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# Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands

## D 5.2 & 5.3 – Report on Life Cycle Assessment and Economic Assessment of ROBINSON case studies

**Lead partner: Paul Scherrer Institut (PSI)**

# Project Contractual Details

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# Executive summary

This report corresponds to the joint Deliverables 5.2 and 5.3 of the ROBINSON project and documents the work performed within Tasks 5.1 and 5.2 that are entitled “Life Cycle Assessment (LCA)” and “Economic Assessment”, respectively. The reason for combining both deliverables in one report is that both the environmental LCA and the economic assessment have been performed together to guarantee consistency. Thus, boundary conditions and input parameters for both assessments are specified in the same way and the analysis of results of both assessments needs to be performed together to allow for the evaluation of co-benefits and trade-offs between environmental and economic aspects.

This document reports all the environmental life cycle and techno-economic assessment results for all three islands (Eigerøy, Western Isles, and Crete) and beyond. As such, it includes the results from different case studies of decentralized energy systems on the three geographical islands. In detail, the report presents the following topics:

- Costs, GHG emissions, and overall environmental burdens of the case studies analyzed.
- Comprehensive figures and table supporting those findings.
- General discussions after evaluating the case studies.
- Implications for future projects and recommendations.

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# List of abbreviations

| | |
|---|---|
| BAU | Business-As-Usual |
| BEV | Battery Electric Vehicle |
| BI | Bakery Industry |
| CAPEX | Capital Expenditures |
| CHP | Combined Heat and Power |
| EMS | Energy Management System |
| GHG | Greenhouse Gas |
| LCI | Life Cycle Inventory |
| LCA | Life Cycle Assessment |
| LCIA | Life Cycle Impact Assessment |
| MES | Multi-Energy System |
| MILP | Mixed Integer Linear Program |
| O&M | Operation & Maintenance |
| OPEX | Operational Expenditures |
| PEM | Polymer Electrolyte Membrane |
| PEMFC | PEM Fuel Cell |
| PV | Photovoltaic |
| WP | Work Package |

# 1. Introduction

The ROBINSON project “smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands” aims at developing integrated energy systems, largely based on renewable energy sources and carriers, to reduce $CO_2$ and GHG emissions, and overall environmental impacts, on geographical islands including industrial symbiosis. Geographical islands can play a crucial role to become a forerunner in the demonstration towards more sustainable decentralized Multi-Energy Systems (MESs), before a large-scale implementation on the mainland. Further, geographical islands are usually isolated and are currently often dependent on imported fossil fuels, which makes them a particularly interesting case study towards full decarbonization through MESs [1], [2]. Here, MESs are used to describe decentralized energy systems on geographical islands since this terminology corresponds to our application that aims at integrating multiple energy vectors, storage technologies, and conversion technologies in the design phase of geographical islands towards full decarbonization.

The aim of ROBINSON is to develop and deploy an Energy Management System (EMS, a report on the validation of the EMS has been completed in ROBINSON D3.4 and D3.5 [3]) for real-time optimization of the integrated, innovative, and cost-efficient MESs. The management operations are based on integrating traditional systems (e.g., connecting the main electrical grid) with local renewable energy sources. However, the work performed in tasks 5.1 and 5.2 as documented in this report extends the current scope by including additional case studies, and their potential performance, beyond traditional systems evaluating (near-) autonomous energy system configurations (without a connection to the power grid) and large-scale hydrogen production systems.

As part of this project, work package 5 has a primary objective to determine the environmental and economic life cycle performance of case studies conducted to enable energy system decarbonization on geographical islands. Deliverable 5.2 and 5.3 corresponds to Task 5.1 that is entitled as “Life Cycle Assessment (LCA)” and “Economic assessment”. LCA is a common methodology used to analyze energy systems and technologies on their total economic and/or environmental performance. The purpose of an LCA and a techno-economic analysis are to determine all environmental impacts and costs, respectively, of a product or service during the entire life cycle. The goal regards the environmental LCA and techno-economic results relate to the demonstration island (i.e. Eigerøy in Norway) and the follower islands (i.e., Crete in Greece and the Western Isles in Scotland).

As such, this report is based on different scientific publications published or submitted to high-impact (international) journals:

1) Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy & Environmental Science, 15(9), 3583-3602. Ref. [4].
2) Terlouw, T., AlSkaif, T., Bauer, C., Mazzotti, M., & McKenna, R. (2023). Designing residential energy systems considering prospective costs and life cycle GHG emissions. Applied Energy, 331, 120362. Ref. [5].
3) Terlouw, T., Gabrielli, P., AlSkaif, T., Bauer, C., McKenna, R., & Mazzotti, M. (2023). Optimal economic and environmental design of multi-energy systems. Applied Energy, 347, 121374. Ref. [6].

4) Terlouw, T., Savvakis, N., Bauer, C., McKenna, R., & Arampatzis, G. (2025). Designing multi-energy systems in Mediterranean regions towards energy autonomy. Applied Energy, 377, 124458. Ref. [7].

The code of the LCA and techno-economic analysis, as well as non-confidential data and the novel developed optimization tool, are available on GitHub[1]. This ensures future usefulness and development of the code and tool beyond ROBINSON. The novelty of the established repository/tool is the full integration of life cycle environmental aspects in a newly developed optimization problem. As such, it enables the possibility to design case studies of decentralized energy systems on geographical islands, and beyond, in a cost- and environmentally-friendly optimal way.

This report is organized as follows:

- Chapter 2 presents general aspects of the three islands.
- Chapter 3 reports the case study, environmental LCA, and techno-economic results for Eigerøy.
- Chapter 4 reports the case study, environmental LCA, and techno-economic results for Crete.
- Chapter 5 reports the case study, environmental LCA, and techno-economic results for Western Isles.
- Chapter 6 provides a general discussion on limitations, replication aspects, and future implications.
- Chapter 7 summarises the key messages and implications of Deliverables 5.2 and 5.3 and provides an outlook for the future usefulness of our work.

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[1] https://github.com/tomterlouw/optimes.

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# 2. General aspects for the three geographical islands

This chapter provides a generic description of the geographical islands involved in ROBINSON. First, Eigerøy is an island in the Eigersund municipality in Rogaland county, Norway. Eigerøy is separated from the mainland by a narrow 13-kilometre long strait. The Eigerøy Bridge crosses the strait, connecting Eigerøy to the mainland. The small island has fish processing industry and other (small) industries.

Second, Lewis and Harris is the largest island in Scotland and belongs to the archipelago of the Outer Hebrides. Furthermore, Lewis and Harris is also the largest British island by extension after Great Britain and Ireland. The main town of Lewis is Stornoway, which is connected by ferries to Ullapool and regular flights to Benbecula, Inverness, Aberdeen, Glasgow, and Edinburgh. Tarbert is connected with ferries to Skye and North Uist.

Third, Crete is a Greek island; the largest and most populous island in the country. Crete is among Greece's main tourist destinations due to its numerous archaeological and naturalistic sites and the particular cultural heritage it possesses, expressed through linguistic, literary, musical and gastronomic specificities. The economy of Crete is mainly based on services and tourism. However, agriculture plays an important role, and Crete is one of the few Greek islands that can independently sustain itself without tourism. As in many regions of Greece, viticulture and olive groves are significant; orange and citron trees are also grown.

*Table 1. Main geographic data*

| **Island** | **Eigerøy - NOR** | **Lewis and Harris - UK** | **Crete - GR** |
|---|---|---|---|
| **Inhabitants** | 2 394 | 19 918 | 623 065 |
| **Surface [km$^2$]** | 19.9 | 2 178 | 8 336 |
| **Latitude [N]** | 58° 26' 16'' | 58° 15' | 35° 9' 21 |

Eigerøy and the Western Isles have an electrical connection to the mainland, while Crete is only partly interconnected (see the case studies in the next section for more explanation).

Despite the different island sizes, in all three cases, the ROBINSON concept would be applied to an industrialized portion of the island, developing an industrial microgrid and evaluating circular economy and industrial symbiosis.

## 2.1 Goals of ROBINSON

The ROBINSON project focuses on a demonstration project on the island of Eigerøy in Norway. The current energy sector in Eigerøy—mainly consisting of industry, some residential households, and mobility—depends on the grid connection and fossil fuels transported from the mainland to Eigerøy (Norway). Nowadays, electricity is transported by underground transmission power cables. The fish industry (Prima Protein)—responsible for 80% of total fossil fuel consumption—has recently expanded at Eigerøy, which required additional electricity demand to avoid an expensive extension of the electricity transmission cables. The primary goal of the ROBINSON project is to reduce the dependency on fossil fuels imported from the mainland and to reduce the consumption of fossil fuels in the LNG boiler — thereby improving the overall environmental and economic performance toward full decarbonization of the energy system in Eigerøy (Norway). The environmental and economic goals of the ROBINSON H2020 project can be summarized as follows:

- $CO_2$ emissions from the total energy sector should be reduced by 20% by the end of the project (2024), aiming to achieve a 100% reduction in the total industry by 2030.
- Fossil fuels used for industrial heat should be reduced by 18.5% at the project's end and 100% by 2030.
- The amount of non-renewables used for loading and unloading boats and cargo should be reduced by 20% at the project's end and 100% by 2030.
- 40% of cars should be fuelled with renewable energy—i.e., electricity or hydrogen—by the end of the project, with 80% by 2030.
- The overall environmental footprint of the island's total energy system should be reduced by 50%.
- The levelized cost of energy on the island should be reduced by at least 30%.
- The system in Eigerøy should be developed using a modular approach to ensure easy application to follower islands (Crete and Western Isles) and other distributed energy systems.

Our work aims to provide tools and insights into whether those goals can be potentially achieved by installing different decarbonization measures. As such, the goals of T5.1 and T5.2 can be summarized as follows.

**T5.1 Life Cycle Assessment (LCA) of energy systems**: Quantify environmental and human health benefits and trade-offs of different energy and EMS concepts compared to a baseline (with fossil fuels and grid connection):

- Assess impacts at regional and global levels.
- Analyze environmental impacts, such as climate change, air quality, and ecosystem quality.
- Use modular LCA design and ecoinvent for background data; Brightway software for calculations.
- Provide new (inventory) data to the public.

**T5.2 Techno-economic assessment of EMS concepts**: Evaluate the economic performance of EMS concepts versus the baseline scenario.

- Consider economic scenarios and indicators such as capital expenditures (CAPEX), operational expenditures (OPEX), annualized costs, and payback period.
- Identify market competition potential and barriers (cost, efficiency, compatibility).

# 3. Eigerøy

This section presents the techno-economic and environmental analysis performed for and the results of the case study in Eigerøy (Norway). The figures and content herein were published in: *Applied Energy*, 347, Terlouw, T., Gabrielli, P., AlSkaif, T., Bauer, C., McKenna, R. & Mazzotti, M. (2023). Optimal economic and environmental design of multi-energy systems, 121374, Copyright Elsevier (2023)[1] licensed under CC BY 4.0[2].

The rest of this chapter describes the case study and scenarios, (briefly) the methods, as well as the results from the environmental LCA and techno-economic analysis.

## 3.1 Multi-Energy System in Eigerøy

Figure 1 shows a schematic of a decentralized MES on the geographical island Eigerøy. The MES comprises hydrogen, natural gas, syngas, and (renewable) electricity as energy sources and carriers and uses a wide set of energy technologies considering grid-connected configurations. This figure shows all technologies considered in the energy system of Eigerøy.

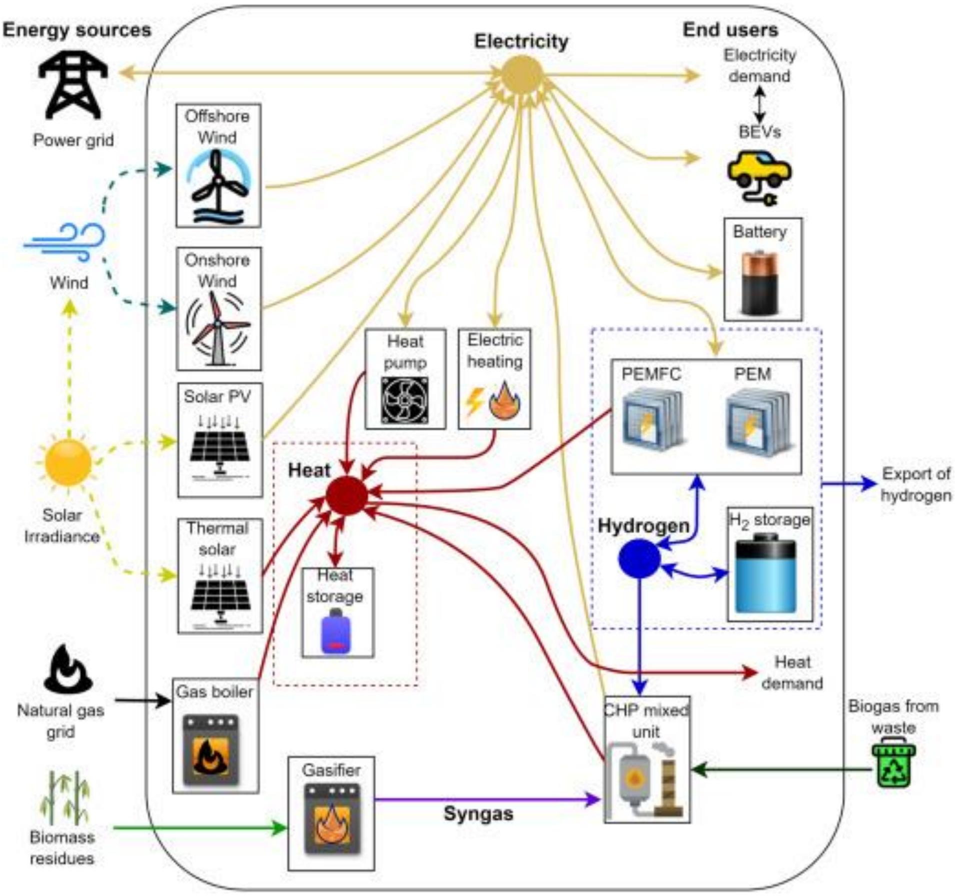

*Figure 1. MES installed on Eigerøy. The figure is obtained from Terlouw et al. [6].*

Notably, a broad portfolio of energy carriers and technologies are considered to enable sector coupling between the residential, industrial, and residential mobility sector. In this MES, electricity

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[1] Terlouw, T., Gabrielli, P., AlSkaif, T., Bauer, C., McKenna, R., & Mazzotti, M. (2023). Optimal economic and environmental design of multi-energy systems. *Applied Energy*, *347*, 121374, 10.1016/j.apenergy.2023.121374. [6].

[2] https://creativecommons.org/licenses/by/4.0/.

can be supplied through various locally installed energy generation technologies, such as onshore and offshore wind, solar PV, or the power grid (when available). Hydrogen production is possible via Polymer Electrolyte Membrane (PEM) electrolyzers powered by the power grid or locally generated renewables. The produced hydrogen can be stored in hydrogen vessels, converted into heat and electricity via an advanced combined heat and power (CHP) unit or a PEM Fuel cell (PEMFC), or exported for use in, for example, transportation (e.g., trucks).

A key component of this multi-energy system is the advanced CHP unit, which can produce both power and high-temperature heat using various low-carbon fuels, such as biogas from biogenic waste, syngas from wood gasification, and hydrogen from the electrolyzer. A gas mixer (not depicted in the figure) is used to mix the gases in the advanced CHP to the appropriate fuel shares. For residential low-temperature heating, alternatives include natural gas boilers, solar thermal heat collectors, fuel cells, electric heaters, and heat pumps. Biogas can be generated from an anaerobic digester, with the waste sourced from residential households or the local (fish) industry.

Additionally, personal transportation is considered, including both Battery Electric Vehicles (BEVs, which serve as flexible loads) and conventional vehicles fuelled by gasoline. It is worth noting that the MES, shown in Figure 1, illustrates a system where all technologies are implemented. In reality, however, many of these technologies are typically excluded from an optimal MES design due to different factors such as cost, environmental considerations, or location-specific constraints.

## 3.2 Optimization problem for designing MESs

Optimization can be used to optimally size and operate MESs on geographical islands during the design phase. As part of tasks 5.1 and 5.2, a novel Mixed Integer Linear Program (MILP) has been developed. MILPs prove to be still mathematical efficient in terms of computational time, while they can be more complex compared to the linear programs. The novel optimization framework includes all technologies described in Figure 1. Here, we briefly describe the optimization problem regarding data requirements, decision variables, and objective function. Interested readers are referred to Terlouw et al. [6] for further reading.

First, the following data is required for the case study in Eigerøy, which has been collected during ROBINSON:

- Hourly weather conditions to determine the output of solar PV, wind power, and residential heat requirements.
- Demand profiles of personal mobility, electricity, and heat. The heat demand profiles consist of separate profiles for residential heat (low-temperature heat) and heat demand required for industrial purposes (high-temperature heat).
- Techno-economic performance of all technologies considered, such as capital expenditures (CAPEX), operation and maintenance (O&M), replacement expenditures, and component lifetimes.
- Energy prices, such as prices of fuels and hourly wholesale electricity prices.
- Environmental Life Cycle Inventory (LCI), which we obtained by either using LCI from an LCA database or by generating new foreground LCI.

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Second, the optimization problem returns different decision variables related to installed capacity of energy technologies, on/off status of conversion technologies, startup and shutdown status of selected technologies (e.g., the advanced CHP), input and output power of technologies, energy stored for storage technologies, and import and export to different grids, such as the power grid, biomass (only import), and hydrogen (only export).

Finally, the optimization problem is designed to consider multiple objectives using one year of system operation. The first objective aims to minimize the total annual cost of the system (measured in €/year), considering one-year time horizon during in which all energy requirements (from residential, industrial, and mobility sector) must be met at each time step. The total annual cost includes several components: annual fuel costs, annualized investments, annual operation and maintenance costs, and annualized replacement costs.

Additionally, we design MESs to minimize their life cycle GHG emissions and other environmental impacts, considering that stricter regulations and policy measures targeting the reduction of GHG emissions and environmental burdens will be widely implemented. We account for environmental burdens from system operation and embodied emissions; the latter are generated during the production and construction of energy system components.

A more detailed description, including equations of the optimization problem, is given in Ref. [6]. Also, the latest version of the optimization framework, including all non-confidential data and code used, will be published on GitHub[1].

## 3.3 Case study and scenarios

The optimization problem is applied to design the MES in Eigerøy, a more generic explanation of the island Eigerøy is given in Section 0. Eigerøy has a grid connection to the mainland with a capacity of 20–30 MW, assumed here to be 22.5 MW [3], [8]. The greenhouse gas (GHG) intensity of electricity from the Norwegian grid is very low nowadays (about 30 $gCO_2/kWh$) [9], due to a large share of hydropower in the Norwegian electricity mix.

The primary energy consumer in Eigerøy is the local fish industry, particularly Prima Protein, located at the harbour, which requires around 40 GWh of high-temperature heat annually. The overall electricity demand is approximately 70 GWh per year. Currently, the fish industry meets its heat demand with a natural gas/propane boiler, which poses the most significant opportunity for decarbonization. Eigerøy also has a woody biomass resource of around 52 tons per day, with an energy density of 3.5 MWh/ton [3], [8]. Additionally, biogas production is estimated at 5 W per capita [10], generated by an anaerobic digester.

Most residents use an electric-based heating system, with 78% of households relying on electricity, half of which is assumed to come from heat pumps, and the other half from electric heaters. Wood stoves or biomass boilers meet the remainder of the residential heating requirement. Due to restrictions on fossil-fuel-based residential heating in Norway, fossil fuel-burning technologies are excluded from our optimization. In the municipality of Eigerøy (Eigersund), personal transport is still largely dominated by fossil fuels (85%, mainly gasoline vehicles), with battery electric vehicles (BEVs)

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[1] Repository available at: https://github.com/tomterlouw/optimes.

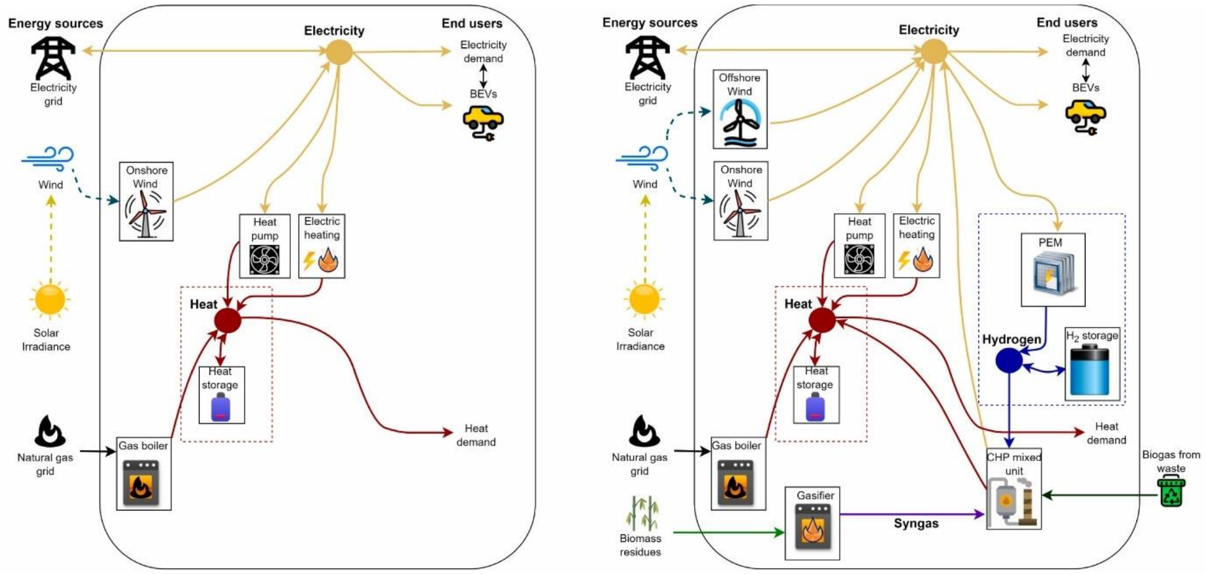
accounting for the remaining 15%. This current state is called the “Business-As-Usual” (BAU) scenario, reflecting the conditions and costs of the energy system in Eigerøy of 2021.

Several possible design scenarios are considered in the optimization process, including two scenarios focusing on the residential sector that exclude high-temperature heat (from Prima Protein) to assess its impact on the design problem. These scenarios are referred to as “Cost-Min-Res” and “Cost-Min-Res-M”. Additionally, a scenario focused on significant GHG emission reductions (90% reduction that can be reached on the Pareto front) within the optimization, called “Cost-GHG90”, is considered. This scenario is of particular interest because the latter part of the Pareto front typically exhibits steep cost increases for little GHG reductions. Here, the main environmental focus is on life cycle GHG emissions, with other environmental impact categories quantified in a post-processing LCA, which are based on the optimal technology sizes and system operations identified in the cost and GHG emission optimization. Thus, although these other environmental impacts are not included in the initial optimization, they are quantified after the optimization to evaluate co-benefits and trade-offs of decarbonization.

Overall, for the comparison between the current energy system (baseline, i.e., BAU) and potential design alternatives, the following scenarios are considered (see x-axis in Figure 3):

- **BAU**: represents the current energy system of Eigerøy in 2021, mainly consuming fossil fuels for heat and low-carbon electricity from the Norwegian grid.
- **Cost-Min-Res**: is a minimum-cost optimization for the residential sector, which excludes environmental considerations in the objective function and excludes high-temperature heat requirements and personal transport (but includes power requirements of the geographical island).
- **Cost-Min-Res-M**: is a minimum-cost optimization for the residential sector, which excludes environmental considerations in the objective function and excludes high-temperature heat requirements.
- **Cost-Min**: is a minimum-cost optimization for all sectors, which excludes environmental considerations in the objective function.
- **Cost-GHG90**: is a minimum-cost optimization for all sectors, with a constraint on life cycle GHG emissions to reach a reduction of 90% compared to a cost optimization (which can be reached on the Pareto front).
- **GHG-Min**: is an optimization of life cycle GHG emissions for all sectors, which excludes cost considerations in the objective function.

Next, the results are presented for these different scenarios considered for Eigerøy.



(a) Optimization on costs (*Cost-Min*). (b) Optimization of life cycle GHG emissions (*GHG-Min*).

*Figure 2. Optimal MES design in Eigerøy for a minimization of costs (left) and life cycle GHG emissions (right). The figure is obtained from Terlouw et al. [6].*

## 3.4 Results

Figure 2 illustrates the optimal MES designs for a minimum-cost (Scenario 4) and minimum-GHG emission (Scenario 6) scenario across all energy sectors considered. The cost-optimal design (Figure 2 (a)) includes GHG-intensive technologies, such as natural gas boilers for heat generation. Interestingly, onshore wind has proven to be already a cost-effective electricity generation option for Eigerøy due to high availbility of wind throughout the year. This cost-optimal design reaches a 14% reduction in costs and a 26% reduction in life cycle GHG emissions compared to the 'BAU' scenario.

In contrast, the minimum-emissions design (Figure 2(b)) features a more complex energy system with diverse energy conversion and storage technologies, including hydrogen, syngas, and electricity. This approach reduces life cycle GHG emissions by nearly 80% compared to the 'BAU' scenario, even with a decarbonized Norwegian power grid. However, this significant reduction in emissions comes with a 59% increase in terms of annual costs.

Figure 3 illustrates the major cost and emissions contributions to the overall expenses and life cycle GHG emissions across all considered scenarios in Eigerøy (see previous paragraph), with each segment of the stacked bars represented in different colors. The scenarios are displayed on the x-axis, annual costs on the primary y-axis, and life cycle GHG emissions on the secondary y-axis. For each scenario, the left bar shows the cost contributions, while the right bar illustrates life cycle GHG emissions. The values above the bars indicate the investment contributions to the overall costs (left bar) and the contributions of embodied emissions to the overall life cycle GHG emissions (right bar). Please note that the second and third scenarios exclude high-temperature heat; the second scenario ('Cost-Min-Res') also excludes personal transport. These scenarios are highlighted with a light grey shaded area.

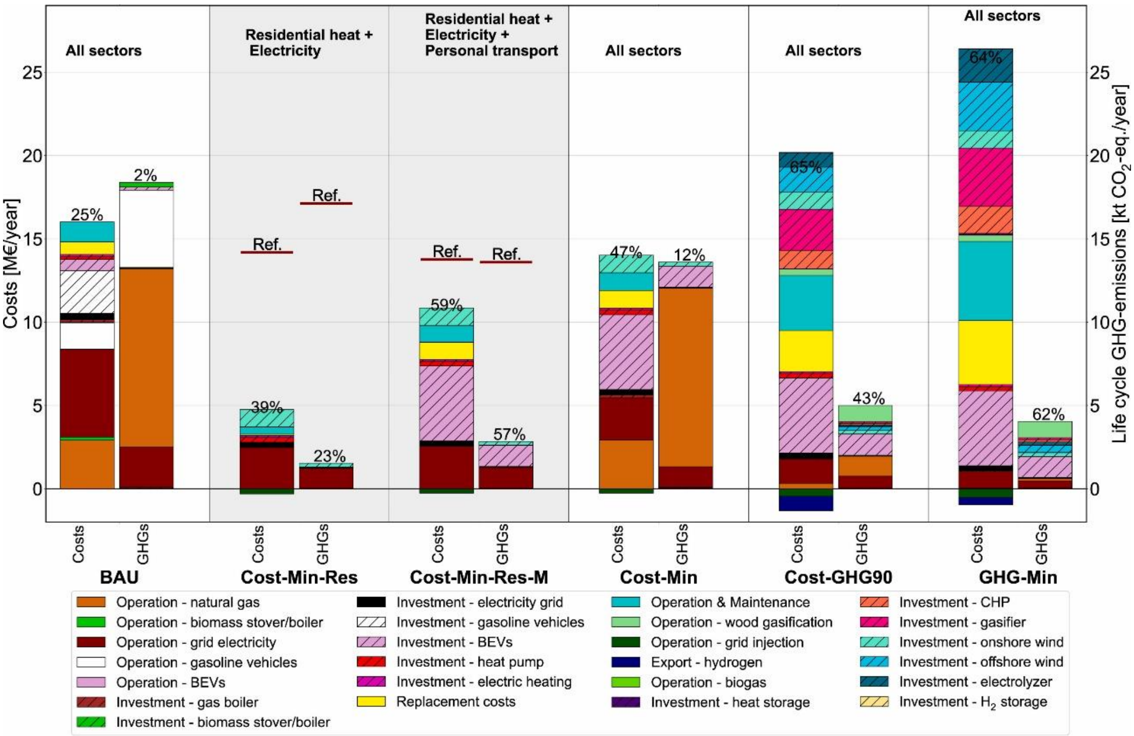


*Figure 3. Main results for costs and life cycle GHG emissions. The figure is obtained from Terlouw et al. [6].*

This latter figure highlights the following findings. First, the optimal design relies heavily on integrating different energy sectors, shown by the shift from scenario ‘BAU’ to ‘Cost-Min’ in Figure 3. Including the industrial and mobility sectors more than doubles the costs and life cycle GHG emissions, requiring additional energy technologies, such as natural gas boilers, advanced CHP units, and hydrogen systems.

Second, Figure 3 reveals that the construction phase can significantly impact total environmental burdens, contributing up to 60% of GHG emissions in low-carbon MES designs. However, this impact could reach 80%, e.g., for human toxicity, metals & minerals, and ozone depletion, highlighting the need to consider embodied (life cycle) emissions in MES analyses.

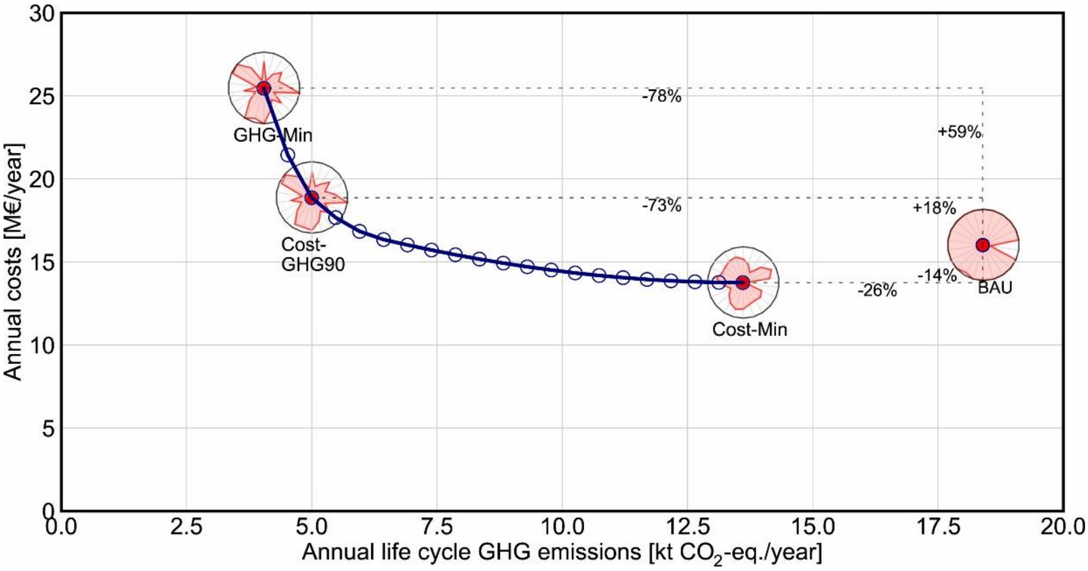


*Figure 4. Pareto front for the case study in Eigerøy. The figure is obtained from Terlouw et al. [6].*

Figure 4 illustrates a Pareto front for the two objectives considered: an optimization on life cycle GHG emissions (on the x-axis) and costs (on the y-axis). Four small spider graphs are presented in the background of these points, representing the scenarios discussed previously, to indicate the environmental performance of these four scenarios.

*Table 2. Techno-economic system performance and design.*

| Technology | Sub | BAU | Cost-Min-Res | Cost-Min-Res-M | Cost-Min | Cost-GHG90 | GHG-Min | Unit |
|---|---|---|---|---|---|---|---|---|
| **Energy generation** | | | | | | | | |
| **Solar PV** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MW] |
| **Onshore wind** | | 0.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | [MW] |
| **Offshore wind** | | 0.0 | 0.0 | 0.0 | 0.0 | 6.8 | 13.4 | [MW] |
| **Solar Thermal** | Residential | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [ha] |
| **Energy storage** | | | | | | | | |
| **Battery electricity** | Energy | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MWh] |
| | Power | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MW] |
| **Hydrogen** | | 0.0 | 0.0 | 0.0 | 0.0 | 19.3 | 20.5 | [MWh] |
| **Heat** | Residential | 0.0 | 1.2 | 1.1 | 1.1 | 2.7 | 12.5 | [MWh] |
| **Energy conversion** | | | | | | | | |
| **Electrolyzer** | | 0.0 | 0.0 | 0.0 | 0.0 | 9.8 | 22.4 | [MW$_f$] |
| **Fuel cell** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MW$_f$] |
| **Gas boiler** | Industrial | 19.4 | 0.0 | 0.0 | 19.4 | 7.4 | 7.4 | [MW$_f$] |
| | Residential | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MW$_f$] |
| **Heat pump** | Residential | 1.5 | 2.2 | 2.2 | 2.2 | 2.3 | 2.0 | [MW$_{th}$] |
| **Electric heating** | Residential | 1.5 | 1.4 | 1.4 | 1.4 | 1.3 | 1.6 | [MW$_f$] |
| **Wood gasification** | Industrial | 0.0 | 0.0 | 0.0 | 0.0 | 21.8 | 31.0 | [MW$_f$] |
| **Mixed CHP** | Industrial | 0.0 | 0.0 | 0.0 | 0.0 | 24.4 | 36.0 | [MW$_f$] |
| **Others** | | | | | | | | |
| **Grid connection** | | 22.5 | 19.8 | 19.8 | 19.8 | 19.3 | 18.3 | [MW] |
| **Performance** | | | | | | | | |
| **Total costs** | | 16.0 | 4.5 | 10.6 | 13.8 | 18.9 | 25.5 | [M€] |
| **Total GHGs** | | 18.4 | 1.5 | 2.8 | 13.6 | 5.0 | 4.0 | [kt CO$_2$-eq.] |
| **Grid reliance** | | n.a. | n.a. | n.a. | -49.1 | -71.4 | -82.5 | [Δ%] |
| **Natural gas reliance** | | n.a. | n.a. | n.a. | -28.2 | -92.0 | -99.2 | [Δ%] |

Figure 4 shows that optimizing for system costs can significantly reduce overall expenses, while life cycle GHG emissions decrease throughout the Pareto front compared to scenario 'BAU'. This is due to integrating cost-effective and low-carbon technologies, such as onshore wind, residential heat pumps, indicating that the BAU system is sub-optimal in terms of both costs and GHG emissions.

However, the optimal design strongly varies, with different design options exhibiting different energy systems, see Table 2. Minimizing GHG emissions with 'GHG-Min' increases costs due to deploying low-carbon energy technologies, which are not cost-effective (yet) compared to conventional alternatives, such as biomass-driven CHP. Energy storage mainly involves hydrogen and heat storage, with no battery storage, and all scenarios show less reliance on grid electricity and natural gas.

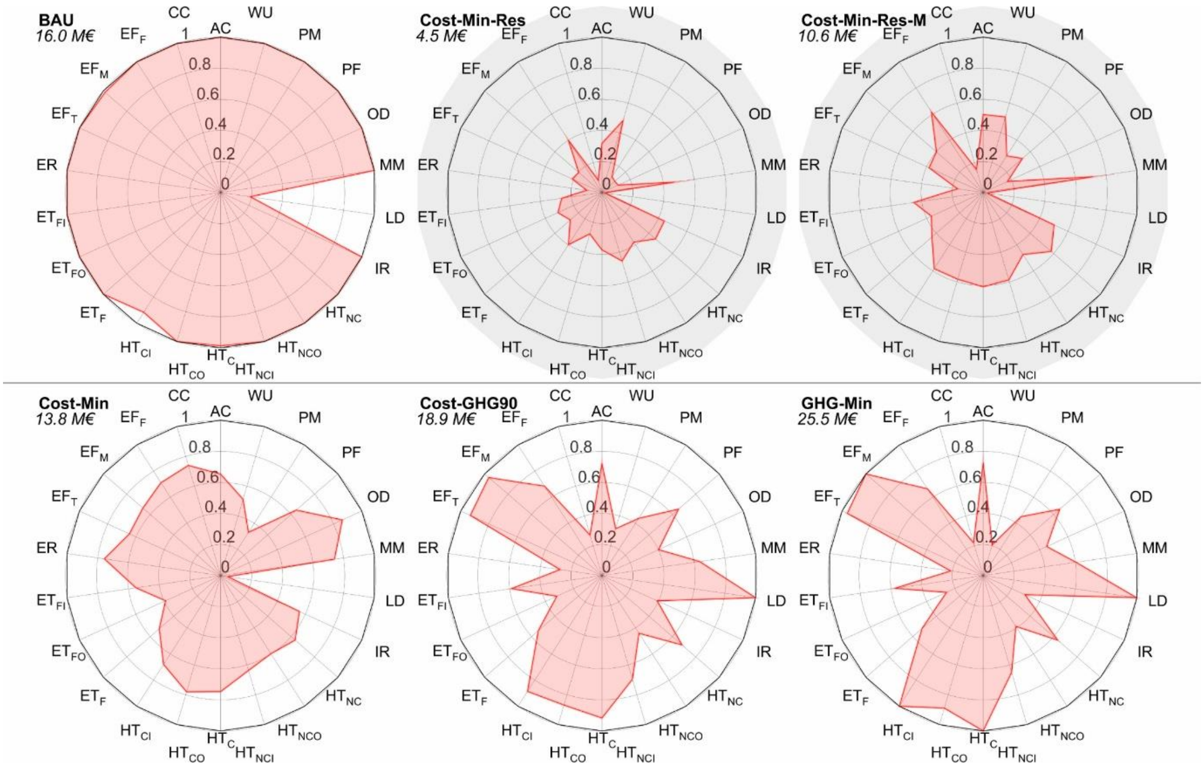


*Figure 5. Spider graph for the different scenarios considered and associated life cycle environmental burdens on selected normalized environmental impact categories. LD = land transformation. AC = acidification. CC = climate change. $ET_F$ = ecotoxicity: freshwater. $ET_{FI}$ = ecotoxicity: freshwater, inorganics. $ET_{FO}$ = ecotoxicity: freshwater, organics. ER = energy resources: non-renewable. $EF_F$ = eutrophication: freshwater. $EF_M$ = eutrophication: marine. $EF_T$ = eutrophication: terrestrial. $HT_C$ = human toxicity: carcinogenic. $HT_{CI}$ = human toxicity: carcinogenic, inorganics. $HT_{CO}$ = human toxicity: carcinogenic, organics. $HT_{NC}$ = human toxicity: non-carcinogenic. $HT_{NCO}$ = human toxicity: non-carcinogenic, organics. $HT_{NCI}$ = human toxicity: non-carcinogenic, inorganics. IR = ionizing radiation: human health. MM = material resources: metals/minerals. OD = ozone depletion. PM = particulate matter formation. PF = photochemical oxidant formation: human health. WU = water use. The figure is obtained from Terlouw et al. [6].*

Figure 5 shows the environmental burdens for all considered impact categories considered of the six optimization scenarios. These impacts are also given in the background of Figure 4. The values are normalized to the highest impact observed in each category throughout all scenarios; with the scale ranging from “0” to “1”, where “1” represents the maximum impact obtained.

The latter figure demonstrates that the BAU scenario has the highest environmental burdens compared to all other scenarios. This indicates that optimal MES designs can significantly reduce environmental impacts. Interestingly, a cost-minimization approach (‘Cost-Min’) also substantially reduces environmental burdens, as some low-carbon energy generation technologies, such as onshore wind, are already cost-competitive. In our case study, environmental impact categories that increase with cost minimization include climate change, non-renewable energy resources, ionizing radiation, and ozone depletion. In contrast, environmental categories that increase its impact with GHG minimization include land transformation, eutrophication, and some human toxicity impacts. However, these trade-offs are very specific to the case study and depend on location-specific conditions, such as the local climate and renewable energy potential (e.g., biomass, solar PV, and wind).

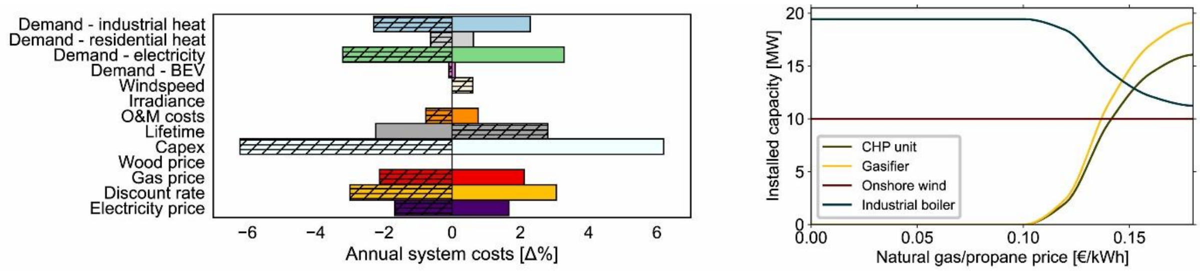
Minimizing life cycle GHG emissions (‘GHG-Min’) results in higher costs and increased environmental burdens in some categories compared to the BAU scenario. This suggests that focusing on GHG emission reduction can shift environmental burdens to other impact categories, such as land use for biomass utilization. Overall, the results indicate that minimizing costs or life cycle GHG emissions does not necessarily lead to an equal reduction in the overall environmental footprint. A comprehensive

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 957752. This publication reflects only the author’s views and the European Union is not liable for any use that may be made of the information contained therein.

environmental assessment should always include additional environmental indicators such as land use, toxicity, and material impacts.

### 3.4.1 Sensitivity analysis

Finally, a sensitivity analysis has been conducted in Figure 6 by adjusting selected parameters by 10% to identify the most critical factors influencing annual MES costs. Parameters changed include electricity and heat demand (residential and industrial), discount rate, grid electricity price, gas price, wood price, capital expenditures (capex), technology lifetimes, operation and maintenance (O&M) costs, average annual solar irradiance, and wind speed. Figure 6(a) shows how annual system costs are affected by these parameters when varied by minus and plus 10% from their reference figures. Figure 6(b) highlights the sensitivity of system design, specifically the installed capacities of advanced CHP units, gasifiers, onshore wind, and industrial boilers, to changes in natural gas/propane prices.



(a) Sensitivity of annual system costs (percentage variation, for a cost optimization) when selected parameters are increased (the non-hatched bars) and decreased by 10% (the hatched bars).

(b) Sensitivity of installed capacities for selected technologies for an absolute increase in natural gas prices.

*Figure 6. Sensitivity analysis on selected fixed input parameters, with special attention to natural gas prices on the right. The figure is obtained from Terlouw et al.* [6].

Figure 6(a) indicates that increases in capital expenditures have the greatest impact on annual costs, mainly due to investments in personal transport. Increased heat and electricity demand, driven largely by the local fish industry, also significantly affects costs. The discount rate is crucial in a cost-optimization due to its effect on capital expenditures. Among fuel prices, natural gas has the largest impact, remaining a common energy source due to its lower cost than alternatives. Rising natural gas and grid electricity prices substantially affect annual costs due to high operational energy needs. Extended technology lifetimes reduce annual costs by decreasing replacement expenditures. Figure 6(b) shows that the advanced CHP unit becomes cost-competitive with natural gas/propane prices above 0.12 €/kWh (0.07 €/kWh assumed in main analysis), reducing the energy delivered by fossil-fuelled industrial boilers for high-temperature heat provision.

## 3.5 Key take-aways

Finally, we provide the following key take-aways from the case study in Eigerøy:

- The energy system on Eigerøy represents significant opportunities for decarbonization, particularly by switching from natural gas boilers in the Fish industry to low-carbon technologies, such as the advanced CHP unit using renewable or low-carbon fuels. The optimal design scenarios show that life cycle GHG emissions can be reduced by up to 80% compared to the BAU scenario, though this might come with substantial increases in costs (59%). Those trade-offs should be analyzed during the design phase, e.g., by cost and GHG optimization, and potentially integrating other environmental indicators.

- Onshore wind is identified as a cost-effective option for electricity generation in Eigerøy due to high wind availability. The cost-optimal scenario achieves a 14% reduction in costs and a

26% reduction in GHG emissions compared to the BAU scenario. In reality, however, constraints related to social acceptance limit the integration of onshore wind.

- Minimizing life cycle GHG emissions reduces various environmental impacts. However, it might increase others, such as land use, eutrophication, and human toxicity. This suggests that focusing solely on GHG reductions may shift environmental burdens to other impact categories, implying that future assessments should integrate a full life-cycle approach in their analysis.

- The analysis shows that embodied emissions (i.e., the construction phase) can significantly contribute to the overall environmental burdens, contributing up to 60% of GHG emissions in low-carbon MES designs, and up to 80% for impacts like human toxicity and ozone depletion. Thus, a full-life cycle approach is essential to capture those aspects.

- The sensitivity analysis indicates that capital expenditures, natural gas prices, and electricity demand (especially from the local fish industry) are the most critical factors influencing annual system costs in Eigerøy. Adjustments in these parameters can significantly change the cost-effectiveness of various energy technologies, particularly in scenarios involving high capital investments. Thus, selecting the right cost values is key to providing reliable results, and a sensitivity analysis should be integrated in such an analysis.

# 4. Crete

This section presents the analysis performed for and the results of the case study in Crete (Greece). The figures and content herein were published in: *Applied Energy*, 377, Terlouw, T., Savvakis, N., Bauer, C., McKenna, R., & Arampatzis, G. (2025), *Designing multi-energy systems in Mediterranean regions towards energy autonomy*, 124458, Copyright Elsevier (2025) licensed under CC BY 4.0[1].

The rest of this chapter describes the case study and scenarios, (briefly) the methods, as well as the results from the environmental LCA and techno-economic analysis.

## 4.1 Multi-Energy System in Crete

Figure 7 shows the layout of a decentralized MES in Crete, illustrating various technologies that can be installed for island decarbonization. This system can integrate several technologies for energy generation, conversion, and storage.

Electricity can be locally generated by installing onshore wind, offshore wind, and solar PV systems. Additionally, this locally produced electricity can be fed into the local power grid, which could also supply the MES if connected to the larger power grid network. However, entirely off-grid MESs would not have this option, which means no power grid connection. Heat can be produced locally as well, using solar thermal systems.

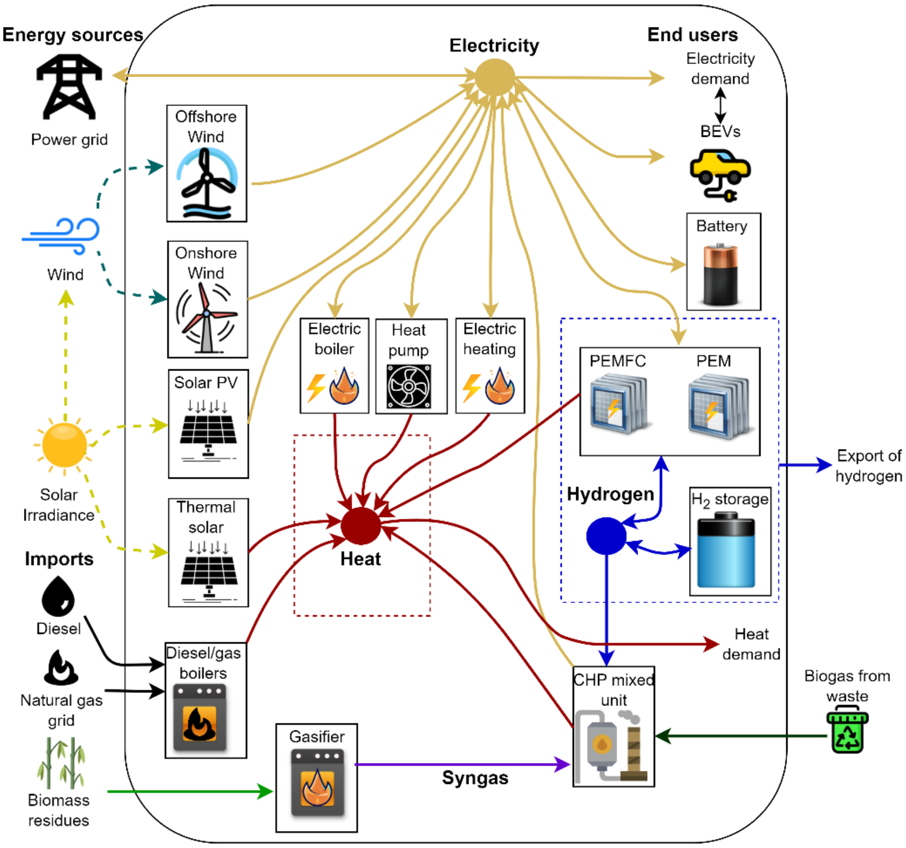


*Figure 7. MES installed in Crete including all possible energy technologies that can be installed. This figure has been adapted and is reproduced from Ref. [6]. The figure is published in Terlouw et al. (2025) [7].*

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This MES in Crete features a wide variety of conversion technologies. Alternatives for converting electricity into heat include electric boilers, residential electric heaters, and air-source heat pumps. It is essential to differentiate between low-temperature heat (below 100°C), typically used in residential applications, and high-temperature heat (above 100°C), which is typically required for industrial processes. Diesel boilers, electric boilers, or advanced CHP units can generate high-temperature heat. These advanced CHP can utilize hydrogen, syngas (a mix of CO and $H_2$ from biomass gasification), and biogas ($CH_4$ and $CO_2$ from anaerobic digestion), with the gases mixed by using a gas mixing unit.

Hydrogen might play a key role in decarbonizing decentralized MESs [4], [6]. As such, PEM electrolyzers and PEMFCs can be installed to generate hydrogen and convert it back into heat and electricity, respectively. The MES includes various energy storage technologies to enhance operational flexibility, including long-term hydrogen storage and batteries. For residential mobility, options include gasoline vehicles or BEVs.

## 4.2 Optimization problem for designing MESs

The MILP formulation is originally developed in Ref. [6]. The MILP is implemented in Python (v.3.10.6) and optimized using Gurobi (v.11) [11], covering a 8760-hour period with hourly resolution to consider long-term (hydrogen) energy storage.

Additional attention is given to the advanced CHP unit, which can utilize syngas, hydrogen, and biogas to produce low-carbon electricity and high-temperature heat for the local industry. This unit, along with the wood gasifier, is modelled with considerations for part load ratios and minimum up- and downtimes to prevent potential component degradation. Other energy conversions technologies, such as fuel cells, electrolyzers, electric heaters, gas and electric boilers, and heat pumps, are modelled based on their energy efficiency ratios. For energy generation technologies, factors such as curtailment and local weather data, derived from a typical meteorological year, are considered.

Battery and hydrogen storage are modelled considering their charging times, self-discharge rates, and storage limits to avoid additional battery degradation. Residential mobility is considered, by introducing BEVs (as flexible loads) and gasoline vehicles. The main updates compared to the previous MES optimization approach (Ref. [6]) include:

- Residential heat storage is excluded due to the limited heating requirement of only five months.
- Cooling demand (air conditioning) is considered in the residential power demand to reflect the increased power needs during the summer months in the Mediterranean climate.
- Two new technologies—diesel and electric boilers—are introduced to possibly provide high-temperature heat to the local bakery industry.
- Only two out of three high-temperature heat technologies (CHP, electric, and diesel) can be installed to simplify system integration. This constraint is implemented by using binary variables.

## 4.3 Case study and scenarios

The case study area in Crete (Kissamos) is characterized by a Mediterranean climate, which experiences mild winters and abundant sunshine throughout the entire year. The solar potential is estimated at 1680–1890 kWh/m²/year [12], thus, it is favorable for solar PV installations. The geographical area in Kissamos also includes 8,042 hectares of olive groves, which provide a significant biomass resource for sustainable energy through, e.g., for gasification or combustion of biomass. The Kissamos area (1,233 inhabitants) is mainly driven by greenhouse crops, olive oil, wine production, tourism, and animal husbandry. The households have a total annual power demand of 2.37 GWh (see Table 3) and a low-temperature heat demand of 0.86 GWh per year. The local bakery industry, a major economic driver in the area, consumes 1.06 GWh of power annually (42% from July to October) [13], where 74% of its total energy consumption is heat used in baking processes at temperatures above 150°C, resulting in 3.04 GWh/a [13]. The total power demand for the MES is 3.43 GWh per year. For residential mobility, only BEVs are considered flexible power demand (one per household, driving 35 km daily), using charging schedules from Ref. [5]. Other energy demands are assumed to be non-flexible.

*Table 3. Description of scenarios and assumptions considered.*

| Scenario | Industrial | Residential | Mobility | Location-specific regulations | Power grid | Cost opt. | GHG opt. | High-temperature heat demand [GWh] | Low-temperature heat demand [GWh] | Power demand [GWh] |
|---|---|---|---|---|---|---|---|---|---|---|
| **BAU (BI)** | x | | | | x | | | 3.04 | 0 | 1.06 |
| **Cost-Min (BI)** | x | | | | x | x | | 3.04 | 0 | 1.06 |
| **Cost-Min-Constr (BI)** | x | | | x | x | x | | 3.04 | 0 | 1.06 |
| **BAU** | x | x | x | | x | | | 3.04 | 0.86 | 3.43 |
| **Cost-Min** | x | x | x | | x | x | | 3.04 | 0.86 | 3.43 |
| **Cost-Min-Constr** | x | x | x | x | x | x | | 3.04 | 0.86 | 3.43 |
| **GHG-Min** | x | x | x | | x | | x | 3.04 | 0.86 | 3.43 |
| **Off-Grid** | x | x | x | | | x | | 3.04 | 0.86 | 3.43 |
| **Balanced Autonomy** | x | x | x | | x | x | | 3.04 | 0.86 | 3.43 |

Legal restrictions appear in Crete on renewable energy system installations, such as a limit on autonomous solar PV installations with a maximum of up to 500 kW. Further, autonomous wind turbines are restricted up to 60 kW under a net metering scheme.

When comparing different MES design options, different scenarios are considered, including those focused on the bakery industry (BI), which requires high-temperature heat. Further, larger-scale MES scenarios are included considering the industry, residential households, and residential (personal) mobility sectors. Due to different system boundaries, direct comparisons are challenging. Table 3 summarizes these scenarios and their energy demands. The BAU is used as a baseline for comparison with the design scenarios given below:

- **BAU (BI)**: The current energy system for the bakery industry in 2022, relying on fossil fuels (diesel boiler) and GHG-intensive power from the local Cretan grid.
- **Cost-Min (BI)**: Minimum-cost optimization for the bakery industry, excluding environmental factors and location-specific regulations.
- **Cost-Min-Constr (BI)**: Minimum-cost optimization for the bakery industry, excluding environmental factors but considering current local regulations (i.e., max. 0.5 MW solar PV, 0.06 MW onshore wind, with a micro wind turbine).

- **BAU**: The current energy system for the entire MES in 2022, including the bakery industry, residential power, cooling, heating, and mobility, relying on fossil fuels and GHG-intensive power from the Cretan grid.
- **Cost-Min**: Minimum-cost optimization for the entire MES, excluding environmental factors and location-specific regulations.
- **Cost-Min-Constr**: Minimum-cost optimization for the entire MES, excluding environmental factors but considering local regulations regarding maximum renewable capacity for onshore wind and solar PV.
- **GHG-Min**: Optimization focusing on minimizing life cycle GHG emissions, excluding cost considerations and location-specific regulations for solar PV and onshore wind capacity.
- **Off-grid**: Minimum-cost optimization for the entire MES without a connection to power and gas grids, operating entirely off-grid and excluding power and hydrogen export.
- **Balanced Autonomy**: Minimum-cost optimization for the entire MES with connections to power and gas grids, ensuring that local renewable power production (from solar PV, wind, and biomass) meets or exceeds annual power consumption, achieving balanced autonomy. This scenario does not allow hydrogen export.

## 4.4 Results

Figure 8 compares the cost and life cycle GHG emissions between the eight scenarios, with the left subplot focusing on the industrial sector and the right illustrating the entire MES. Each scenario includes two stacked bars—annual cost on the left and annual GHG emissions on the right. The colored stack segments represent contributions from different technologies and energy carriers. Dashed lines (with percentages) indicate changes in cost due to location-specific regulations versus ‘unconstrained’ conditions.

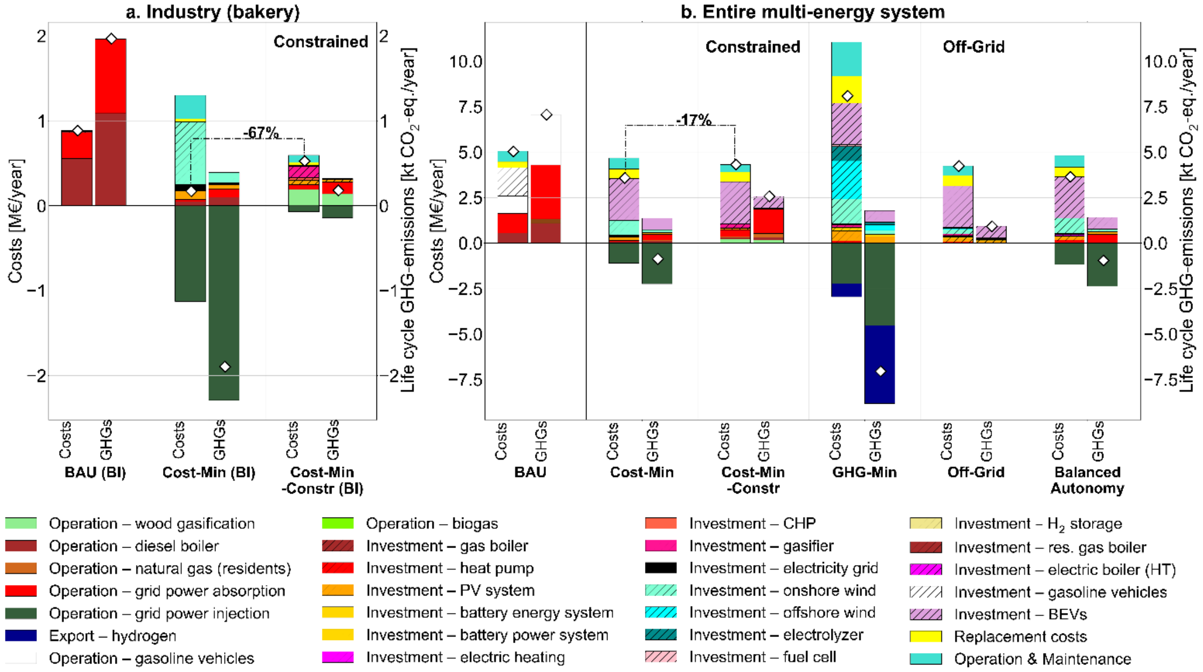


*Figure 8. Overall results: annual cost and life cycle GHG emissions of optimal MES designs in Crete. The diamond markers represent the net annual costs and GHG emissions. The figure is published in Terlouw et al. (2025) [7].*

The results reveal that implementing MESs can significantly reduce costs and GHG emissions in Crete. For the bakery industry, costs can be reduced by up to 81%, while the entire MES could reach a 30% cost reduction compared to the BAU scenarios. Even under location-specific regulations and constraints, cost and GHG reductions are substantial, although cost savings for the entire MES are halved to approximately € 0.8 million.

Current regulations, such as limits on wind and solar PV capacity, reduce the decarbonization potential, primarily due to restrictions on exporting power to the grid. An unconstrained design, however, could reduce costs by over 67% through the potential export of locally generated renewable energy.

*Table 4. Techno-economic results and technology sizing of the different scenarios considered.*

| Technology | Sub | BAU (BI) | Cost-Min (BI) | Cost-Min - Constr (BI) | BAU | Cost-Min | Cost-Min - Constr | GHG-Min | Off-Grid | Balanced Autonomy | Units |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Energy Generation** | | | | | | | | | | | |
| **Solar PV** | | 0.0 | 1.0 | 0.5 | 0.0 | 1.7 | 0.5 | 6.4 | 2.2 | 2.2 | [MW] |
| **Onshore wind** | | 0.0 | 5.4 | 0.1 | 0.0 | 5.9 | 0.1 | 10.0 | 1.9 | 6.1 | [MW] |
| **Offshore wind** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.6 | 0.2 | 0.0 | [MW] |
| **Solar Thermal** | Residential | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [ha] |
| **Energy Storage** | | | | | | | | | | | |
| **Battery electricity** | Energy | 0.0 | 0.2 | 0.3 | 0.0 | 0.9 | 1.5 | 7.8 | 4.5 | 1.9 | [MWh] |
| | Power | 0.0 | 0.1 | 0.1 | 0.0 | 0.3 | 0.5 | 2.3 | 1.1 | 0.6 | [MW] |
| **Hydrogen** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 20.9 | 46.6 | 0.0 | [MWh] |
| **Energy Conversion** | | | | | | | | | | | |
| **Electrolyzer** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 4.9 | 0.1 | 0.0 | [MW$_f$] |
| **Fuel cell** | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.1 | 0.0 | [MW$_f$] |
| **Diesel boiler** | Industrial | 1.3 | 0.6 | 0.0 | 1.3 | 0.6 | 0.8 | 0.0 | 0.0 | 0.0 | [MW$_f$] |
| **Electric boiler** | Industrial | 0.0 | 0.9 | 0.8 | 0.0 | 0.9 | 0.0 | 1.0 | 0.9 | 1.1 | [MW$_f$] |
| **Gas boiler** | Residential | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.9 | 0.0 | 0.0 | 0.0 | [MW$_f$] |
| **Heat pump** | Residential | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.1 | 0.1 | [MW$_f$] |
| **Wood gasification** | Industrial | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 1.1 | 0.7 | 0.4 | 0.0 | [MW$_f$] |
| **Advanced CHP** | Industrial | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.9 | 0.7 | 0.9 | 0.0 | [MW$_f$] |
| **Electric heating** | Residential | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 0.0 | 0.1 | 0.5 | 0.6 | [MW$_f$] |
| **Oil boiler** | Residential | 0.0 | 0.0 | 0.0 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | [MW$_f$] |
| **Others** | | | | | | | | | | | |
| **Grid connection** | | 0.3 | 5.0 | 0.5 | 1.5 | 5.0 | 1.1 | 5.0 | 0.0 | 5.0 | [MW] |
| **Performance** | | | | | | | | | | | |
| **Total costs** | | 0.88 | 0.17 | 0.53 | 5.16 | 3.59 | 4.32 | 8.09 | 4.23 | 3.64 | [M€] |
| **Total GHGs** | | 1.97 | -1.90 | 0.18 | 7.07 | -0.86 | 2.57 | -7.04 | 0.92 | -0.96 | [kt CO$_2$ -eq.] |
| **Curtailment** | Solar PV | 0.00 | 0.09 | 0.00 | 0.00 | 0.11 | 0.00 | 0.45 | 0.25 | 0.12 | [-] |
| **Curtailment** | Onshore | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.35 | 0.32 | 0.01 | [-] |
| **Curtailment** | Offshore | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.74 | 0.00 | [-] |

Optimal MES designs differ substantially between scenarios in Crete, see Table 4. Unconstrained cost minimization for the entire MES favours solar PV, onshore wind, and batteries, while constrained scenarios rely more on fossil-fuel-based technologies due to significant limitations on renewables. Unconstrained GHG optimization results in a more complex MESs integrating various low-carbon fuels, storage, and renewables, with increased energy storage and curtailment. Off-grid MESs show promising potential for total decarbonization with a marginal 15% cost increase, although they require significant upfront investments. These systems can reduce life cycle GHG emissions by 87% compared to the BAU. However, such configurations might involve some environmental trade-offs.

Figure 9 illustrates six spider graphs showing the environmental trade-offs of the optimal MES designs across the six scenarios. The impacts are normalized against the scenario with the highest impact in each category. The BAU scenario shows the worst overall environmental performance, with the largest dark blue area, driven by substantial fossil fuel utilization and GHG-intensive grid electricity. In contrast, scenarios with energy export, especially those allowing a power grid connection and hydrogen export, show avoided environmental burdens (negative impacts, thus shown as ‘zero’ impact). Optimization scenarios generally reduce environmental burdens due to the increased implementation of cost-effective solar PV and onshore wind resulting in lower environmental burdens for most environmental impact categories. However, the ‘Cost-Min-Constr’ scenario faces trade-offs in land use, mainly from biomass needed for the advanced CHP to generate industrial high-temperature heat. Off-grid MESs exhibit trade-offs in material use, water consumption, and human toxicity due to the oversizing of renewables (and curtailment) and energy storage installations.

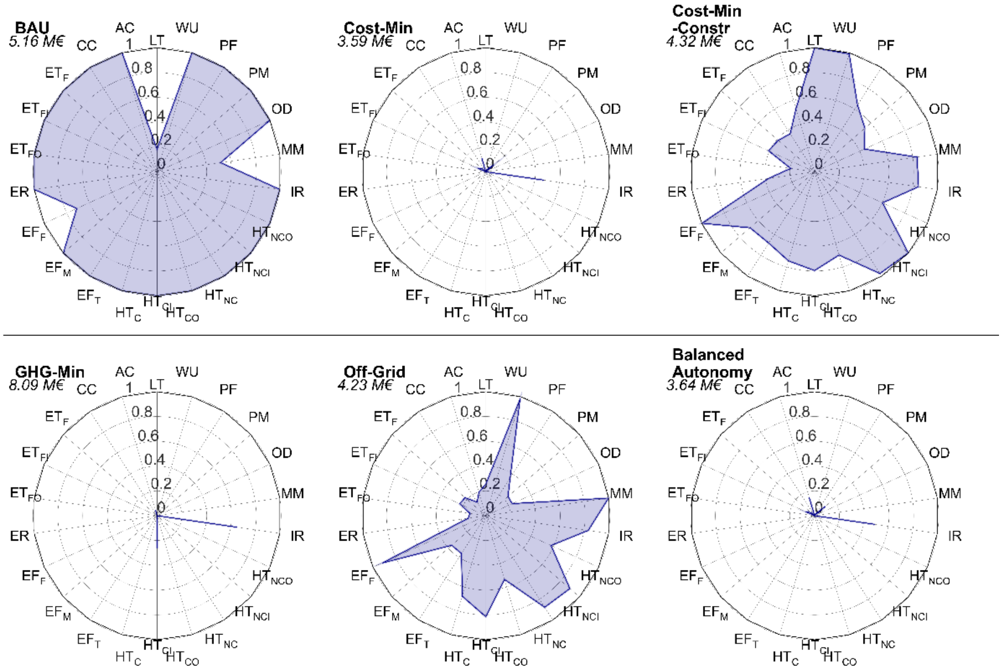


*Figure 9. Spider graph with the different scenarios considered for the entire MES in Crete, and associated life cycle environmental burdens on selected normalized environmental impact categories. LT = land transformation. AC = acidification. CC = climate change. $ET_F$ = ecotoxicity: freshwater. $ET_{FI}$ = ecotoxicity: freshwater, inorganics. $ET_{FO}$ = ecotoxicity: freshwater, organics. ER = energy resources: non-renewable. $EF_F$ = eutrophication: freshwater. $EF_M$ = eutrophication: marine. $EF_T$ = eutrophication: terrestrial. $HT_C$ = human toxicity: carcinogenic. $HT_{CI}$ = human toxicity: carcinogenic, inorganics. $HT_{CO}$ = human toxicity: carcinogenic, organics. $HT_{NC}$ = human toxicity: non-carcinogenic. $HT_{NCO}$ = human toxicity: non-carcinogenic, organics. $HT_{NCI}$ = human toxicity: non-carcinogenic, inorganics. IR = ionizing radiation: human health. MM = material resources: metals/minerals. OD = ozone depletion. PM = particulate*

*matter formation. PF = photochemical oxidant formation: human health. WU = water use. The figure is published in Terlouw et al. (2025)* [7].

Figure 10 and Figure 11 illustrate stacked plots showing the weekly system operation for the 'Cost-Min' scenario during a representative winter and summer week, respectively, considering the operation of the entire MES. The operation during these two weeks addresses three distinct energy demand requirements: electrical power, low-temperature heat, and high-temperature heat (and hydrogen balancing in Figure 11). In these plots, produced power (electrical or thermal) is shown as positive, while consumed power is visualised as negative. The secondary y-axis in the first subplot shows the energy stored in the battery. Notably, the summer week excludes residential low-temperature heat (i.e., the second subplot is omitted), as the MES is modeled for the Mediterranean climate in Crete (residential tap water has been excluded).

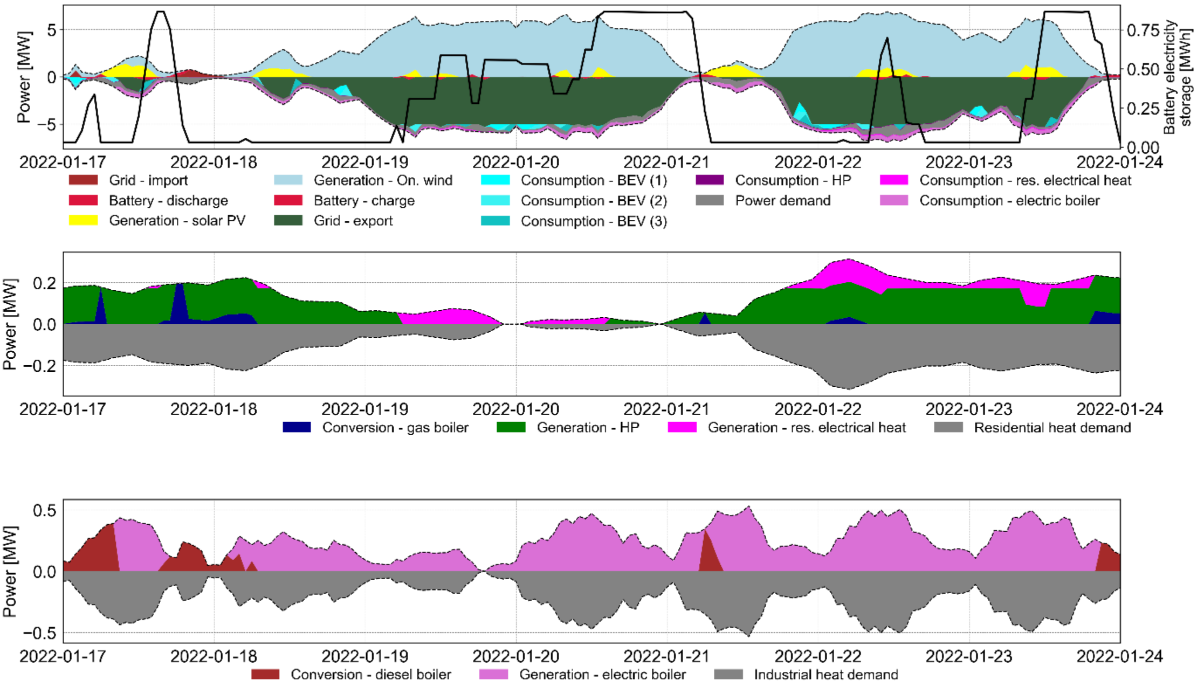


*Figure 10. Weekly system operation during a winter week for the entire MES, with subplots showing from top to bottom: balancing power demand, low-temperature residential heat, and high-temperature industrial heat. The labels BEV (1), BEV (2), and BEV (3) refer to different charging schedules for BEVs. The figure is published in Terlouw et al. (2025)* [7].

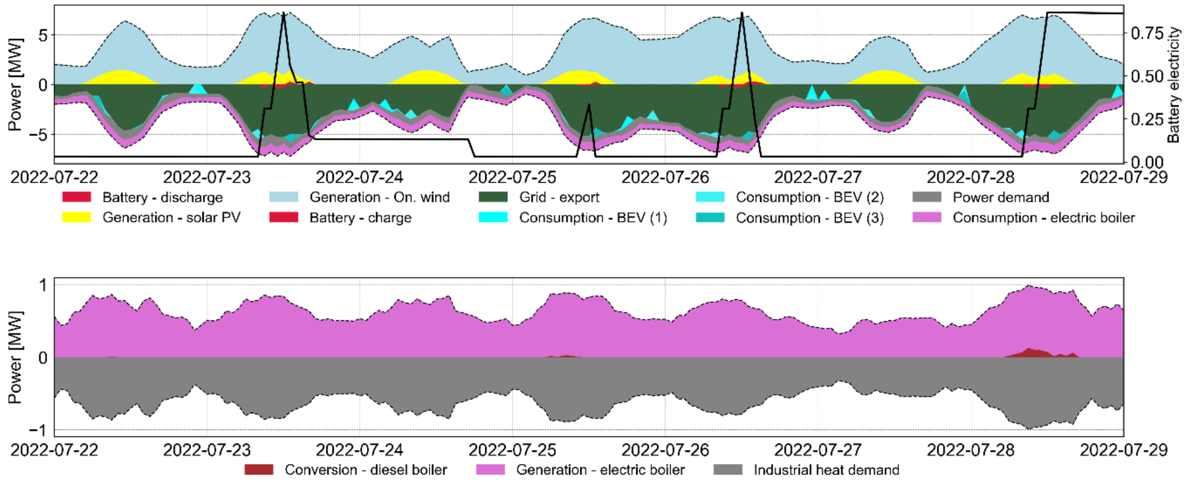


*Figure 11. Weekly system operation during a summer week for the entire MES, with subplots showing from top to bottom: balancing power demand and high-temperature industrial heat. The figure is published in Terlouw et al. (2025)* [7].

These figures illustrate that a cost optimization strategy results in installing a cost-effective battery to store locally generated renewable energy, which is used during low renewable energy generation periods. This strategy also allows for selling excess power to the local grid. The low-temperature heat demand is mainly met by residential heat pumps, supplemented by electric heating and gas boilers during peak demand periods. BEVs can be charged during the day using solar PV generation under one charging schedule, while the other two schedules restrict BEV charging during nighttime.

The high-temperature heat required for the local industry is mainly supplied by an electric and a diesel boiler (the latter only in the 'Cost-Min' scenario). In contrast, in the 'GHG-Min' scenario, the advanced CHP unit powered by low-carbon fuels is employed (see Table 4, Figure 20, and Figure 21 in the Appendix). However, the potential to decarbonize the high-temperature heat supply with the advanced CHP unit is constrained by technology-specific limitations, such as minimum up- and downtimes, to prevent increased component degradation. The CHP and biomass gasification units do not entirely provide all electricity supply, even when emissions are minimized, due to their minimum (uptime) power constraints and gas-mixing restrictions. As a result, a 1 MW electric boiler is installed as a backup to meet the remaining high-temperature industrial heat demand in the 'GHG-Min' scenario.

### 4.4.1 Sensitivity analysis

#### *Influence of power grid network cost on off-grid MESs*

Figure 12 shows how increasing the cost of power grid connection per unit of capacity (x-axis) affects the installed capacities of different energy technologies within the MES (y-axis). The secondary y-axis shows the share of power grid network investment relative to the total investment in the MES in Crete, visualized by the grey-shaded area. This figure highlights a couple of important insights.

The optimal MES design is highly sensitive to the cost of connecting to the power grid. When grid connection costs are low, a larger grid capacity is being installed, along with significant onshore wind capacity. However, as grid costs increase, the installed capacities for both the power grid and onshore wind decrease. To compensate for the reduced grid capacity, the system increases solar PV and battery storage capacities, which provide the necessary flexibility and storage capacity to compensate the 'storage' buffer of the power grid. Interestingly, the generation profiles of solar PV and wind complement each other, helping to offset the impact of higher grid costs. As the cost of the grid increases, the installed capacity of onshore wind decreases, making energy exports less profitable, while solar PV capacity increases to smooth the renewable energy generation profile.

Overall, it becomes more cost-effective to install additional energy storage and solar PV when the grid network investment exceeds 4% of the total annualized upfront investment, roughly around 500 €/kW of grid network cost. Even if grid costs increase, coupling the MES to the grid remains a preferred option from a cost perspective, with a phase-out of the grid connection only occurring when the cost reaches approximately 11,000 €/kW of grid capacity.

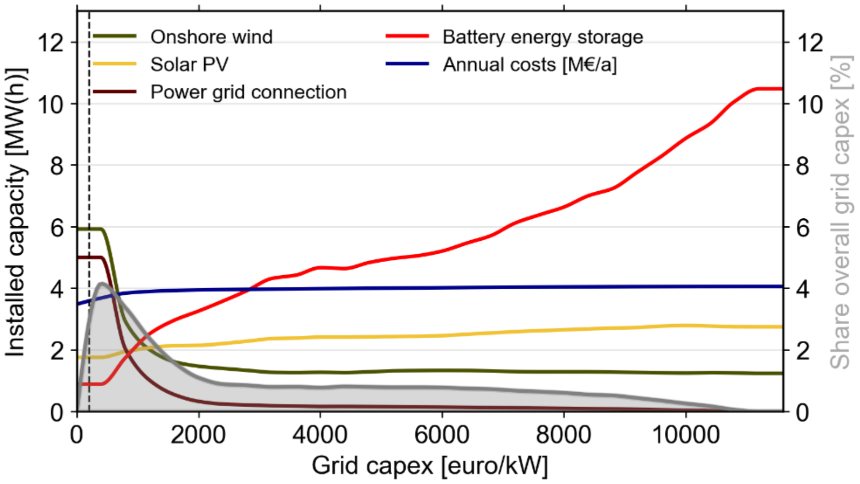


*Figure 12. The impact of increasing power grid costs. The units for technologies are given per MW, except for battery electricity storage (per MWh) and annual costs [M€/a]. The vertical dashed line represents the considered cost for the power grid network connect. The figure is published in Terlouw et al. (2025)* [7].

### *Overall sensitivity for off-grid MESs*

Figure 13 shows a local sensitivity analysis for off-grid MESs. It examines how a 10% increase (solid bars) or decrease (hatched bars) in various techno-economic parameters affects the annualized cost of the entire MES. Here, we examine off-grid MESs, as the key parameters for grid-connected MESs have already been studied (see e.g., Ref. [6]). The parameters analyzed include diesel prices, electricity and heat demand (both residential and industrial), power demand for BEVs, discount rate, upfront investments (capex) for all technologies, lifetimes of all technologies, O&M costs for all technologies, average annual solar irradiance, and wind speed.

The results demonstrate that capital expenditures are the most sensitive parameter for off-grid MESs, given the significant upfront investments required to integrate a diverse set of low-carbon technologies. The discount rate and the lifetimes of components also have a significant impact since they directly influence upfront costs. Additionally, changes in temperature and wind speed play a substantial role; for instance, higher temperatures reduce residential heating needs, which in turn lowers annual costs. Similarly, an increase in wind speed increase onshore wind output, leading to a cost reduction with cost-effective onshore wind.

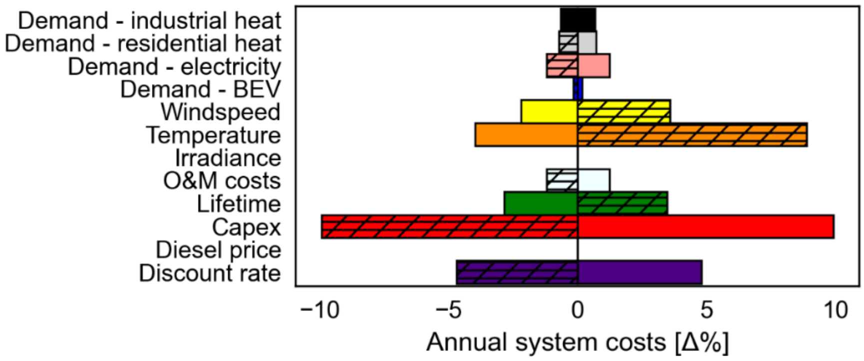


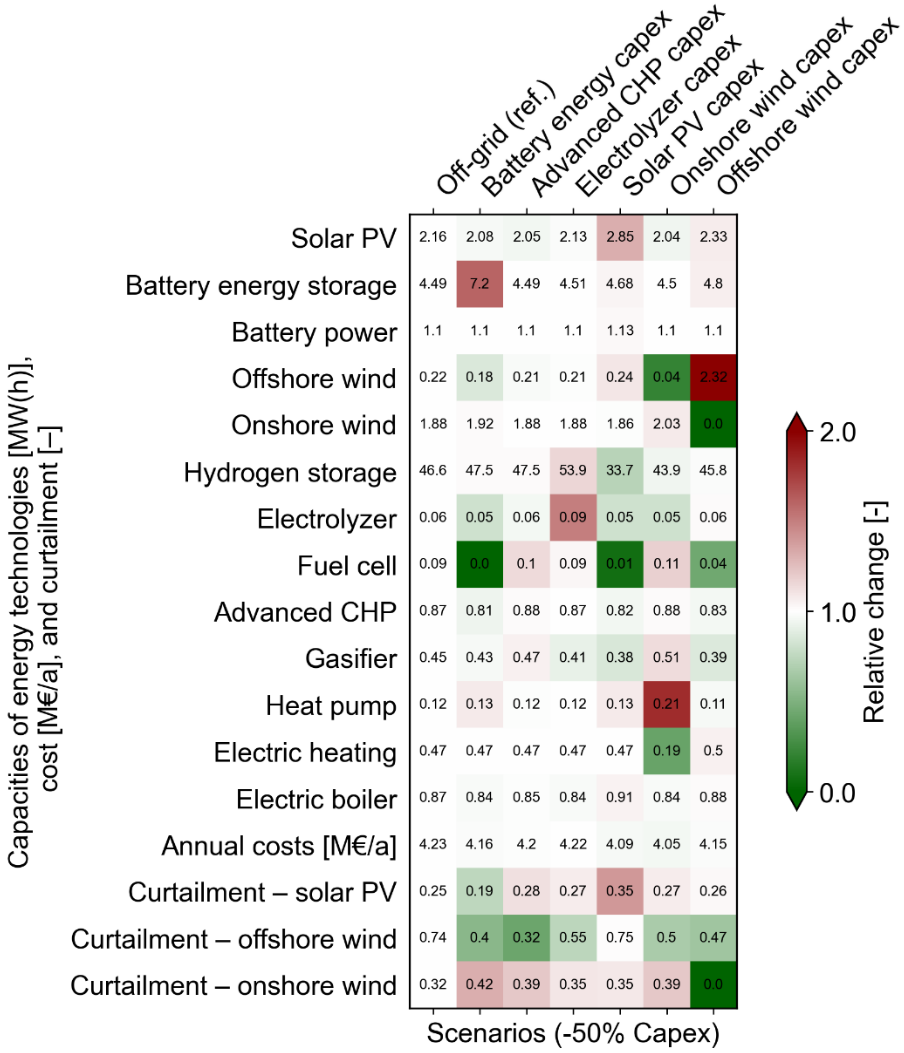
*Figure 13. Local sensitivity analysis on selected parameters for off-grid MESs. The figure is published in Terlouw et al. (2025) [7].*

### Influence of reducing capex of low-carbon technologies on optimal off-grid MES design

As indicated, capital expenditures are the most sensitive techno-economic parameter in off-grid MESs. To explore this further, we examine the impact of a 50% reduction in capital expenditures for selected low-carbon energy technologies on the optimal (unconstrained) off-grid MES design. Those technologies include battery electricity storage, advanced CHP units, electrolyzers, solar PV, and onshore wind since those are expected to be crucial technologies in future decarbonized (off-grid) MESs.

Figure 14 shows how the optimal design of these technologies changes relative to the baseline off-grid MES in Crete when their capex is reduced by 50%. Red areas indicate an increase in relative installed capacity, total costs, and curtailment, while green areas represent a relative decrease. The figure provides absolute values for each parameter, with scenarios listed at the top.

The results indicate that reducing capex for onshore wind and solar PV has the strongest impact on overall system costs. This is largely due to the ability to generate cheaper low-carbon electricity, which can also be converted to heat. This finding emphasizes the importance of developing effective policies to support renewable energy, as previously highlighted in our case Cretan study. Additionally, reducing the capex of solar PV significantly lowers hydrogen generation and storage capacities, whereas a reduction in wind capex has a lesser effect on hydrogen storage and generation. This suggests that solar PV is more suited for short-term battery storage, while converting wind power to hydrogen is more suitable for long-term hydrogen storage, aligning with previous findings [6], [14], [15]. Finally, reducing the capex of renewable technologies slightly increases curtailment for those technologies, as the economic impact of energy generation and losses due to curtailment becomes less significant.



| | Off-grid (ref.) | Battery energy capex | Advanced CHP capex | Electrolyzer capex | Solar PV capex | Onshore wind capex | Offshore wind capex |
|---|---|---|---|---|---|---|---|
| Solar PV | 2.16 | 2.08 | 2.05 | 2.13 | 2.85 | 2.04 | 2.33 |
| Battery energy storage | 4.49 | 7.2 | 4.49 | 4.51 | 4.68 | 4.5 | 4.8 |
| Battery power | 1.1 | 1.1 | 1.1 | 1.1 | 1.13 | 1.1 | 1.1 |
| Offshore wind | 0.22 | 0.18 | 0.21 | 0.21 | 0.24 | 0.04 | 2.32 |
| Onshore wind | 1.88 | 1.92 | 1.88 | 1.88 | 1.86 | 2.03 | 0.0 |
| Hydrogen storage | 46.6 | 47.5 | 47.5 | 53.9 | 33.7 | 43.9 | 45.8 |
| Electrolyzer | 0.06 | 0.05 | 0.06 | 0.09 | 0.05 | 0.05 | 0.06 |
| Fuel cell | 0.09 | 0.0 | 0.1 | 0.09 | 0.01 | 0.11 | 0.04 |
| Advanced CHP | 0.87 | 0.81 | 0.88 | 0.87 | 0.82 | 0.88 | 0.83 |
| Gasifier | 0.45 | 0.43 | 0.47 | 0.41 | 0.38 | 0.51 | 0.39 |
| Heat pump | 0.12 | 0.13 | 0.12 | 0.12 | 0.13 | 0.21 | 0.11 |
| Electric heating | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.19 | 0.5 |
| Electric boiler | 0.87 | 0.84 | 0.85 | 0.84 | 0.91 | 0.84 | 0.88 |
| Annual costs [M€/a] | 4.23 | 4.16 | 4.2 | 4.22 | 4.09 | 4.05 | 4.15 |
| Curtailment – solar PV | 0.25 | 0.19 | 0.28 | 0.27 | 0.35 | 0.27 | 0.26 |
| Curtailment – offshore wind | 0.74 | 0.4 | 0.32 | 0.55 | 0.75 | 0.5 | 0.47 |
| Curtailment – onshore wind | 0.32 | 0.42 | 0.39 | 0.35 | 0.35 | 0.39 | 0.0 |

*Figure 14.* Impact of reducing capex of selected low-carbon energy technologies by 50% on the optimal design. The absolute numbers are provided, while the colors indicate relative changes (refer to the color bar). *The figure is published in Terlouw et al. (2025)* [7].

## 4.5 Key take-aways

Finally, we provide the following key take-aways from the case study in Crete:

- Substantial reduction in terms of costs (up to 30%) and GHG emissions (up to 87%) can be reached in Mediterranean regions due to the cost-effective integration of solar PV and wind. The local bakery industry can be fully decarbonized with electric boilers and advanced CHP units.
- However, current (and future) location-specific regulations, especially targeting local renewables, can substantially reduce the cost and decarbonization potential, implying that effective policy guidelines are essential for further decarbonization.
- Off-grid MESs show promising potential for further decarbonization due to less reliance on the (current GHG-intensive) power grid network; however, off-grid MESs might lead to some trade-offs regarding material utilization and land use.
- Off-grid MESs are very sensitive to capex and discount rates of some low-carbon technologies since they require a large upfront investment.

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# 5. Western Isles

This section presents the results of the case study in Western Isles (Scotland). Most of the figures and content herein were published in: Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). *Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy & Environmental Science,* 15(9), 3583–3602. Reproduced from Ref. [4] with permission from the *Royal Society of Chemistry.* Licensed under CC BY 3.0.

The rest of this chapter describes the case study and scenarios, (briefly) the methods, as well as the results from the environmental LCA and techno-economic analysis. It is worth noting that we solely focus on large-scale hydrogen production on Western Isles since (i) current roadmaps in Western Isles show the promising potential for hydrogen production, use, and export on those islands [16], (ii) a dedicated case study with different energy carriers and sectors (as with the other ROBINSON islands) has not been established due to implementation constraints of ROBINSON partners from Western Isles.

## 5.1 Large-scale hydrogen production systems in Western Isles

In general, geographical islands and coastal areas present opportunities for low-cost and low-carbon power generation due to abundant wind and/or solar potential. In addition, geographical islands typically have sufficient land and sea areas for renewable electricity installations. Further, the infrastructure needed for long-distance hydrogen transportation, such as hydrogen shipping, might be more easily rolled out on geographical islands. As such, large-scale hydrogen production can enable economic development and could establish new industries on geographical islands.

*Figure 15. Selected European geographical islands on a map with the Western Isles indicated in the black box on top of the figure. The figure is obtained from Terlouw et al.* [4].

Several European islands, such as Crete, Eigerøy, and the Western Isles, aim to develop MESs that minimize dependence on non-renewable energy sources. Hydrogen is typically integrated as a key component in those initiatives. Here, we examine the potential for large-scale hydrogen production on five geographical islands in Europe, with a special focus on the Western Isles in Scotland (UK). These islands have been chosen for their potential for large-scale hydrogen production. The selected islands include – besides the Western Isles (Scotland, UK) – Crete (Greece), Eigerøy (Norway), Tenerife (Spain), and Borkum (Germany), which is illustrated in Figure 15. Expanding the scope of the analysis beyond the Western Isles allows for a more comprehensive analysis and the representation of a broader range of location-specific boundary conditions, which in turn allows for drawing more generalized conclusions regarding the economic and environmental performance of hydrogen production on (European) islands.

The Western Isles have substantial wind energy availability throughout the year, which makes them well-suited for wind-based hydrogen production. Unlike, for example, Eigerøy, where onshore wind potential is limited due to land constraints and current challenges in implementing wind power, the Western Isles benefit from more extensive land availability. Thus, the Western Isles potentially offer greater potential for onshore wind development. In addition to onshore and offshore wind energy, the availability of solar PV on the Western Isles is also considered, with constraints applied to reflect realistic land usage on the island(s).

## 5.2 Optimization problem for designing hydrogen production systems

Energy system optimization is needed for the optimal design and operation of hydrogen production systems. Here, we use a MILP [17], which is a well-established technique for optimizing the scheduling and design of energy systems [18], [19], [20]. The optimization problems are formulated to design hydrogen production systems based on one full year of system operation using hourly data. Three different energy system configurations are considered: grid-connected (to the power grid), hybrid (both connected to renewables and the power grid), and autonomous (entirely disconnected from the power grid), which is illustrated in Figure 16 and are described in the next section.

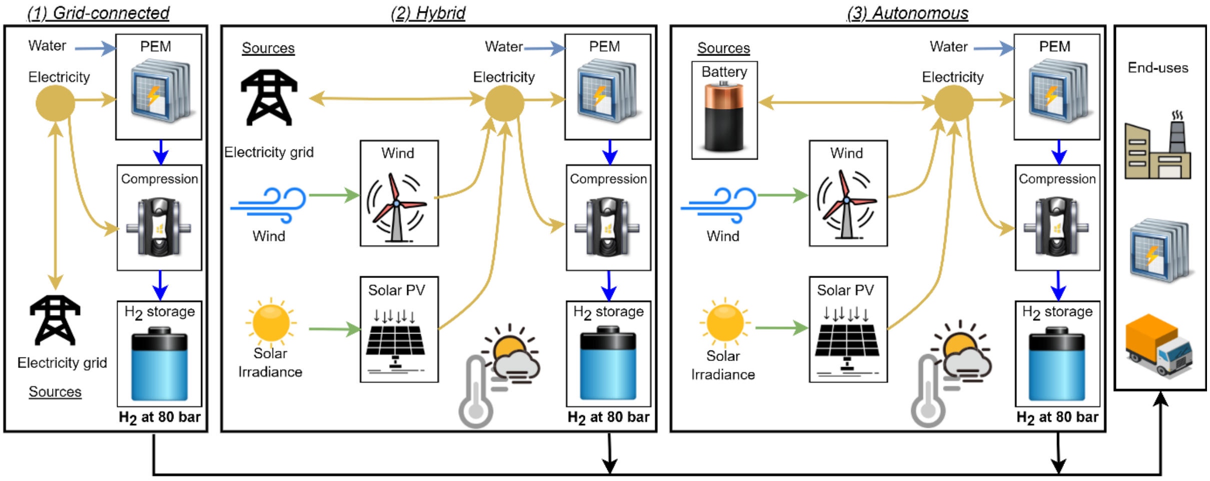

*Figure 16. Simplified illustration of the system boundaries of the three considered hydrogen production configurations: (1) grid-connected, (2) hybrid, and (3) autonomous, from left to right (with details provided in section 5.3). Potential end uses are visualized but are not considered in our system boundaries. The figure is obtained from Terlouw et al.* [4].

Initially, the three energy system configurations are optimized based on annualized costs, which include capital expenditures (CAPEX), operational costs, fixed operation and maintenance (O&M) costs, and replacements. The supplementary information of the main manuscript of the journal article provides detailed explanations of the optimization problem and the specific constraints for each configuration; interested readers are referred to Ref. [4].

In addition to cost optimization, the hydrogen production systems are also evaluated regarding life cycle GHG emissions. The environmental evaluation considers both operational and embodied emissions, thus, creating a multi-objective MILP. Pareto fronts are used to illustrate the trade-offs between annualized costs and GHG emissions, which is a well-known method in multi-objective optimization for energy systems [18], [19], [20]. It is important to note that Pareto fronts are generated only for the hybrid hydrogen production system. The hybrid system is connected to both the power grid—which can have a high GHG impact in some regions—and renewable energy sources, which have a low GHG impact, making it the most sensitive to GHG emissions during operation.

## 5.3 Case study and scenarios

Different hydrogen production configurations are considered. Here, we focus on large-scale, cost-optimized hydrogen production. Unlike previous studies that focused on smaller hydrogen production systems, our goal is to generate a daily amount of 10 tonnes of hydrogen.

The three hydrogen production configurations are provided below, using a cradle-to-gate analysis to supply hydrogen at 80 bar pressure. We use a PEM electrolyzer for hydrogen production, which is the best alternative for integration with intermittent renewable energy sources due to its operational flexibility and fast response times [21]. The electricity required for the entire hydrogen production facility—including electrolysis, desalination, and compression—could come from various energy generation technologies (see Figure 16), i.e., onshore and offshore wind, solar PV, the local grid, or a battery. Finally, hydrogen is compressed from 30 to 80 bar and stored to ensure a stable hydrogen supply.

- **Grid-connected:** the PEM electrolyzer is connected to the national power grid. The system is optimized to produce 10 tonnes of hydrogen per day, with the grid supplying all the electricity needed. Hydrogen is stored in a tank with a storage capacity of one day. The optimization determines the optimal electrolyzer capacity to meet the production target.
- **Hybrid:** The hybrid configuration combines grid power and renewable energy sources, such as solar PV, onshore, and offshore wind. This approach could utilize low-cost renewable energy while using the grid as a backup/storage. Here, the system is optimized to minimize either costs or life cycle GHG emissions.
    - **Hybrid-Green:** This variation of the hybrid configuration is constrained by a maximum allowable GHG emission limit. This limit ensures that the hydrogen produced qualifies the 'green hydrogen' standards from CertifHy (less than 4.4 kg $CO_2$-eq./kg $H_2$) [22]. If this level cannot be met, the optimization will minimize GHG emissions.
- **Autonomous**: The autonomous configuration operates entirely off-grid, powered by locally generated renewable energy sources. The system is optimized to produce 50 tonnes of hydrogen over five days, allowing for some flexibility in production, which reduces the need for oversized renewables (and curtailment). A larger storage capacity (five days, or 50 tonnes of hydrogen) is required, and a battery could be installed to enhance system flexibility further.
    - **Autonomous-injection:** This sub-configuration allows excess renewable electricity to be sold back to the grid, potentially generating additional revenue from power export. It is worth noting that the system remains autonomous by preventing the absorption of grid electricity.

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## 5.4 Results

Figure 17 illustrates the hydrogen production costs across different system configurations for the Western Isles (and other European islands). The stack segments show cost contributions, while the secondary y-axis indicates climte change impacts (in kg $CO_2$-eq./kg $H_2$).

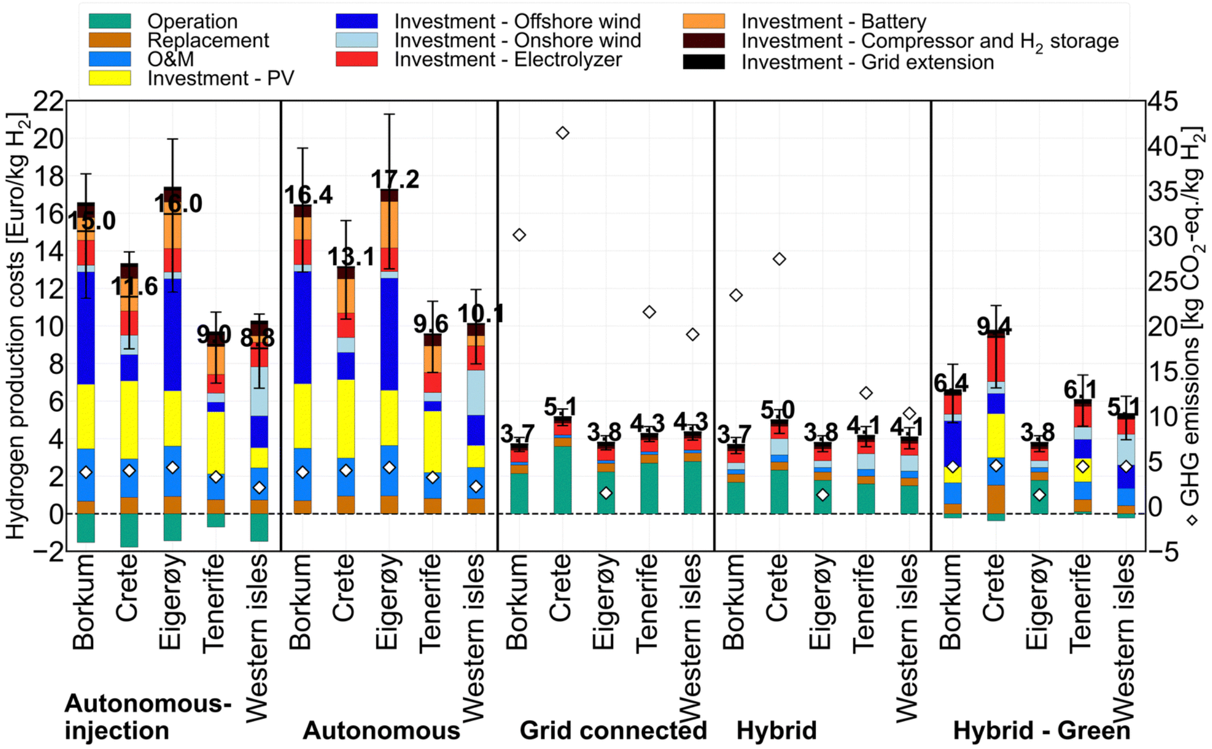

*Figure 17. Contribution analysis of hydrogen production costs [€/kg $H_2$]. The figure visualizes the contributions with different colors regarding the operation, investments, replacement as well as the fixed O&M costs. The costs and/or GHG emissions per MJ hydrogen production can be obtained by dividing the figures with the lower heating value of hydrogen (120 MJ $kg^{-1}$). Further, the error bars visualize a pessimistic scenario (highest $H_2$ costs) and optimistic scenario (lowest $H_2$ costs) for the current situation. The figure is obtained from Terlouw et al.* [4].

For the Western Isles, hybrid systems exhibit the lowest hydrogen production costs, around 4.1 €/kg $H_2$. Hybrid systems benefit from using the power grid network for selling surplus power while integrating low-cost renewable energy without needing additional (expensive) energy storage. However, hybrid systems sometimes exceed the green hydrogen standard of 4.4 kg $CO_2$-eq./kg $H_2$, also for Western Isles due to fossil-fuel-based energy sources in the current grid electricity mix. The 'Hybrid-Green' configuration, designed to generate low-carbon hydrogen, achieves this at slightly higher costs (5.1 €/kg $H_2$), where costs are the highest in regions with GHG-intensive power grids.

Grid-connected systems, which rely on historical day-ahead electricity prices (from the year 2019), generally perform well in terms of cost, with Western Isles achieving 4.3 €/kg $H_2$. However, the Western Isles, with abundant renewable resources, may achieve similar or better results for hybrid systems depending on grid integration and pricing.

Autonomous configurations have higher hydrogen production costs (9.6–17.2 €/kg $H_2$). The Western Isles are better suited for this configuration than more land-constrained islands such as Eigerøy and Borkum. The increased costs result from oversized renewable energy systems (and curtailment) and battery electricity storage to ensure sufficient daily hydrogen production.

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Autonomous-grid injection configurations, which sell excess electricity back to the grid, slightly reduce costs (8.8–16.0 €/kg $H_2$). As such, this configuration reduces curtailment and improves the economic viability, particularly for the Western Isles, where excess renewable energy might be sold to generate additional revenue.

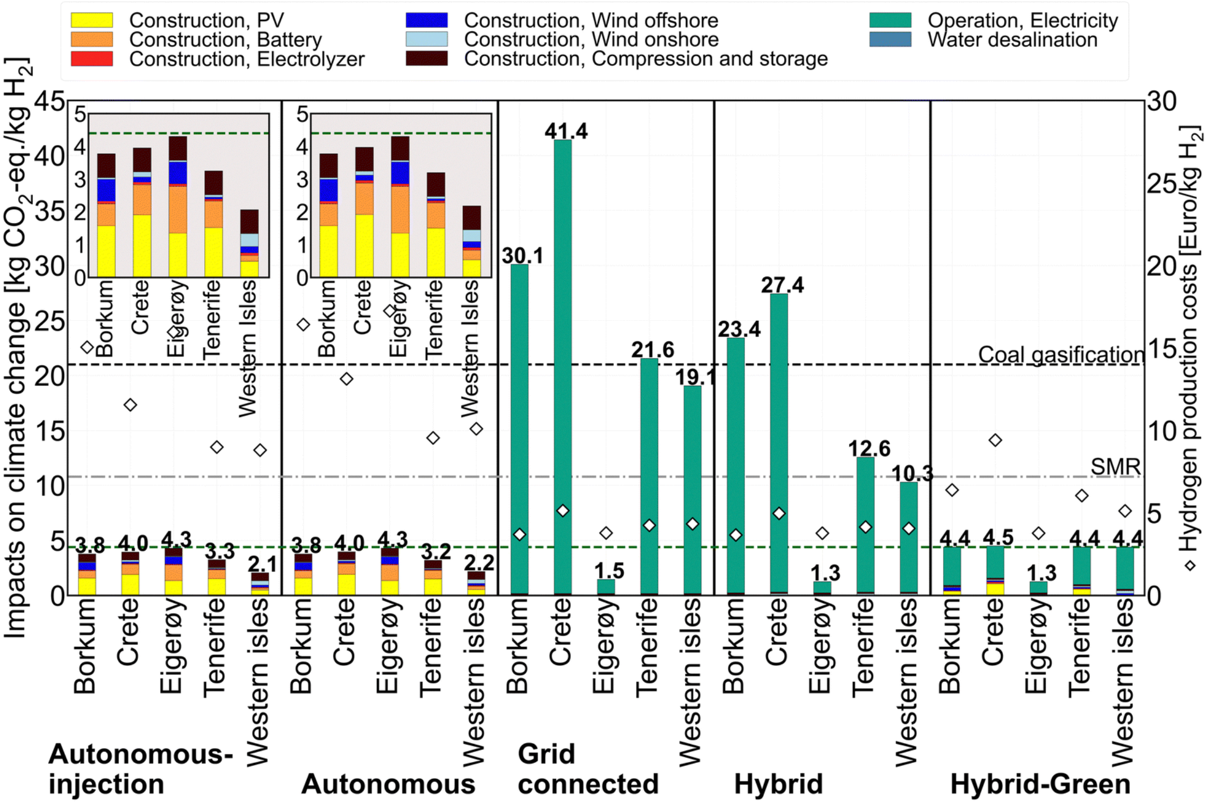

*Figure 18. Contribution analysis regarding life cycle GHG emissions of hydrogen production [kg $CO_2$-eq./kg $H_2$]. The zoom (on the top left) of the figure provides more details for autonomous system configurations. The colored horizontal lines indicate the climate change impact of green hydrogen (green), gray hydrogen (in grey, dash-dotted) and black hydrogen (in black) [23]. The figure is obtained from Terlouw et al. [4].*

Figure 18 illustrates the life cycle GHG emissions (in kg $CO_2$-eq./kg $H_2$) for the various hydrogen production configurations, with different colors of stack segments indicating the contribution of different processes within the supply chain. The Western Isles exhibit some of the lowest GHG emissions among the studied locations due to the high capacity factor of wind in this geographical region. However, grid-connected hydrogen production could still result in considerable GHG emissions in Western Isles.

Autonomous configurations in the Western Isles exhibit low GHG emissions, ranging from 2.1–2.2 kg $CO_2$-eq./kg $H_2$, due to lower GHG impact during the construction of wind turbines. In contrast, configurations that rely more heavily on solar PV show slightly higher emissions (3.2–4.3 kg $CO_2$-eq./kg $H_2$) due to the lower capacity factor of solar PV and the more GHG-intensive production of PV wafers.

Hybrid configurations exhibit very different performance in terms of GHG emissions, with emissions ranging from 1.3–27.4 kg $CO_2$-eq./kg $H_2$. In the Western Isles, hybrid systems effectively reduce GHG emissions by optimally integrating local wind energy, however, keeping emissions within acceptable levels for low-carbon ‘green’ hydrogen production can only be reached by using ‘Hybrid-Green’ scenarios.

Overall, the Western Isles are well-positioned for large-scale hydrogen production, particularly through autonomous and hybrid (‘Hybrid-Green’) systems that maximize the use of locally generated wind energy. As such, these configurations can meet green hydrogen standards, making the Western Isles a suitable location for large-scale hydrogen production. However, achieving low-cost and low-emission hydrogen requires careful consideration of grid integration, renewable energy capacity, and energy storage needs, especially with grid networks (partly) relying on fossil fuels.

*Table 5. Assumed electricity prices as well as the GHG intensity of the electricity grid for the year 2040.*

| Location | Pessimistic (2040) | | Average (2040) | | Optimistic (2040) | |
|---|---|---|---|---|---|---|
| | Price [€/kWh] | GHG Intensity [kg $CO_2$-eq./kWh] | Price [€/kWh] | GHG Intensity [kg $CO_2$-eq./kWh] | Price [€/kWh] | GHG Intensity [kg $CO_2$-eq./kWh] |
| **Crete, Greece** | 0.095 | 0.208 | 0.083 | 0.032 | 0.071 | 0.028 |
| **Eigerøy, Norway** | 0.058 | 0.115 | 0.051 | 0.020 | 0.043 | 0.013 |
| **Western Isles, UK** | **0.073** | **0.208** | **0.064** | **0.032** | **0.054** | **0.028** |
| **Tenerife, Spain** | 0.071 | 0.208 | 0.062 | 0.032 | 0.053 | 0.028 |
| **Borkum, Germany** | 0.056 | 0.208 | 0.049 | 0.032 | 0.042 | 0.028 |

## Future costs and GHG emissions of hydrogen production

Here, we examine a future scenario in 2040 using the assumptions provided in Table 5 and of the scenarios explained in Ref. [4]. By 2040, hydrogen production costs in the Western Isles are projected to fall significantly. Figure 19 highlights potential costs under various scenarios—optimistic, average, and pessimistic. For hybrid configurations, which utilizes available wind energy sources in the Western Isles, hydrogen production costs could reach as low as 1.8–3 €/kg $H_2$ in the optimistic and average scenarios, reaching parity with fossil fuel-based hydrogen via stem methane reforming.

Autonomous configurations also experience substantial cost reductions, ranging from 3.7–6.5 €/kg $H_2$ in Western Isles, depending on the scenario. These reductions are driven by lower investments, longer system lifetimes, and a lower discount rate assumed.

Figure 22 (in the Appendix) presents prospective GHG emissions for hydrogen production in 2040. In the Western Isles, GHG emissions could be reduced to less than 2 kg $CO_2$-eq./kg $H_2$ for all configurations under the optimistic and average scenarios, due to decarbonized grid electricity and reduced embodied emissions of renewable energy technologies. However, in a pessimistic scenario, where the grid is less decarbonized, GHG emissions could exceed 10 kg $CO_2$-eq./kg $H_2$, particularly for grid-connected systems.

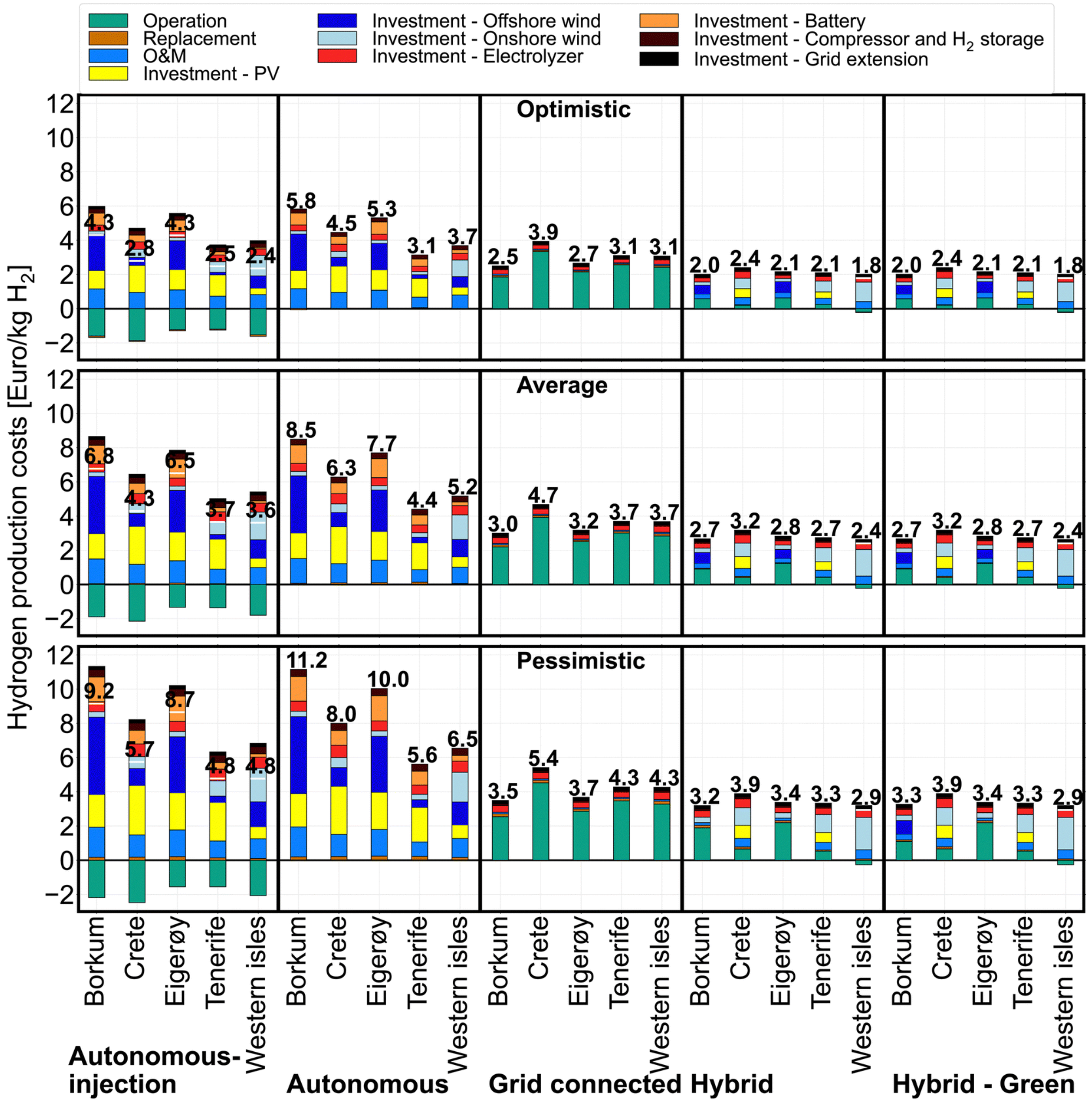

*Figure 19. A contribution analysis of future hydrogen production costs valid for year 2040 [€/kg H$_2$]. The figure visualizes the contributions with different colors regarding the operation, investments, replacement, and the fixed O&M costs. The figure is obtained from Terlouw et al. [4].*

## 5.5 Key take-aways

Finally, we provide the following key takeaways and considerations from the case study in Western Isles:

- The Western Isles are well-suited for large-scale hydrogen production hubs, especially for (Green-)hybrid hydrogen production systems, which combine wind energy potential on the islands with a (small) grid connection. Hybrid systems currently offer the most cost-effective solution, with current production costs of around 4.1 €/kg $H_2$. By 2040, costs could be reduced to 1.8–3 €/kg $H_2$, which might make low-carbon electrolytic hydrogen cost-competitive with hydrogen production via fossil fuels.
- The Western Isles have the potential to achieve low GHG emissions from hydrogen production with hybrid and autonomous configuration systems. However, it is crucial to

ensure that local power grid networks are increasingly decarbonized in the future to enable low GHG emissions when coupled with the power grid. An appropriate amount of additional renewables (primarily onshore and offshore wind power) should be installed to absorb the additional grid power needed for electrolytic hydrogen production.

- Implementing large-scale hydrogen production in the Western Isles will require robust and effective regulatory frameworks, particularly around grid integration and land utilization needed for renewables. Upgrading electricity grids and hydrogen transportation networks to process additional renewable energy and hydrogen production, respectively, will be critical.
- Hydrogen production in the Western Isles might face challenges related to land use and/or renewable energy installations, which may face resistance due to their impact on local landscapes. Additionally, the scarcity of materials, such as iridium for PEM electrolyzers, could limit the scale of hydrogen production globally.
- Despite of not being within the scope of the analysis, the design and scale-up of a hydrogen storage and transport infrastructure should be planned in parallel with hydrogen production to fully exploit the opportunities on the Western Isles. It is also recommended to identify large-scale hydrogen users to profit from stable boundary conditions.
- Overall, the success of hydrogen projects in the Western Isles will depend heavily on local involvement of stakeholders and social acceptance. Transparent communication about the benefits, potential impacts, and long-term economic opportunities for the region will be key to gain public support.

# 6. Discussion

The assessment of decentralized MESs on the three ROBINSON islands is influenced by several important factors, such as system boundaries, local climate, location-specific regulations, and the objective for designing such systems (economic and/or environmental criteria). Additionally, there are other considerations essential for interpreting our results. The following paragraphs will elaborate on those factors, as well as the associated limitations, recommendations, and potential solutions. Here, we limit our discussion to the five most critical points; please refer to Refs. [6], [24] for further discussion.

First, we demonstrate that costs and environmental burdens can be substantially reduced by optimally designing MESs on geographical islands during the design phase. As such, current (baseline) fossil-fuel-based island energy systems offer huge decarbonization potential and cost reduction potential. However, our design optimization algorithm uses one year of operational data. It cannot (yet) capture (i) future cost improvements by technological learning and (ii) the potential impacts of human-induced climate change. As such, the system design might be optimal in the near term but is most likely to change and non-optimal in the future due to cost reductions (and climate change); thus, it could be better designed by considering multiple design years during the design phase. Further, robust MES designs that could resist future climate change events is another aspect that has not been considered [25], [26]. For example, climate change exhibits more extreme weather events, such as more extreme droughts, severe storms, and wind and solar "droughts" (i.e., little wind and solar energy yields for several days to weeks) [27]. Including such events in future MES designs would increase the robustness of the MESs, increasing resilience and energy security.

Second, geographical islands exhibit substantial potential for decarbonization and cost improvements, given their current reliance on (sometimes expensive) GHG-intensive fossil fuels. However, the real implementation of low-carbon initiatives faces several challenges. The substantial upfront investment required for some low-carbon technologies and systems, such as off-grid MESs, can delay or prevent actual implementation, especially if the payback period is perceived as too long by commercial companies and local industries (as in Eigerøy). Additionally, geographical islands often face higher costs for importing materials and equipment, logistical complexities, and a lack of established infrastructure, all of which could further exacerbate the costs and risks associated with low-carbon energy technologies. Innovative financing models and effective policy frameworks—such as subsidies, feed-in-tariffs, and tax incentives—are crucial to overcome such barriers [28].

Another factor potentially impeding the implementation of renewables is the response from local communities [29], [30]. For example, implementing renewables has proven to be more complex than initially anticipated; in Eigerøy, installing micro-wind turbines faces substantial resistance from local residents, who are concerned about the visual impact, noise, and potential disruption to their environment. To overcome such challenges, it is essential to engage local communities and stakeholders already during the design phase of MESs. This can be achieved through transparent communication, involving them in decision-making processes, and addressing their concerns by offering benefits from installing renewables, such as community ownership models or revenue-sharing schemes [31]. Additionally, it is critical to consider how the costs and benefits of MESs are distributed among different stakeholders, including low-income households or marginalized communities [32]. This implies that a participatory process during the design phase of MESs should

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reduce environmental impacts and costs and provide economic opportunities and social benefits to all community members and stakeholders.

Fourth, we prove that it is critical to develop effective and suitable policy frameworks for deploying locally generated renewable energy sources. Thus, the successful implementation of MESs on geographical islands (and beyond) depends not only on economic and environmental optimization but also on regulatory, social, and institutional factors [31]. These factors should be integrated into the design process to ensure the feasibility and public acceptance of MESs. In the case study of Crete, we integrated some of the regulatory factors by limiting the installation of solar PV and (onshore) wind, which showed that including such regulations could significantly limit both costs and GHG emissions reductions. Future MES designs should integrate more of those factors and should aim to consider stakeholder preferences and local communities during the design phase.

In addition to focusing on GHG emissions, we show that it is important to consider a wide set of environmental impact categories, such as land use and water resources. Integrating MESs within the broader regional or national energy system is also essential, as it allows for energy import/export and strengthens connections with the grid networks of the mainland. Finally, ongoing monitoring and evaluation are crucial for ensuring that MESs remain (cost-)effective and can be adjusted based on real-world implementation and performance.

# 7. Conclusions and wider implications

The deliverables D5.2 and D5.3 (i.e., this report) summarize the economic and environmental performance of decentralized novel energy systems for the case studies conducted in the context of ROBINSON.

Assessing decentralized MESs on the ROBINSON islands highlights several key conclusions and implications. Here, we provide the main key messages from techno-economic analysis and environmental Life Cycle Assessment during ROBINSON:

- Cost-effective and low-carbon MESs on ROBINSON islands are already achievable today due to the integration of widely available wind energy sources and solar energy (in Southern European geographical islands) to replace fossil fuels. Our case studies show a potential cost reduction of up to 30% in terms of annual costs for the entire MES and up to 90% reduction in terms of life cycle GHG emissions using currently available technologies. These opportunities to reduce costs and climate impacts at the same time should not be missed – especially considering uncertainties regarding future developments and expected upward trends of fossil fuel and $CO_2$ prices.
- Potential environmental trade-offs (regarding e.g., land use or resource consumption) should be carefully considered during the design phase to avoid environmental burden shifting. Our novel developed optimization tool/repository could be helpful for achieving this in future assessments.
- Reducing GHG emissions of industrial processes on geographical islands turns out to be more challenging than decarbonizing the residential sector – mainly due to the need for high-temperature heat and specific demand profiles.
- Electrolytic hydrogen production hubs on geographical islands prove to be promising in terms of potential and performance due to low-cost electricity from renewables and their strategic position for hydrogen export, which could stimulate economic development and new jobs on the islands.
- However, the actual implementation of low-carbon energy initiatives encountered substantial resistance due to upfront investments and social acceptance, implying the critical need for stakeholder participation and effective policy frameworks.
- Current regulations might impede the large-scale roll-out of low-carbon MESs (such as in Crete), and some of those regulations should be revised to accelerate future decarbonization and increase cost-effectiveness.
- Future real-world case studies are needed to validate the results and to gain more experience, and to enable adaptations based on the actual implementation of low-carbon MESs on geographical islands (and beyond).

Overall, decentralized MESs on geographical islands exhibit substantial opportunities for reducing costs and GHG emissions. However, addressing implementation challenges through stakeholder engagement, regulatory frameworks, and equity considerations is critical. Our analysis and optimization tool for the design phase is helpful for future analyses and further development of the tool to consider those aspects (beyond this project). As such, our work contributes to the transition towards cost-effective, low-carbon, and environmentally friendly MESs on geographical islands.

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# Appendix

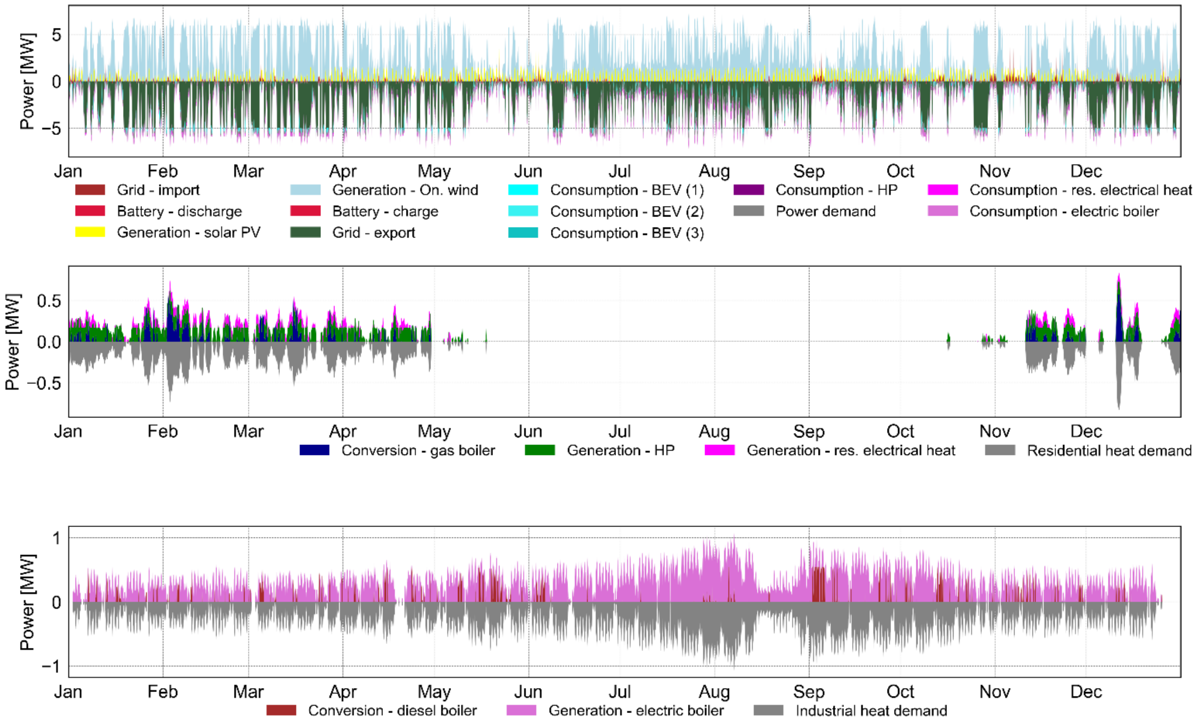

*Figure 20. Annual system operation for the entire MES in Crete for a cost optimization with subplots from top to bottom: balancing power demand, low-temperature residential heat, and high-temperature industrial heat. The figure is published in Terlouw et al. (2025)* [7].

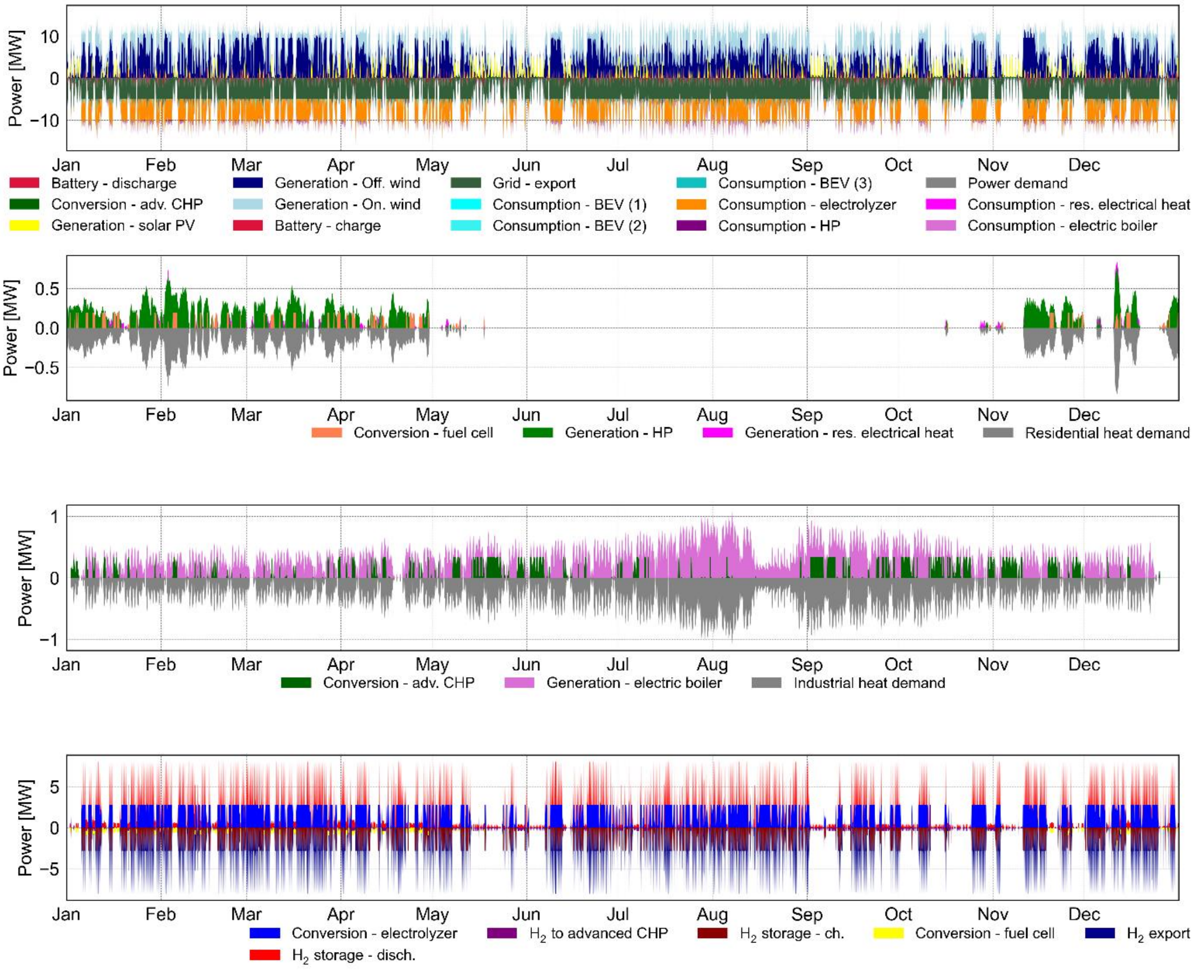

*Figure 21. Annual system operation for the entire MES in Crete for a GHG optimization with subplots from top to bottom: balancing power demand, low-temperature heat, high-temperature industrial heat, and hydrogen. The figure is published in Terlouw et al. (2025)* [7].

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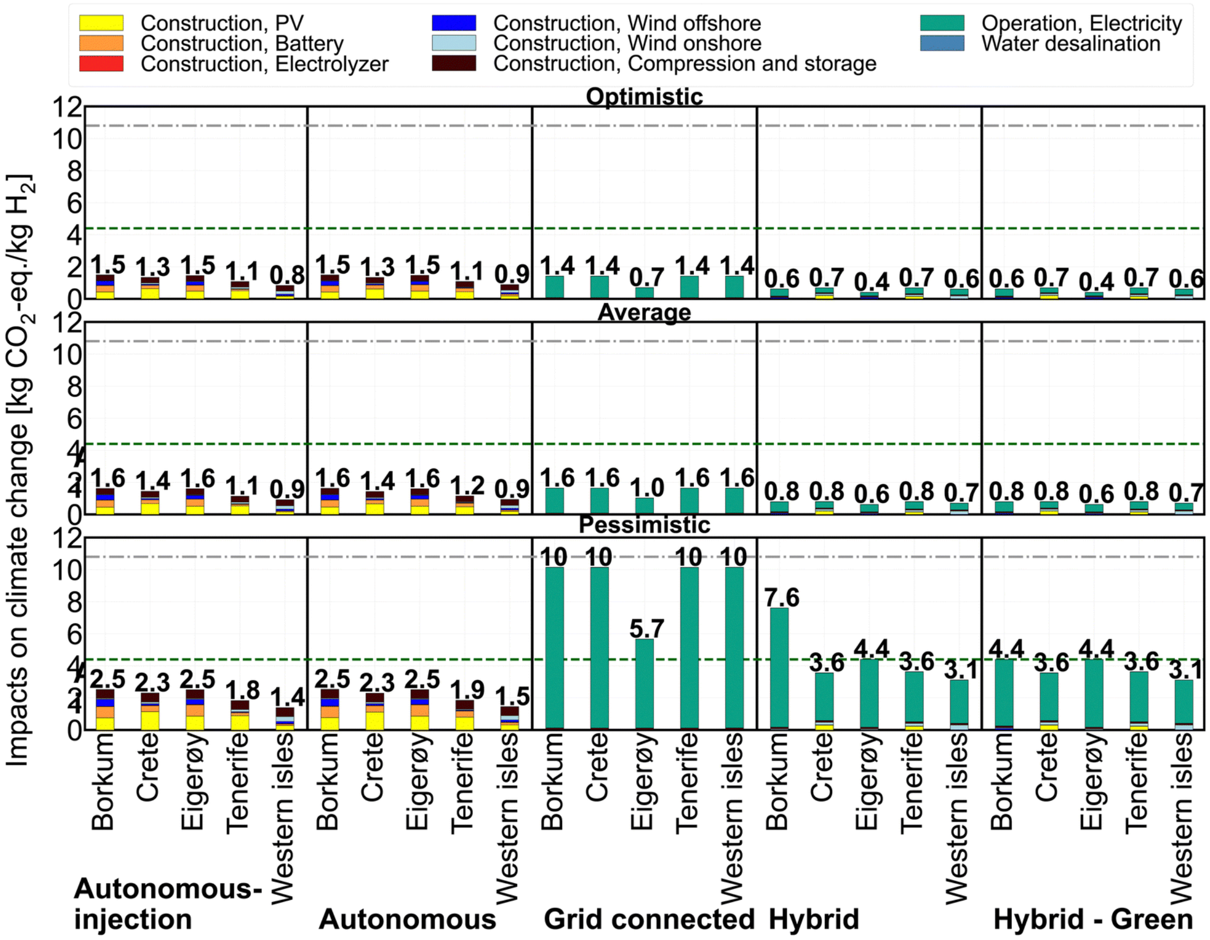

*Figure 22. A contribution analysis of future GHG emissions emitted from hydrogen production valid for 2040 [kg $CO_2$-eq./kg $H_2$] using The REgional Model of INvestments and Development (REMIND) scenarios* [33], [34]. *Contributions from processes are visualized with different colors. The figure is obtained from Terlouw et al.* [4].