systems (BESS), and hybrid energy storage systems (HESS), extensive literature and market data from reputable sources are readily available; however, these resources are neither sufficiently referenced nor utilized.

Multiple optimization scenarios are considered, but the rationale for selecting these scenarios is not discussed. For instance, in one case, the battery cost is assumed to be one-tenth of the actual market price, yet no justification is provided for this assumption.

The overall writing quality is not adequate for indexing at this level. The authors are strongly encouraged to substantially improve the manuscript's organization, clarity, and technical articulation.

Some of the limitations identified by the authors are, in fact, realistically achievable within a linear programming framework. For example, more comprehensive economic modeling could be incorporated to evaluate long-term operation and return on investment (ROI). Such aspects represent extensions of the optimization formulation rather than inherent limitations or constraints.

Finally, the data repository is incomplete. Not all files referenced in the “Data Availability” section are provided, which prevents reproducibility of the results.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Renewable Energy, Microgrid, DC Systems.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 28 January 2026

https://doi.org/10.21956/openreseurope.23147.r68034

© 2026 Tirkolaee E. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Erfan Babaee Tirkolaee
Istinye University, Istanbul, Turkey

The manuscript presents an LP-based decision support tool as well as a well-documented case study. However, the scientific contribution is not clear, and a limited critical discussion is made. Clarifying novelty, articulation of the literature gap, and enhancing result interpretation would significantly improve the quality of this work. My main comments are as follows:
1. The authors should explicitly state what is new beyond existing optimization models (e.g., modular structure, EV integration, specific scenario logic, or software implementation).
2. The review lists related works, yet it does not clearly state what limitations in prior studies this paper addresses.
3. Many constraint equations are presented with full notation, which interrupts readability. Several of these can be moved to an appendix, while the main text should focus on explaining the model logic conceptually. Moreover, a summary table of variables and parameters is recommended.
4. A sensitivity analysis of key parameters (e.g., battery efficiency) is missing, which will provide a very useful managerial tool for further analysis.
5. Several scenarios use “one tenth of the technology cost” without justification!
6. The research must benefit from a deeper discussion on why certain technologies dominate, and what policy or planning lessons emerge.
7. The model outputs are not compared against real system behavior, other optimization tools, or benchmark studies.
8. All in all, please polish the English of the text. There are recurring issues with long sentences, missing articles, inconsistent tenses, and occasional typos.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Operations Research, Machine Learning, Mathematical Modeling, Fuzzy Programming, Supply Chain Management, Waste Management

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.