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

D5.1 – Technology specifications

Lead partner: Paul Scherrer Institute (PSI)

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[1] Dissemination level: **PU** = Public, PP = Restricted to other programme participants (including the JU), **RE** = Restricted to a group specified by the consortium (including the JU), **CO** = Confidential, only for members of the consortium (including the JU)

[2] Creation, modification, final version for evaluation, revised version following evaluation, final

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Executive summary

This deliverable aims to provide an initial technology specification of the technologies installed in the European H2020 project: *Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands* (ROBINSON). First, the background and goals of ROBINSON are provided. Second, the main technology specifications are determined, in terms of technology characteristics, costs, land requirements and life cycle inventory (*i.e.,* material and energy flows). Further, missing data or further requirements are identified per system component. The following set of technologies are supposed to be installed on the islands and are included in this deliverable: CHP unit (mixed fuel), Steam boiler, (novel) wind turbine, electrolyzer, anaerobic digestion coupled with bio-electrochemical system (AD-BES), biomass gasifier, gas fuel mixer, photovoltaics (PV) systems and several types of energy storage mediums, such as hydrogen and battery energy storage. This deliverable is an essential requirement for the life cycle cost as well as the environmental analysis of the newly installed energy system on three geographical islands in ROBINSON: Eigerøy (Norway), Crete (Greece) and Western Isles (Scotland).

The current version of this document has a focus on the energy system components to be installed on Eigerøy (as the primary demo island). Subsequent versions will include more details regarding follower islands: Crete and the Western Isles. This document must therefore be considered as a living document, to include future updates regarding system components of ROBINSON partners.

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List of abbreviations

AE = Alkaline Electrolyzer

AD-BES = Anaerobic Digestion assisted by Bio-Electrochemical unit

CAPEX = capital expenditures

CHP = Combined Heat and Power

EMS = Energy Management System

LCA = Life Cycle Assessment

LCC = Life Cycle Cost

LCI = Life Cycle Inventory

LCIA = Life Cycle Impact Assessment

LFP LIB = graphite anode, lithium iron phosphate cathode

LIB = Lithium-Ion Battery

LTO LIB = lithium titanium oxide anode, lithium nickel cobalt aluminum oxide cathode

NCA LIB = graphite anode, lithium nickel cobalt aluminum oxide cathode

NMC LIB = graphite anode, lithium nickel manganese cobalt oxide cathode

OPEX = operational expenditures

O&M = Operation & Maintenance

PEM = Polymer Electrolyte Membrane

PSI = Paul Scherrer Institute

PV = PhotoVoltaics

REST = Renewable Energy Systems & Technology UG

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

TRL = Technological Readiness Level

UniGe = University of Genoa

WP = Work Package

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1. Introduction

The H2020 project - *Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands* (ROBINSON) - aims to implement a real demonstration project on the island Eigerøy (Norway) to improve the self-sufficiency in terms of energy supply, economic performance as well as the environmental performance on Eigerøy and on follower European islands. This will be achieved by integrating locally available (renewable) energy sources, electrical and thermal networks as well as innovative short-term and long-term energy storage technologies - all coordinated by an energy management system (EMS) developed by the University of Genoa (UniGe). The developed system approach will be adjusted and replicated (fully or partly) on follower islands Crete (Greece) and Western Isles/Lewis and Harris (Scotland) and should therefore benefit from the modular system design developed during ROBINSON. An overview of the main island characteristics - of the three European islands - is provided in Table 1.

Table 1. Main characteristics of the considered islands in Robinson, this table has been reproduced from Task 1.3. Note, however, that an (industrialized) portion of the island will be chosen as case study in Lewis and Harris as well as in Crete.

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

Technology specifications are an essential element in the development of modular island energy systems. The aim of ROBINSON is to design a modular energy system, and it should therefore be easy to scale up using a similar set of up- or downscaled technologies on follower islands. This deliverable aims to provide an initial technology specification of the energy system in Eigerøy and follower islands. The scope of this deliverable are all three islands with a focus on the first demonstration island – *i.e.* Eigerøy (Norway) – since this is the first demonstration island of ROBINSON and therefore most information is available. Furthermore, the exact scope of analysis for the two follower islands in terms of specification of the system boundaries – *i.e.,* determining, which energy consumers and supply options will be included in the analysis – is still under discussion. Updated and extended versions of this document, to be released during the upcoming months, will include more detailed technology and system specifications for the two follower islands.

It is worthwhile to mention that this specification is preliminary, and can be (slightly) different compared to the final component specification. Further, this document represents many similarities with Deliverable 1.3; 'Components and system specification report' as well as Deliverable 2.1 'Description and documentation of the models and characteristics collected'. Some data and information are therefore adopted from these deliverables. This document – Deliverable 5.1 - will be freely available online, and therefore no confidential data will be published. It is worthwhile to mention that this technology specification will have fewer details on the component level – especially regarding system operation - compared to Deliverable 1.3, since the main goal of this deliverable is to obtain life cycle inventory data and economic data (see next paragraph) as well as due to confidentiality issues.

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The technology specification will be used as starting point for life cycle inventory required for a thorough life cycle assessment (LCA) of the overall energy system in Eigerøy. Further, this document gives an initial estimation of capital expenditures (CAPEX), replacement expenditures (REPEX) operational expenditures (OPEX), operation and maintenance costs (O&M) as well component lifetimes. These parameters are required for the life-cycle cost (LCC) assessment. This document is therefore a crucial input for work package (WP) 5. It is worthwhile to mention that literature data will be used in case no specific data is available at the moment of writing. Further, we see data collection as an iterative approach, and therefore the environmental and economic data will be (continuously) updated during ROBINSON.

Structure of this document

The structure of this document is as follows. Chapter 2 presents the background and goals of ROBINSON. After that, Chapter 3 explains the approach to perform a comprehensive system analysis on European islands. Chapter 4 describes the technology specification, land use, economic parameters and (already available) life cycle inventory per system component on Eigerøy. Chapter 5 and 6 present the technology specification, land use, economic parameters and (already available) life cycle inventory per system component on Western Isles and Crete, respectively. Chapter 7 presents the summary of this document. And lastly, we provide references and Appendices at the end of this document.

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2. Background and goals of ROBINSON

This chapter describes the background with information regarding the goals of ROBINSON as well as the current situation and future situation of the energy system in Eigerøy. The focus in this section is on Eigerøy.

Goals of ROBINSON in Eigerøy

The environmental and economic goals of ROBINSON (in Eigerøy) can be summarized as follows:

- CO_2-emissions of the total energy sector should be reduced by 20% at the project end (2024), and the ambition is a reduction of 100% by the total industry in 2030. Please note that the reference year is the moment of writing the ROBINSON proposal.
- Fossil fuels used for industrial heat should be reduced by 18.5% and 100% at the project end and in 2030, respectively. Please note that the reference year is the moment of writing the ROBINSON proposal.
- The number of non-renewables used for un- and loading of boats and cargo should be reduced by 20% and 100% at the project end and in 2030, respectively.
- 40% and 80% of the total vehicles should be fuelled with renewable energy – *i.e.,* renewable electricity or hydrogen - at the project end and in 2030, respectively.
- The overall environmental footprint of the total island system should be reduced by 50%.
- The levelized costs of energy on the islands should be reduced by (at least) 30%.

And lastly, the system in Eigerøy should be developed using a modular approach to ensure an easy replication on follower islands (Crete and Western Isles) and other European island as well as distributed energy systems in general. The next paragraphs describe the approach to achieve these goals.

Proposed technology specification in Eigerøy (Norway)

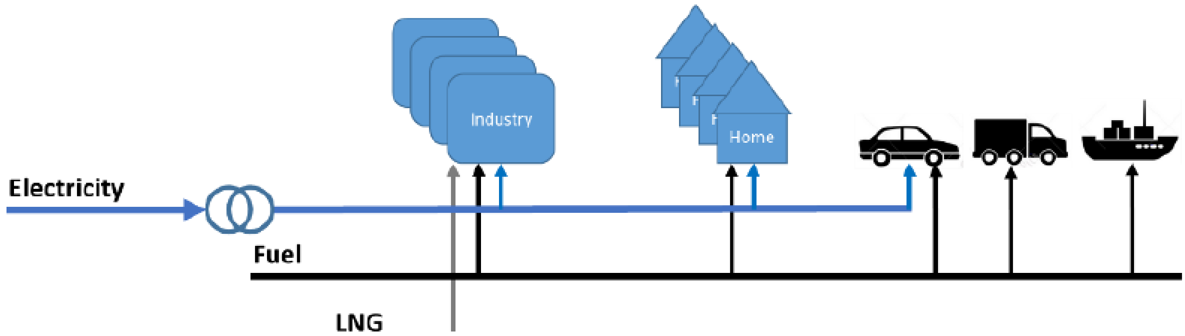

Figure 1. Current situation of energy supply and system components in Eigerøy. The figure is obtained from the ROBINSON H2020 proposal.

Current situation

Figure 1 demonstrates the current situation – regarding the energy system lay-out - in Eigerøy (Norway). The Figure reveals that the entire energy sector - mainly consisting of industry, some residential households, and mobility - is dependent on the grid connection and fossil fuels transported from the mainland to Eigerøy (Norway). Nowadays, electricity is transported by underground transmission power cables (with an average load of 7.9 MW). Figure 2 demonstrates the hourly electrical load on Eigerøy during three-quart year; grid electricity absorption peaks up to 18.5 MW are

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reached during this time-period. Further, Figure 3 demonstrates that industry is (by far) responsible for most electricity demand on Eigerøy, with monthly contributions between ~78% and ~93%.

Fish industry (Prima Protein) - responsible for 80% of total fossil fuel consumption - has recently expanded, which requires additional heat demand - nowadays generated with a LNG-boiler (26,500 MWh/year) - to avoid an expensive extension of the electricity transmission cables. One important goal of ROBINSON is to reduce the dependency of fossil fuels imported from the mainland and to reduce the consumption of fossil fuels in the LNG boiler, which should lead to an improved overall environmental and economic performance towards a deep decarbonization of the current energy system on Eigerøy.

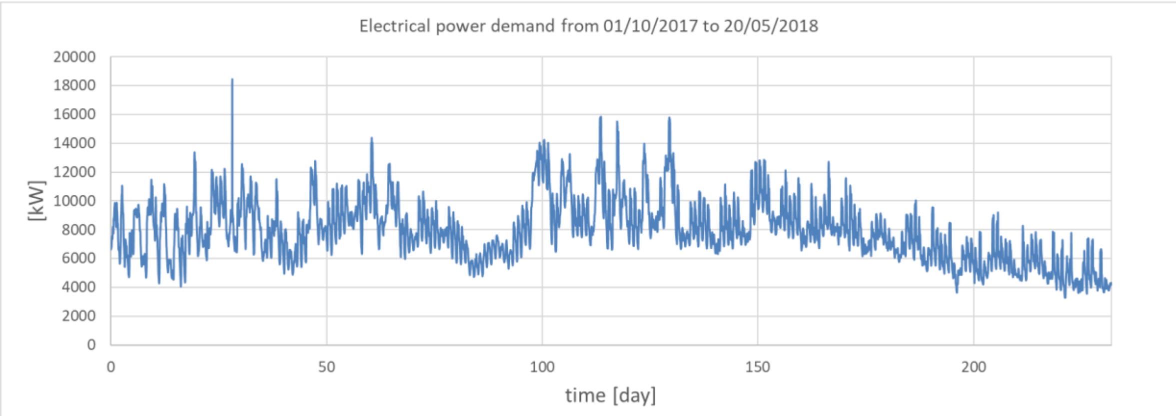

Figure 2. Typical hourly electrical power demand on Eigerøy, figure has been reproduced from ROBINSON deliverable 1.3.

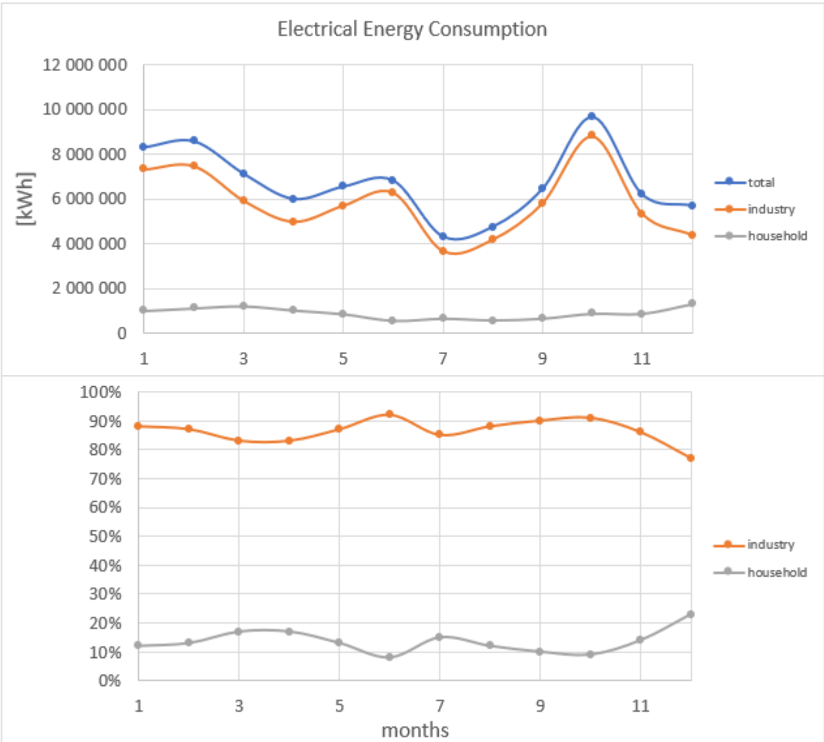

Figure 3. Monthly power consumption in Eigerøy. Figure has been reproduced from ROBINSON deliverable 1.3.

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Potential of PV and wind electricity generation

The potential of PV and wind electricity is important to identify the suitability of for example renewable hydrogen production and the need for energy storage mediums. The left subplot of Figure 4 visualizes the monthly PV electricity generation, while the second subplot in Figure 4 shows the monthly wind electricity generation (more details regarding assumptions are provided in the caption of this figure).

The left subplot of Figure 4 demonstrates that the potential of PV electricity generation is small during winter months in Eigerøy - mainly due to low solar irradiation – resulting in an annual capacity factor of ~11% in 2019-2020 (Pfenninger and Staffell, 2016). The potential for especially wind electricity generation is high on Eigerøy, with an annual capacity factor of ~44% in year 2019-2020 (Staffell and Pfenninger, 2016). The right subplot of Figure 4 shows that wind sources are abundant during the entire year with peaks during winter months.

Greece shows comparatively higher PV electricity generation potential due to higher annual solar irradiation (ESMAP *et al.*, 2020), while the wind electricity potential is significantly lower on Greece. On the contrary, Western isles has a comparatively low potential for PV electricity generation, while the wind electricity potential is the highest on Western Isles due to higher average wind speeds.

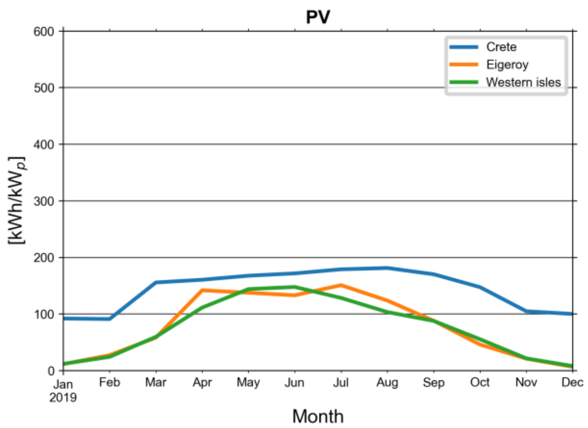

Figure 4. The left subplot shows the monthly PV electricity generation (per kW_p solar panel with a tilt of 35° and solar azimuth of 180°) on Crete (blue), Eigerøy (orange) and Western Isles (green) in year 2019-2020. The right subplot shows the monthly wind electricity generation (per kW_p, for a Vestas V90 2000) on Crete (blue), Eigerøy (orange) and Western isles (green) in year 2019-2020. Wind and PV electricity generation data is obtained from renewables.ninja using the MERRA-2 dataset and using the above specifications (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016).

It is worthwhile to mention that ROBINSON also integrates other low-carbon or renewable energy sources. For example, biomass and/or waste feedstock will be used in the concept of industrial symbiosis. Industrial symbiosis can be defined as a concept '*which allows entities and companies that traditionally be separated, to cooperate among them in the sharing of resources, contributes to the increase of sustainability with environmental, economic and social benefits*' (Neves *et al.*, 2020) and it therefore should result in a more circular economy. To achieve this in ROBINSON, different (unused) waste streams are determined on geographical islands, and will serve as feedstock in different waste-to-energy plants.

Future situation

Different solutions are proposed in ROBINSON to achieve the environmental and economic goals, as described in the ROBINSON proposal and in the first paragraph of this chapter. Figure 5 demonstrates

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the proposed system lay-out on the island of Eigerøy (Norway) to achieve the economic and environmental goals. We shortly discuss the most important system components to be installed in the proposed energy system design of Eigerøy.

The future energy system on Eigerøy will integrate renewable energy sources, mainly wind and PV electricity as well as sustainably produced heat sources, such as biomass and (renewable) hydrogen. Figure 5 reveals the implementation of different energy generators and innovative energy storage technologies on the island Eigerøy. The EMS aims to balance the energy supply and demand during all times considering the constraints of all system components.

An electrolysis unit will be installed to produce hydrogen primarily with excess (renewable) electricity. Grid electricity can be used to generate hydrogen, in case grid electricity prices are very low as well when no excess electricity can be generated with a novel wind turbine and/or solar PV. Next, the produced hydrogen can be stored – for example in pressured hydrogen storage tanks - and can be consumed during time periods with an increased energy demand. Further, an anaerobic digestion (AD) assisted by a bioelectrochemical unit (AD-BES) will produce biogas (targeting biomethane quality standards), by biological conversion of the organic matter content of a fish-processing wastewater (*i.e.* industrial symbiosis from liquid waste from fish industry). The produced biogas represents an additional energy source. Additionally, biomass is gasified with biomass gasification to generate syngas. Hence, hydrogen, syngas and biomethane function as important energy carriers. The fuels will be blended in a mixing station before they will be consumed in the novel combined heat and power (CHP) plant. The CHP plant aims to (partially) cover the electricity demand of the island and aims to cover the steam demand required for the fish industry (Prima Protein). Hence, this significantly reduces the dependency on imported fossil fuels. The LNG boiler is expected to provide 81.5% of electricity at the end of the ROBINSON project, but will be gradually phased out in the coming decade(s). The system components considered in the technology specification of Eigerøy are the following technologies:

- CHP unit (mixed fuel)
- Steam boiler
- (Innovative) wind turbine
- Electrolyzer
- AD-BES
- Gasifier
- Fuel mixer
- Photovoltaics (PV) systems
- Energy storage

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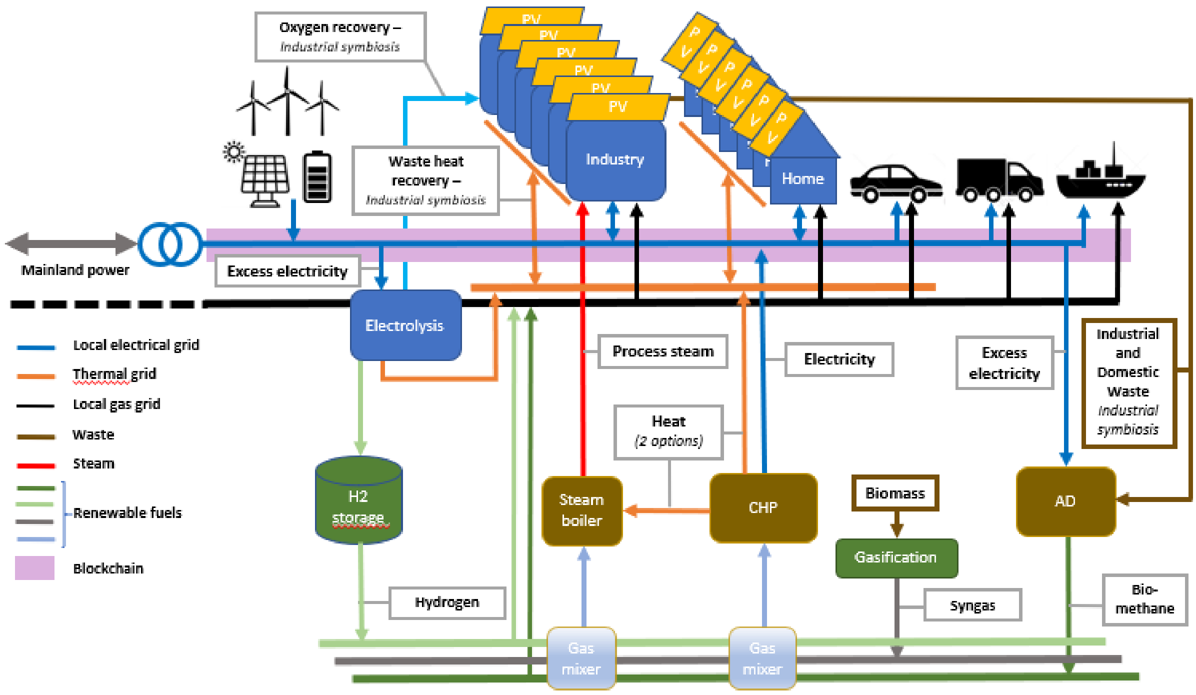

Figure 5. Future situation of energy supply, system components and innovative storage technologies in Eigerøy. The figure is reproduced from the ROBINSON H2020 proposal.

A detailed map of Eigerøy is presented in Appendix A. Most of the system components of the demonstrator will be installed on the production site of Prima Protein, the main consumer of fossil fuels in Eigerøy nowadays. Figure 6 shows the availability of sufficient space to install the gasification unit, the CHP unit (mixed fuel), the electrolyzer as well as the AD-BES. Further, wood will be stored in the harbor, approximately some hundred meters from the wood gasification unit: thereby reducing transportation distances and ensuring small distance gas connections. The electrolyzer and potential hydrogen storage can be installed next to the gasification unit. The CHP unit has a compact size – *i.e.,* it fits in a standard sized ship container - and could therefore be installed in the steam boiler hall. Electrical connections to the grid are provided by Dalane Energi: the local grid electricity operator.

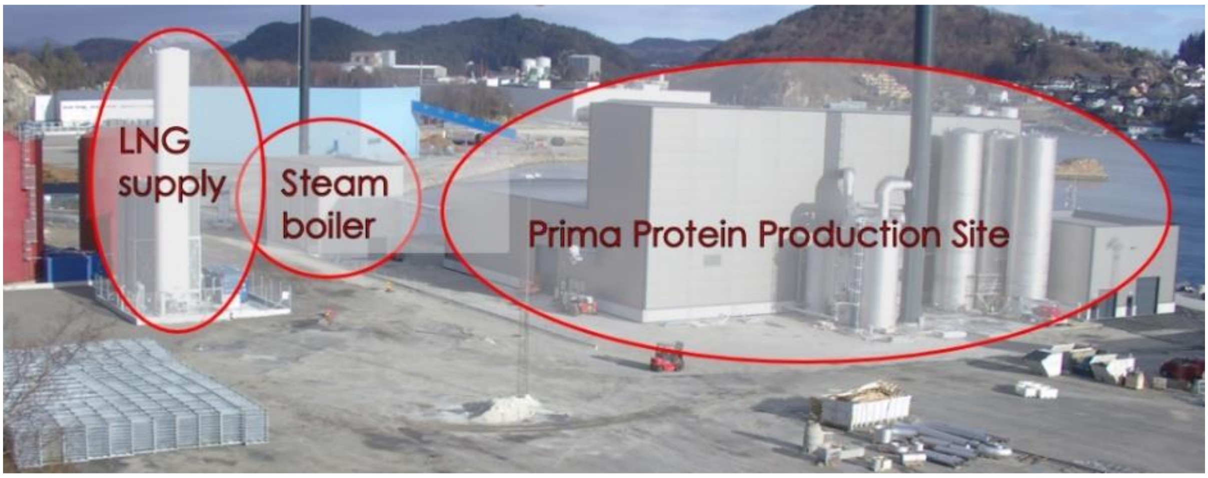

Figure 6. Production site of Prima Protein nowadays, demonstrating available space for novel system components. Figure is reproduced from the ROBINSON proposal.

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The novel wind turbine will also be installed nearby the harbour. The proposed location for the novel wind turbine is presented in Figure 7. Additionally, PV systems can be installed on available rooftop areas on industrial buildings and residential rooftops, the estimated available area equals to 28,000 m^2.

Figure 7. Proposed location of the novel wind turbine on Eigerøy, indicated with the red coloured circle.

It is worthwhile to mention that ROBINSON will be applied to an industrialized area of the three selected islands, thereby allows for installing an industrial microgrid in combination with industrial symbiosis. The concept is therefore also applicable to distributed (multi-)energy systems. Further, Eigerøy and Western isles have an electricity grid connection with the mainland nowadays, while Crete has not.

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3. Methodology: life-cycle system analysis

This chapter shortly describes the methodology to provide a comprehensive environmental and cost analysis of the newly installed energy systems on the three demonstration islands.

Environmental life cycle assessment

One of the main goals of WP5 is to conduct a comprehensive LCA to determine the environmental benefits as well as environmental trade-offs coming along with the installation of the novel energy system designs on European islands. LCA is a method to determine all environmental impacts during the life-cycle of a product or service (Hellweg and Milà i Canals, 2014; Terlouw *et al.*, 2021). In this way, environmental impacts are included from (among others) the operation, the production of components as well as from the end-of-life stage/decommissioning.

An LCA consists of different stages: a goal and scope definition, life cycle inventory analysis (data collection), life cycle impact assessment (LCIA) and the interpretation of the results. Especially the determination of the life cycle inventory – or data collection – is a time-consuming task, since technology information regarding energy and material consumption has to be collected for each system component. To achieve comprehensive environmental results, a wide set of environmental impact categories should be considered in the protection areas climate change, ecosystem quality, human health, and resources.

The ILCD 2.0 LCIA method contains of a wide set of environmental impact categories and has been commonly used in the last few years (Fazio *et al.*, 2018). Hence, most environmental impact categories of the ILCD 2.0 life cycle impact assessment will be adopted. These ILCD impact categories are provided in Table 2. Further, critical materials can be determined by aggregating elementary flows, such as cobalt and lithium consumption in the proposed energy systems. Technology specifications – and life cycle inventories – are obtained for the most important system components by sending a questionnaire to ROBINSON partners responsible for (novel) system components. This questionnaire is available in Appendix B. Questionnaire.

If not available or in case of well-developed technologies, we identify readily available life cycle inventory for the system components based on existing background LCA databases (ecoinvent v3.8), previous work at PSI or literature.

Table 2. Initial selection of life cycle impact assessment categories in the LCA.

Life cycle impact assessment method	Protection area	Category
ILCD 2.0 2018 midpoint	climate change	climate change total
ILCD 2.0 2018 midpoint	ecosystem quality	freshwater and terrestrial acidification
ILCD 2.0 2018 midpoint	ecosystem quality	freshwater ecotoxicity
ILCD 2.0 2018 midpoint	ecosystem quality	marine eutrophication
ILCD 2.0 2018 midpoint	ecosystem quality	terrestrial eutrophication
ILCD 2.0 2018 midpoint	ecosystem quality	freshwater eutrophication
ILCD 2.0 2018 midpoint	human health	carcinogenic effects

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ILCD 2.0 2018 midpoint	human health	ionising radiation
ILCD 2.0 2018 midpoint	human health	non-carcinogenic effects
ILCD 2.0 2018 midpoint	human health	ozone layer depletion
ILCD 2.0 2018 midpoint	human health	photochemical ozone creation
ILCD 2.0 2018 midpoint	human health	respiratory effects, inorganics
ILCD 2.0 2018 midpoint	resources	fossils
ILCD 2.0 2018 midpoint	resources	land use
ILCD 2.0 2018 midpoint	resources	minerals and metals
ReCiPe 2016, 1.1 (20180117)		Water consumption

Life cycle cost assessment

Different economic performance indicators can be adopted for the cost assessment. We focus on life cycle costs (LCC) to include all costs generated during the entire life-cycle of an energy system. The LCC includes all costs during the life-cycle of a system component; the CAPEX, operation costs, O&M and REPEX[3]. Initial cost figures are therefore collected for all considered system components in this document.

[3] REPEX are replacement expenditures required for the replacement of components, for components that have a smaller lifetime then the common system lifetime.

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4. Technology specifications - Eigerøy

This section provides the technology specification for Eigerøy (Norway). The structure of this chapter is based on the most important system components to be installed on the island Eigerøy. General information is provided for the technology under study, land use coverage of the technology, economics as well as other special requirements for system components. And lastly, missing data and additional requirements are identified.

Gas turbine (Aurelia)

Table 3 shows the main technology parameters of the novel gas turbine developed by Aurelia.

Table 3. Technology parameters of the gas turbine.

Parameter	Value	Unit	Comment	Source
Capacity	400	[kW_e]		Personal communication with Aurelia (2021)
Electric efficiency	40.2	[%]		Personal communication with Aurelia (2021)
Thermal efficiency	Up to 50	[%]		Personal communication with Aurelia (2021)
Operation hours	8322	[hours/year]	Assuming ~95% availability	Personal communication with Aurelia (2021)
Lifetime	20	[years]	Following preventive maintenance schedule	Personal communication with Aurelia (2021)

Technology specification

The novel gas turbine – a combined heat and power (CHP) unit (*Aurelia® A400*, see Figure 8) – is able to run on a mixture of biomethane, hydrogen and syngas. The specific composition of this mixture is provided by a gas mixer, as described in Section 'Gas fuel mixer'. The technological readiness level (TRL)[4] of the A400 turbine is identified with TRL '5', although it expected to reach TRL '7' at the end of ROBINSON. Major development is the validation of the product operating at site-specific conditions. The Aurelia turbine aims to target both commercial and small industrial markets.

The main fuels of the CHP unit are syngas (generated from the gasification of locally available waste wood), hydrogen as well as biomethane (from the AD-BES). A mixing station aims to blend these (renewable) fuels. The CHP gas turbine should be able to process different fuel mixtures and shares of (renewable) energy sources. Heat recovery equipment is not included in the novel gas turbine. The CHP unit provides dispatchable energy to the electricity grid as well as exhaust heat. The gas turbine has a maximum electrical power output of 400 kW, an electrical efficiency of ~40% and a thermal efficiency of up to 50%.

[4] The TRL indicates the maturity of a technology on a level from 1 (lowest – basic principles observed) to 9 (highest – actual system proven in operational environment).

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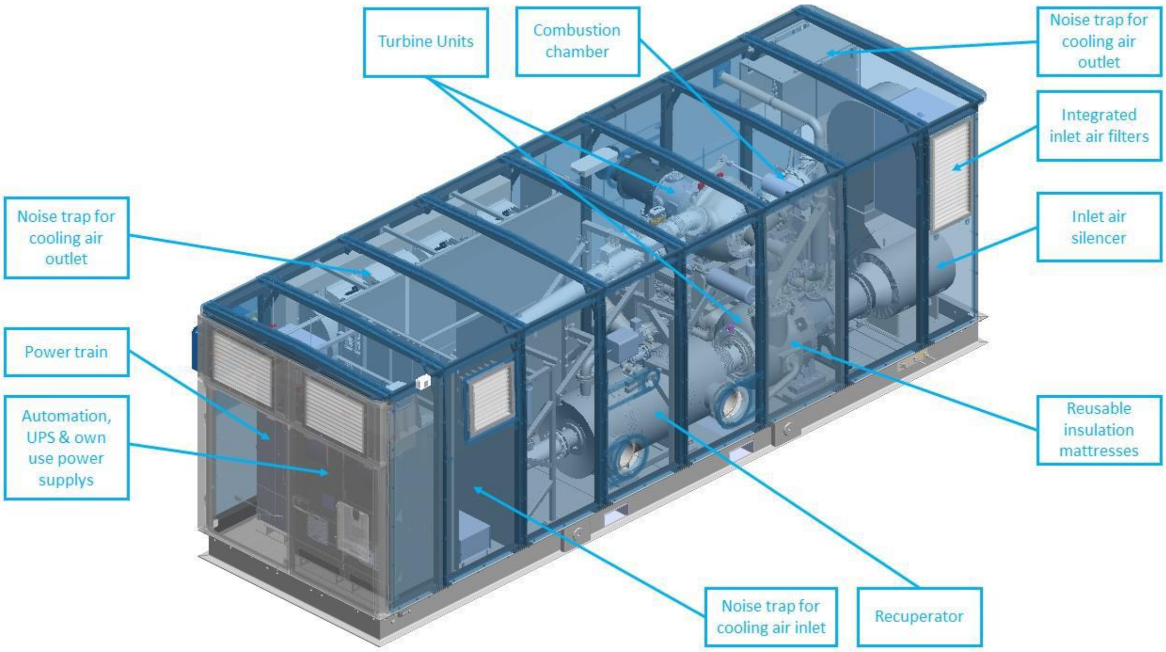

Figure 8. The A400 gas turbine of Aurelia. This figure shows the specific components within the 'container'.

Different fuels can be fed into the novel gas turbine. These fuel specifications are presented in Table 4. For example, pure natural gas, different combinations of biogas/flare gas as well as syngas can be fed into the gas turbine.

Table 4. Fuel specifications of the novel gas turbine of Aurelia, adopted from ROBINSON deliverable 1.3.

Fuel specification	Natural gas	Biogas 1/ Flare gas 1	Biogas 2/ Flare gas 2	Syngas 1	Syngas 2
CH_4 [vol%]	98	75	30	65	5
H_2 [vol%]	0	2	0	28	30
CO_2 [vol%]	0	10	0	2	12
N_2 [vol%]	2	13	70	5	53
Molar mass [g/mol]	16.3	20.1	34.2	13.3	21.5
Density at 1.013 bar & 273 K [kg/m^3]	0.7	0.9	1.5	0.6	1.0
LHV [MJ/kg]	48	30	8	44	5
Fuel $q_{m,min}$ [g/s]	4	7	25	5	40
Fuel $q_{m,max}$ [g/s]	23	37	125	25	256
Max thermal power [kW]	1104	1110	1000	1100	1280
Supply pressure	7…8 bars (abs)				
Supply temperature	-10…+80 °C				

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The gas turbine is assembled in Lappeenranta (Finland) and system components are obtained from different European suppliers, situated in Finland, Germany, Italy and Belgium. The components are divided into the power train, automation cabinet, recuperator, insulations, cables, enclosure, piping, supports, turbine units, combustor + fuel trains as well energy requirements for assemblage.

Table 5 shows targeted emissions for NO_x and CO.

Table 6 presents exhaust gas emissions of the Aurelia A400 turbine at the nominal point, respecting the emission limits presented in Table 5.

Table 5. Targeted emission levels (to be confirmed during site commissioning), this table has been reproduced from ROBINSON Deliverable 1.3.

Compound	Targeted limit	Fuel
NOx	< 20 ppm	Natural gas
NOx	< 30 ppm	Biogas, Flare gas & syngas
CO	< 65 ppm	All

Table 6. Example of exhaust gas emission at nominal point, this table has been reproduced from ROBINSON Deliverable 1.3.

Exhaust gas composition	Natural gas	Biogas 1/ Flare gas 1	Biogas 2/ Flare gas 2	Syngas 1	Syngas 2
CO_2 [vol%]	1.7	1.9	1.8	1.5	2.3
H_2O [vol%]	3.3	3.9	4.0	4.1	5.8
O_2 [vol%]	17.2	17.1	16.1	17.2	15.2
NOx [ppm]	< 13	< 20	< 25	< 20	< 29
CO [ppm]	< 42	< 43	< 53	< 42	< 63

Land use

The land use and volume requirements of the 400 kW turbine are 28.2 m^2 (3m x 9.4m) and 93.1 m^3 (3.3m height).

Economics

The gas turbine has an initial cost of 400,000 euro, which makes a specific investment cost (*i.e.,* CAPEX) of 1000 euro/kW_e. Currently, there are small economies of scale expected, only applicable to the balance of plant. Future cost reductions are expected to be ~30% in 2025 and ~40-50% in 2050 (based on personal communication with Aurelia).

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Table 7. Economic parameters of the gas turbine.

Cost parameter	Value	Unit	Source
CAPEX	1000	[euro/kW_e capacity]	Aurelia, 2021
REPEX	tbd		
Operation	Depends on operation/fuel inputs	[-]	Aurelia, 2021
OPEX	6.5%/CAPEX/year	[euro/year]	Aurelia, 2021
Residual value	25000 (total value)	[euro]	Aurelia, 2021
Lifetime	20	[years]	(Herenčić *et al.*, 2021)

Life cycle inventory

Life cycle inventory of the gas turbine has been generated using a questionnaire, as attached to the end of this document.

Further information and data to be added

Aurelia already provided most information. Full life-cycle inventory has been generated.

Steam boiler

The steam boiler is included in this proposal; however, it will be gradually phased out after ROBINSON and, therefore, should be replaced by heat based on renewable energy sources to reduce environmental impacts.

Table 8. Important technology characteristics of the steam boiler.

Parameter	Value	Unit	Comment	Source
Capacity	22,000	kW_{th}	Maximum capacity installed by Prima Protein	(Weishaupt, 2021)
Efficiency	98	%	Maximum boiler efficiency	(Weishaupt, 2021)
Lifetime	25	years	Estimation	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)

Technology specification

Prima Protein – the local fish industry on Eigerøy – utilizes a steam boiler to generate steam at a temperature level of 180°C for their industrial processes. The steam boiler consumes liquid natural gas (LNG). The steam boiler – the Weishaupt WKG80/3-A, ZM-NR (Weishaupt, 2021) – is designed to deliver 22,000 kW thermal power, with a minimum possible thermal output of 3,200 kW in combination with a maximum boiler efficiency of 98% (Weishaupt, 2021). The design pressure is 13 bar with an operational pressure of 10 bar, considering a temperature in- and outflow of 105°C (water)

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and 180°C (steam), respectively. The maximum water capacity limit of Prima Protein is identified as 30 ton/hour. The Weishaupt LNG boiler benefits from a modular design and therefore can be easily scaled up or down.

The gas boiler has relatively long start-up times up to 1 day, due to large gas volumes and consistent thermal inertia. One of the innovative characteristics - of the Weishaupt WKG80/3-A ZM-NR - is their multiflam® technology resulting in very low NO_x emissions and thereby setting new benchmarks. The selected gas boiler technology is therefore especially appropriate in countries with strict environmental regulations, such as Switzerland. More information is provided in a factsheet (Weishaupt, 2021), an example WK burner is shown in Figure 9 including the most important system components.

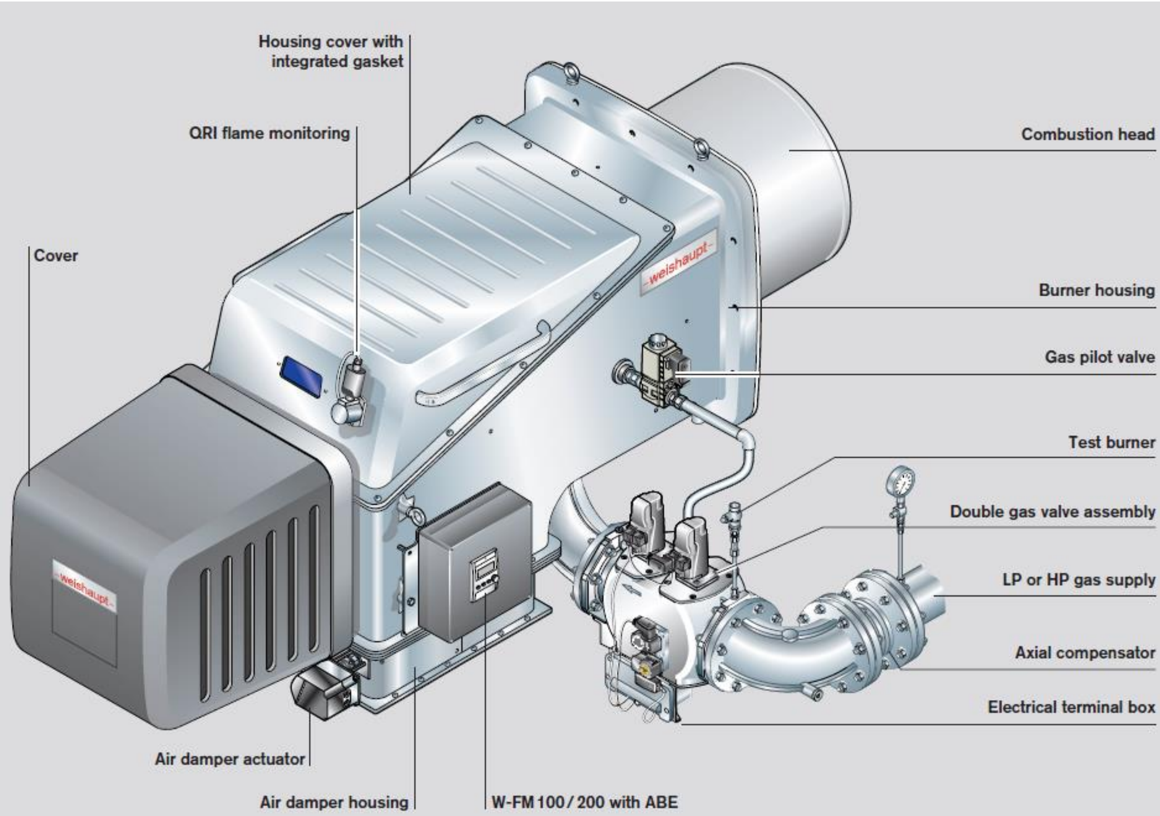

Figure 9. A WK-burner from Weishaupt, reproduced from (Weishaupt (SE), 2021).

Land use

No information regarding the land use requirements is identified. However, the expectation is that the land area requirements of the gas boiler are rather small. Alternatively, the building - where the boiler has been installed - can be used as an approximation regarding the total land area requirement.

Economics

Table 9. Economic parameters for the gas boiler. Economic data is based on literature, more specific cost data is expected to be generated in the future.

Cost parameter	Value	Unit	Source
CAPEX	420	[euro/kW_{th}]	(Herenčić *et al.*, 2021)

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REPEX	420	[euro/kW_{th}]	(Herenčić *et al.*, 2021)
OPEX	8.4	[euro/kW_{th}]	(Herenčić *et al.*, 2021)
Lifetime	25	years	(Herenčić *et al.*, 2021)

Life cycle inventory

Life cycle inventory for the gas boiler can be adopted from the ecoinvent database (ecoinvent, 2020), since generic life cycle inventories for gas burners are readily available. For example, the ecoinvent dataset 'gas boiler production' can be scaled-up to achieve the higher thermal capacity as applied with the Weishaupt gas burners.

Further information and data to be added

Detailed life cycle inventory and exhaust emissions would be preferable. Further, specific cost data could be obtained for the Weishaupt, specified for the geographical location. It is still unclear what to do with the different heat flows required and produced.

Wind turbine

Technology specification

Larger wind turbines on the megawatt scale are widely available on the market. Smaller wind turbines are usually more expensive, but are essential in smaller energy systems for an optimal system design and this might increase local acceptance of residents.

The novel wind turbine (the *V-Twin 100*) has a nominal power output of 100 kW – *i.e.,* 2 turbines with 50 kW each – and is developed by Renewable Energy Systems & Technology UG (REST) to optimally use wind as the (dominant) energy source on Eigerøy. The wind turbine will be integrated in the microgrid of Prima Protein. A modular approach with two-blade rotors - mostly produced from steel - will be installed in order to reduce the number of components as well as area requirements. The wind turbine does not require a gearbox, which logically reduces complexity and material consumption (without oil). An example (sketch) of this prototype wind turbine is shown in Figure 10.

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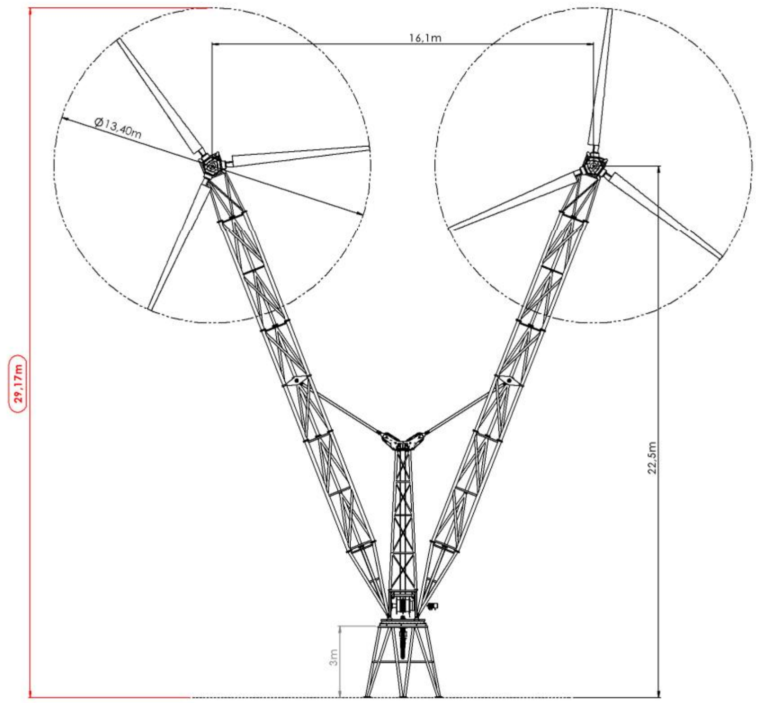

Figure 10. Sketch of the novel wind turbine developed by REST.

Table 10. Important characteristics of the novel wind turbine, table has been partly adopted from ROBINSON Task D2.1.

Parameter	Value	Unit	Source
Nominal power output	100	kW	Communication with REST (2021)
Max net. delivered power	90	kW	Communication with REST (2021)
Max. electrical power gradient	45	kW/s	Communication with REST (2021)
Min. electrical power gradient	0.5	kW/s	Communication with REST (2021)
Operation hours/capacity factor	~44 (Eigerøy)	%	Per kW_p, for a Vestas V90 2000, based on data from (Staffell and Pfenninger, 2016)

Further, the wind turbine is designed in a flexible way, since the blades can be unfolded to be situated near to the ground. This should ease maintenance of the wind turbines, an example is shown in Figure 11.

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Figure 11. The V-Twin 100 is flexible and can be unfolded to make maintenance easier.

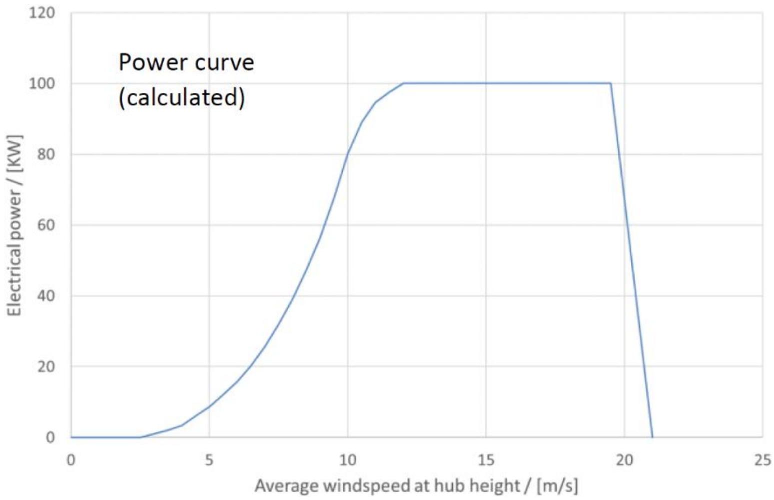

Figure 12. The calculated power output profile of the V-Twin 100.

The power curve of the *V-Twin 100* is provided in Figure 12. As indicated, the maximum electrical power of 100 kW can be reached at wind speeds between ~12-19.5 m/s (at hub height). A cut-off is applied when wind speeds are higher than ~19.5 m/s.

Land use

The novel wind turbine has a total height of 29.2 meter (including the rotors), a width of ~30 meters and length of ~3 meter when used to generate wind energy. The novel wind turbine can be unfolded to make maintenance easier, which makes the height as low as ~6 meters and a width of 56 meter.

Economics

Once serial production of the wind turbine has been achieved an investment cost of around 150,000 euro is targeted, which makes a specific investment cost – or CAPEX – of 1500 euro/kW_p.

Table 11. Economic parameters of the novel wind turbine of REST.

Cost parameter	Value	Unit	Source

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CAPEX	1500	[euro/kW$_p$]	REST, 2021
REPEX	1500 (depends on component)	[euro/kW$_p$]	REST, 2021
OPEX	32	[euro/kW$_p$/year]	(Herenčić *et al.*, 2021)
Lifetime	20-30	[years]	REST, 2021

Life cycle inventory

Life cycle inventory of the novel wind turbine is, and will be generated in collaboration with REST. The wind turbine is a novel technology and therefore life cycle inventory is not available yet.

Further information and data to be added

The economic and technological data should be continuously updated based on the best available information.

Electrolyzer

Technology specification

The electrolyzer utilizes electricity to convert water into hydrogen and oxygen. Oxygen recently received more attention as a consequence of the COVID-19 pandemic, and therefore oxygen could be of additional economical value. Hydrogen production is preferred during times with excess generation of renewable electricity or with (very) low or even negative grid electricity prices to minimize hydrogen production costs (Bauer *et al.*, 2021). The specific size and type of the electrolyzer are still under evaluation, but a decision is expected in the next few months. A hydrogen production rate of 200 kg/day or 500 kg/day is currently under evaluation.

The electrolyzer technology will be based on either Alkaline electrolyzer (AE) or polymer electrolyte membrane (PEM). PEM electrolyzers are preferable due to their operational flexibility, such as fast start-up and response times in combination with comparably low investment costs (Bauer *et al.*, 2021). The efficiency of PEM electrolyzers are around 60% (Bauer *et al.*, 2021; Herenčić *et al.*, 2021), which corresponds to a specific electricity consumption of ~56 kWh/kg hydrogen production. Alkaline electrolyzer generally have less operational flexibility compared to PEM, although the investment costs are significantly lower for this more mature electrolyzer technology (Bauer *et al.*, 2021). Further, AEs have an efficiency of around 67% (Bauer *et al.*, 2021), corresponding to a specific electricity consumption of ~50 kWh/kg hydrogen production.

Land use

No information regarding the land use requirements is identified. However, the expectation is that the land area requirements of the electrolyzer are small. Further, the specific land area requirements for the electrolyzer can be identified during the data exchange with Dalane Energi (responsible for delivering the electrolyzer in Eigerøy).

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Economics

Table 12. Economic parameters of the electrolyzer. Electricity costs and water costs are not presented here, since these are very specific for geographical locations.

Cost parameter	Value (PEM)	Value (AE)	Unit	Source
CAPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW$_e$]	(Bauer *et al.*, 2021; Herenčić *et al.*, 2021)
REPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW$_e$]	
OPEX	19		[euro/kW$_e$]	(Herenčić *et al.*, 2021)
Lifetime	60,000	75,000	[hours]	(Bauer *et al.*, 2021)

Life cycle inventory

Life cycle inventory of electrolyzers is already available and can be obtained from both the ecoinvent database and from earlier projects at PSI. Alternatively, new life cycle inventory can be generated based on the specific electrolyzer installed during ROBINSON. The final decision - regarding (specific) life cycle inventory – will take place in the coming months.

Further information and data to be added

The final decision on the type (AE or PEM, probably AE) and size of electrolyzer still has to be determined. Specific economic data and life cycle inventory can therefore not be obtained yet.

AD-BES

Technology specification

Industrial symbiosis concepts will be applied on the three islands. Liquid wastewater of Prima Protein (local fish industry) will be used as feedstock in the AD-BES on Eigerøy. The AD-BES technology allows efficient treatment of wastewater, generated by the fish industry. To achieve this, an anaerobic digester in combination with a bio-electrochemical system (1 m^3 volume) produces biomethane – up to a purity of 95% – due to microbial conversion of organic matter content of wastewater. The BES unit is supplied with electricity at a voltage near 1 V, in order to upgrade the AD unit in terms of process kinetics and CH_4 content of produced biogas. The technology has several advantages, such as high process efficiency under mild operation conditions, high flexibility regarding power fluctuation and plant size as well as the opportunity for seasonal energy storage in the form of biomethane. Leitat develops the AD-BES unit, while Hysytech builds the AD-BES unit. Some characteristics foreseen for AD-BES units are presented in Table 13. Current TRL of the technology is 4 and the objective of ROBINSON is to bring the technology at TRL 6. Therefore, the technology does not yet present a high maturity level. Operation parameters and target biogas productivity will be updated during the project, after first trials at laboratory scale.

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Table 13. Operational parameters of the AD-BES.

Parameter	Value
Production rate	0,12 – 0,22 Nm^3/day (min value)
Delivery temperature	37 °C
Delivery pressure	0,02 bar_g
Composition of biogas (range values)	CH_4 65 mol% (min value) H_2O 6 mol% CO_2 29 mol% Minor gas components
AC electrical power need	3,5 kW
DC Voltage of BES stack	1 V approx.
Wastewater demand	100 L/day (min value) 5 °C - 40 °C 2 – 8 bar_g

Land use

No information regarding the land use requirements is identified yet. The specific land area requirements for the AD-BES can be identified during the data exchange with ROBINSON partner Leitat.

Economics

Table 14. Economic parameters of the AD-BES.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW_e]	
REPEX	tbd	[euro/kW_e]	
OPEX	tbd	[euro/kW_e]	
Lifetime	20	years	Leitat, 2021

Life cycle inventory

Life cycle inventory of the novel AD-BES will be generated in collaboration with Leitat. The AD-BES is a novel technology and life cycle inventory is not widely available yet. We therefore provided a questionnaire to Leitat to generate new life cycle inventory as well as economic data to be used in the LCA and LCC.

Further information and data to be added

Details of the technology, life cycle inventory and costs will follow after more discussion between LEITAT and Hysytech, and must be confirmed once lab-scale results are available.

Gasifier

Technology specification

A Syncraft gasifier is currently under evaluation for wood gasification in Eigerøy, producing syngas to be mixed in the gas fuel mixer and subsequently supplied to the CHP unit. The gasification unit

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converts wood into syngas by making use of several processes (see Figure 13). The Syncraft gasifier is very flexible regarding the type of feedstock used; all forest residues can be fed into the gasifier thereby avoiding expensive feedstock, such as pure wood pellets (Syncraft, 2021). The fixed bed gasification technology allows for this raw material feedstock flexibility and high conversion efficiency. On the contrary, the operational flexibility of the gasification unit is limited. This results in for example slow start-up times – around 20-30 minutes – and cold start-up times of more than three hours.

The raw materials are first converted during a pyrolysis process - heating up the wood materials up to 1000°C - resulting in a decomposition of the raw materials into gases and charcoal (or biochar). Biochar (potentially) allows for negative GHG emissions when applied to soils, and could be interesting to compensate for hard to decarbonize (industrial) processes in ROBINSON (Terlouw *et al.*, 2021). Next, the floating bed reactor allows filtering out impurities. Further, it selects the gas particles - containing of hydrogen, carbon monoxide, carbon dioxide as well as light hydrocarbons (Molino, Chianese and Musmarra, 2016) - by making use of gravity in the floating fixed bed reactor. Subsequently, the gas can be used to drive a gas engine to generate heat and electricity. Alternatively, the gas and charcoal can be used as feedstock in follow-up processes. Electricity is required for biomass drying, the air compressor, air blower and water pumps.

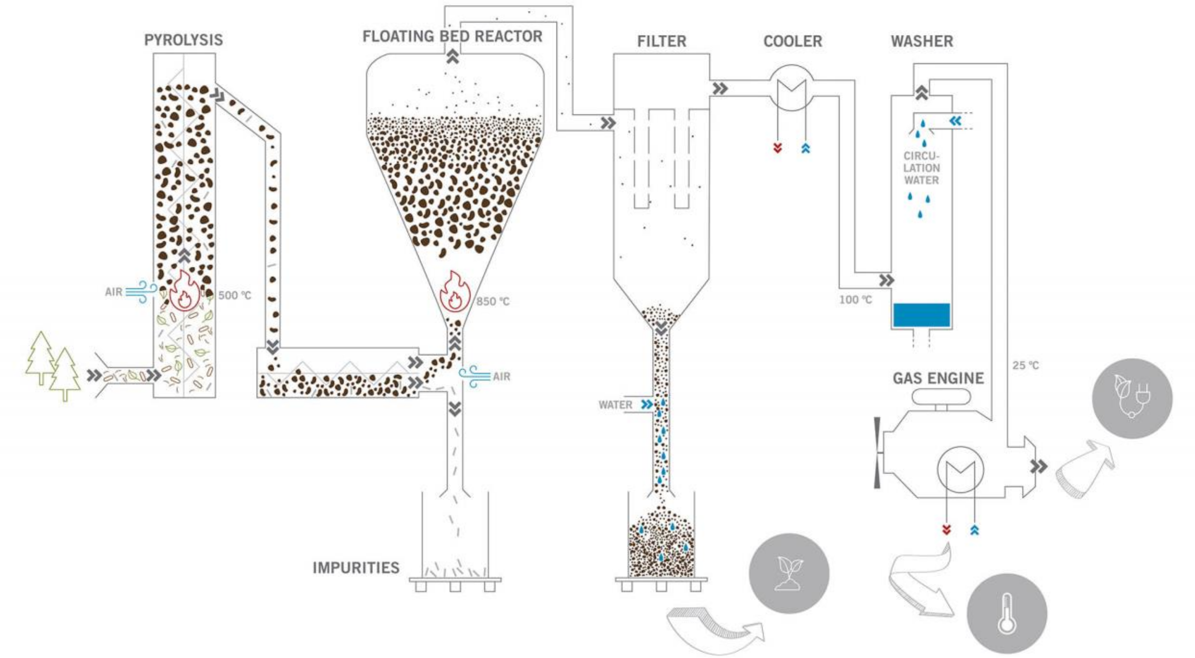

Figure 13. The gasification process of Syncraft (Syncraft, 2021).

The fuel biomass specification should comply with certain limits/characteristics. Non-contaminated wood chips are preferred, although fines and bark are acceptable in the fuel mix. The acceptable water content should be lower than <10% (weight) before the biomass is fed into the gasification unit, which can be achieved with a drying process. Feedstock storage is also required and can be installed outdoors.

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Land use

The total land requirement is currently estimated on 57.6m*18m = 1037 m^2 (ground floor). However, the total footprint is estimated to be higher, since the installation contains of 2.5-3 floors in total.

Economics

Table 15. Economic parameters of the gasifier.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/$kW_{th,high}$]	
REPEX	tbd		
OPEX	tbd	[euro/$kW_{th,high}$]	
Lifetime	20	[years]	Excel Syncraft

Life cycle inventory

Life cycle inventory for biomass gasification is available in the ecoinvent database with the activity 'synthetic gas factory construction'. Alternatively, life cycle inventory can be generated in collaboration with Syncraft, in case interested.

Further information and data to be added

The type of gasifier and size are still under evaluation. More specific information and details are needed before specific life cycle inventory as well as cost data can be generated.

Gas fuel mixer

Technology specification

The gas mixer utilizes and mixes the fuels generated with the electrolyzer (hydrogen), gasification (syngas) and AD-BES unit (biomethane). The generated gas mixes are prepared to be used in the novel CHP unit of Aurelia – please refer to Section 'Gas turbine (Aurelia)' for more information regarding the specific gas mixes used in the CHP unit. The mixed gas fuels must therefore respect the gas mixtures and requirements of the CHP unit. The Paul Scherrer Institute (PSI) developed a tool to determine the characteristics of these fuel mixtures.

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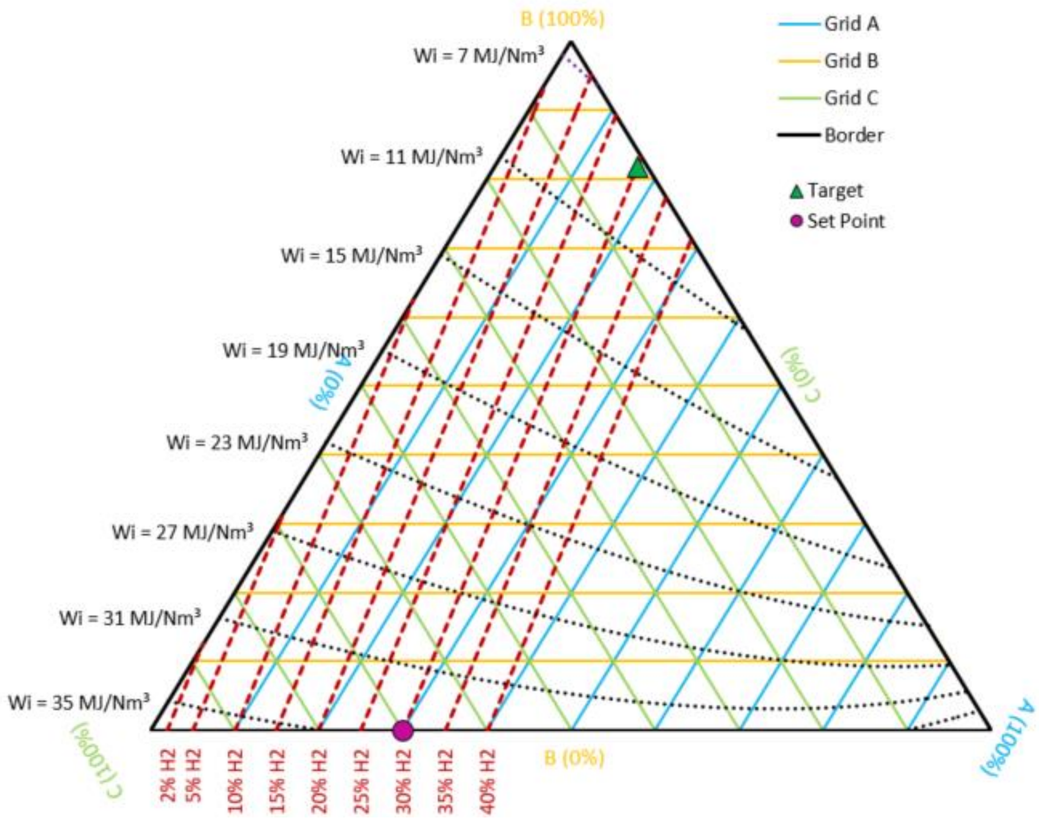

Figure 14. Triplet of fuel mixes. A = Hydrogen from electrolysis, B = Syngas from gasification and C = Biomethane from anaerobic digestion produced by the AD-BES.

Land use

No information regarding the land use requirements is identified yet. A first estimation regarding land use is 2m * 2m = 4 m^2, although this estimation does not consider the buffer tanks and must be confirmed in the coming months.

Economics

Table 16. Economic parameters of the gas mixer.

Cost parameter	Value	Unit	Source
CAPEX	tbd		
REPEX	tbd		
OPEX	tbd		
Lifetime	tbd		

Life cycle inventory

No information yet available.

Further information and data to be added

More general information regarding the sizing is required, although this logically depends on the sizing of other system components. Further, cost and life-cycle inventory data are missing and still need to be generated.

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PV systems

Technology specification

Polycrystalline silicon cells – a form of multicrystalline PV panels – are selected as PV arrays, representing mainstream PV technology nowadays. Two type of PV panels are selected, both the “265 CS4” and “270 CS4” with a maximum power output of 265 W_p and 270 W_p, respectively. The panels are produced in Germany (IBC Solar). Figure 15 demonstrates the reduction of the power output as well as the power warranty of the selected PV systems, which have a module efficiency of 16.6% in combination with a system lifetime of 25 years.

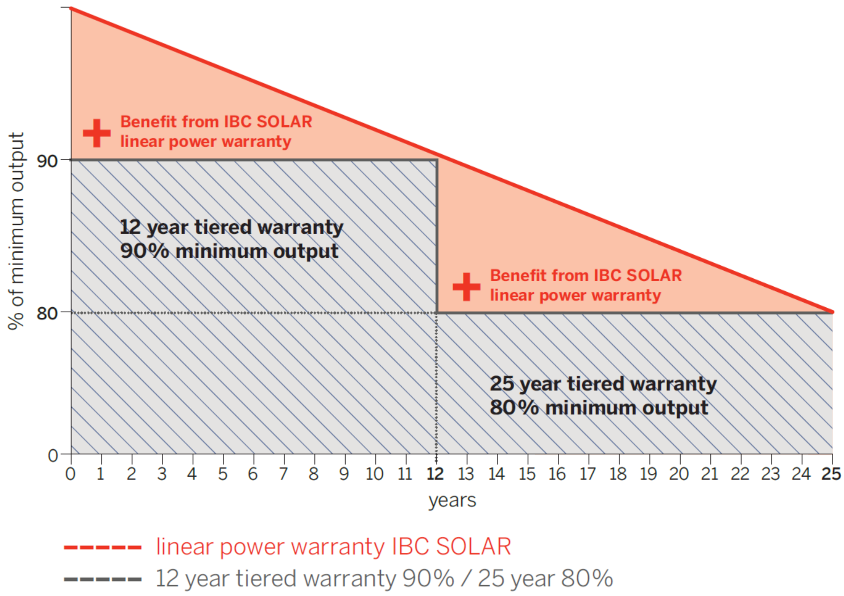

Figure 15. Power and lifetime warranty of the selected PV systems.

Land use

Land use requirements are obtained from life cycle inventory data available in the ecoinvent database, around 7 m^2/kW_p. However, if panels are installed on roofs of existing buildings, no additional land is required.

Economics

Table 17. Economic parameters of the PV system. These values are based on literature.

Cost parameter	Value	Unit	Source
CAPEX	1100	[euro/kW_p]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
REPEX	1100	[euro/kW_p]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
OPEX	13-22	[euro/kW_p/year]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
Lifetime	25-30	[years]	Factsheet of IBC Solar and (Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; ecoinvent, 2020)

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Life cycle inventory

Life cycle inventory of multi-crystalline PV panels are readily available in the ecoinvent database. These inventories can be adopted.

Further information and data to be added

More specific cost data must be obtained from the PV system supplier. Further, life cycle inventory could be generated in case substantial differences are expected between available life cycle inventory in the ecoinvent database and the specific PV system under consideration.

Energy storage systems

Technology specification

Storing electricity in electrochemical energy storage systems - such as batteries - is one of the popular forms of electricity storage nowadays, also on European islands. Batteries are preferable due to their high conversion efficiency, enhanced system stability and low standby losses (Terlouw, Zhang, *et al.*, 2019; Bauer *et al.*, 2021). Battery energy storage systems are, however, only preferable for short-term electricity storage due to standby losses, comparably high (and scarce) material requirements and relatively high investment costs compared to other storage mediums (Terlouw, Zhang, *et al.*, 2019; Bauer *et al.*, 2021). More specifically, lithium-ion batteries are considered for short-terms electricity storage, due to their comparably low investment costs, representing mainstream battery technology nowadays (Schmidt *et al.*, 2019; Terlouw, Zhang, *et al.*, 2019).

Besides electricity storage, hydrogen storage is considered, which is preferable for long-term energy storage. Large quantities of hydrogen can be stored, and can be easily sold and transported over long-distances to other countries (Bauer *et al.*, 2021). Hydrogen is therefore identified as an important energy carrier in future energy systems and on European islands. Hydrogen can be stored above the ground in pressurized tanks, such as metal hydride tanks (Bauer *et al.*, 2021). Alternatively, a lower cost option is to store hydrogen in salt caverns, although this is a constrained storage option due to geographical limitations (Bauer *et al.*, 2021). Currently, hydrogen of a pressure of 300 bar is under evaluation, so that it can be consumed in the transport sector in and around Eigerøy.

Further, gas storage will be implemented to store the gas and to control the amount of gas flowing into the gas mixer. And lastly, biomass will be stored in the form of (waste) wood chips, to be consumed for biomass gasification. The type and size of these storage mediums are still under evaluation.

Land use

Land use requirements for the battery storage system are expected to be negligible, and can be obtained from earlier generated life cycle inventory. Further, it has to be decided whether sub-components in terms of energy storage – such as gas buffer tanks – are allocated to the component itself or will be treated separately as energy storage medium.

Economics

Table 18 and Table 19 present the cost parameters for battery electricity storage and hydrogen storage, respectively.

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Table 18. *Cost parameters for battery electricity storage. Generic cost data is obtained from recent literature.*

Cost parameter	Value	Unit	Source
CAPEX	180 (per kWh energy capacity) and 143 (per kW power capacity)	[euro/x]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
REPEX	180 (per kWh energy capacity) and 143 (per kW power capacity)	[euro/x]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
OPEX	10	[euro/kW]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
Lifetime	13 (for battery pack) and 20 (for balance of system)	[years]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)

Table 19. Cost parameters for hydrogen storage. Table has been reproduced from a recent report of Bauer et al. (Bauer *et al.*, 2021).

Storage	Gaseous	Liquefied	Caverns	Metal hydrides	LOHC	Unit
Storage Pressure	15-700	~1	45-300	~10-60	2 – 70	bar
CAPEX	220-2200	~330	1-3	1400-3600 (tank plus hydride material)	No data	CHF/kg H_2 storage
OPEX	2%	2%	2%	No data	4%	Of CAPEX/year
Lifetime	20-25	20	30-50	25	n.a.	years

Life cycle inventory

Life cycle inventory for the battery systems is obtained from earlier work presented in (Schmidt *et al.*, 2019) with an update regarding electricity consumption for battery production performed in Bauer *et al.* (Bauer *et al.*, 2021). The latter work includes different lithium-ion battery (LIB) technologies, such as LFP LIB (graphite anode, lithium iron phosphate cathode), NMC LIB (graphite anode, lithium nickel manganese cobalt oxide cathode), NCA LIB (graphite anode, lithium nickel cobalt aluminum oxide cathode) and LTO LIB (lithium titanium oxide anode, lithium nickel cobalt aluminum oxide cathode).

Life cycle inventory of the hydrogen storage units is not readily available yet, and literature will be reviewed to find appropriate life cycle inventory.

Further information and data to be added

More specific data on the hydrogen storage technologies, regarding size and type, are required. Currently, some generic assumptions and data are provided, we expect to receive more specific data in the coming months.

Cost and environmental data of energy carriers

Table 20 shows prices for different feedstock and energy carriers, specified for Eigerøy.

Table 20. Feedstock and energy carrier prices in Eigerøy.

Cost parameter	Value	Unit	Source
Feedstock			
Waste Wood	0 – 10	€/t	Communication Prima Protein
White Wood	20	€/t	Communication Prima Protein
Lower heating value	3.50	kWh/kg	Communication Prima Protein
Energy prices at Prima Protein			
LNG Cost (2020)	43.19	€/MWh	Communication Prima Protein
CO_2 tax (2020)	14.35	€/MWh	Communication Prima Protein
Electricity Nordpool (av. 2020)	33	€/MWh	Communication Prima Protein

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5. Technology specifications – Western Isles

This section provides the technology specification for Western Isles (Scotland). The structure of this chapter is based on the most important system components to be installed on Western Isles. General information is provided for the technology under study, land use coverage of the technology, economics as well as other special requirements for system components. And lastly, missing data and additional requirements are identified.

The case study of Western Isles is focused on the Waste Management Facility: the Creed Enterprise Park (Creed IWM Facility) on the Isles of Lewis and Harris, Scotland.

Combined heat and power unit

Technology specification

Biogas is used as primary energy source for the CHP unit. The CHP generator converts biogas into electricity and heat. The CHP unit has an electrical and thermal capacity of 240 kW_e and 370 kW_{th}, respectively (Fabiano *et al.*, 2018). The maximum amount of biogas used is 125 m^3/h with a methane content up to 60%. Some performance data and energy generated during one year of system operation is presented in Table 21.

Table 21. CHP performance data for year 2020, reproduced from deliverable 1.3.

Month	Carbon Savings (kg of CO_2)	Hours of Run (h)	Gas Consumed (kWh)	Heat Generated (kWh)	Electricity Generated (kWh)	Average Heat Efficiency (%)	Average Electricity Efficiency (%)
Jan	8135	347.2	231692	110955	72520	0.479	0.313
Feb	4914	231.0	139948	67020	43804	0.479	0.313
March	3946	186.7	112388	53822	35178	0.479	0.313
Apr	5000	226.5	142406	68197	44573	0.479	0.313
May	7195	323.0	204927	98137	64142	0.479	0.313
June	4781	219.4	136180	65215	42624	0.479	0.313
July	3350	172.4	95407	45689	29862	0.479	0.313
Aug	4442	207.9	126521	60590	39601	0.479	0.313
Sep	5971	285.2	170066	81443	53231	0.479	0.313
Oct	4658	223.0	132658	63529	41522	0.479	0.313
Nov	3300	177.5	93980	45006	29416	0.479	0.313
Dec	3124	172.3	88976	42610	27850	0.479	0.313

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Land use

Not available.

Economics

Specific costs for this CHP technology are not provided yet.

Table 22. Economic parameters of the CHP unit. Generic cost data is used here, based on available literature.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW$_e$ capacity]	
REPEX	tbd	[euro/kW$_e$ capacity]	
Operation	Depends on location + feedstock	[euro/MWh]	
OPEX (fixed)	tbd	[euro/kW$_e$ capacity/year]	
Lifetime	25	[years]	(Danish Energy Agency, 2020), valid for most CHP units and has engines

Life cycle inventory

Readily available life cycle inventories of gas turbines on ecoinvent and the web can be used for this purpose, since the expectation is that this gas turbine represents mainstream turbine technology already available in the ecoinvent database.

Further information and data to be added

Cost data and specific information regarding life cycle inventory is missing. Further, it should be verified whether a normal gas turbine proxy is sufficient to cover this specific gas turbine.

Steam boiler

Technology specification

An electric steam boiler is installed with a power rating of 180 kW and a thermal efficiency of 100% (Fabiano *et al.*, 2018). The electric steam boiler consumes (renewable) electricity provided by a wind turbine. Next, the generated thermal energy is supplied to a heat storage medium. Additionally, a kerosene boiler can be used in case the thermal heat demand is high and the steam boiler does not supply sufficient heat to cover the total heat demand. The kerosene boiler has an efficiency of 85% in combination with a rated power of 150 kW, and supplies heat at a maximum temperature of 85°C (Fabiano *et al.*, 2018).

Land use

No information regarding the land use requirements is identified. However, the expectation is that land area requirements of the boiler are rather small.

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Economics

Table 23. Economic parameters for the gas boiler. Non-specific cost data is used as approximation here.

Cost parameter	Value	Unit	Source
CAPEX	420	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
REPEX	420	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
OPEX	8.4	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
Lifetime	25	years	(Herenčić *et al.*, 2021)

Life cycle inventory

Life cycle inventory for the gas boiler can be adopted from the ecoinvent database (ecoinvent, 2020), since generic life cycle inventories for gas burners are readily available. For example, the ecoinvent dataset 'gas boiler production' can be scaled-up to achieve the higher thermal capacity.

Further information and data to be added

Detailed life cycle inventory and exhaust emissions would be preferable. Further, cost data should be obtained, specified for Western Isles.

Figure 16. The wind Turbine under consideration at Creed IWM Facility on Western Isles, obtained from Fabiano et al. (Fabiano *et al.*, 2018).

Wind turbine

Technology specification

A 300 kW Enercon (Type: E-33) has been installed on the Creed IWM Facility, see Figure 16. The wind turbine has the following dimensions: a diameter of 33.4 meter with a hub height of 37 meter. Different power constraints are active on the grid turbine to avoid imbalances. The delivered power to the mainland (grid) is limited to 225 kW, as set by the local distribution network operator (Fabiano et al., 2018). The maximum amount of power delivered to the IWM Facility is 200 kW (Fabiano et al., 2018).

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The power curve of the wind turbine is visualized in Figure 17, and it visualizes that the maximum power output is reached at wind speeds of 12 m/s or more.

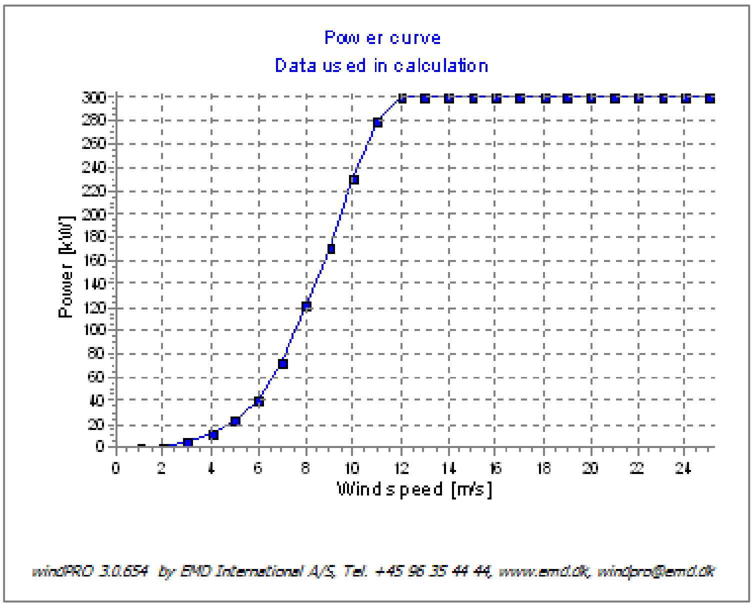

Figure 17. Power curve of the Enercon (Type: E-33), reproduced from deliverable 1.3.

Land use

Not available, although might be obtained from already existing data proxies in the ecoinvent database, assuming that the turbine under consideration represents mainstream wind turbines.

Economics

Table 24. Economic parameters of the wind turbine. Generic data is used from literature as approximation.

Cost parameter	Value	Unit	Source
CAPEX	1350	[euro/kW$_p$]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
REPEX	1350	[euro/kW$_p$]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
OPEX	25-32	[euro/kW$_p$/year]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
Lifetime	25	[years]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)

Life cycle inventory

The life cycle inventory can be obtained *via* the ecoinvent database, since it is expected that the wind turbine technology under consideration represent mainstream technology for wind turbines.

Further information and data to be added

The economic and technological data should be verified and possibly updated.

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Electrolyzer

Technology specification

A 31 kW alkaline electrolyzer is installed at the Creed IWM Facility to consume excess (renewable) electricity generated by the wind turbine (see previous paragraph) to produce hydrogen and oxygen (Fabiano et al., 2018). The hydrogen production rate is 5.3 Nm^3/h or 0.45 kg/h with a hydrogen purity of 99.3% and oxygen production rate of 7.94 kg O_2/kg H_2 (Fabiano et al., 2018). The efficiency of the electrolyzer varies – mainly dependent on the operational temperature – between 60% (at 60°C) and 55% at 20°C. The time to warm up – *i.e.,* to reach an operational temperature 60°C - the electrolyzer can be as long as one full hour and therefore has limited operational flexibility.

Land use

No information regarding the land use requirements is identified. However, the expectation is that the land area requirements of the electrolyzer are small.

Economics

Table 25. Economic parameters of the electrolyzer. Electricity costs and water costs are not presented here, since these are very specific for certain situations. Generic costs and data from literature are used as an approximation.

Cost parameter	Value (PEM)	Value (AE)	Unit	Source
CAPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW_e]	(Bauer *et al.*, 2021; Herenčić *et al.*, 2021)
REPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW_e]	
OPEX	19		[euro/kW_e]	(Herenčić *et al.*, 2021)
Lifetime	60,000	75,000	[hours]	(Bauer *et al.*, 2021)

Life cycle inventory

Life cycle inventory of electrolyzers is already available and can be obtained from the ecoinvent database and/or from earlier projects at PSI.

Further information and data to be added

The type of electrolyzer is still unclear as well as the cost and other technology data of the electrolyzer.

Anaerobic digestion (AD)

Technology specification

A dry thermophilic flow digester is installed on the Creed site. Kitchen and garden waste serve as feedstock/waste input to produce the biogas. The volume of the anaerobic digester (AD) is 960 m^3 with a fluid volume of 700 m^3. Some thermal power is required to process the feedstock, around 90 kW. Working temperatures of the AD unit are between 57°C and 81°C. The heating system is operated with cooling water obtained from the gas turbine. A fuel-operated boiler will be used in case the biogas production is non-operational. The AD temperature must at least be more than 57°C for five hours during one day to process the waste flows.

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It is worthwhile to notice that fish waste is treated before fed into the AD unit. To achieve this, the fish waste is pasteurised at temperatures higher than 70°C for a minimum duration of one hour.

Land use

Not available yet.

Economics

Table 26. Economic parameters of the AD-BES.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW_e]	
REPEX	tbd	[euro/kW_e]	
OPEX	tbd	[euro/kW_e]	
Lifetime	tbd	years	

Life cycle inventory

Not available yet.

Further information and data to be added

No much information provided yet; economic details and life cycle inventory of the technology are unclear.

PV systems

Technology specification

Thirty-eight multi-crystalline PV modules of type BenQ Green Triplex are installed on the Creed IWM Facility, each having a peak power output of 240-260 W. This results in a total installed capacity of 9.75 kW_p and a subsequent annual PV electricity production of around 7668 kWh. The PV system is connected to the electrical distribution system *via* AC/DC isolators and a three-phase inverter. The total amount of annual PV electricity is verified and is provided to the electricity provider. It is worthwhile to mention that there is no injection/export of electricity to the main grid, since the PV panels are not expected to generate sufficient electricity compared to the baseload electricity demand of the facility.

Land use

Land use requirements are obtained from life cycle inventory data available in the ecoinvent database, around 7 m^2/kW_p. However, if panels are installed on rooftops of existing buildings, no additional land is required.

Economics

Table 27. Economic parameters of the PV system. Generic data is used from literature.

Cost parameter	Value	Unit	Source

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CAPEX	1100	[euro/kW$_p$]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
REPEX	1100	[euro/kW$_p$]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
OPEX	13-22	[euro/kW$_p$/year]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
Lifetime	25-30	[years]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; ecoinvent, 2020)

Life cycle inventory

Life cycle inventory of multi-crystalline PV panels are readily available in the ecoinvent database. These inventories can be used.

Further information and data to be added

More specific life cycle inventory could be generated in case substantial differences are expected between available life cycle inventory in ecoinvent and the PV systems under consideration. Cost data – specified for Western Isles – would be preferable.

Energy storage systems

Technology specification

The hydrogen storage media on Western Isles consist of two storages: a low-pressure and a high-pressure storage medium. The electrolyzer is connected to the low-pressurized hydrogen storage medium (9-12 bar) (Fabiano et al., 2018). The latter storage medium receives hydrogen directly from the electrolyzer and therefore the hydrogen mass flow corresponds to the hydrogen production of the electrolyzer (0.08-0.45 kg H_2/h). Next, the hydrogen is delivered to the high-pressurized hydrogen storage medium (350-420 bar). To achieve this, a compressor is installed with a capacity of 15 kW.

Further, thermal energy storage is implemented as well. Hot water storage is used to store excess heat from the CHP unit, the electric boiler and/or the kerosene boiler. The water temperatures in the hot storage medium are usually between 71.4-78.2°C (Fabiano et al., 2018). The entire range of possible water temperatures is between 65-90°C. For example, a temperature of 70°C is required for the AD, and 80°C is needed for the pasteurisation process. The volume of water storage medium is 30 m^3, corresponding to a thermal energy storage capacity of 875 kWh (a pressure of 1-3 bar). A thermal loss of ~10.5 kW – corresponding to a temperature drop ~0.3°C/h - can be assumed for the heat storage medium.

Land use

Land use requirements are not known at the moment.

Economics

Table 28 and Table 29 present the cost parameters for water storage and hydrogen storage, respectively.

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Table 28. Cost parameters for water storage. The values used are from literature and are used as an approximation.

Cost parameter	Value	Unit	Source
CAPEX	120	[euro/kWh heat]	(Terlouw, AlSkaif, *et al.*, 2019)
REPEX	120	[euro/kWh heat]	(Terlouw, AlSkaif, *et al.*, 2019)
OPEX	0	[euro/kWh heat]	(Terlouw, AlSkaif, *et al.*, 2019)
Lifetime	20	[years]	(Terlouw, AlSkaif, *et al.*, 2019)

Table 29. Cost parameters for hydrogen storage. Table is reproduced from a recent report of Bauer et al. (Bauer *et al.*, 2021).

Storage	Gaseous	Liquefied	Caverns	Metal hydrides	LOHC	Unit
Storage Pressure	15-700	~1	45-300	~10-60	2 – 70	bar
CAPEX	220-2200	~330	1-3	1400-3600 (tank plus hydride material)	No data	CHF/kg H_2 storage
OPEX	2%	2%	2%	No data	4%	Of CAPEX/year
Lifetime	20-25	20	30-50	25		years

Life cycle inventory

Life cycle inventory of the hydrogen storage units is not readily available yet, and literature will be reviewed to find appropriate life cycle inventory. Several proxies exist in the ecoinvent database for hot water storage and these can be adopted, such as ‘Hot water tank production, 600 l’ and ‘Heat storage production, 2000 l’.

Further information and data to be added

Specific cost data and life cycle inventory data of storage systems are missing.

Cost and environmental data of energy carriers

To be added when more information will be available.

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6. Technology specifications - Crete

This section provides the technology specification for the case study of Crete (Greece). The structure of this chapter is based on the most important system components that could be installed on Crete. General information is provided for the technology under study, land use coverage of the technology, economics as well as other special requirements for system components.

Combined heat and power unit

Technology specification

Currently there is no biogas CHP unit installed in Crete. Based on the energy demands of the case study for Crete, a biogas CHP delivering 3.5 MW electrical power and 4.5 MW thermal power at nominal operation could be installed.

Land use

Not available.

Economics

Not available.

Table 30. Economic parameters of the CHP unit. Generic cost data from literature is used.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW$_e$ capacity]	
REPEX	tbd	[euro/kW$_e$ capacity]	
Operation	Depends on location + feedstock	[euro/MWh]	
OPEX (fixed)	tbd	[euro/kW$_e$ capacity/year]	
Lifetime	25	[years]	(Danish Energy Agency, 2020), valid for most CHP units and has engines

Life cycle inventory

Readily available life cycle inventories of CHP units available on ecoinvent and the web can be used for this purpose, since the expectation is that this CHP unit represents mainstream turbine technology already available in the ecoinvent database.

Further information and data to be added

Cost data and specific information regarding life cycle inventory is missing.

Steam boiler

Technology specification

Same technological specification/characteristics as applied to Eigerøy in case this is deemed an appropriate component of the ROBINSON solution for the case study of Crete.

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Land use

No information regarding the land use requirements is identified. However, the expectation is that the land area requirements of the gas boiler are rather small.

Economics

Table 31. Economic parameters for the gas boiler.

Cost parameter	Value	Unit	Source
CAPEX	420	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
REPEX	420	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
OPEX	8.4	[euro/kW$_{th}$]	(Herenčić *et al.*, 2021)
Lifetime	25	years	(Herenčić *et al.*, 2021)

Life cycle inventory

Life cycle inventory for the gas boiler can be adopted from the ecoinvent database (ecoinvent, 2020), since generic life cycle inventories for gas burners are readily available. For example, the ecoinvent dataset 'gas boiler production' can be scaled-up to achieve the higher thermal capacity.

Further information and data to be added

Detailed life cycle inventory and exhaust emissions would be preferable. Further, cost data should be obtained, specified for Crete.

Wind turbine

Technology specification

The total amount of wind capacity installed on Crete is approximately 200 MW. Based on the energy demands of the case study for Crete, a 5 MW wind power project could be installed. The exact type and capacity of the wind turbines is not determined yet. The existing wind farms in Crete utilize wind turbines with a nominal capacity below 1MW.

Land use

Land use of mainstream wind turbines can be obtained from the ecoinvent database, though specific land use requirements are preferred.

Economics

Table 32. Economic parameters of the wind turbines. Generic data is used, based on available literature.

Cost parameter	Value	Unit	Source
CAPEX	1350	[euro/kW$_p$]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
REPEX	1350	[euro/kW$_p$]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
OPEX	25-32	[euro/kW$_p$/year]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)

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Lifetime	25	[years]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)

Life cycle inventory

The life cycle inventory can be obtained *via* the ecoinvent database, since it is expected that the wind turbine technology under consideration represent mainstream wind turbine technology nowadays.

Further information and data to be added

Not much information yet. Specific economic and technological data should be added.

Electrolyzer

Technology specification

Same technological specification/characteristics as applied to Eigerøy, in case this is deemed an appropriate component of the ROBINSON solution for the case study of Crete.

Land use

Same technological specification/characteristics as applied to Eigerøy.

Economics

Table 33. Economic parameters of the electrolyzer. Generic data has been used. Electricity costs and water costs are not presented here, since these are very specific for certain situation.

Cost parameter	Value (PEM)	Value (AE)	Unit	Source
CAPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW$_e$]	(Bauer *et al.*, 2021; Herenčić *et al.*, 2021)
REPEX	385-2068 1182 (avg.)	571-1268 988 (avg.)	[euro/kW$_e$]	
OPEX	19		[euro/kW$_e$]	(Herenčić *et al.*, 2021)
Lifetime	60,000	75,000	[hours]	(Bauer *et al.*, 2021)

Life cycle inventory

Same technological specification/characteristics as applied to Eigerøy.

Further information and data to be added

Waiting on the final decision regarding the type and size of electrolyzer (most likely depends on the decision in Eigerøy).

AD-BES

Technology specification

Tomato residues are the primary (biomass-based) waste feedstock - which can be in used in a CHP plant – for the specific case study in Crete. Crete has a large agricultural sector and the chosen case

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study located at the Western coastline has a total crop area of approximately 800,000 m^2. The total annual amount of tomato residues to be used in the CHP plant equals 800 tonnes (when assuming 1 tonne of residues tomatoes per 1000 m^2) up to 4,000 tonnes (when assuming 5 tonnes of residues tomatoes per 1000 m^2, *e.g.,* during years with crop diseases).

The biogas that could potentially be produced by the AD-BES - in case such a technology is used within the ROBINSON solution developed for this case study - could then be used by a CHP unit to supply electricity and heat to energy-consuming facilities. For example, the bakery industry "The Manna" has a significant electricity and heat demand on Crete. Further, the touristic sector is large on Crete, and especially the small size hotels around Kissamos, where the case study is situated, could benefit from ROBINSON.

Land use

No information regarding the land use requirements is identified yet. The specific land area requirements for the AD-BES can be estimated during the data exchange with ROBINSON partner LEITAT.

Economics

Table 34. Economic parameters of the AD-BES.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW_e]	
REPEX	tbd	[euro/kW_e]	
OPEX	tbd	[euro/kW_e]	
Lifetime	tbd	years	

Life cycle inventory

To be determined after a decision has been made.

Further information and data to be added

No information provided yet; details of the technology are unclear.

Gasifier

Technology specification

Same technological specification/characteristics as applied to Eigerøy, in case this is deemed an appropriate component of the ROBINSON solution for the case study of Crete.

Land use

No information regarding the land use requirements are identified yet. The specific land area requirements for the gasifier can for example be obtained from readily available ecoinvent activities, scaling up or down the ecoinvent activity to the size of the considered gasification unit.

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Economics

Table 35. Economic parameters of the gasifier.

Cost parameter	Value	Unit	Source
CAPEX	tbd	[euro/kW$_{th,high}$]	
REPEX	tbd		
OPEX	tbd	[euro/kW$_{th,high}$]	
Lifetime	20	[years]	Excel Syncraft

Life cycle inventory

Life cycle inventory for biomass gasification is available in the ecoinvent database with the activity 'synthetic gas factory construction'.

Further information and data to be added

The type of gasifier and size are under evaluation. More specific information and details are required before specific life cycle inventory can be generated and cost data can be obtained.

Gas fuel mixer

Technology specification

Same technological specification/characteristics as applied to Eigerøy, in case this is deemed an appropriate component of the ROBINSON solution for the case study of Crete.

Land use

No information regarding the land use requirements is identified yet.

Economics

Table 36. Economic parameters of the gas mixer.

Cost parameter	Value	Unit	Source
CAPEX	tbd		
REPEX	tbd		
OPEX	tbd		
Lifetime	tbd		

Life cycle inventory

No information yet available.

Further information and data to be added

No information yet.

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PV systems

Technology specification

Crete has very beneficial solar PV potential with annual solar irradiation of approximately 1800 kWh/m^2/year (ESMAP *et al.*, 2020). The total amount of PV capacity installed in the island of Crete is 80 MW$_p$.

Land use

Land use requirements are obtained from life cycle inventory data available in the ecoinvent database, around 7 m^2/kW$_p$. However, if panels are installed on roofs of existing buildings, no additional land is required.

Economics

Table 37. Economic parameters of the PV system. Generic data from literature is used.

Cost parameter	Value	Unit	Source
CAPEX	1100	[euro/kW$_p$]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
REPEX	1100	[euro/kW$_p$]	(Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
OPEX	13-22	[euro/kW$_p$/year]	(Danish Energy Agency, 2020; Herenčić *et al.*, 2021)
Lifetime	25-30	[years]	Factsheet and (Bauer *et al.*, 2019, 2021; Danish Energy Agency, 2020; ecoinvent, 2020)

Life cycle inventory

Life cycle inventory of multi-crystalline PV panels are readily available in the ecoinvent database. These inventories can be used.

Further information and data to be added

More specific life cycle inventory could be generated in case substantial differences are expected between available life cycle inventory in ecoinvent and the PV systems under consideration. Cost data – specified for Crete – would be preferable.

Energy storage systems

Technology specification

No information available yet. Same technological specification/characteristics as applied to Eigerøy, in case this is deemed an appropriate component of the ROBINSON solution for the case study of Crete.

Land use

Land use requirements for energy storage systems are expected to be negligible, and can be obtained from earlier generated life cycle inventory.

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Economics

Table 38 and Table 39 present the cost parameters for battery electricity storage and hydrogen storage, respectively.

Table 38. Cost parameters for battery electricity storage. Generic data from literature is used.

Cost parameter	Value	Unit	Source
CAPEX	180 (per kWh energy capacity) and 143 (per kW power capacity)	[euro/x]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
REPEX	180 (per kWh energy capacity) and 143 (per kW power capacity)	[euro/x]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
OPEX	10	[euro/kW]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)
Lifetime	13 (for battery pack) and 20 (for balance of system)	[years]	(Schmidt *et al.*, 2019; Bauer *et al.*, 2021)

Table 39. Cost parameters for hydrogen storage. Table is reproduced from a recent report of Bauer et al. (Bauer *et al.*, 2021).

Storage	Gaseous	Liquefied	Caverns	Metal hydrides	LOHC	Unit
Storage Pressure	15-700	~1	45-300	~10-60	2 – 70	bar
CAPEX	220-2200	~330	1-3	1400-3600 (tank plus hydride material)	No data	CHF/kg H_2 storage
OPEX	2%	2%	2%	No data	4%	Of CAPEX/year
Lifetime	20-25	20	30-50	25		years

Life cycle inventory

No information available yet.

Further information and data to be added

No information available yet.

Cost and environmental data of energy carriers

There is no thermal grid on the island of Crete. Stand-alone suppliers therefore supply electricity and heat demand. For example, petrol stations sell energy with spot prices and deliver energy by tank trucks. The electricity costs depend among others on the size of the industry. In general, an electricity price between 0.10-0.20 €/kWh can be used as benchmark on Crete. These values have to be re-evaluated following the expected increase due to the natural gas price changes.

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Appendix C demonstrates the electricity demand profiles of the industrial facility chosen as the case study for the island of Crete: the bakery industry "the Manna". Some important findings can be derived from the figures.

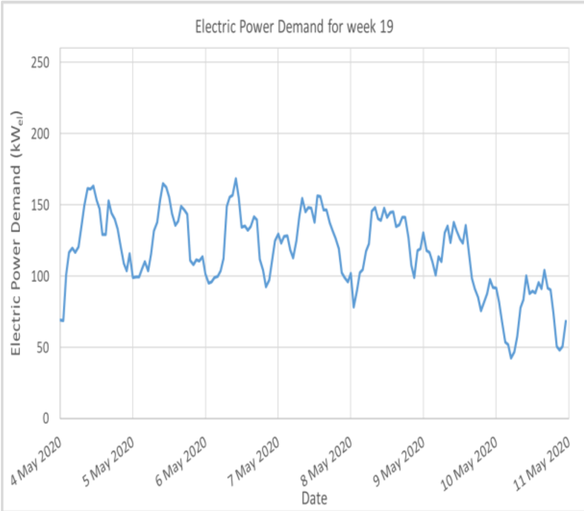

Figure 18. Active power demand during a spring week in May 2020.

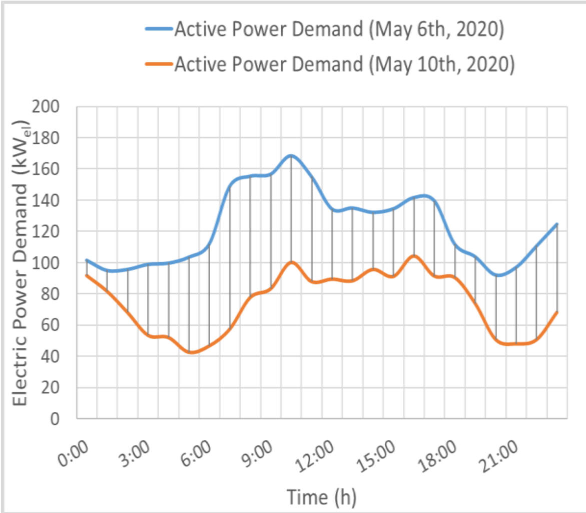

Figure 19. Comparison of the electric power demand in selected spring weekdays (6th of May) and weekend days (10th of May)

First, the figures show seasonality: more electricity is consumed during the summer months (*e.g.,* ~121 MWh in July 2020) compared to the winter months (*e.g.,* ~66 MWh in December 2020). Second, the peak power demand is reached in August 2020, with a peak of more than 270 kW$_{el}$. Further, there are several periods with limited operation in the bakery, for example during Christmas and during a summer pause of rusk production. In addition, Figure 18 and Figure 19 demonstrate that more power is consumed during daytime and during weekdays (compared to weekend days).

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5. Summary

ROBINSON aims to implement a real demonstration project on the geographical island Eigerøy (Norway), with follower islands Crete (Greece) and Western Isles (Scotland). The main goal of ROBINSON is to improve the environmental as well as the economic performance on these geographical islands. First, this deliverable aimed to provide a background of ROBINSON, such as the energy consumption and potential for renewable electricity generation on the three islands. Second, initial technology specifications were given in terms of type, size, costs and life cycle inventory used for the technologies installed during ROBINSON - with a focus on the first demonstration island Eigerøy (Norway). Subsequent versions will provide more details regarding Crete and the Western Isles. And lastly, this document gives an indication on the missing information and data needed for a comprehensive assessment of the economic and environmental performance of the three demonstration islands of ROBINSON. This deliverable is therefore an essential requirement for the life cycle cost as well as the environmental analysis of the newly installed energy systems.

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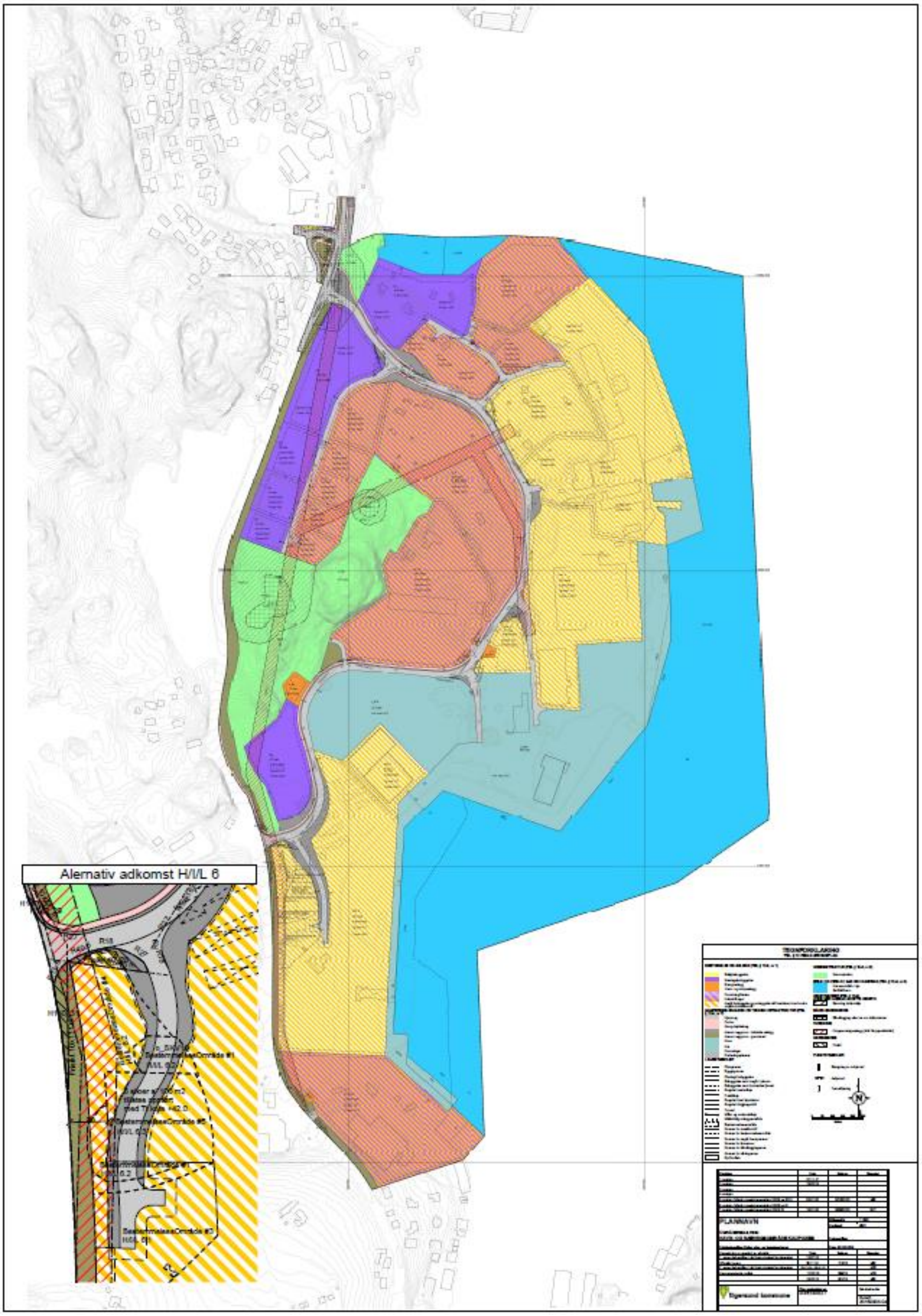
Appendix A. Map of Eigerøy.



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Appendix B. Questionnaire.

Questionnaire: Data exchange between company X and PSI with the goal to perform an environmental life cycle assessment and life cycle cost assessment

Life cycle assessment (LCA) is a method to quantify/estimate total environmental impacts during the lifetime of a product or a service. To achieve this, data collection is an important element in LCA, to present a comprehensive and detailed analysis.

Please note that not all questions have the same relevance/priority, and that LCA usually follows an iterative approach. We are aware that some information is already available on Microsoft Teams, however, we have also heard that some of the provided documents (on MS Teams) are outdated. Therefore, we would like to ask for the most complete information in this document. In case of any questions or clarities, please do not hesitate to discuss them with us.

Important parameters to get started, general technology specifications:

Parameter	Value(s)	Unit
Capacity (nominal and actual)		
Type of technology		
Efficiency (LHV/HHV?)		
Operation hours/capacity factor		
Lifetime of the technology		

1. Environmental life cycle assessment

Technology specifications

- Could you provide a technological description of the technology under study?
  - When available, a flow diagram could be helpful (with technical flows and or materials/energy flows).
- What are the proposed sizes of the technology (for Eigerøy, Greece and Western Isles)?
  - What is the sensitivity of weather conditions on hydrogen generation of the technology under study?
  - How flexible is the technology regarding electricity consumption (considering start-up time/ ramp-up times, maximum and minimum power requirements)?
  - Are there any by-product produced? What is there energetic and/or economic value?
  - Could you perhaps provide some current and expected (future) market sizes of the technology?
- Lifetime.
  - How sensitive is the lifetime parameter (by giving a maximum, minimum and median value)?
  - Is there an amount of maximum number of cycles the technology can run (*i.e.* cycle lifetime, e.g. start-up times)?

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- What is the calendric lifetime (*i.e.* maximum number of years before it has to be replaced irrespective to the number of cycles)?

Production of the technology

- In which location are the components of the technology produced/assembled?
- Are there business flights made to negotiate before the technology will be installed?
    - How many business flights - as an indication - are (usually) made before a technology is finally installed?
    - And during operation or monitoring?
- What are the material requirements for the production of the technology?
    a. This should (at least) include the material name, production location, material type and the amount per material. For example:

Technology	Production location	Pieces	material	weight per piece [kg]	Absolute weight [kg]
Fabrication					
low-alloyed steel	Europe	100	low-alloyed steel	22	2200
polyvinylchloride	China	100	plastic	1	100

    b. Further, please also specify the energy requirements to assemble the technology.
    c. Are there any special/toxic materials or metals used in the infrastructure of the technology?
        i. If yes, how much material per unit of product, and where are these materials usually harvested?

Please find attached ('example.xlsx.') an example inventory and how it can be used in our life cycle inventory analyses (with linkages). This is an example and materials requirements and amounts are just an example. For example, the sheet "raw_materials" can be used as starting point as input for your data provision and to serve as starting point for our analysis. Please note that we are not limited to the materials provided in this sheet (e.g. steel, copper, plastics) but can include many other materials - such as chemicals, energy types and other infrastructure materials - from our background LCA database. Please also note that it may be of interest to provide material inputs per specific sub-component of the technology (e.g. auxiliaries, fuel, housing) so that it can be evaluated which components (or process steps) of the assembled component are causing the highest impacts on the environment.

Operation

- Is there any maintenance involved during the lifetime of the component? If yes, what are the energy/materials requirements?
    - How many times is maintenance performed?
    - What are the electricity/fuel requirements for the component during operation (for example lubricants/oil)?
    - How sensitive are these energy requirements (by giving a maximum, minimum and median value)?
- What is the area requirement needed for the component (length, width and height in meters)?

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- What is the additional area required around the component, for example for transportation, noise or protection of the component unit?
- What are the exhaust emissions per unit of fuel input?

End-of-life

- Is there any knowledge regarding the end of life of the component, in terms of recycling, incineration or disposal?
- Design for end of life: Is it easy to decompose / re-use elements etc.

Sensitivity analysis

- What are the most uncertain parameters for the component according to your experience?
    - Hence, which parameters would you include in a sensitivity analysis?
- Are there other parameters or uncertainties, which should be considered?
- What is the technology readiness level (TRL) of the component under study? Which (major) developments do you expect?

2. Life-cycle cost assessment

A life cycle cost (LCC) assessment is used to determine the total costs of a system or service over the entire lifetime, including capital expenditures (CAPEX), operating/fuel costs (OPEX), operation and maintenance costs (O&M) as well as the residual value of the asset at the end of life. We therefore would kindly ask you to fill in the following table:

Cost parameter	Value	Unit
CAPEX per unit capacity		[euro/kW capacity]
OPEX of fuels used during operation		[euro/kWh electricity]
O&M per year		[euro/kW capacity/year]
Residual value at end of life		[euro/kW capacity]
Depreciation/interest rate		[%]

- Are there any economies of scale regarding the CAPEX? If yes, do you know a cost relation, which can be used?
- Are there any technology-specific taxes or subsidies expected?

Further, we are also interested about possible future cost developments of the component.

- To what extent are annual costs improvements expected? How is this dependent on the total installed capacity/number of sold units of the component?
    - One could (for example) provide a cost estimation for future years 2025, 2030, 2040..? An optimistic, average and optimistic cost scenario is also very much appreciated for these years.
- Do you have any idea regarding experience rates of the technology?

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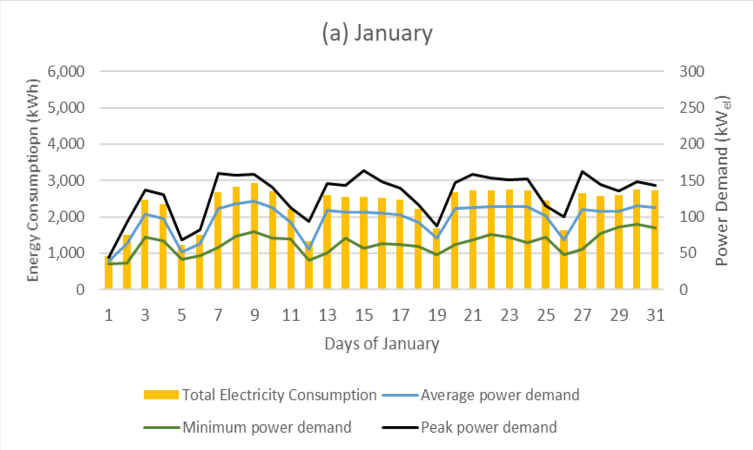
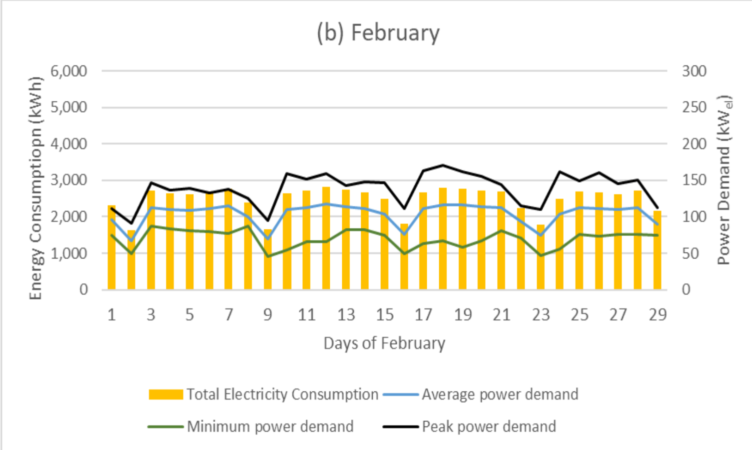
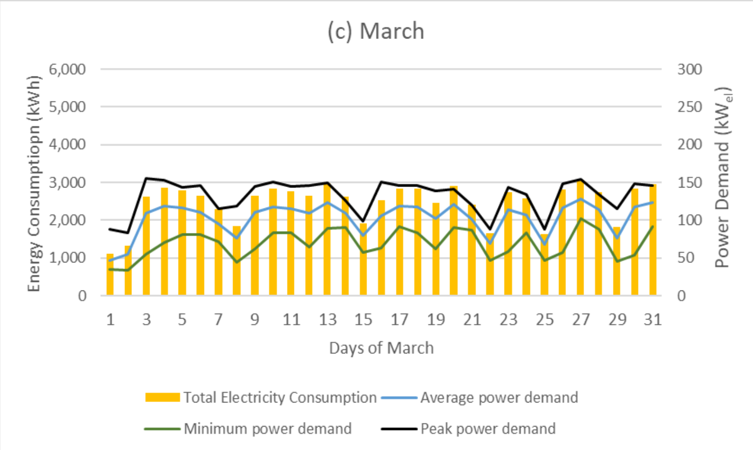
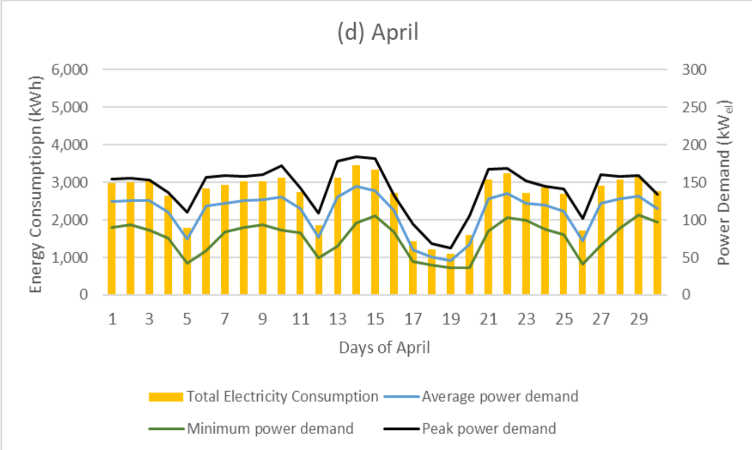
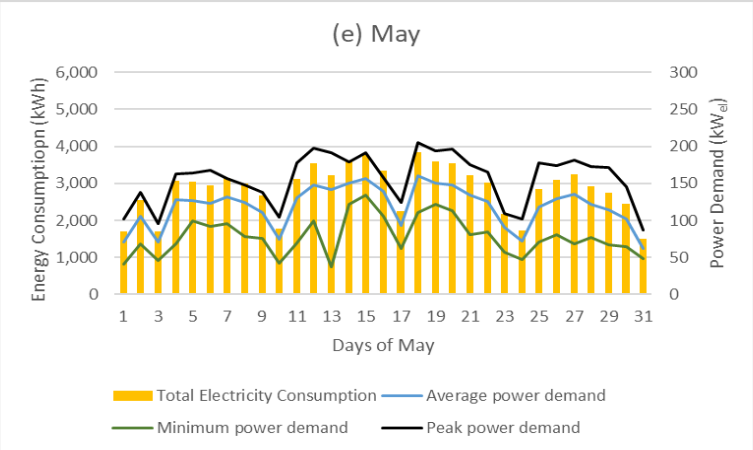
Appendix C. Electricity demand profiles in Crete of bakery industry “the Manna”

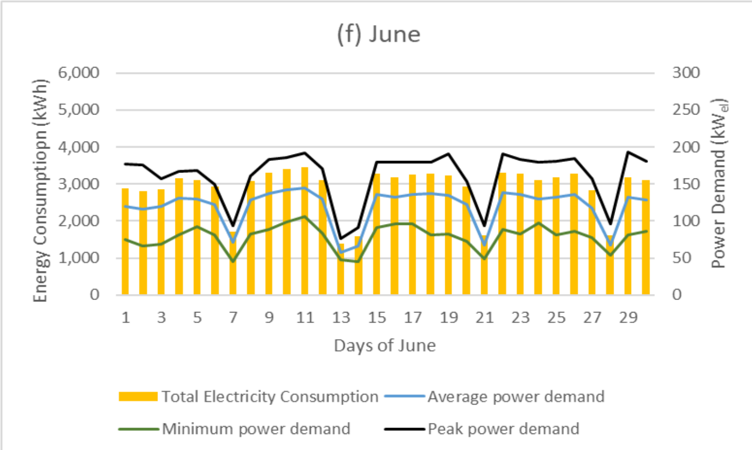












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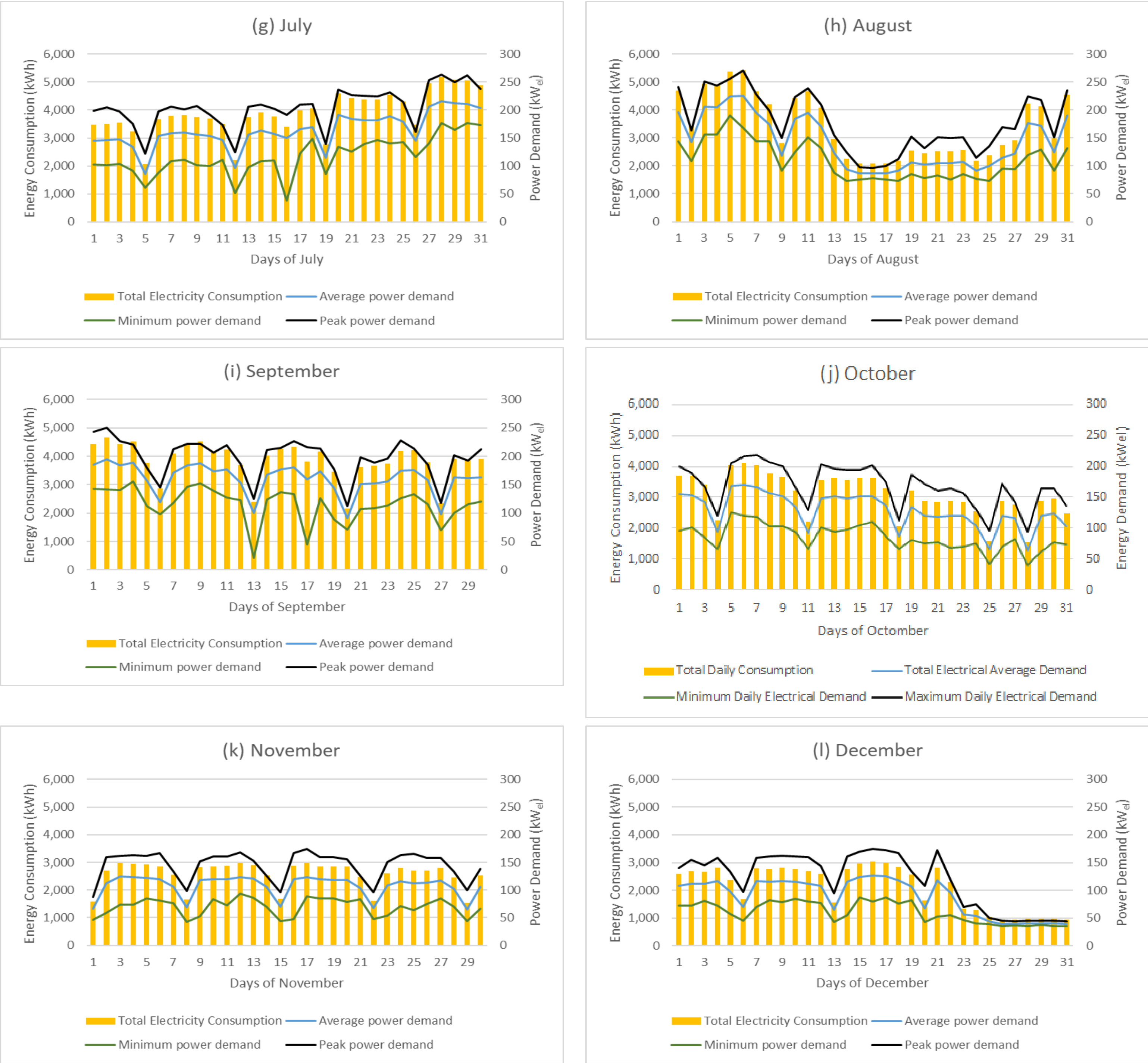

Figure 20. Variation of the electricity usage in the production line during the selected months of 2020.

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