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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 1.5 – Benchmark report

Lead partner: NORCE

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Executive summary

Deliverable 1.5 of the ROBINSON project corresponds to Task 1.5 that is entitled “Benchmarking”. One of the objectives of this task was to find and compare the ROBINSON energy system that is going to be installed in Eigerøy with existing concepts, installations, and available case studies (including the projects in the Clean Energy for EU Islands Initiative). In addition, the task aimed at performing some preliminarily scenario development and analysis evaluating the outlook of energy demand and use for Eigerøy. As such, laying necessary foundations to perform techno-economic benchmarking of the system against other concepts considering the current boundary conditions and some variations in those (such as changed electricity prices) was also within the scope of this task.

After performing a literature survey and finding the lack of necessary information to carry out a thorough benchmarking, a mixed-integer linear programming framework was selected for techno-economic modelling of some predefined scenarios. Within scenarios, onshore and offshore wind farms, as well as utility-scale solar photovoltaic were considered for harnessing renewable energy. All of them were found to have conditions for which their deployment was reasonable. In addition, to cover the high temperature heat demand in Eigerøy, a heating system, composed of a biomass gasifier, a combined heat and power system with a gas boiler as backup unit, was also considered and analysed. Parameters were identified in which the combination of all three thermal units represented the best system option. This report presents a summary of the activities performed in connection to Task 1.5 and the findings of the energy system modelling and analysis performed in this regard.

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Abbreviations

AC	Active current
BRP	Balance responsible parties
CAPEX	Capital expenditures
CHP	Combined heat and power
DER	Distributed energy resources
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EMS	Energy management system
EV	Electric vehicle
GB	Gas boiler
GHI	Global horizontal irradiance
GIS	Geographic information system
HES	Hybrid energy storage
HVDC	High-voltage direct current
ICT	Information and communications technology
IoT	Internet of things
IPT	Investment planning tool
IPTO	Independent Power Transmission Operator

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IT	Information technology
LNG	Liquefied natural gas
LPB	Local power balancing
MILP	Mixed Integer Linear Programming
MITS	Modular integrated transportable substation
OPEX	Operational expenditures
PV	photovoltaic
P2P	Peer-to-peer
RES	Renewable energy sources
TOTEX	Total expenditures
V2B	Vehicle to building charging
V2G	Vehicle to grid
VPS	Voltage power supply
VVP	Virtual power plant
WACC	Weighted average cost of capital
WF	Wind farm
WG	Wood gasifier
WP	Work package

1. Introduction

1.1. Background information

To stabilise the greenhouse gas (GHG) concentrations in the atmosphere; hence, reducing adverse impacts of climate change, many measures on different sectors have been implemented during the last couple of decades. Energy systems that are still predominantly based on fossil fuels are amongst those sectors. In EU27 countries, for example, energy supply has contributed with about 26% to the total GHG emissions (European Environment Agency, 2021) in 2020. In the same year, about 69% of the final energy consumption of the EU (that was 57,742 PJ) was supplied by fossil fuels, as shown in Figure 1 (European Union, 2021).

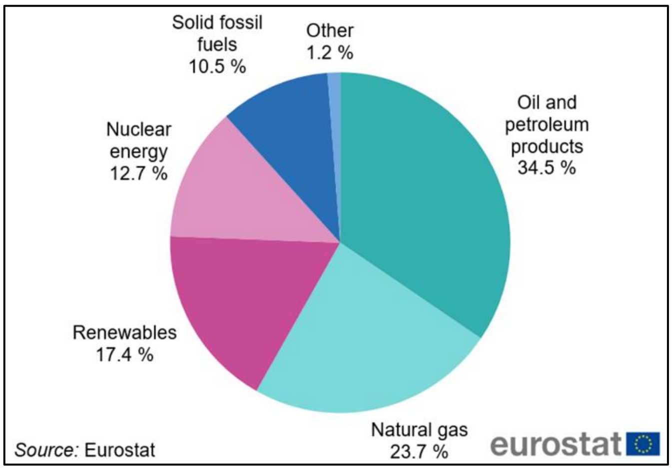

Figure 1. Dependency of the European Union to fossil fuels.

To actively support and accelerate the transformation of the global energy system towards a low-carbon one, while securing the energy supply and its affordability, as also stipulated in several energy and climate agreements (such as the Paris Agreement and the EU Green Deal), different potential areas have been targeted including geographical islands. This has been carried out via implementing several measures and launching different programs and initiatives. Small Island Developing States (SIDS) Lighthouses Initiative from the International Renewable Energy Agency (IRENA) (IRENA, 2021), or Clean Energy for EU Islands Initiative (Clean energy for EU islands secretariat, 2021; European Commission, 2017) are amongst relevant initiatives for geographical islands. In general, geographical islands are more vulnerable to climate change (Taibi, 2017). They are also notably facing various energy challenges due to geographic insularity that makes them special in the context of decarbonisation of the energy system. Two main energy challenges are:

- security of energy supply, in many cases reliance on imported fossil fuels, despite of having access to renewable energy sources (RES) (European Commission, 2017), and
- high energy costs due to several reasons e.g., additional transport of fuel supply, limited or lack of connection to the main energy markets (Pfeifer A. P., 2020), as well as unable to profit from economies of scale because of small energy consumption profiles (in case of small islands) (Duic, 2003).

At the same time, islands pose a great potential to be involved as living labs for hosting pilot projects and for demonstration of sustainable development pathways (Smart Islands Initiative, 2016; Bénard-

Sora, 2018). The mentioned challenges and the potential for energy system transition on islands have resulted in several development activities in this regard including the ongoing ROBINSON project (ROBINSON, 2020).

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 an innovative, flexible, cost-effective, and integrated energy system to contribute to islands' decarbonisation. This will be done by utilisation of locally available renewable energy sources (RES), and reducing the dependency on fossil fuels, without adversely affecting the energy supply security and costs through the following items:

- Better integration and optimised utilisation of local RES, power and heat networks, and storage infrastructure.
- Biomass/bio-waste and wastewater valorisation, and industrial symbiosis.
- optimisation and validation of innovative technologies.
- Development of an innovative, adaptable, and modular energy management system (EMS) integrating different energy vectors, both existing and newly developed energy and storage technologies (for electricity, heat, and gas).

1.2. Overview of Task 1.5

As part of the ROBINSON project, Work Package 1 – WP1 has main objectives specifying boundary conditions at the demonstration island (Eigerøy, Norway), as well as on the follower islands (Crete, Greece and Western Isles, Scotland).

To dive into different topics of Task 1.5, it is good to present some basic information of the involved islands in the ROBINSON project from the previous project's deliverables. In this regard, Table 1 illustrates that the islands are so different from an energy system point of view because of large differences in population, climates, sizes, available resources etc.

Table 1. Basic information of the islands.

Name	Eigerøy	Western Isles (or the Outer Hebrides)	Crete
Country	Norway	Scotland	Greece
Location	Southwest coast of Norway	A chain of islands off the west coast of Scotland	Approximately 160 km south of the Greek mainland
Size	20 km^2	3,059 km^2	8,336 km^2
Population	About 2,500 within	More than 26,000	About 635,000
Number of households	800 households	12,500 households	214,150 households
Climate	Mild and oceanic with high wind speed	Mild and oceanic with high wind speed	Mainly Mediterranean

As mentioned earlier, the energy systems of the concerned islands are very different and are of different scales.

In Eigerøy (demonstration island), almost 100% of the electricity is provided through cables from the mainland, and this power is generated mainly from hydropower (≈89%), onshore wind power (≈10%) and thermal power (1%)[1]. 88% of the electricity consumption is from industry. However, in the

[1] https://energifaktanorge.no/norsk-energiforsyning/kraftforsyningen/

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industrial sector on Eigerøy, there are a considerable amount of fossil-fuel based thermal energy used especially in the fish industry. In the island, there are plans for more factories raising the need for both thermal energy and electricity. It is expected that the current energy system is not able to handle the upcoming demand. Therefore, several different activities (including those in the frame of the ROBINSON project) in this context are on-going to supply the increasing demand in more sustainable ways.

In Western Isles, the Isles are reliant on imported liquid and gaseous fuels. The electricity supply to the isles is mainly based on two subsea cables providing 22 MW in total. However, the peak consumption is 30 MW, and the mismatch is covered by on-island diesel generators. On the positive side, Western Isles is home to a rich resource of renewable energy, especially wind, wave and tidal which could be harvested. And there is a plan for new high voltage direct current (HVDC) link to the mainland that will unlock the potential of import of considerable amounts of renewable power, or in case of harnessing large amounts of renewable energy sources on the islands, exporting power to the mainland through the new cable.

In Crete, the energy supply is mostly based on fossil fuels including electricity produced from thermal power plants, whereas the share of renewable power is about 21% (about 17% from wind and 4% from solar photovoltaic panels). It is roughly estimated that more than 60% of the residential buildings in Crete has at least one or two solar collectors installed on their roofs for hot water production. Transportation is based on imported fossil fuels. A new interconnection with the mainland grid is under construction, with the first cable providing 400 MW capacity.

In addition to determining the status of islands (from an energy system perspective), WP1 of ROBINSON has another objective that is benchmarking the ROBINSON energy system against other solutions. Deliverable 1.5 is corresponding to Task 1.5 entitled as “Benchmarking”. The task’s goal is to find suitable benchmarking case studies and compare them with the ROBINSON energy system using different performance indicators. Such case studies can be existing installations and outcome of other projects including for example the pilots of the Clean Energy for EU Islands Initiative. This report presents how Task 1.5 has been approached and summarises the outcomes of this task.

2. Benchmarking methodology and scope

To perform the benchmarking task, the first target was to find and identify relevant case studies that like the ROBINSON project aims at decarbonising the society via a decentralised and integrated energy system. Such case studies could be for example existing installations and outcome of other European projects. Accordingly, different projects (mainly H2020 projects), information and publications available on internet (with specific focus on scientific articles) were reviewed to find similar concepts and establish necessary comparative performance metrics. The following sub-sections present a summary of the activities that have been carried out to identify benchmarking case studies. In addition, the methodology to perform the energy system modelling and analysis is presented, as also described below, performing a benchmarking activity using the available information in the literature and from the previous projects could not be accomplished.

2.1. Reviewed projects

Different projects like the ROBINSON project with the main objective to contribute decarbonising geographical islands have been identified and reviewed. Initially around twenty projects were identified, but they were shortlisted based on considering soft and hard measures in those projects, as explained below.

Projects with “soft” measures are herein defined based on the definition by Crawford and Pollack, as projects in which the product or asset is intangible (Crawford, 2004). Putting this into the context of the ROBINSON project and Task 1.5, such projects can be characterised by those that aim to improve the efficiency of the existing energy system through developing software solutions for better system management (including managing electrical, heating or gas grids), developing new business models for better integrating and installation of renewable resources, load and production forecasting tools, improving awareness and policy changes (for example with local communities, stakeholders or policy makers) to help and foster adopting to green energy transition and decarbonising the society. Based on a similar classification, projects with “hard” measures are those in which the product or asset is tangible (Crawford, 2004). Again, to make it relevant for the ROBINSON project, these projects are herein defined as those involving both hardware installation and soft initiatives on demonstration sites. The hardware installed can include the development of integrated or non-integrated innovative solutions in efforts of decarbonising islands.

Next, relevant information such as objectives and summaries of the projects were collected for the shortlisted projects and compiled (as presented in the Appendix 1, Table A1). Collected information include solutions and technologies each project is working on, whether any hardware installation is involved or not, does it include gas, thermal electrical, or microgrid. Table 2 presents the topics that are covered by the chosen projects. The matrix indicates that there might be projects (for example “Islander”) used for benchmarking, but detailed information on their targets and status was not available. A detailed benchmarking beyond the content of Table 2 is therefore not possible.

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Table 2. An overview of the selected projects.

Project (website & lifetime)	Electricity/ smart grid/ VPP	Thermal grid	Gas grid	Micro grid	Storage	Hardware installations
SMILE – Smart Island Energy System (https://www.h2020smile.eu/) May 2017 – Oct. 2021	✓	✗	✗	✗	✓	✓
IntegrAted SolutioNs for DecarbOnisation and Smartification of Islands (https://ianos.eu/) Oct. 2020 – Sep. 2024	✓	✓	✗	✗	✓	✓
GIFT – Geographical Islands Flexibility (https://www.gift-h2020.eu/) Jan. 2019 – Jun. 2023	✓	✗	✗	✗	✓	✓
MESHA- Mayotte Replication model of Smart energy system (https://www.maesha.eu/) Nov. 2020 – Oct. 2024	✓	✗	✗	✗	✓	✓
REACT- Renewable Energy for self-sustAinable island CommuniTies (https://react2020.eu/) Jan. 2019 – Jun. 2023	✓	✗	✗	✓	✓	✓
MUSE Grids- Multi Utility Smart Energy Grids (https://www.muse-grids.eu/) Nov. 2018 – Oct. 2022	✓	✗	✗	✓	✓	✓
INSULAE- Innovative solutions for EU islands decorbanization (http://insulae-h2020.eu/) Apr. 2019 – Nov. 2023	✓	✗	✗	✓	✓	✓
Accelerating the decarbonisation of islands' energy systems (https://islander-project.eu/) Oct. 2020 – Sep. 2024	✓	✓	✓	✗	✓	✓

Note: Green check mark indicates consideration of a highlighted energy aspect, while the red cross mark indicates exclusion of an aspect.

2.2. Reviewed scientific articles

The energy-related challenges and the potential for energy system transition on islands have attracted the research and development community in the recent years. In this regard, different researchers have

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investigated the energy systems of islands (mainly power systems) from different perspectives and using different methodologies. A few examples of available studies focusing on geographical islands are listed in Table 3. The available publications have mainly focused on scenarios assessment and theoretical studies considering increase in the share of RES for power generation in the energy systems.

Table 3. Examples of relevant research activities in the context of decarbonisation of geographical islands' energy systems.

Reference	Focus areas	Methodology	Geographical scope
Duić et al. (Duic, 2003)	Scenario analysis for emission reduction via use of clean development mechanism of Kyoto Protocol	Estimated increase in RES share in power production	The Island of Santiago (Cape Verde)
Duić et al. (Duić, 2008)	Scenario analysis for energy and resource planning	Establishment of a new energy planning method (RenewIslands)	Few islands in the Adriatic Sea (Croatia)
Yue et al. (Yue, 2016)	Potential assessment for 100% local RES – electricity	Simulation of optimal RES integration using EnergyPLAN	Wang-An Island (Taiwan)
Thomas et al. (Thomas, 2016)	Potential assessment for isolated microgrids using different share of local RES – electricity	Techno-economic analysis using HOMER	Agios Efstratios Island (Greece)
Gils and Simon (Gils, 2017)	Scenario analysis for 100% local RES – electricity, electric vehicles, electric heating, and hydrogen use	Model coupling between a long-term energy system balancing tool (Mesap-PlaNet) and a deterministic high resolution energy system optimisation model (REMix)	The Canary Islands, Spain
Hall and Swingler (Hall, 2018)	Scenario analysis for 100% local RES – electricity	Time-series simulations and modelling of power generation, consumption, and storage with and without curtailment for variable RES	Prince Edward Island (Canada)
Maïzi et al. (Maïzi, 2018)	Scenario analysis for 100% local RES – electricity	TIMES model and introduction of power system's reliability and robustness indicators	Reunion Island (France)
Selosse et al. (Selosse, 2018)	Scenario analysis for 100% local RES – electricity	TIMES model	Reunion Island (France)
Pfeifer et al. (Pfeifer A. D., 2018)	Scenario analysis for 100% local RES – electricity, transport such as vehicle-to-grid (also including marine transportation), also thermal energy	Energy planning method using EnergyPLAN and embedded MultiNode tool	Few islands in the Adriatic Sea (Croatia)
Dorotić et al. (Dorotić, 2019)	Scenario analysis for 100% local RES – electricity, transport such as vehicle-to-grid (also including marine transportation), also thermal energy	Energy planning method using EnergyPLAN	Korčula (Croatia)
Ma and Javed (Ma, 2019)	Dimensioning of integrated hybrid PV-wind-battery energy system (electricity only)	Techno-economic and reliability modelling	Jiuduansha (China)
Marczinkowski and Østergaard (Marczinkowski, 2019)	Scenario analysis for increased local RES – energy system (also thermal energy)	Different energy planning approaches using EnergyPLAN	Samsø Island (Denmark) and Orkney Island (Scotland)
Pfeifer et al. (Pfeifer A. P., 2020)	Scenario analysis for zero emission marine transportation (ferry lines)	Energy planning method using EnergyPLAN	Few islands in the Adriatic Sea (Croatia)
Calise et al. (Calise, 2021)	Scenario analysis for energy and resource planning – energy system	Energy planning model using EnergyPLAN	Sardinia (Italy)

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Within the list provided in Table 3, there are only a few research studies that also considered the thermal energy as part of the studied energy systems. Acknowledging that the list is not an exhaustive one, further development of integrated energy systems obviously requires more demonstration projects also considering sector coupling, multiple energy vectors, different energy storage options and transportation infrastructure. As several of similar initiatives are still in the implementation phase, and because of lack of implementation of an identical case study as the energy system proposed by the ROBINSON, energy system analysis specifically made for the case of Eigerøy was pursued.

2.3. Energy system modelling and scenario development

As the evaluation of already ongoing projects, as well as literature review does not allow for a more detailed benchmark, it was decided to base the benchmark on modelling and simulation of the energy system on the demonstrator island. Several scenarios were evaluated technically, as well as economically to allow a benchmark of different concepts for decarbonisation. Therefore, this section focuses on the techno-economic evaluation of possible renewable energy systems deployable on the island of Eigerøy, as a master copy for any other geographical island. Eigerøy includes a residential area, and an industrial sector. The industrial partner of ROBINSON in Eigerøy, i.e., Prima Protein, currently relies strongly on fossil fuels, such as LNG and propane for its processes. In this regard, electricity and high-temperature heat demands of the industry, and electricity demand of the residential area need to be considered and satisfied. Accordingly, technologies investigated are photovoltaic (PV) panels, onshore and offshore wind farms, and a combined heat and power (CHP) system using micro-gas turbine technology. To valorise the local biomass resources, a biomass gasifier integrated with the CHP system is also considered.

A mathematical optimisation model is used to perform the desired investigation. This report shows the impact of a single renewable technology (solar, wind, biomass) on the current energy supply system, and how stable (in terms of supplying the demand) a given solution is concerning a parametric change, indicating also the most economically feasible solution given the assumptions made and the boundary conditions used.

The investigation of the research questions outlined above requires a quantitative approach. Consequently, the Mixed Integer Linear Programming (MILP) optimisation technique is found suitable performing this task. Each energy technology is described with an (energy conversion) equation i.e., inputs, outputs, and eventual losses all in hourly resolution. A similar description follows for the local grid of each energy vector carrier i.e., electricity and heat. Since the study aims to find a set of economically feasible solutions, additional equations describing financial parameters are considered. The resulting overall set of equations is solved to minimise total yearly expenditures. Details are regarding this activity is presented in the following sub-sections.

2.3.1. Demand profiles on Eigerøy

Electricity consumption for the island is obtained for the year 2021 on an hourly basis, and the high-temperature heat demand[1] of the fish factory on a daily scale, shown in the Figure 2. For the heat demand, the delivered data on the daily basis had to be adapted to the resolution of the model i.e.,

[1] Note that heat demands of other industrial actors in Eigerøy are excluded from the analysis, mainly due to the lack of information.

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hourly basis. For simplicity, the heat demand of the concerned industry in hourly resolution was obtained by distributing its daily heat demand equally over 24 hours (assuming the fish processing happens continuously in day and night shifts).

The total yearly electric and heating energy demands reach 74 GWh, and 40 GWh, respectively. It is noticeable that the electricity demand is not equally distributed over the year, but subject to a strong seasonality. It is seen a higher electricity consumption in the first 1,500 hours of the calendar year, mainly because the domestic heating systems (as reported above are mostly based on electric resistance heaters) used in the winter season. The heat demand also varies over the year with the highest consumption rate in spring and the first half of the summer, being the high season for fish processing.

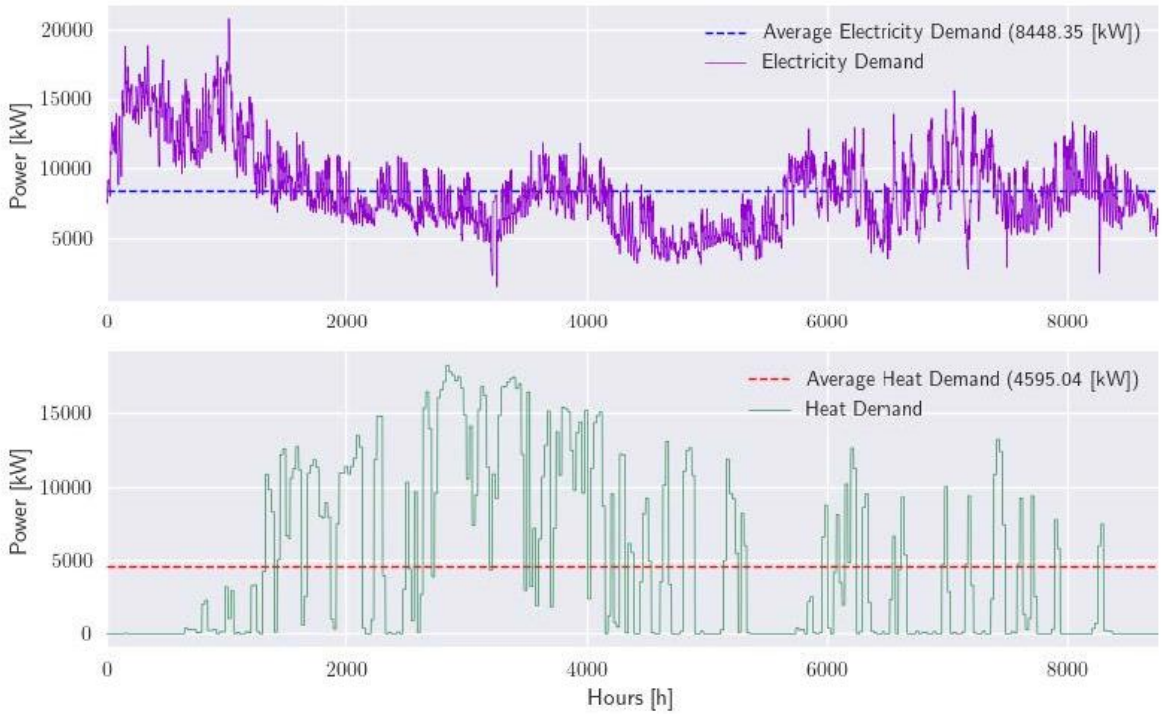

Figure 2. Electricity (entire island) and heat demand (only Prima Protein) of the Eigerøy island in hourly basis, 2021.

2.3.2. Energy Prices

The price of electricity in Norway was relatively low before 2020. In 2021, the electricity prices have raised almost by a factor of two as shown in the Figure 3 (Group, Nord Pool, 2022), becoming the country with the highest electricity price change in Europe from 2020 to 2021 and the trend over the next years is not expected to change direction. For comparison, the electricity price in Crete in January 2021 started at around 0.05 €/kWh, but most of the time the price was above 0.12 €/kWh. The average price for the second half of the year 2021 was 0.17 €/kWh in Crete (Eurostat, 2022).

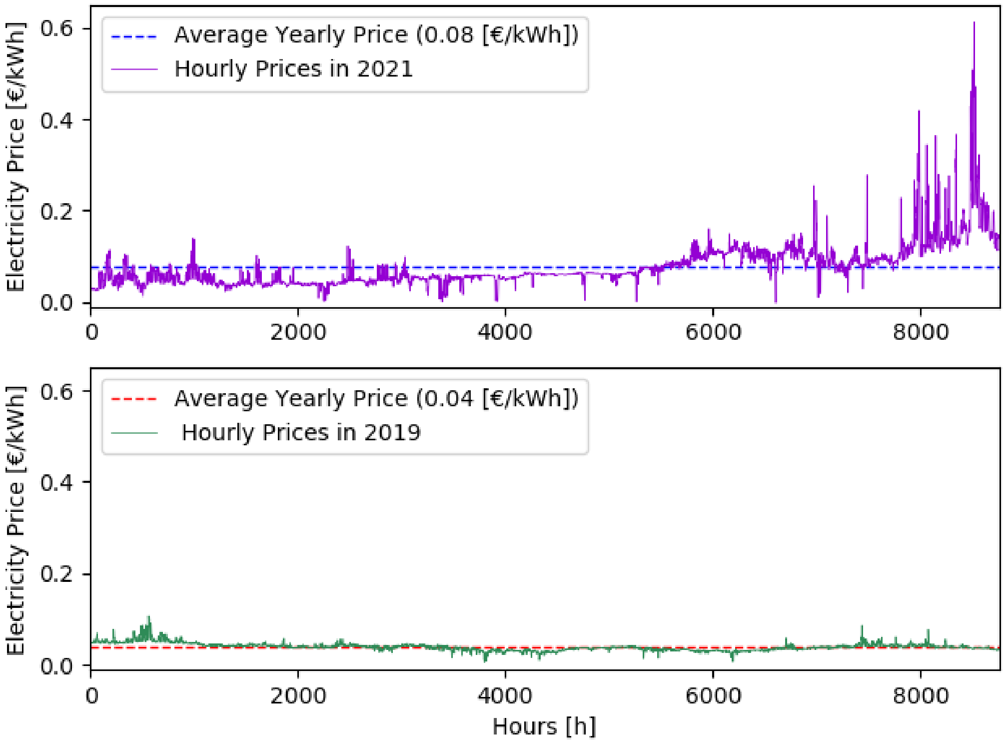

Figure 3. Electricity Price in Norway in hourly resolution over for 2019 and 2021.

Because of very high energy prices, the industry in Eigerøy is also using propane to satisfy their process heat demand, instead of using liquified natural gas (LNG) as before. The LNG price for 2022 is estimated to be around 0.12 €/kWh, while it is estimated to be 0.07 €/kWh for propane.

2.3.3. Natural Resource Availability

To have a better estimate on the potentials for using available renewable energy resources, their availability in Eigerøy is presented here.

2.3.3.1. Solar Irradiation

The global horizontal irradiance (GHI) for Eigerøy can be seen in the Figure 4, where it is also shown the irradiation level in Crete, Greece (for comparative purposes). The mean irradiation power in Eigerøy reaches 0.12 kW/m^2, while for Crete the value is almost double i.e., 0.23 kW/m^2. The data were taken from *renewables.ninja*, a web tool for energy source prediction (Pfenninger, 2021), using data presented in (Pfenninger S., 2016).

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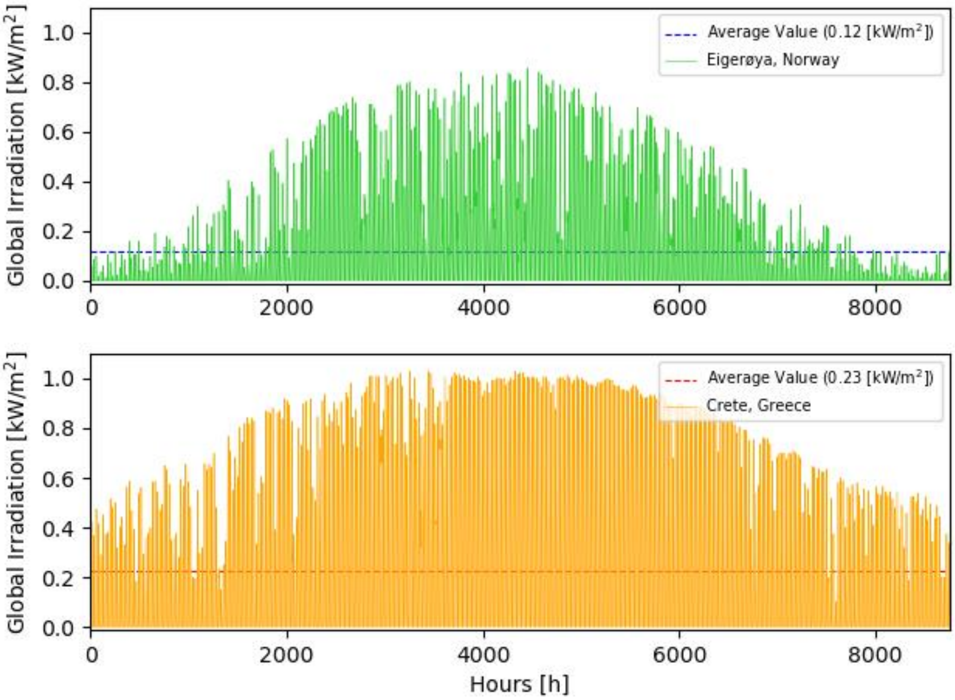

Figure 4. The global horizontal irradiance intensity in hourly profile for Eigerøy and Crete islands.

2.3.3.2. Wind power

The wind power density in the Eigerøy region is relatively high, creating a potentially advantageous condition for wind farm (WF) installation. As evaluation of both onshore and offshore wind farms are of interest, two sets of data are needed, accordingly.

The wind speed data are from The NASA's POWER Project (Nasa Power, 2022), which works based on similar principles as *renewables.ninja* (Pfenninger, 2021). The tool provides hourly resolute wind speed data at the height of 50 m above the ground. For this, data are extracted for both onshore and offshore wind farms (5 km from the island coast). Another aspect is the wind speed variation with the height. The steady-state wind tends to have a lower wind speed at lower altitudes but increases with height, which is due to the friction of moving air mass with the ground. A common way to describe the wind speed variation with height is the log-law (C. Lopez-Villalobos, 2022). The height of the wind turbine hub varies with its capacity, i.e., the higher the capacity, the bigger the rotor and the bigger the rotor, the longer the hub is. For a wind turbine with around 1 MW power rate output, the hub height is expected to be 60 m, while for a 4.5 MW wind turbine, altitudes of 120 m might be reached (Mercado, 2011). Since the wind farm capacity is unknown, 80 m as the reference height is defined for the calculation here. The wind speed onshore and offshore for Eigerøy is shown the Figure 5. The wind speed onshore for the island of Crete is also shown for comparison in Figure 6.

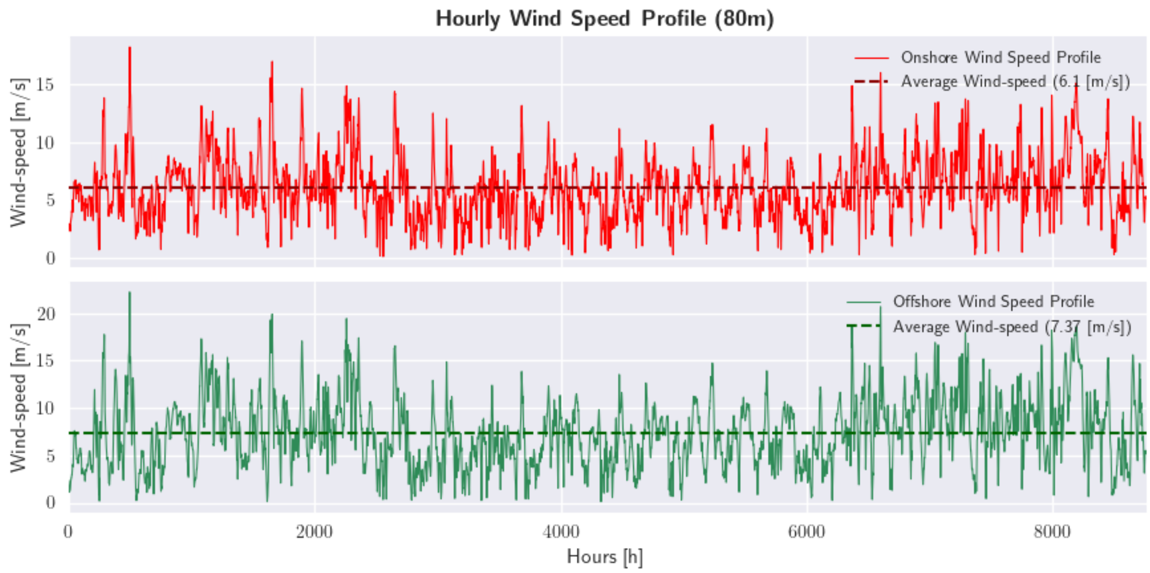

Figure 5. Hourly profiles of wind speed in Eigerøy (onshore) and at the distance of 5 km from the cost (offshore), 2021.

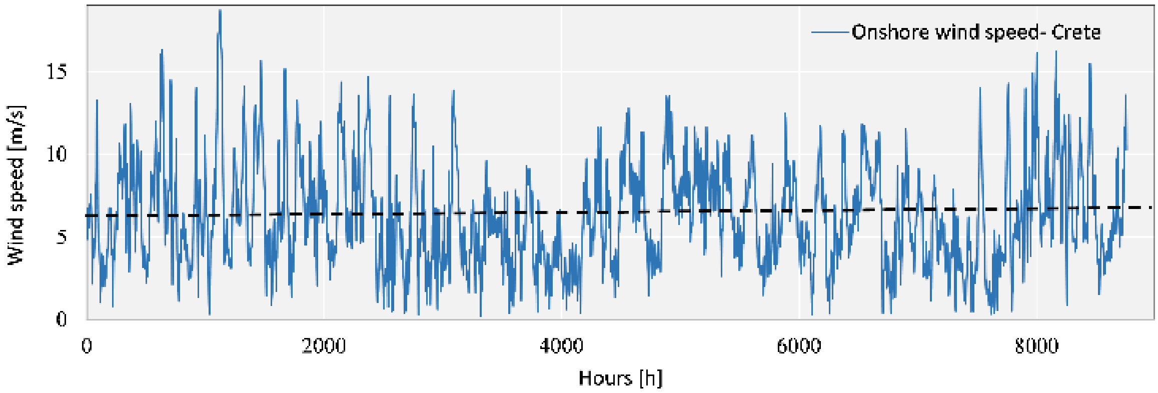

Figure 6. Hourly onshore wind speed profile in Crete with the average of 6.4 m/s, 2021.

2.3.3.3. Biomass Availability

The availability of biomass on the island is estimated to be roughly 52 t/day (SIMEONI, 2022). With a wood heating value of 3.5 kWh/kg, it is estimated that the island would have 14 GWh of wood energy annually available for power and heat. The wood, however, comes with a cost, which is considered to be 5.7 €/MWh for this study.

The availability of biogas is also evaluated in this project. The biogas can be mixed with the syngas and fed to the CHP system. To estimate the amount of generated biogas, the average power production potential from municipal waste per capita i.e., 5 W/person is used (Madi, 2016). In a year, this makes an energy potential equivalent to 109 MWh for a population of 2,500 people. The wastewater from the fish processing industries is not considered for this report. As the expenditure related to biogas production is assumed to be negligible in this study, the resource is considered to be available at no cost.

2.3.4. Energy system modelling

As previously mentioned, with the MILP framework, the problem is defined through a set of mathematical equations and then solved with a proper algorithm. In this case, the commercial Gurobi Optimizer (Bixby, 2007) is used as the solver for a model written with Python syntax. As shown in

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Figure 7, the model inputs are technical properties of each unit, natural resources parameters such as GHI and wind profiles and economic variables. For economical evaluation of this defined energy system, the concept formalised in the doctoral thesis of P. Stadler (Stadler, 2019) is considered. In simple words, for economic evaluation, a set of equations links the technological deployment, fuelling costs with the physical sizes of different systems, and their respective rate of fuel consumption.

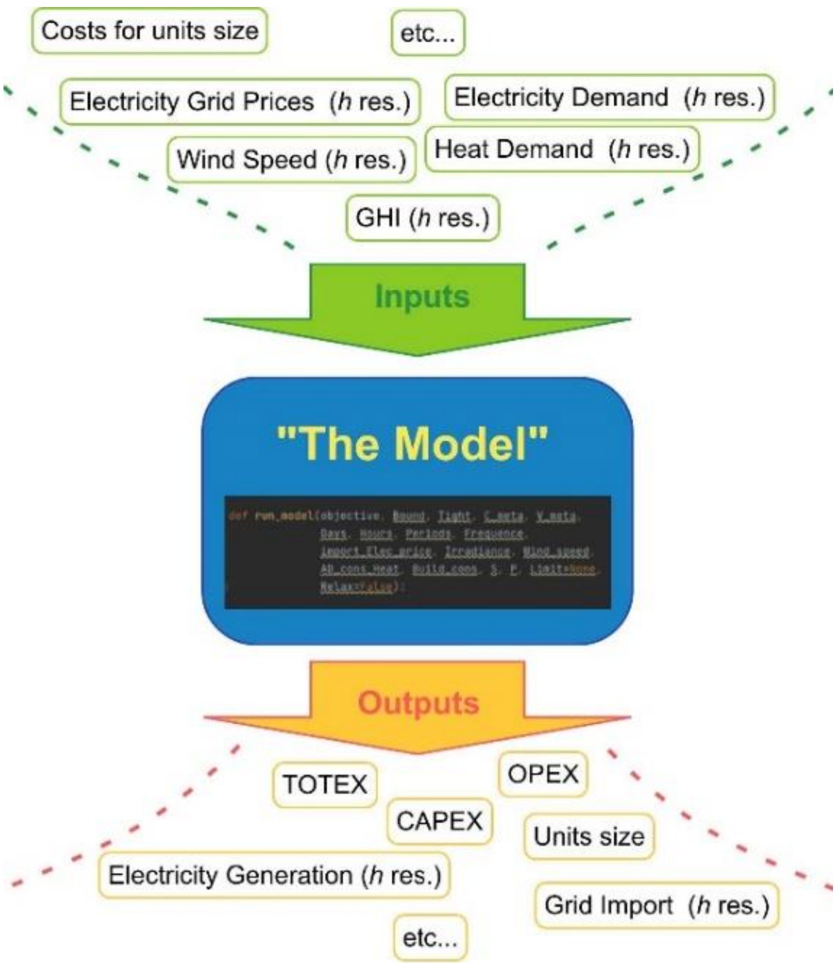

Figure 7. Visualisation of the approach, inputs, and outputs.

The objective of the model is to minimise the annual total expenditures (TOTEX) [€/year] defined as the sum of the annual capital expenditures (CAPEX) and the annual operational expenditures (OPEX). In general, for capital expenditures to be paid upfront, this often requires a loan with a payback system, based on annual repayment. In addition, each loan is subjected to the weighted average cost of capital (WACC) i.e., a more general expression for interest rate. The goal of the model is to satisfy the energy demand with the energy supply system minimizing total cost. Energy demand and supply are resolved on an hourly basis; thus, the energy balances or/and conversion equations are defined for each individual hour of the year.

2.3.4.1. Energy conversion units

There are six technologies defining the energy supply system; five of them generate directly the required useful type of energy (electricity, heat), while one operates as a fuel conversion unit.

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Photovoltaic installations, offshore- and onshore wind farms (WF) generate electricity only; CHP systems generate both electricity and heat, while the gas boiler (GB) output is heat only. The WG plays the role of fuel conversion unit by converting wood chips into syngas. PVs and WFs use solar irradiation and wind energy for power production, while CHPs and GBs run on fuels. In the model, the CHP units can consume only the available biogas and the syngas produced by the WGs, while GB consumes only LNG or propane. Table 4 shows a summary of the parameters used in the model for each unit.

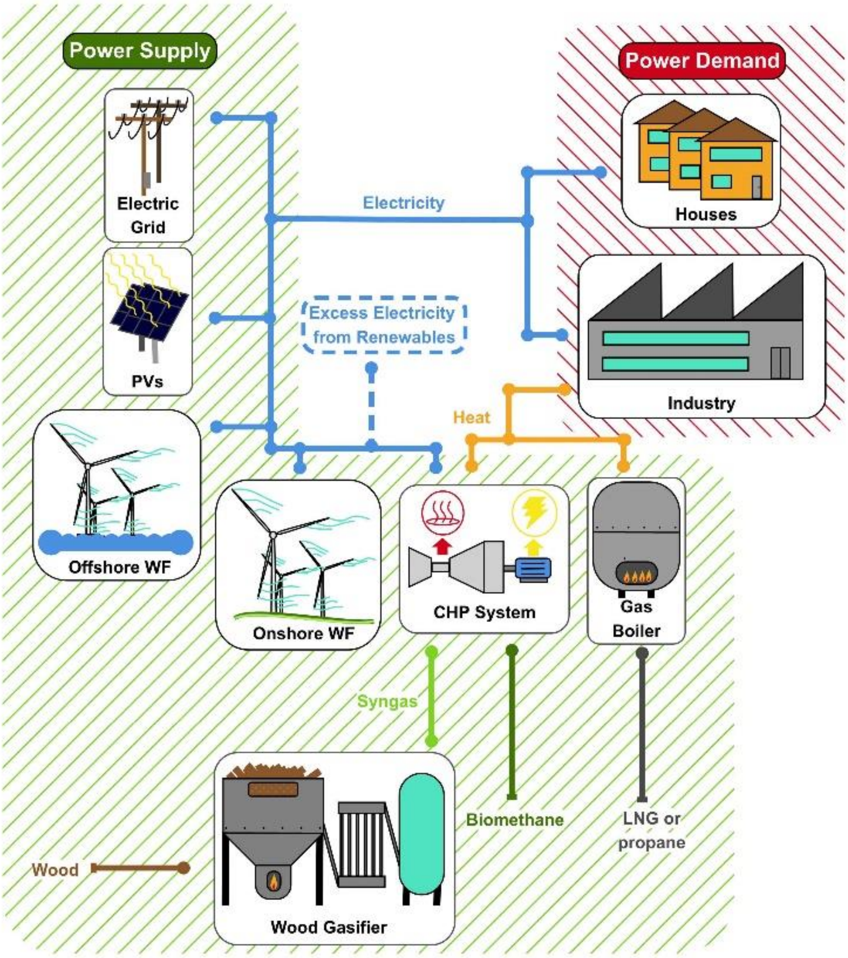

Figure 8. The energy system model in Eigerøy.

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Table 4. Summary of the parameters used in the model for each unit.

	PV	onWF	offWF	WG	CHP	GB
CAPEX (€/kW)	550	1300	3000	1400	1400	100
OPEX (%)	1.7	2.5	2.5	3	3	5
WACC (%)	5	7	8	10	10	2.5
η_{el} η_{th} η_{HHV}	15 - -	- - -	- - -	- - 84	43 50 -	- 98 -
Lifetime (years)	20	20	20	20	20	20
References	(Steffen, 2020) (Lindahl, 2022) (Vartiainen, 2020)	(Njiri, 2019) (Sens, 2022) (Duffy, 2020)		(An internal ROBINSON report)		

2.3.4.2. Green hydrogen production

The main energy system may fail to match the produced electrical power with the demand because of the intermittent nature of renewables. Thus, a fraction of generated electricity will be unused, which can be injected into the mainland grid free or be used for hydrogen generation for selling. To understand which option is more feasible, a separate MILP model is defined. They are two units: battery (BAT) and hydrogen electrolyser (H-EL), Figure 8. Nowadays, the cost of battery storage has dropped drastically (I. Y. L. Hsieh, 2019), while electrolysers are still expensive (refer to Table 5). It may be reasonable to have some storage capacity to distribute more evenly the peaks of electric power and reduce the required capacity of the electrolyser.

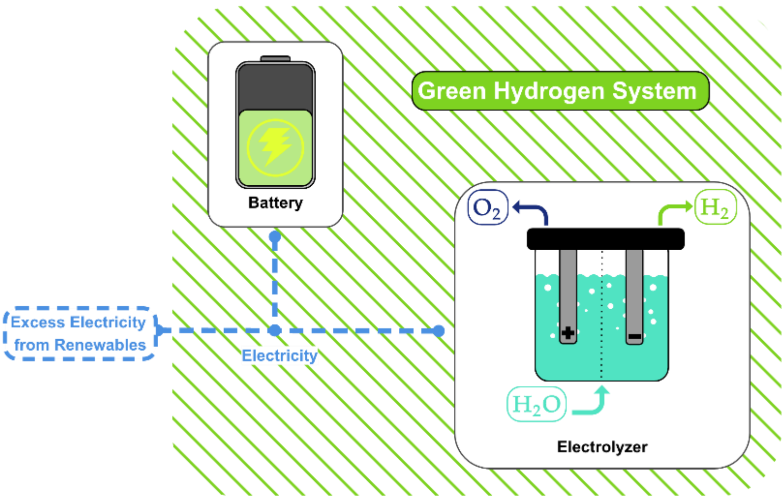

Figure 9. Green Hydrogen production system for Eigerøy.

Table 5. Summary of economical parameters for the electrolyser and battery system.

	Electrolyser	Battery (Li-ion battery)
CAPEX	1300 (€/kW)	275 (€/kWh)
OPEX (%)	2	2.5
WACC (%)	10	11
Efficiency	70	100
Lifetime (years)	15	15
References	(Christensen, 2020)	(Vartiainen, 2020)

2.3.4.3. Sensitivity analysis

To study the parameter uncertainty/instability, the sensitivity analysis is used as the main approach. The sensitivity analysis consists of studying the repose of a deterministic model to the changes in single parameters. It means that while one parameter is changed between different model executions, the other parameters are kept fixed. The results of different variations can then be collected and analysed to identify the most important variables (most sensitive ones to the changes) in the model. Here, some parameters that are typically more influential are selected, and the effects of variations on TOTEX and the advised size capacity of a unit are investigated.

2.3.5. Scenario definition

In this section, the electric system of Eigerøy is being studied, with the possibility of using PV, offWF and onWF as stand-alone or combined technological solutions. A sensitivity analysis is performed to understand under which conditions renewables will become more competitive. For single technology scenarios, four indicators are investigated namely, potential of the natural resource[1], TOTEX, WACC, and electricity price (EL-Price). The scenarios are:

- Scenario Zero; current situation.
- Scenario A; the role of PV.
- Scenario B; the role of onWF and offWF.
- Scenario C; combination of PV and WFs.
- Scenario D; the role of biomass in the decarbonisation of the CHP operation.

[1] This is selected to show the effect of location change (for example on GHI) on the economic performance of the system, while the other parameters are kept similar.

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3. Results and discussion

This section discusses only the results of techno-economic modelling and simulation (as described in Section 2.3), as also mentioned earlier the evaluation of other ongoing EU projects, as well as available publications do not provide a sufficient base for benchmarking.

3.1. Scenario Zero – Current situation

The current situation consists of complete electric power dependency to the mainland and a GB that covers the heat demand of Prima Protein (as illustrated in Figure 10). The scenario uses the electricity prices profile of 2021 and LNG price. The total yearly expenditure is estimated to be about 9.05 M€/y, which 5.6 M€ goes for electricity and 2.87 M€ for propane. The installed capacity represents the maximal yearly heat demand, about 18,300 kW. The electric energy supply from the mainland grid follows the same pattern as energy demand from the Figure 2.

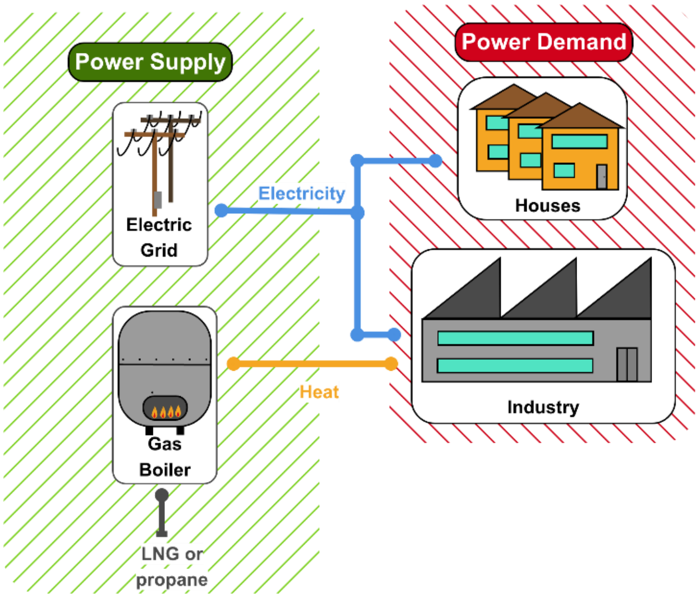

Figure 10. Schematic of the current situation in the island (Scenario Zero).

A sensitive analysis is performed over the electricity (EL)- and fossil fuel (FF) prices to foresee the possible effects on the island energy expenditures. Figure 11 represents the TOTEX related to the overall energy needs of the island as a function of energy price variations (EL and FF). The reference price for electricity is 0.08 €/kWh (price at 2021) and for the heat is propane at 0.07 €/kWh. The change is performed with a percentage multiplier.

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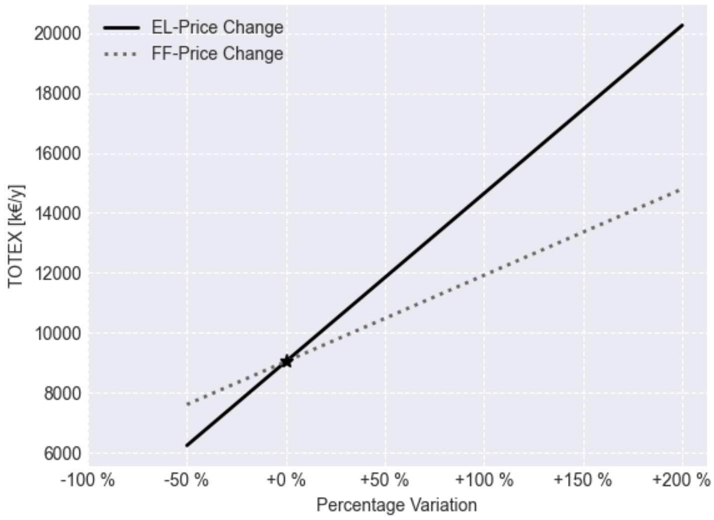

Figure 11. Sensitivity analysis for the Scenario Zero. Effects on the TOTEX.

3.2. Scenario A – The role of PV

The schematic of the Scenario A, i.e., when PV panels are integrated into the current energy system is illustrated in Figure 12.

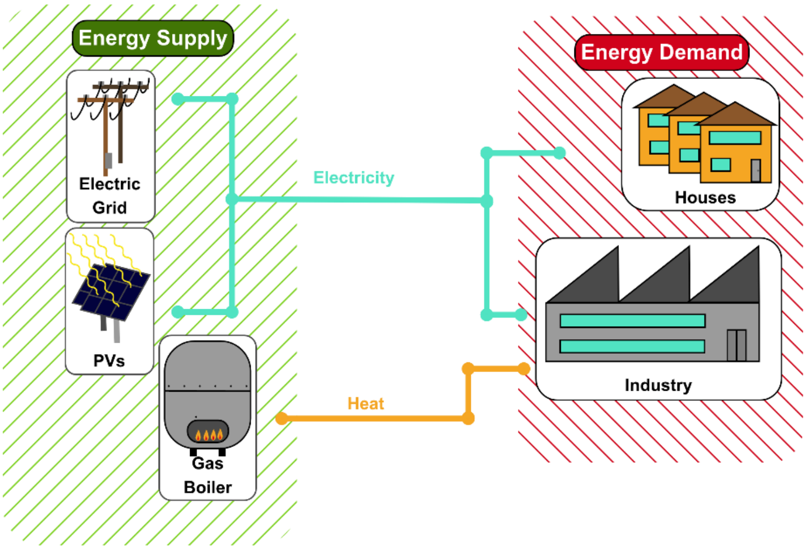

Figure 12. Schematic of the Scenario A, the role of PV.

The sensitivity analysis for PV is performed by varying GHI, CAPEX & OPEX, electricity price, and WACC. The represented in

Figure 13, TOTEX and installed PV capacities show different behaviours. On one side, the TOTEX exhibits continuity with parameters variation, while the installed capacity of PVs seems to have breakpoints, after which the size of PVs increases drastically. The total expenditure shows a variation with WACC, unit expenditures, and GHI only as soon as some PVs are installed. The variation of those parameters is not projected in substantial TOTEX change. On the other hand, the EL-Price dimension

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shows a much higher effect on the TOTEX, leading to larger changes in the values. The influence seems almost linear; however, the red line representing Scenario Zero clearly shows the change in slope after the PV deployment.

It is also true that the top floor limit for PV size is set to 20 MW for this project, and after the maximal capacity is reached, at about +75%, the TOTEX increases linearly, i.e., the fraction of electricity to be imported would be constant at the maximal PV size, with which the linear effect is generated again.

With increasing GHI intensities, the capacity increases until reaching a peak at around +80% and then follows a slight decrease but generally remains stable at 10 MW. The WACC, and CAPEX & OPEX variation are explored in a decreasing direction since lowering those decreases the relative cost of electricity produced by PVs, becoming more concurrent to the mainland's power supply. Overall, this analysis shows that PV may become a more convenient solution with increase of 15% in electricity price, decrease of capital costs by 10%, WACC reduction by 43%, or 15% increase in the GHI (i.e., finding a location with higher irradiation).

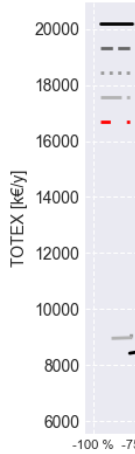

Figure 13. Sensitivity analysis for the Scenario A; Effects on the installed capacity (upper) and TOTEX (lower).

Scenario A – Hydrogen system

The excess electricity must be considered to understand if the hydrogen system can potentially compete with the market as a green hydrogen production plant. Since hydrogen production was considered for all sensitivity analysis scenarios, a graph representing the hydrogen production cost can be estimated by taking the total produced hydrogen and dividing it by the cost of the plant (as shown in Figure 14). From this graph, we can see that the lowest price is at the highest PV installed capacity. However, the cost of hydrogen production in such a configuration is relatively expensive, accounting for the lower value of 2.5 €/kWh or 83 €/kg$_{H2}$ (without considering the GHI level) in comparison to the market price for green hydrogen is about 5 €/kg, which transform to 0.15 €/kWh.

An example of the hydrogen system (H-SYS) operation profile is shown in the Figure 15. An electrolyser unit of 5.6 MW, and battery size of 8 MWh is taken into account. The electrolyser is operated based on the excess electricity from PV, which is peak shaved by the battery for smoother operation and more economical solution.

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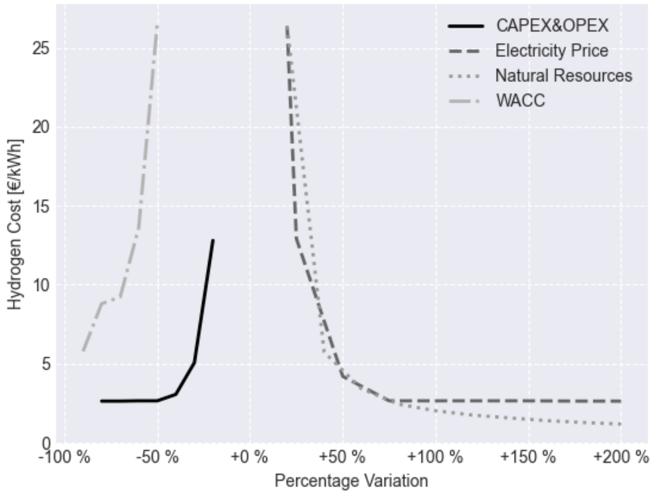

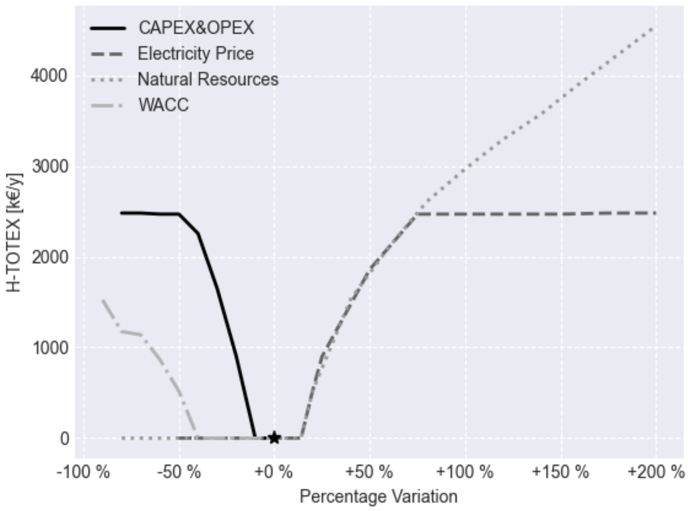

Figure 14. Sensitivity analysis for hydrogen production in Scenario A.

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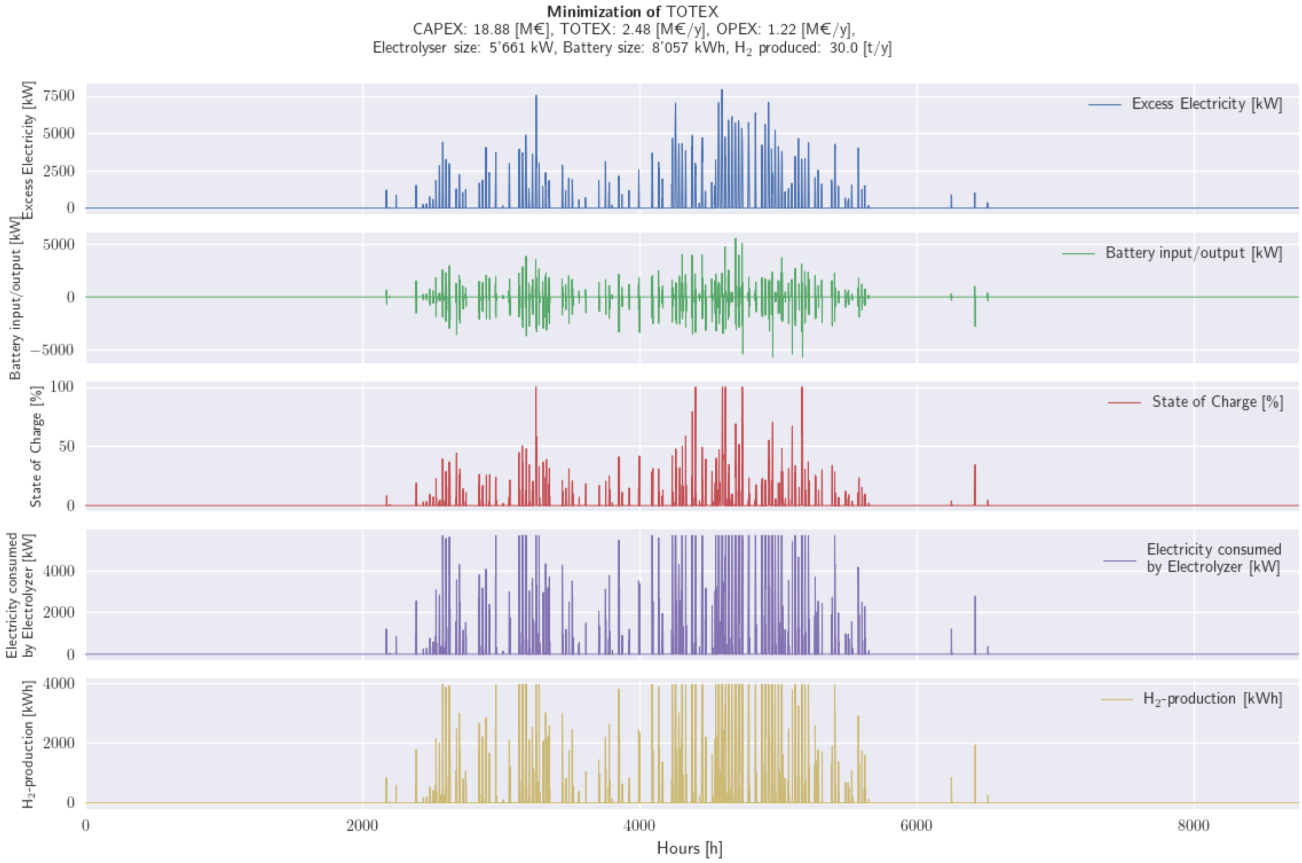

Figure 15. Operation profile of H-SYS for H_2 production in Scenario A.

3.3. Scenario B – The role of onWF and offWF

The schematic of the Scenario B, i.e., when onshore and offshore wind farm are integrated into the current energy system is illustrated in Figure 16.

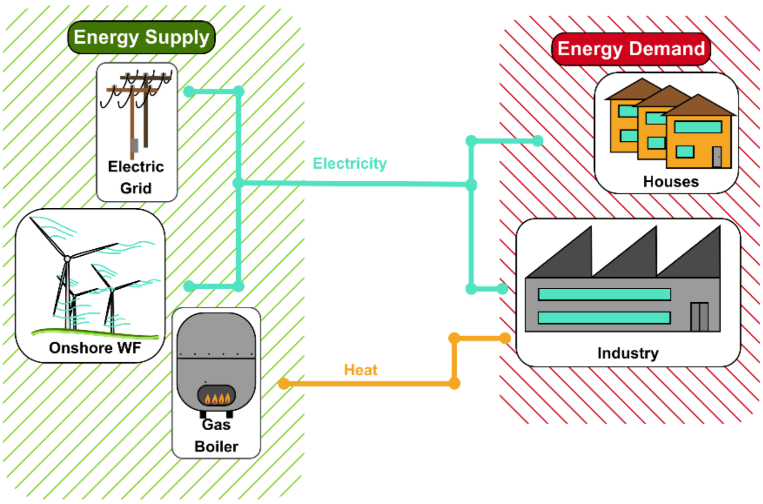

Figure 16. Schematic of the Scenario B, the onshore wind farm.

Like the PV scenario, the variables of interest for wind farms are installed capacity and TOTEX for onWF as shown in the Figure 17. The sensitivity analysis of onWF and offWF (not shown here) show very

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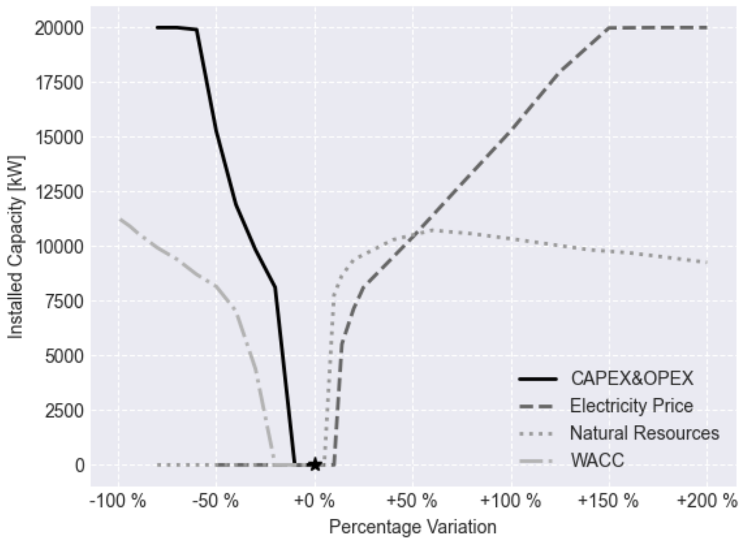
similar behaviour to PVs in dependency on WACC and unit CAPEX and OPEX, although the wind farms have a more significant influence on TOTEX than PV. The difference is seen with the EL-Price increase. Here the suggested capacity for installation increases linearly from the breaking point to the top floor capacity (20 MW) in a gentler manner compared to PV. This means that with less installed capacity, it is possible to compensate for the more expensive electricity. Thus, the total capacity factor is higher for onWF than for PV. Another interesting point can be seen with the variation of wind speed. The capacity factor function of the wind farms has a cut-off wind speed threshold (25 m/s); thus, too high wind speed may become counterproductive. In general, offWF have higher average wind speed and expenditure is more than double compared to the counterpart, i.e., onWF.



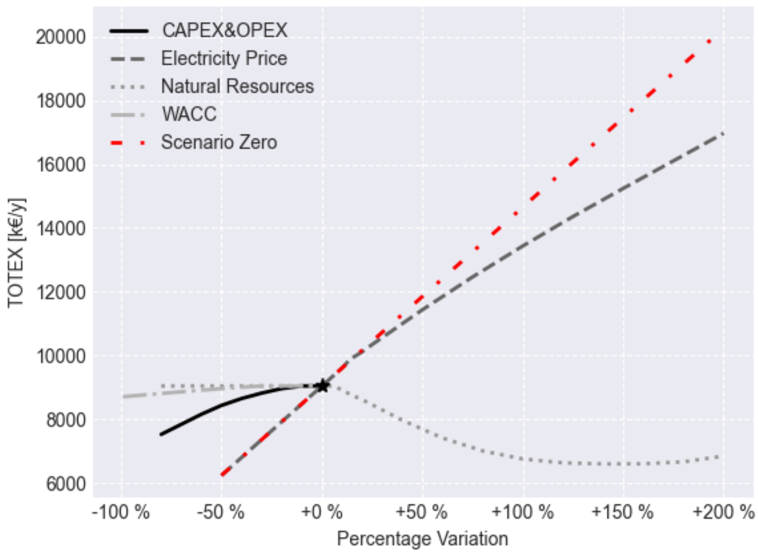


Figure 17.Sensitivity analysis for Scenario B; Effects on the installed capacity for onshore WF (upper) and TOTEX (lower).

Table 6 summarises the different breaking points for both onWF and offWF (these percentages are relative to the values presented in Table 4). The parameters generally show a slightly smaller percentage variation compared to the PV for reaching a breakpoint. For example, the increase in the wind speed by 5% (in onshore wind farms) can be simply reached with increasing the hub height. With the help of log law, it was estimated that at 100 m above the ground, such the desired mean wind

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speed would be reached. Nowadays, wind turbines of 5 MW capacity reach dimensions of 120 m height and more.

Table 6. Summary breakpoints for onWF and offWF.

	onWF	offWF
Wind speed	5% increase (6.3 m/s)	40% increase (9.9 m/s)
Electricity price	10% increase (0.09 €/kWh)	60% increase (0.13 €/kWh)
CAPEX	10% reduction (1,170 €/kW)	30% reduction (2100 €/kW)
WACC	25% reduction (5.25%)	90% reduction (0.8%)

Scenario B – Hydrogen system

The hydrogen production costs are estimated following the same logic as for PV scenarios. The production price graph shows that the lowest price is at the highest installed capacity. The produced excess of electricity at 20 MW of installed PV accounts only for ca. 1,500 MWh/year against 8,000 MWh/year, which leads to a lower production cost of hydrogen. However, in the best-case scenario, the price reaches a bottom of 0.85 €/kWh (28 €/kg_{H2}), Figure 18. Operation profile of the hydrogen system in Scenario B is shown in the Figure 19.

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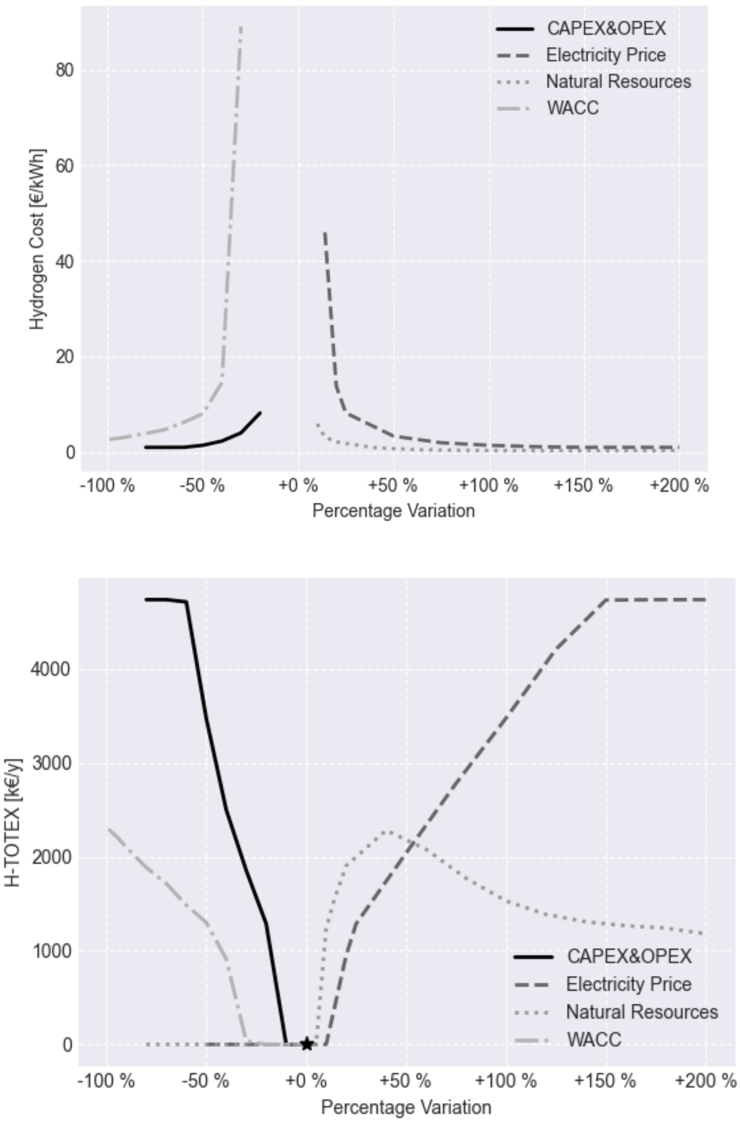

Figure 18. Sensitivity analysis for hydrogen production in Scenario B.

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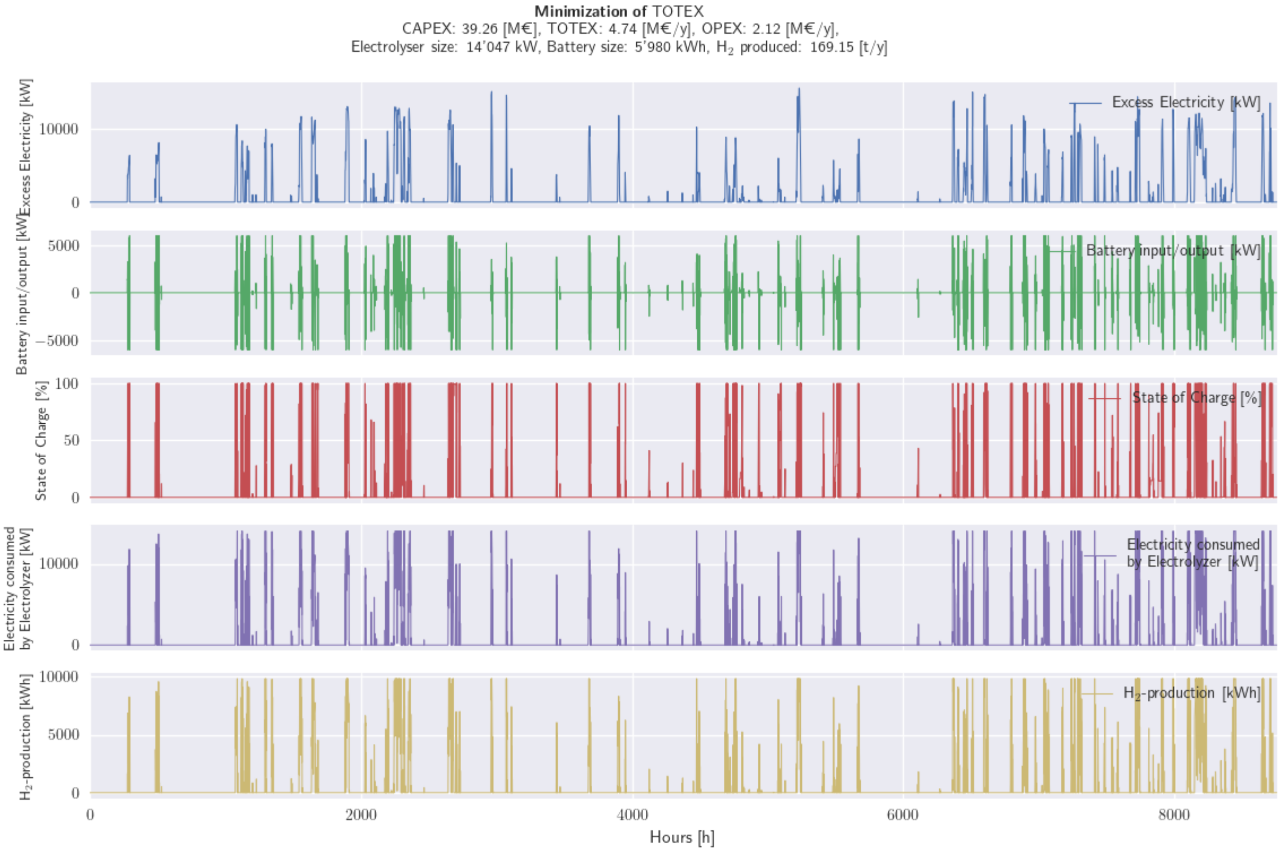

Figure 19. Operation profile of H-SYS for H2 production in Scenario B.

3.4. Scenario C – Combination of PV and onWF

From single technologies scenarios analysis, it can be seen that the most influencing parameters are CAPEX and EL-Price, with EL-Price playing the main role in TOTEX evolution and an important role in the optimal size of technology.

For the combination of technologies, the sensitivity analysis is performed only along the EL-Price dimension for different discrete sets of CAPEX values. From the Figure 20, it is observed how fast CAPEX influences a specific technology grows with increasing size, i.e., starting at different CAPEX, the same technology grows at a different rate with EL-Price increase. It is also curious that at some point, even if one technology starts to appear at a specific price increase as a stand-alone solution, with a further increment of the price, also the other counterpart appears. According to these results, the consideration of both technologies would lead to a cheaper solution as it would be for a stand-alone case. Electricity profile from a 7-MW PV plant in combination with a 7-MW onWF is shown in Figure 21.

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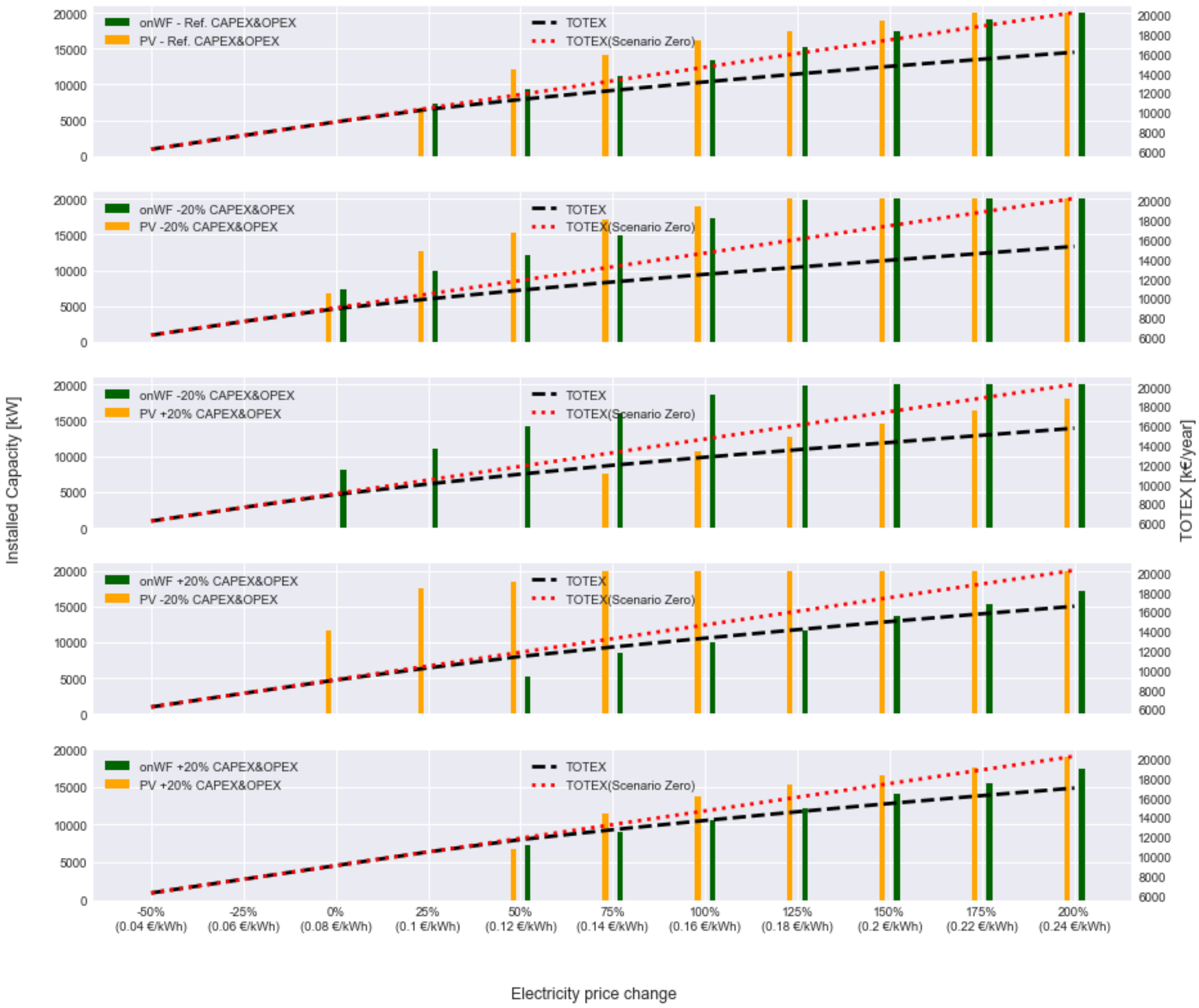

Figure 20. Sensitivity analysis for the Scenario C; TOTEX variation by increasing the EL-Price.

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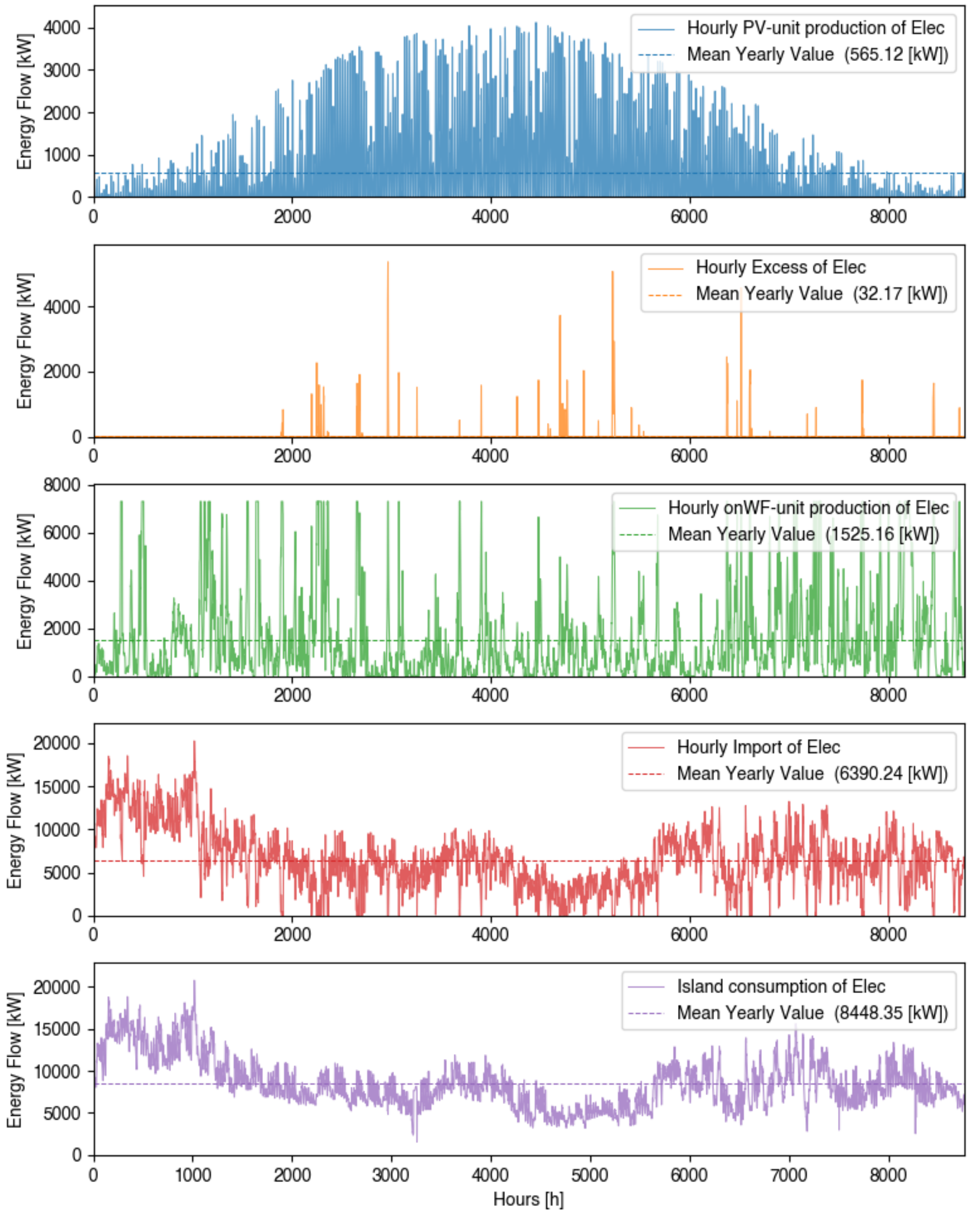

Figure 21. Electricity profile from a combination of a 7-MW PV plant and a 7-MW onWF.

Scenario C – Hydrogen system

Like the single case scenario, the hydrogen price is calculated here. Logically, the scenario with the most excess electricity should be that one with the highest installed capacity in the set of conditions since the natural resource is fixed. Thus, in this configuration, with the capacity of both 20 MW each, the hydrogen price still is considerably high, i.e., 0.86 e/kWh or 28 €/kg$_{H2}$.

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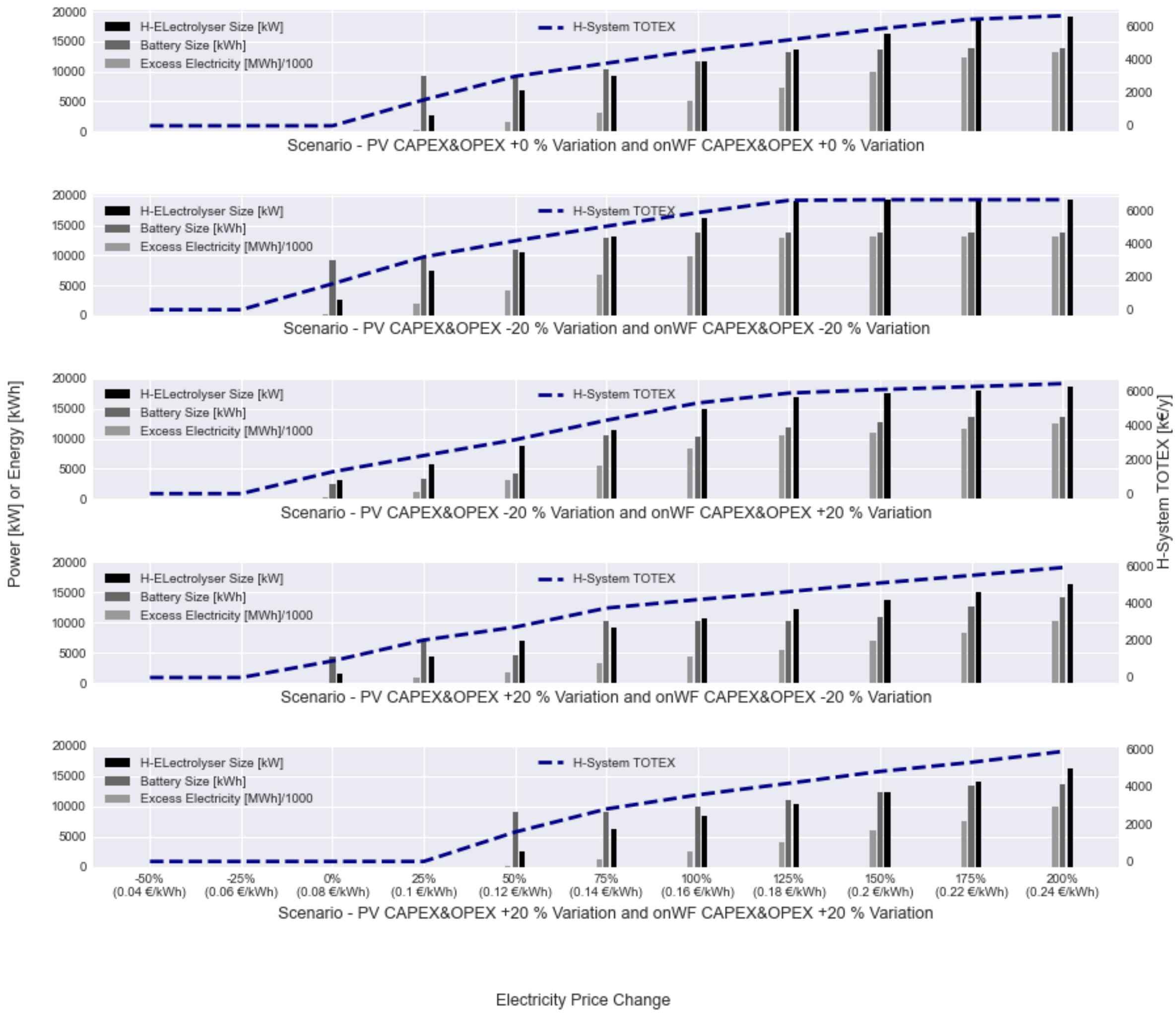

Figure 22. Sensitivity analysis of the H-SYS for the Scenario AB.

3.5. Scenario D – The role of biomass

An integrated wood gasifier with CHP-system, which consumes the wood-wastes and biogas is investigated. The full coverage of heat demand just with the WG-CHP system could be, to some extent, seen as unrealistic mainly for two reasons: the reported wood availability account for 19000 t/y, which, if converted into energy units is equivalent to 66.5 GWh/y. The total biomass conversion efficiency into heat with the WG-CHP system accounts for 43%. The yearly heat demand of Prima Protein sums up to 40 GWh, meaning that the wood supply should be at least 93 GWh/y, i.e., 40% more than available. The second reason is the low flexibility of the WG in the operation, but to satisfy the fluctuating energy demand, the heat supply system must be highly flexible. For this reason, a gas boiler is also operated next to the WG-CHP system.

The synergy between the WG-CHP system and the gas boiler is investigated with two assumptions: flexible and inflexible operation of the wood gasifier. In flexibility operation, the WG can be operated at the whole capacity range. However, in the case of inflexibility, a condition is introduced, which would not allow the WG to be operated below its 10% max load.

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3.5.1. Flexible operation of gasifier

The fish processing factory also uses propane for its heating system, as it is cheaper (0.07 €/kWh) compared to LNG (0.12 €/kWh). The fuel price and the biomass costs are the two parameters with the highest uncertainty in the Model. Figure 23 shows that with the fuel prices at the LNG range, it would be convenient to install about a 5 MW WG-CHP system with a some saving potentials.

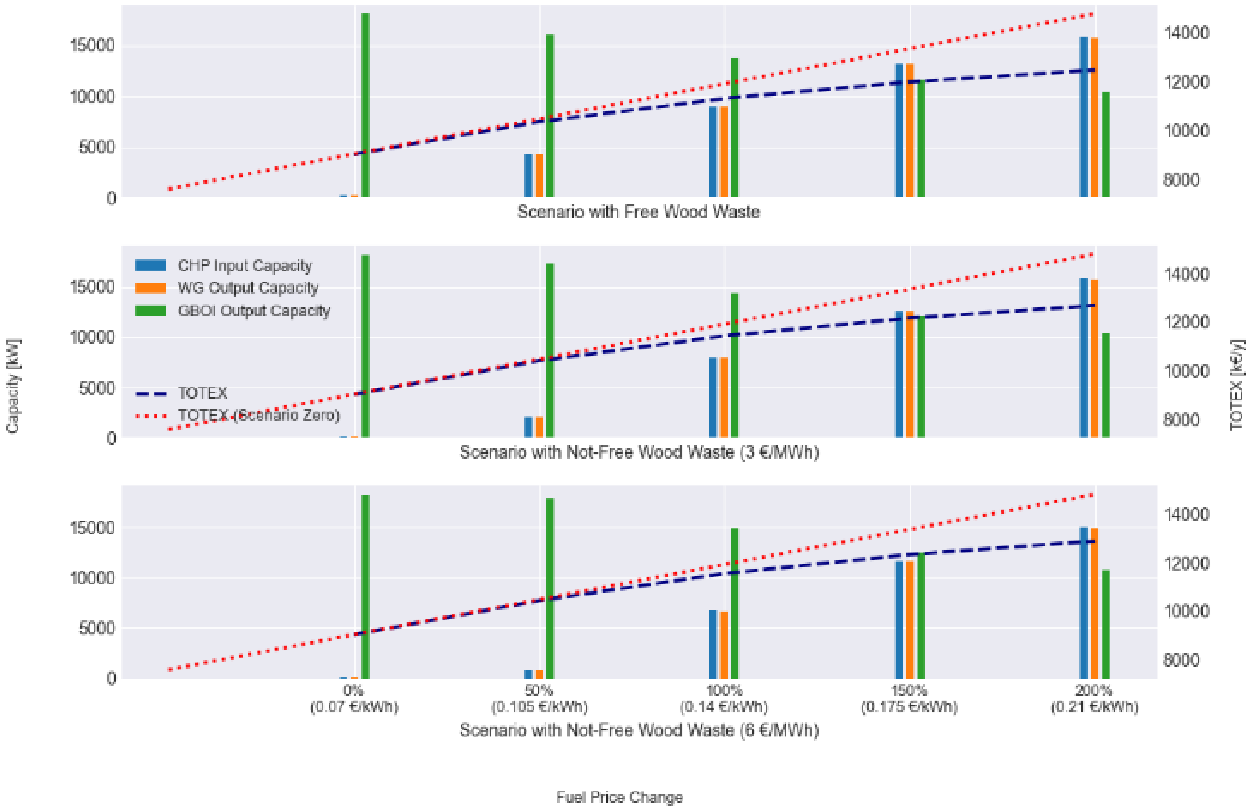

Figure 23. Sensitivity Analysis of operationally flexible WG-CHP system in combination with the gas boiler.

Figure 24 shows the operation profile of the WG-CHP system and the gas boiler in the support. As the WG is flexible in its operation, even the low range of heat demand can be covered. Nevertheless, this is technically not possible as wood gasifiers are not very flexible, i.e., cannot be operated below a certain load (here 10%). The calculation is performed for the biomass cost of 3 €/MWh and the fossil fuel at the cost of 0.14 /€kWh.

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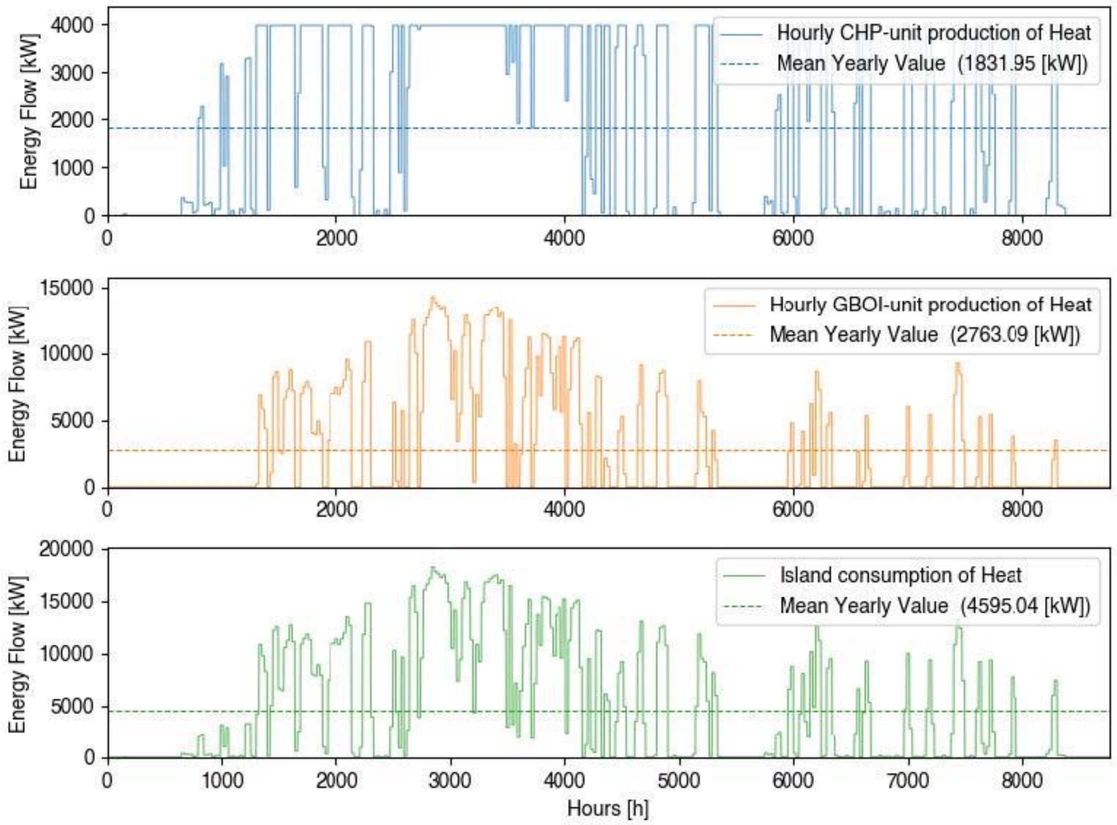

Figure 24. Operation profile of the WG-CHP system and the gas boiler in the support. Biomass cost is 3 €/MWh and the fossil fuel cost of 0.14 €/kWh.

3.5.2. Inflexible Operation of gasifier

As mentioned, in practice, wood gasifiers cannot be operated at very low loads for instance below 10% of their nominal loads. Figure 25 indicates only in two scenarios the WG-CHP system might be installed. Introducing the inflexibility condition, the capacity factor is reduced. Based on the results shown, the possibility of WG-CHP system usage is limited to some intermediate conditions, and only at very high fuel prices, i.e., increase of 200% in fuel price (0.21 €/kWh). The operation profiles of the CHP and the gas boiler is shown in the Figure 26.

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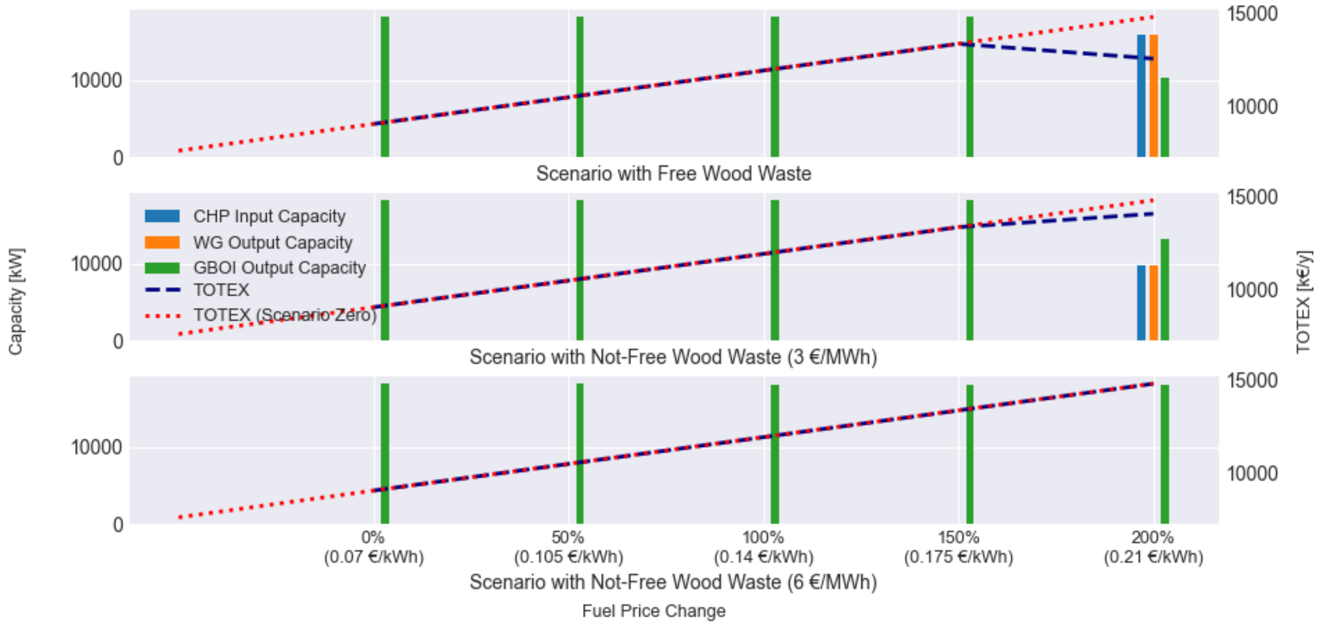

Figure 25. Installed capacity and TOTEX across different scenarios.

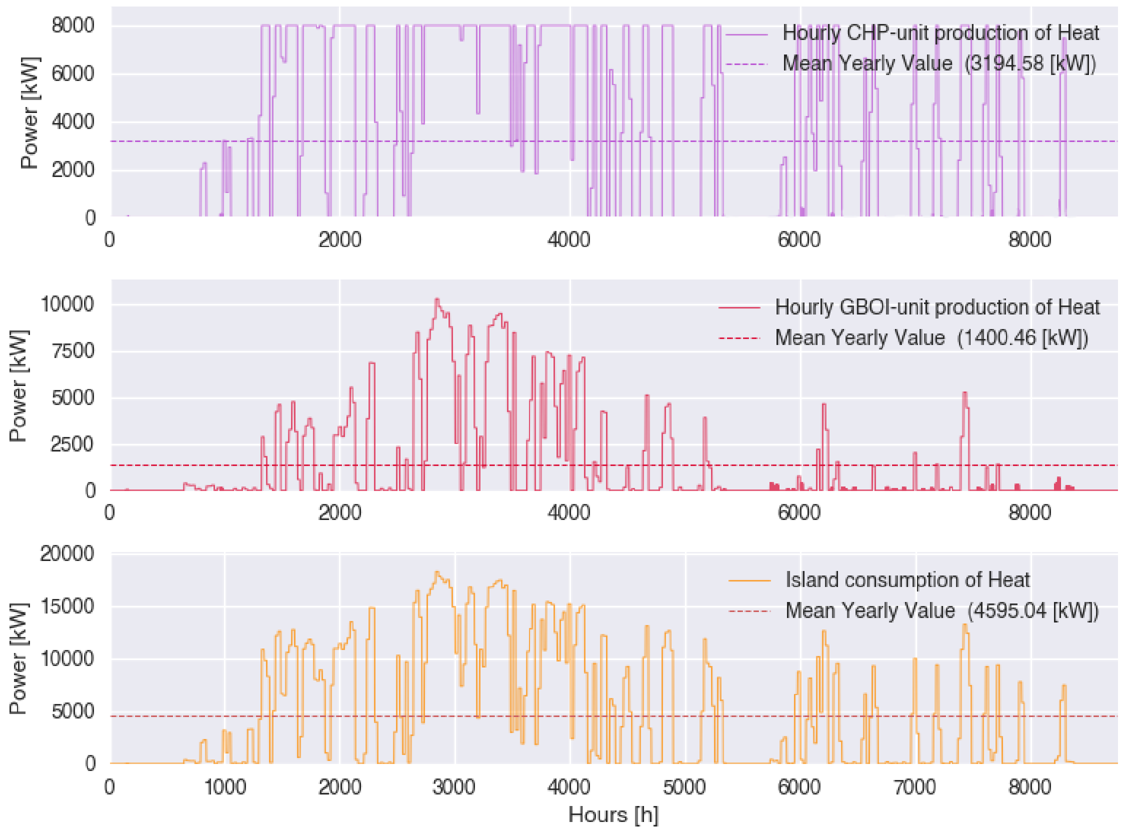

Figure 26. Operation profile of the WG-CHP system and the gas boiler in the support. Free biomass considered with the fossil fuel price of 0.21 €/kWh.

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4. Summary and future works

This report summarises the activities related to benchmarking task. These started by identifying relevant case studies that like the ROBINSON project targeted decarbonising the society via a decentralised and integrated energy system, including for example existing installations and outcome of other European projects, and the available information in the literature. As several of similar initiatives are still in the implementation phase, and because of lack of implementation of an identical case study as the energy system proposed by the ROBINSON project, energy system analysis specifically made for the case of Eigerøy, i.e., the demonstrator island, was pursued.

For this purpose, several scenarios were evaluated techno-economically using a mathematical optimisation model to allow a benchmark of different concepts for decarbonisation. The investigation was performed using a Mixed Integer Linear Programming – MILP optimisation technique. Solar PV panels, onshore, and offshore wind turbines have been studied as stand-alone solutions, as well as in combination, to identify potential technologies for the renewable energy-based electrification of the island of Eigerøy. The report also indicated the most economically feasible solution given the assumptions made and the boundary conditions used.

The results showed that the additional cost for an installation of PV panels could not be recovered. However, by varying some of the boundary conditions, PV panels become quite attractive (positive business case). This was seen with even a small increase (15%) in electricity cost. The same also holds for a (small) decrease (10%) in capital cost. These results indicate that the levelized cost of electricity produced by the PV panels is at the same level as the price of electricity imported from the mainland. A similar situation was observed for onshore wind turbines. This technology also can produce electricity at competitive prices. The most interesting scenarios for the electrification geographical islands seem to be those with combinations of technologies (such as PV, wind, and biomass), as they show evident synergies. The total installed capacity is typically smaller than that of a single technology, which reduces investment cost and consequently leads to lower levelized cost of electricity.

During the sensitivity analysis, data regarding the electricity produced by the onshore wind farms, offshore wind farms, and PV panels were used to estimate the necessary capacity of the battery unit and the capacity of the electrolyser with associated costs. Accordingly, the cost of hydrogen production for each scenario was estimated and reported in "Results and discussion". The lowest production costs were those with a large installed capacity of renewable technologies, which produced a vast amount of excess electricity. Considering the best case of each scenario (often even with exaggerated and unrealistic parameters) it was observed that the production costs do not reach the market price levels. The best price obtained was about 28 €/kg, which is several times higher than today market price (i.e., 5 €/kgH_2). Therefore, considering the boundary conditions and assumptions used, the green H_2 production in Eigerøy does not seem to be an economically viable solution.

Biomass has also a major role to play for the decarbonisation of industrial processes, which require a significant amount of high temperature heat (steam). The partial replacement of a conventionally fuelled (LNG, LPG) gas boiler is an attractive option. The present analysis for a fish factory on the island of Eigeroy (Norway) shows that the deployment of an integrated wood gasification CHP system becomes competitive already with only a small rise in fossil fuel prices (or in the case of rising taxes on emissions). Thus, an installation of such a system could be very reasonable even today, as the rising prices of all kinds of fuels have become a reality in Europe and elsewhere.

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It is worth noting that within the lifetime of the ROBINSON project, there will be some on-going and future activities to improve the quality of energy system modelling and analysis. Some of the expected improvements relevant to this domain are listed below:

- There is an important note related to uncertainties in the results mainly because of different uncertainties in the assumptions/parameters used. As an example, there is a large uncertainty in the results presented for wind power (more specifically the mean yearly value of wind power production). This is because the capacity factor used for this report is based on the NASA data base (https://power.larc.nasa.gov/) and this can be improved significantly via using the measurements available for the wind resources on the demonstrator and other follower islands.
- Another aspect that can be studied with more details is the effects of rising emission taxes in Norway and globally. (see for example https://www.regjeringen.no/no/aktuelt/avgift-pa-utslipp-av-klimagasser-og-veibruksavgift/id2884952/ stating the significant rise in CO_2 tax in Norway). In this study, the fossil fuel prices considered already included the emission taxes and the effects of rising taxes of GHG emissions is implicitly considered when varying the fuel prices in the technoeconomic analysis. As part of future analysis, the emission taxes can be investigated, separately.
- The tool and models used during the benchmarking are planned to be aligned with planned activities in WP3 and WP5 of the project. It will be used to evaluate energy scenarios resulting from the fast-changing boundary conditions in the energy sector (dramatically increasing energy prices in the recent months). Such dramatic changes caused challenges for project partners involved, but also has led to the idea of further adapting the energy system with an even higher pace than expected when the project and activities were planned. In this regard, several initiatives are ongoing that are associated somehow to the project ranging from establishing new customers in the demonstrator island, the fast change towards cost-efficient and fossil-free energy sources, and even more intensive re-use of so far unused resources, such as wastes and waste heat. Also, the tighter integration of and connection to other sectors such as transport is in discussion. The tool used for benchmarking is very well suited for the evaluation of various scenarios, and therefore will be further used and modified within the project.

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Appendix

Table A1. Objectives and description of the selected projects.

Project	Objectives	Main activities	Demo & follower islands
SMILE – Smart Island Energy System (https://www.h2020smile.eu/)	Development of smart grid solution technologies in three large scale pilot projects in different islands of Europe with same topography but different policies.	•Develop a Smart Grid system that integrates innovative technologies. •Develop and demonstrate nine technologies such as battery technology integration, power to heat, power to fuel, pumped hydro, electric vehicles, electricity storage on boats, energy demand management, Predictive algorithms that can be replicated anywhere globally. •Transform a semi-smart grid system that can manage only the power generation into a fully smart system, enabling generation and demand management •Use existing grid infrastructure and integrate new communications and control systems, new controllable energy demand for heat and transport.	Madeira (Portugal), Orkney Islands (UK), Samsø (Denmark)
IntegrAted SolutioNs for DecarbOnisation and Smartification of Islands (https://ianos.eu/)	Development of virtual power plant (VVP) based on artificial intelligence to optimise energy generation and supply and demand balance of energy on the islands.	•Develop solutions adapted for renewable energy resources, wind, solar, tidal, geothermal, green gas, and waste. •Study the impact of different energy storage mediums, e.g., hydrogen, electricity, and thermal. •Develop and test innovative grid components and resource forecasting tools using Artificial Intelligence algorithms and Pattern recognition intelligence to enhance grid operation and monitoring. •Within the Virtual Power Plant architecture, test novel demand-side management (DSM) and peer-to-peer (P2P) transactive energy schemes. •DSM related technologies: Fuel cells, hybrid heat pumps, hybrid transformers, smart energy router.	Pilot: Ameland (Netherlands), Terceira (Portugal) Follower: Lampedusa (Italy), Bora Bora (French Polynesia), Nisyros (Greece)

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Table A1 (continued). Objectives and description of the selected projects.

Project	Objectives	Main activities	Demo & follower islands
GIFT – Geographical Islands Flexibility (https://www.gift-h2020.eu/)	Development of innovative systems such as VPP, EMS, supply, and demand prediction though geographic information system (GIS) platform, and innovative storage system with synergies enabling islands to integrate vast amount of renewable energy resources.	•Efficiently allow the integration of various renewable energy sources to various energy grids (electricity, heating, and transportation) of the islands to decarbonize the energy mix. •Develop solutions (VPS, EMS, storage system with synergies, Integration of Flexibility market system involving localized DSOs and BRPS) to overcome the difficulties that hinder the integration of RES. •Develop Synergies through electricity, heating, cooling, water, transport network storage. Electricity through batteries and hydrogen, transportation through the vehicle to grid (V2G), and innovative heat storage device. •Reduce the usage of hydrocarbons through effective use of islands RES. •Study the replication, sustainability, and scalability of the solutions to demonstrate on replication islands effectively	Pilot: Hinnøya (Norway), Procida (Italy) Follower: Favignana (Italy), Eubée (Greece)
MESHA- Mayottle Replication model of Smart energy system (https://www.maesha.eu/)	Decarbonizing energy systems on geographical islands by promoting large-scale deployment of RES through installation of customised innovative flexibility services based on detailed analysis and modelling of local energy systems and community structures.	•Develop an innovative smart platform that aggregates multiple flexibility services such as decentralized RES, Demand response flexibility, heat, and cold storage networks, charging points for e-vehicles to give flexibility for island grid stabilization. •With tight coordination between local energy utilities, communities, modelers, and flexible solution suppliers, reach up to 70% to 100% RES penetration. •Create synergy between electricity and other systems by Controlling electricity/heat/cold production and systems, such as cogeneration with small biomass networks, and developing Vehicle-to-Grid solutions, which can assist reduce GHG emissions sectors that are now decoupled from the electric grid. •Create awareness and involvement of local inhabitants for better acceptance of energy transition. •Demonstrate the worldwide solution on the island of Mayotte at full scale. •Ensure that the solutions developed through the follower islands are replicable. •Create a publicly available toolkit and a user-manual for wide replicability to give perspective to the project beyond the follower islands.	Pilot: Myotte (French Overseas Territory) Follower: ST Barth (French Overseas Territory), Gran Canaria (Canary Island), Favignana (Italy), Wallis & Futuna (French Overseas Territory), Gozo (Maltese Archipelago

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Table A1 (continued). Objectives and description of the selected projects.

Project	Objectives	Main activities	Demo & follower islands
REACT- Renewable Energy for self-sustainable island communities (https://react2020.eu/)	Attaining energy independence for the island through renewable energy generation and storage, a demand response platform, and user engagement in a local energy community.	•Create a smart, integrated, and digitalized grid using a cloud-based ICT system that combines high-flexibility distributed generating technologies, demand response, and energy storage to achieve full energy independence. •Deploy high-capacity, environmentally friendly lithium-ion, and aluminium-carbon batteries, as well as traditional lead-acid batteries and power-to-gas systems. •Improved grid operation monitoring to detect and localize grid breakdowns during operations in a high intermittent RES penetration and storage scenario into the island energy system. •Study the impact on the existing grids using tangible technology assets and computational modelling and simulation of physical systems by interacting with electric vehicle charging stations. •Study water desalination as a type of energy storage and integration with water network. •Develop innovative business models and exploitation plans to increase the penetration of RES.	Pilot: La Graciosa, Canary Islands (Spain), San Pietro, Sardinia (Italy), Inis Mór, Aran Islands (Ireland) Follower: Gotland Island (Sweden), Lesbos Prefecture (Greece), Isle of Wight (Uk), Majorca Island (Spain), Reunion Island (France)
MUSE Grids- Multi Utility Smart Energy Grids (https://www.muse-grids.eu/)	Promotion of energy grid interaction towards thedevelopment of smart and clean local energy communities.	•Demonstrate a range of technological and non-technological alternatives to local energy independence via promoting smart energy systems in two demo sites. Technologies include Advanced E.V. management schemes (V2B-V2G), Power to heat and smart electrical thermal storage, and Large insulated outdoor water tanks. •Optimise and aggregate energy grid management systems in multi-energy demand-side management. •Promote a multi-objective smart controller that will be able to optimise the integration of RES, and production and demand prediction, storage systems management, and demand response strategies. •Develop an assessment framework to assist energy utilities and cities in making integrated energy planning choices on their future energy mix and investment in alignment with national policy.	Pilot: Osimo (Italy), Oud Heverlee (Belgium)

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Table A1 (continued). Objectives and description of the selected projects.

Project	Objectives	Main activities	Demo & follower islands
INSULAE- Innovative solutions for EU islands decorbanization (http://insulae-h2020.eu/)	Fostering the deployment of innovative solutions and thereby islands' decarbonisation by offering an investment planning tool (IPT) that will allow the islands to establish action plans for generating their own sustainable and low-cost energy.	•Develop a ready-to-use Investment Planning Tool to assist EU islands decision-makers (energy system planners, utility owners, project promoters, and public bodies) in developing cost-effective Action Plans for decarbonizing their energy systems. •Smart integration and control of water and energy systems (cost reduction, enable the use of RES to power desalination plants) •Empowerment of islands' energy communities through 5G and IoT technologies for flexibility services (boost islands decarbonisation, strengthen islands local economy, improve grid's performance) •Local bio-based economies supporting the electrical, thermal and transport systems integrated management (decrease in fossil fuels use, increase in the air quality, improvement of local economy) •Electrification of the islands' transport looking to grid frequency and voltage regulation	Pilot: Unihe (Croatia), Bornholm (Denmark), Madeira (Portugal)
Accelerating the decarbonisation of islands' energy systems (https://islander-project.eu/)	Implementation of a smart energy management solution aggregating distributed energy resources (DER) and development of a roadmap for a decarbonisation of the demonstration island.	•Undertake various new energy-related activities to decarbonise islands. Renewables, storage, electromobility, active prosumers, and district heating are among the creative initiatives. To that purpose, several technologies will be deployed on the island (such as hydrogen-based storage system, smart I.T platform, solar PV plant, onshore wind turbine, seawater district heating system, EV charging station, power intensive energy storage system, PV and battery building/household solutions, demand response app for residents, street lighting network) to holistically design the size and subsequent operation in the natural environment. •The development of a sophisticated, innovative I.T. platform that will manage DER in conjunction with hybrid energy storage (HES) while also including demand response (DR) and local power balancing (LPB) utilizing cutting-edge mathematical optimisation approaches. •The development of a methodology for the large-scale design of optimal distributed DER+HES systems. •Promote establishing an energy community on Borkum, which will enable local inhabitants to support and participate in the island's energy transformation.	Pilot: 1: Borkum (Germany) Follower: 1: Orkney (SCOTLAND) 2. Cres (CROATIA) 3. Skopelos (GREECE) 4. Lefkada (GREECE)

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