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AN INTEGRATED ENERGY SYSTEM TO DECARBONISE ISLANDS – GAS TURBINE ROLES AND REQUIREMENTS

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ABSTRACT

Energy supply on geographical islands is relatively costly compared to the mainland. Therefore, large-scale deployment of local renewable energy sources and storage systems brings economic benefits, while contributing to decarbonise the energy system of islands.

The main objective of the EU H2020 ROBINSON project is geographical islands' decarbonisation through developing a flexible and modular energy management system, better integration of renewable energy sources, and biomass and wastewater valorisation. The ROBINSON concept will be demonstrated on the island of Eigerøy (Norway), and lab-scale level replication studies will be conducted for the island of Crete (Greece) and the Western Isles (Scotland). The concept is based on integration of different energy vectors (electricity, heat, and gas), and existing and newly developed energy conversion and storage technologies. A micro gas turbine based combined heat and power unit plays a central role in the concept, supported by an anaerobic digester assisted by bio-electrochemical systems, a mobile innovative wind turbine, a gasifier to covert bio-waste, and hydrogen-related technologies (electrolyser and storage system).

This paper describes the current energy system of the island of Eigerøy, the ROBINSON concept and its main sub-system, i.e., the gas turbine based combined heat and power unit.

INTRODUCTION

Energy systems that are predominantly based on fossil fuels are amongst the most important sources of greenhouse gas (GHG) emissions, hence causing climate change. In 2019, energy supply has contributed with about 27% to the total GHG emissions in EU27 (European Environment Agency, 2021) In the same year, about 60% of the final energy consumption of the EU was based on fossil fuels, namely oil and petroleum products with 37%, natural gas with 21%, and solid fossil fuels with 2% (European Union, 2021).

The European Commission published in 2019 the plans to significantly reduce the GHG emissions by - amongst others - increasing the share of renewable energy sources (RES), energy sector integration and energy efficiency improvement (European Commission, 2019). Distributed energy generation has been also one of EU's pillars to decarbonise the energy system, specifically via wind and solar power that can be connected directly to the distribution grid, thus also reducing transmission losses (IRENA, 2018). To support the transition of the European energy system towards a low-carbon one, the EU has launched several programs and initiatives in cooperation with national programs for research and development.

All these initiatives and measures in Europe and worldwide have resulted in a significant increase in the share of renewable energies in the electricity capacity. Worldwide (in Europe), the share of renewable energy sources has been increased from 25% (34% in Europe) in 2011 to about 37% (49.8% in Europe) in 2020 (IRENA, 2021A). This capacity expansion has been done mainly in fluctuating renewables like solar and wind and to a minor extend based on more dispatchable sources like hydro power or bioenergy (IRENA, 2021B). Due to the increase in the share of fluctuating renewable energy in the energy system, providing high flexibility via e.g., smart grid solutions (Lammers and Diestelmeier, 2017), and backup power, as well as the integration of energy storage are essential (Tooryan et al., 2020).

In mainland locations, grid support with other regions in terms of energy exchange is possible because of integration into large energy grids and systems. The situation for islands is however different from this perspective. Islands often have either no or limited connection to either neighbouring ones or the mainland resulting in less opportunities for services such as balancing (matching of demand and generation) or backup for fluctuating renewables.

A currently ongoing ROBINSON project funded by the European Commission in the frame of the H2020 program aims at developing and installing a demonstrator of an integrated energy concept on the island of Eigerøy at the south-west coast of Norway. Lab-scale level replication studies will be conducted for the island of Crete (Greece) and the Western Isles (Scotland). This concept was developed within a nationally funded project and is based on utilisation of locally available RES to cover growing energy demand and reducing the use of fossil fuel, while at the same time providing secure energy supply and avoiding the costly installation of additional transfer capacity to and from the mainland.

This paper describes the concept and the resulting challenges and requirements for a local combined heat and power (CHP) unit based on gas turbine technology using renewable fuel only.

ENERGY SYSTEM ON EIGERØY

The island of Eigerøy is located at the south-west coast of Norway, connected to the mainland and the city of Egersund via a bridge. Eigerøy has several huts used during vacation and at weekends, a residential area, agriculture, and industries co-located with the harbour area Kaupanes.

Current energy system

The energy system on the island is currently based on electricity "imported" via a sea cable and use of fossil fuel. Fossil fuel is used for transport (diesel and gasoline) and in industry (as liquefied natural gas – LNG) that is imported via trucks. A minor amount of wood is also used for heating in some of the houses. The current energy system is visualized in Figure 1.

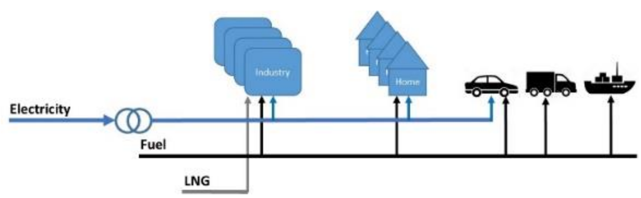

Figure 1: Current energy system on the island of Eigerøy

The electricity in the grid is based on the typical energy mix of Norway that is dominated by hydropower (93%), followed by wind power (4%), and a small amount of thermal power plant (3%) (some coal is also used only on Svalbard) (SSB, 2021). Solar energy is growing but its contribution in the grid is negligible as it predominantly locally used and seldom fed into the grid. Figure 2 visualises energy fluxes on Eigerøy in a Sankey diagram. While electricity is used for any appliances, charging of electric vehicles, and heating/cooling, fossil fuel is mainly used for transport (not visualised in Figure 2, as not being quantifiable), and for generating process steam.

Electricity on Eigerøy is provided by a sea cable connection with a capacity of 20 MW. Measurements of the electrical energy transferred to Eigerøy and collected between 01.10.2017 and 15.05.2018 (as shown in Figure 3) indicate the volatility in demand and that it is close to reaching the capacity limit of the of the cable for very few hours of the year (data from Dalane Energi AS).

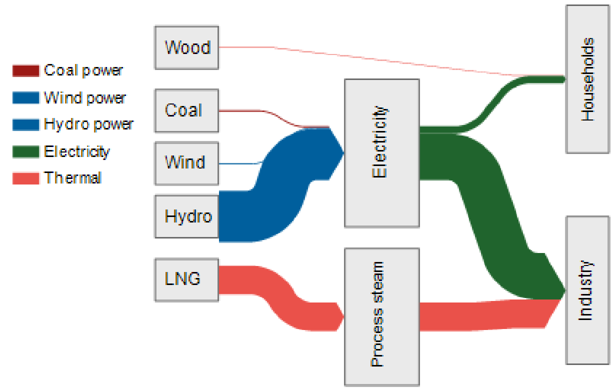

Figure 2: Energy fluxes on Eigerøy

Given the expected increase in consumption due to additional industries (estimated to be in the frame of about 3–8 MW in average), as well as energy need for transport (e.g., for charging of vehicles, but even more important providing electricity to ships while lying in the harbour) the demand in future will exceed the existing cable capacity.

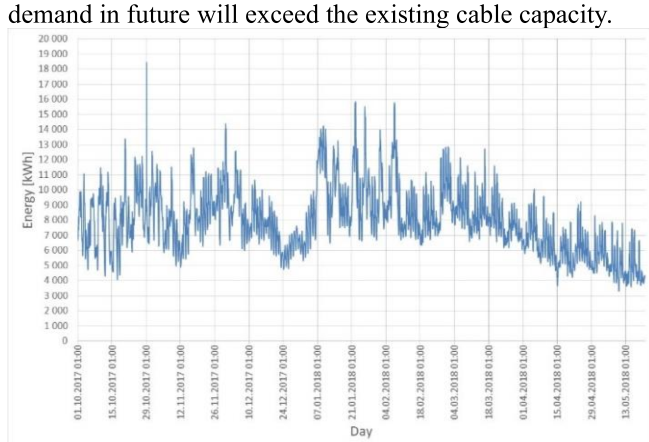

Figure 3: Measured electricity demand on Eigerøy

Available renewable energy sources

The available renewable energy sources that can be considered for the island of Eigerøy are solar, wind, and biomass.

The solar radiation and wind profiles on the earth surface depend on the geographical location, as well as on the local weather conditions. So, for different locations and years, different capacity factors for both systems are obtained. The calculation of the capacity factors is based on (Pfenninger and Staffell, 2016) and is provided by the internet site *www.renewables.ninja*. The PV and wind daily capacity factor profiles for Eigerøy for the year 2019 are shown in Figure 4, and Figure 5, respectively.

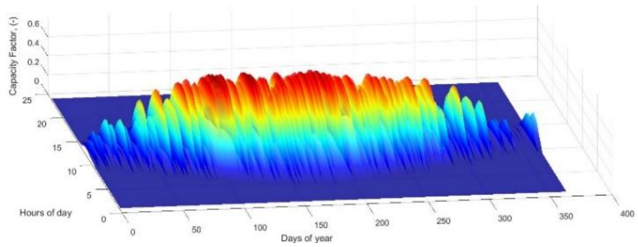

Figure 4: Capacity-factor profile of the PV system in 2019 for the site in Eigerøy, Norway

Wind conditions on Eigerøy are well suited, with relatively high average wind speeds, which are even higher if the wind turbines will be placed on top of the hill.

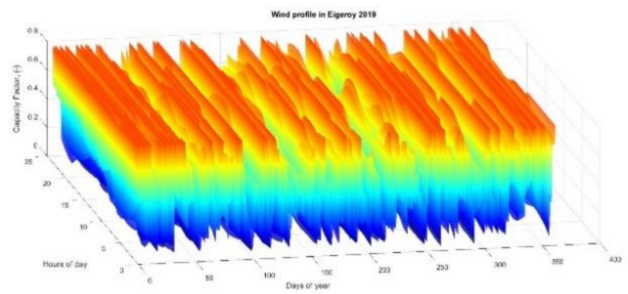

Figure 5: Capacity-factor profile of the wind system in 2019 for the site in Eigerøy, Norway

Biomass is another source on Eigerøy. Available two sources are a) waste woods, and b) organic wastes from fish companies.

a) A recycling company currently collects waste wood and sells / export it to e.g., Sweden or the UK. Waste wood is available of different quality, either in form of treated waste wood resulting from demolishing old houses or untreated waste wood from e.g., old pallets. This biomass might be either directly combusted and used for steam generation or gasified and used in a combined heat and power (CHP) unit for local power generation and process steam production.

b) Companies processing fish (e.g., for filet production, fish oil or protein) have waste streams containing organic matter. This forms a source for biogas production and a fuel as input to a CHP unit.

Table 1: Wind speed measured on Eigerøy

Month/year	Average wind speed [m/s]	Max. wind speed [m/s]
May 2017	6,4	18,5 May 16
Jun. 2017	7	18,8 Jun 26
Jul. 2017	7	22,4 Jul 31
Aug. 2017	6,9	18,2 Aug 3
Sep. 2017	7,9	19,7 Sep 5
Oct. 2017	10,2	27.2 Oct 29
Nov. 2017	9,3	24,7 Nov 17
Dec. 2017	8,3	27,8 Dec 8
Jan. 2018	8,9	27,1 Jan 15
Feb. 2018	7,4	27,6 Feb 15
Mar. 2018	7,7	22,8 Mar 16
Apr. 2018	7,1	21,5 Apr 5
May 2018	6,9	19,9 May 16

Robinson demonstration concept

During the second half of 2018 and beginning of 2019, within the frame of a national (Enova) and industrial funded project, an energy concept was developed, which aims at covering the growing energy demand on the island using locally available renewable energy sources and replacing LNG. The energy concept for Eigerøy was developed as being based on all locally available sources in combination with the existing cable connection to the mainland with the goal to avoid a costly additional or extended sea cable. The concept is visualized in Figure 6.

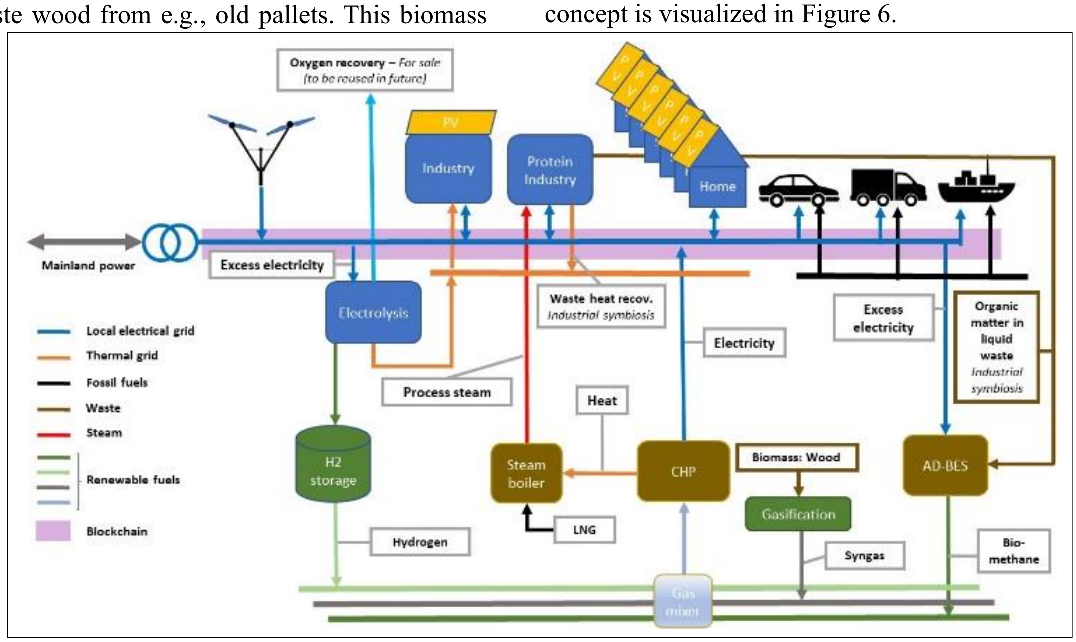

Figure 6: Energy concept for the island of Eigerøy

Wind turbine and PV are connected to the electrical grid. Surplus electricity will be used to produce hydrogen via electrolysis, and for an anaerobic digestion supported by a bioelectrochemical system (AD+BES) to produce biomethane. Waste wood will be gasified to produce syngas. These three fuels (H_2, syngas, and biomethane) will be, via a gas mixing station, serves as fuel towards the CHP unit. The CHP itself will feed electricity to the grid, as well as providing heat for steam generation and replacing LNG.

Low temperature waste heat will be integrated into the concept for heating the buildings, reducing the water content of feedstock to the gasifier or AD+BES.

This concept is now in the process of being prototyped and tested during the H2020 EU funded project ROBINSON, not as full-scale installation, but replacing about 20% of the currently used LNG. It is planned to be scaled up after successful demonstration of the reliable operation of the integrated system to contribute to replacing all LNG use.

The demonstrator will be installed at the premises of one of the project partners (Prima Protein AS) and connected to the local energy system and aims at contributing to covering the local energy demand. The energy demand in this plant is dependent on the availability of feedstock for protein/fish food production and varies with the availability of fish and fish residues. An example of the heat and electricity demand profiles (relative to the maximum values that is corresponding to the maximum protein production) are shown in Figure 7, and Figure 8, respectively.

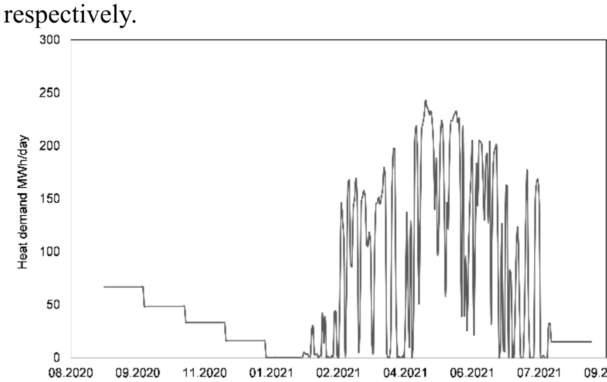

Figure 7. Variation of relative heat demand of the industrial plant (data from 2021 are actual data and those from 2020 are predicted ones)

Both figures indicate the share of electricity and heat demand relative to the maximum consumption. It needs to be noted that the profiles will vary throughout the years. The energy demand of the industry is not subject to large fluctuations under standard operating conditions due its thermal inertia. Ramping up from stand-by operation (in average about 15% boiler load) to 75% load takes for example up to 7 hours.

THE CHP UNIT

The CHP unit will be based on an Aurelia gas turbine (Aurelia® A400), an intercooled and recuperated twin shaft gas turbine, with an electrical power output of 400 kW and a thermal output of 500 kW.

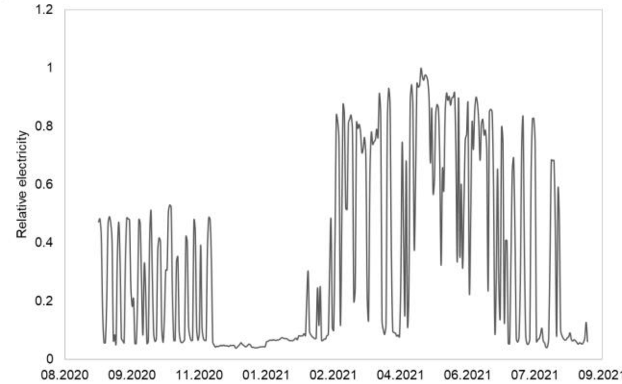

Figure 8: Variation of relative electricity demand of the industrial plant (data from 2021 are actual data and those from 2020 are predicted ones)

This micro gas turbine is currently under development to handle a wide range of fuels with various compositions. It will, together with the grid connection (sea cable), a wind turbine and PV panels feed electricity into the grid.

The heat in the exhaust gas of the gas turbine is used as heat input to the process steam generator. This will be performed via preheating the fresh air entering the boiler that produces process steam. Preheating the air will reduce the required LNG consumption by up to 375kW.

The CHP unit will serve as central element within the energy system providing a reliable energy supply to the local industry. Within the local/island energy system and due to its dispatchability, the CHP also serves as a balancing unit, compensating the fluctuation and seasonal availability of other local renewable sources.

The contribution of the CHP unit to stabilise the local grid will also be evaluated to pave the way for a full-scale installation at Eigerøy and the follower sites.

The gas turbine package is being developed to fulfil all the requirements of generators connected to the distribution network to support dynamic electrical conditions fluctuations.

The fuel supply system within the project is considered as a component of the CHP unit. The fuel supply system will provide a fuel mixture of hydrogen, biomethane, and syngas according to the specification that is determined by the CHP. The development of the fuel mixing system utilised with the gas turbine are key to flexible and reliable system operation.

This allows the electrolysed hydrogen from wind power, biogas from the AD-BES, and syngas from the gasification system to be blended and utilised when available, and will include fuel conditioning processes including compression, flow control, heating and condensate removal, as well as short term fuel storage to maintain fuel composition changes within specification for the gas turbine.

The development of the combustor used in the gas turbine will allow the use of the wide range of fuels in the project without stopping the gas turbine or changing internal components.

It is anticipated that this combustor will enable the combination of multiple smaller scale fuel sources to supply a single generator prime mover, that until now required separate generators with separated combustion systems.

This will have the effect of dramatically reducing the number of generators required and improving the financial proposition of follow-on projects.

Demand side requirements

Within the energy system and its design, the CHP unit has a central role with two main interfaces:

1. Delivery of energy for the process and grid
2. Interaction with the fuel supply system

The advantage of demonstrating the concept covering only 20% of the required energy via the new components and systems is to limit disturbances to the production process (protein/fish food). The interface with the power system is not critical as the grid connection exists as back-up to ensure secure electricity supply. On the thermal side, the steam boiler could be compensated for possible loss of thermal energy (coming from the exhaust gas of the gas turbine) via increased LNG use. Nevertheless, the aim is to demonstrate the capability of the CHP unit to reliably cover the electricity demand, while not relaying on the grid support, as well as to result in a reduced heat input via LNG use to the burner of the steam boiler.

Fuel side requirements

As indicated above, it is planned for three different sources as renewable fuel to the CHP unit. Each of those is to be considered as having a different characteristic and availability that affects the design of the fuel system and the required fuel flexibility of the CHP unit.

In this regard, boundary conditions for the electrolysis and gasification units are better known compared to that of the AD+BES system. This is because the latter technology is of lower technology readiness level (TRL), while the first two are components that are already available in the market.

<u>a) Fuel A – Hydrogen from the electrolysis unit</u>

The electrolyser for producing hydrogen is to be purchased either of the alkaline (AEL) type or of the proton exchange membrane (PEMEL) type. Typical parameters that are relevant for the integration with the CHP unit are listed in Table 2, below (Butler and Spliethoff, 2018).

The average need of hydrogen is estimated to be around 90-100 kg/day with the maximum demand of 220 kg/day. The most probable installation is expected to consist of two alkaline electrolysers with a nominal production of 8.1 kgH_2/hour. These are expected to consume 6837 MWh of electricity and producing 4252 MWh of hydrogen (LHV basis).

As indicated by the Table 2, the pressure level is exceeding the required fuel pressure of the CHP unit (that is about 7-8 bara). While the response rate during operation seems to be matching the requirements of the CHP unit, the slow start-up of the AEL requires a H_2 buffer tank to cover the start-up phase.

Table 2: State-of-the-art parameters of two water electrolysis technologies (Butler and Spliethoff, 2018)

Parameter	AEL	PEMEL
Cell temperature [ºC]	60–90	50–80
Typical pressure [bar]	10–30	20–50
Load flexibility (% of nominal load)	20–100	0–100
Cold start up time	1–2 h	5–10 min
Warm start up time	1–5 min	< 10 sec
Nominal stack efficiency [%]	63–71	60–68

<u>b) Fuel B – Syngas from the gasification unit</u>

The gasification unit, which is planned to supply the main fuel source (syngas), will most probably be of the stepped co-current fixed bed gasification technology. The gasifier, due to its design, has a high thermal inertia in comparison to the CHP unit. A hot start-up of the gasification system can take about 20-30 minutes, while a cold start-up can take up to three or even more hours.

The operational flexibility of the gasifier is limited due to its large volume. Due to the feeding process, the gasification unit is operating at close to ambient pressure, thus requiring a fuel (syngas) gas compressor to achieve a fuel pressure matching the need of the CHP unit. In addition, a gas tank is necessary that can act as a buffer to match different dynamics of the fuel generation units and the CHP energy demand profile.

Currently ongoing is the evaluation of a possible gasifier. A system like for example a product from SYNCRAFT with the nominal energy input of 1800 kW might be selected (SYNCRAFT, 2021). The technology is illustrated in Figure 9. Note that the figure shows a complete package integrating with a gas engine. This is not a case for the Robinson project in which a gas turbine is used for production of power and heat.

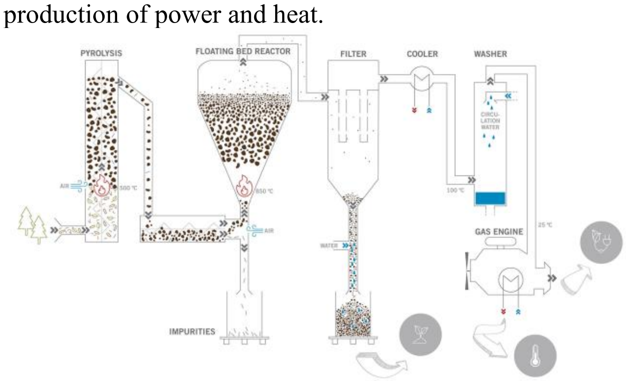

Figure 9. The wood gasification technology (SYNCRAFT, 2021)

<u>c) Fuel C – Biomethane from the AD+BES unit</u>

As mentioned earlier, the third fuel generation unit (i.e., the AD+BES) is still in a low TRL level and therefore subject to ongoing development and adaptation activities. Consequently, this will add an uncertainty to the fuel system, which needs to be considered. Anaerobic digestion itself is a process that is preferably operated in a close to steady-state operation due to the process (based on microorganisms' activities) and its volume. Within the Robinson project, this is it closely connected to the production process of the protein/fish feed industry, as it uses the organic content of the wastewater of the plant. Feedstock to the AD+BES unit is therefore only available when the plant is in operation.

The bioelectrochemical (BES) system is designed not to affect the operation of the anaerobic digestion (AD) unit. In consequence, the process can be operated with and without the BES part ensuring fuel production even in case of a malfunction of the BES process. The fuel composition would then differ, being closer to biomethane or raw biogas when the BES is in operation or not, respectively. The AD+BES system will also operate at close to atmospheric pressure so that a fuel gas compressor is required to achieve the fuel gas pressure level required by the CHP unit. Also here, a buffer biofuel tank is necessary for operational reasons.

The prototype for the demonstration project has the volume of approximately 1 m^3 and produces 900 l/day of biomethane, or 3 MWh biomethane per year. The AD+BES process is currently in the development and testing phase, using composition of the feedstock (from the wastewater of the plant) based on available samples.

A system integration scenario

Figure 10 shows the schematic of this scenario. All the units in this scenario are operated in the steady-state mode. Electricity from the grid is used to run the electrolysis. H_2 is stored in a pressurized tank. A part of that is mixed with the syngas from the gasifier and the other part goes for transport applications. To control the H_2 concentration in the fuel to the CHP (up to 30 vol.%), 34% of the produced H_2 from the electrolyser with the energy content of 1474 MWh/year is fed to the CHP unit.

The yearly amount of biomethane is up to 3 MWh, which compared to the other fuels (i.e., H_2 and syngas) is small. The biomethane will be mixed with the syngas before injection to the CHP.

The electrical efficiency of the micro gas turbine is considered to be 40.2%, i.e., the thermal input is around 1 MW_{th}. Steady-state operation of the CHP system is considered with the operation of 7880 hours/year. The system produces around 3152 MWh/year of electricity and 3940 MWh/year of heat.

A V-Twin 100 wind turbine with nominal delivering power of 100 kW will be installed on the island, close to Prima Protein plant. The electricity production from the wind turbine is calculated using the capacity factors from the Figure 5, and the results are shown in the Figure 11. For this calculation, 5% of loss between the converter and the point of connection to the grid/customer is taken into account. The power generated for one year is expected to amount to 384 MWh.

The electricity demand profile of the protein/fish food industry and the produced electricity from the CHP unit and the wind turbine are shown in Figure 12. In this figure, the red line shows the electricity production from the wind turbine and the yellow line the sum of CHP and wind electricity. According to this figure, there is excess of electricity specifically from December to February. This excess of electricity can be used to run the electrolysis/ sell to the grid.

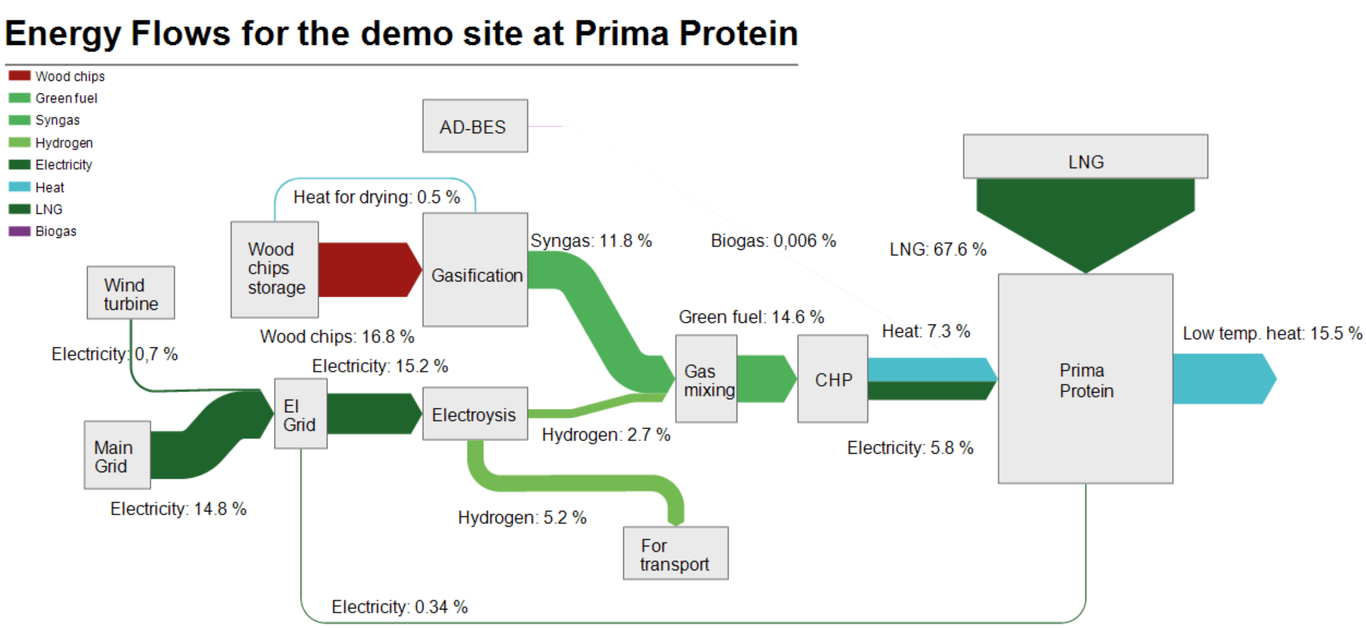

Figure 10: Sankey diagram for the demo site in Eigerøy (percentages are related to the total energy input to the site)

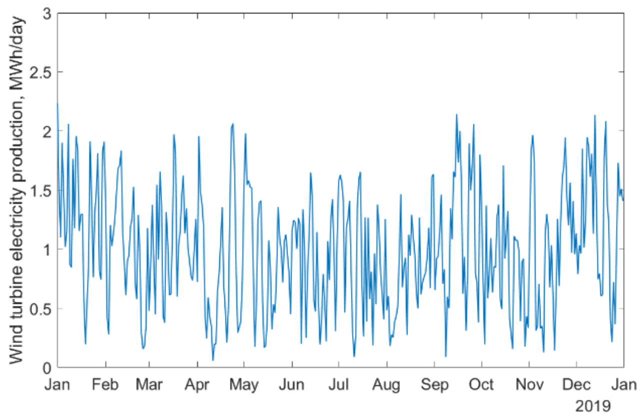

Figure 11: Wind turbines electricity production profile (2019) for the site in Eigerøy, Norway

Alternatively, the load of the gasifier and consequently the CHP unit can be reduced in these periods. There is more demand for electricity from March to August, which needs be purchased from the grid.

CONLUSION

Even though the project is still in an early stage of implementation, this paper highlighted the importance of the interactions of all components within a tightly integrated energy system. The CHP unit, in this context, has a central role to safely cover part of the energy demand of the plant.

The CHP unit must balance the available primary energy sources (wind, sun, biomass) and the different characteristics and dynamics of the components to produce fuel with the det demand. The close to continuous production of biomethane, as well as relatively high operational inertia of the gasification unit, and dynamic hydrogen production in the electrolysis unit, require the CHP unit to reliably operate with different fuels and changing fuel mixes.

In terms of electricity and heat generation, the energy demand profile of the pilot plant needs to be met. An advantage of the selected pilot is that the demand profiles of electricity and heat match, thus not requiring specific flexibility in this respect. Dimensions of storage devices need to be chosen to match the needs of operation to avoid burning excess fuel in case fuel generation continues, while the demand of the plant is reduced to zero.

In case of larger imbalance and to match energy supply and demand, grid connection could of course be used. However, such an approach might not be economically viable for the user. In this context, recent activities in the project demonstrate the importance of operational and market constraints resulting from regulations, feed-in tariffs, and energy and emission costs that can significantly influence the economic viability of such a concept.

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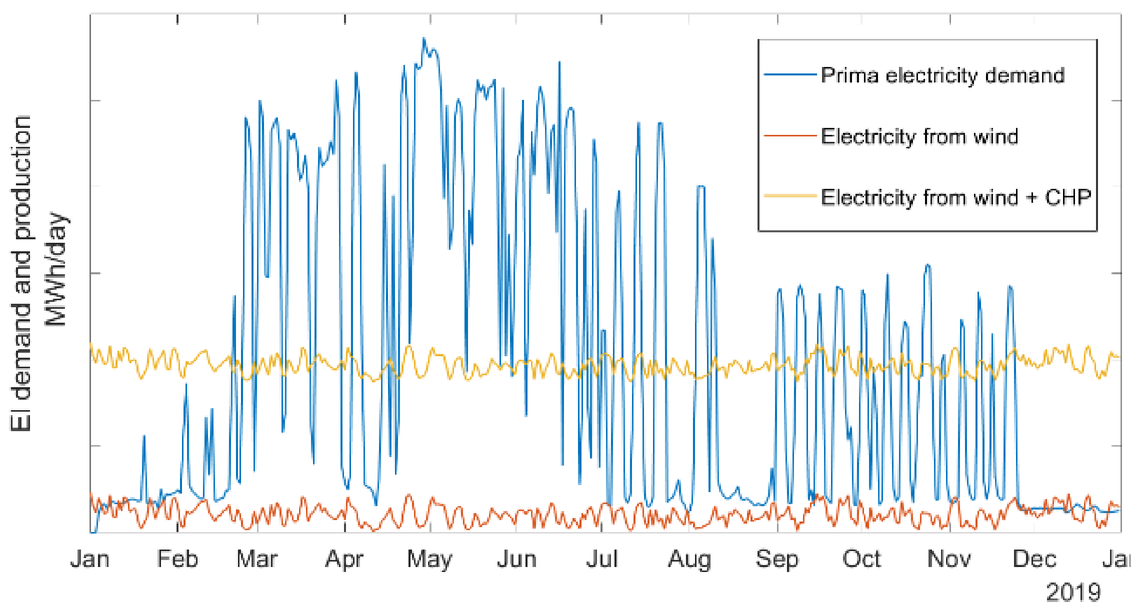

Figure 12: Electricity demand profile of Prima Protein in 2021 (blue), electricity production from the 100 kW Twin wind turbine (red), and the total electricity from 400 kWel-CHP and wind (yellow)

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