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D6.5 Bornholm Large-Scale Replication Action Plan

WP6 – Demonstration in Bornholm

INSULAE
Maximizing the impact of innovative energy approaches in the EU islands

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ABBREVIATIONS

APC	Active power control
BESS	Battery energy storage system
BMS	Battery management system
CCS	Combined charging system
CHP	Combined heat and power
DER	Distributed energy resource
DHP	District heating plant
DSO	Distribution system operator
EMS	Energy management system
EV	Electric vehicles
HCS	Hybrid charging system
HPC	High-power charger
ICE	Internal combustion engine
KPI	Key performance indicator
MeOH	Methanol
MPPT	Maximum power point tracking
PV	Photovoltaic
RES	Renewable energy sources
SNG	Synthetic natural gas
SMR	Steam methane reforming
SOC	State of charge
SOH	State of health
UCs	Use cases
VPP	Virtual power plant

EXECUTIVE SUMMARY

This deliverable D6.5 outlines the replication action plans based on the results of the demonstration activities performed in UC4 and UC5 within the Lighthouse Island Bornholm. UC4 investigated the transition to DC microgrids, while UC5 focuses on local bio-based economies supporting the electrical, thermal, and transport systems.

The island of Bornholm anticipates a substantial increase in electric vehicles (EVs), projected to grow from the current 350 EVs (2022) to 5600 EVs by 2030, and 28,000 EVs by 2050. To meet the rising charging demand in the upcoming years, a sufficient network of public charging infrastructure is required. While the demand for high-power chargers (> 100 kW) in Bornholm is comparatively lower than in other Danish municipalities, the island will still require three high-power chargers by 2030, 16 by 2040, and 21 by 2050. UC 4 focused on the demonstration of a DC microgrid comprising a 314 kWh battery system, two connectors for EV high-power charging at 175 kW each, a 61 kWp PV installation, and an inverter serving as an interface to the local 43 kW distribution grid. Deliverable D6.5 summarizes key insights from more than one year of operation with this Hybrid Charging System (HCS) and evaluates the performance based on various key performance indicators (KPIs). Subsequently, a replication study for UC4 is conducted that projects the deployment of multiple HCSs across the island to meet the targets for public high-power chargers. The replication plan of UC4 will ultimately increase the PV capacity installed in Bornholm's HCSs by 1.3 MW by 2050, generating 1.4 GWh of renewable energy annually. The integrated batteries in the HCSs play a crucial role, providing a total storage capacity of 6.6 MWh. This storage capacity enables the utilization of 58 % of the PV energy directly for EV charging, with the surplus being exported to the grid. Furthermore, the batteries facilitate the seamless integration of high-power chargers into Bornholm's distribution network, eliminating the need for upgrades to the existing grid infrastructure. In comparison with conventional gas stations for ICE vehicles, the HCS solution substantially reduces CO2 emissions by 94 % in the year 2030, and by 98 % in the year 2050. Hence, the HCS demonstrated in UC4 emerges as a key solution on the journey to sustainable transportation on Bornholm.

The aim of UC5 is to demonstrate the functioning of a renewable-based virtual power plant (VPP) to successfully coordinate different energy sectors (electricity, heat, gas, transport). The key findings of the demonstration activities in small scale at the 60/10 kV substation of Aakirkeby revolve around the controllability of RES units, the untapped potential of biogas and biogas plant processes, as well as the valuable role of hydrogen assets for Bornholm's power system. Consequently, the work presented in this deliverable aims at simulating distinct steps for Bornholm's energy system future to reach full decarbonization. These replication action plans involve the integration of renewable generation capacity, enhancing biogas capabilities and e-fuel, as well as the local integration of the Baltic Energy Island which is currently under development. The scenarios explore ongoing energy system developments, underlining the need for flexibility, sector coupling and storage options. Specifically, these scenarios detail RES upscaling, the transition to 100% EV penetration, waste heat utilization of power-to-X facilities and district heating network

integration. A common result from all the simulated scenarios is that flexible (demand-side) assets are necessary in reducing curtailment (especially in case of limited interconnection to the mainland), while also highlighting that flexibility needs to compensate efficiently for lower operating hours of individual assets. As different developments might have contradictory effects on the island's energy system, the design must carefully consider future plans to avoid stranded assets and bridging solutions. Furthermore, this report compares simulation results from the existing *Bornholm Energy System Model* and the Investment Planning Tool (IPT), developed within INSULAE, showcasing their distinct characteristics. The promising potential of the IPT is acknowledged, yet further exploration and finetuning might be necessary to fully exploit its capabilities in planning and analysis.

The lessons learned, action plans and simulation results outlined in this deliverable provide a clear roadmap for stakeholders and policymakers on the impact of individual interventions on Bornholm's energy system.

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1 INTRODUCTION

This deliverable D6.5 puts forward strategic replication actions plans derived from the recommendations of the interventions investigated on the Lighthouse Island Bornholm. The aim is to outline a pathway from specific demonstration to island-wide application with the goal of fostering the decarbonization of the island. The work of this deliverable builds upon the evaluation of the specific interventions implemented in the two Use Cases (UCs) investigated on the island.

The general focus of this deliverable is set on describing the operating results of the two UCs 4 and 5 of the INSULAE project, and subsequently developing replication plans to assess their impact through previously defined key performance indicators (KPIs). Section 1.1 and Section 1.2 provide a short description of UC4 and UC5, respectively.

1.1 UC4 – Transition to DC grids

Within UC4, a prototype of a DC microgrid has been developed and installed at Campus Bornholm, an educational institution in the main town, Rønne. The setup comprises a novel type of battery system (312 kWh), two 175 kW EV fast chargers, a 61 kWp PV installation, and a 43 kW connection to the local AC distribution grid [1]. In the following, this system will be referred to as a hybrid charging system (HCS).

Figure 1 provides an overview of the installation at Campus Bornholm. The battery energy storage system (BESS), as a power and energy buffer, facilitates full usage of the power capability of both the PV system and EV chargers, despite the grid capacity being lower rated than the system components. The energy storage consists of three reconfigurable battery strings of 104 kWh each, which have the intrinsic capability to control their voltage during operation [2]. This allows them to directly connect to the other system components without the need for interfacing power converters [3][4].

In July 2021, the HCS was deployed in the parking lot of Campus Bornholm. This location offered public accessibility of the two fast chargers, and charging was free of cost. The prototype was in operation for more than one year, and eventually decommissioned in September 2022. While the EV chargers were accessible throughout the entire period, the grid export of excess PV energy was only possible from May 2022, since this operation required permission from the grid operator.

Section 3 summarizes the operation results from the demonstration activities, and subsequently conducts a replication study to assess the impact of an increasing number of HCSs on the island.

Figure 1: DC microgrid installation in Rønne, Bornholm.

The system is deployed on Campus Bornholm (bl) located in Rønne (tl), and the fast chargers are publicly accessible for residents of the island and tourists. Since the commissioning in June 2021, the charging infrastructure was frequently used and provides even high power demand for vehicles such as the Porsche Taycan or Tesla Model 3 (tr). The consumed energy is partially provided by the local PV system (br). Adopted from [5].

1.2 UC5 – Local bio-based economies supporting the electrical, thermal and transport systems integrated management

Use Case 5 has been focusing on the increase of local bio-based generation for supporting the electrical, thermal and transport systems on the island of Bornholm. In particular, the core of the investigation was to understand the capability of the biogas plant at the substation of Aakirkeby to provide flexible combined heat and power production in the context of establishing a virtual power plant (VPP), see Figure 2. In this regard, several experimental tests have been carried out with the biogas plant to analyse relevant KPIs for the joint operation with local renewable energy sources (RES). As UC5 did not introduce one specific technological intervention, the conducted activities aimed at the experimental demonstration with these local units in Bornholm. The modelling and demonstration plans have been presented in deliverable D6.1, the key results of the interventions in D6.4, while this deliverable provides the replication action plans. Section 4 summarizes the results from the demonstration activities in UC 5, and subsequently conducts a replication study to assess the impact of future developments on the island's energy system.

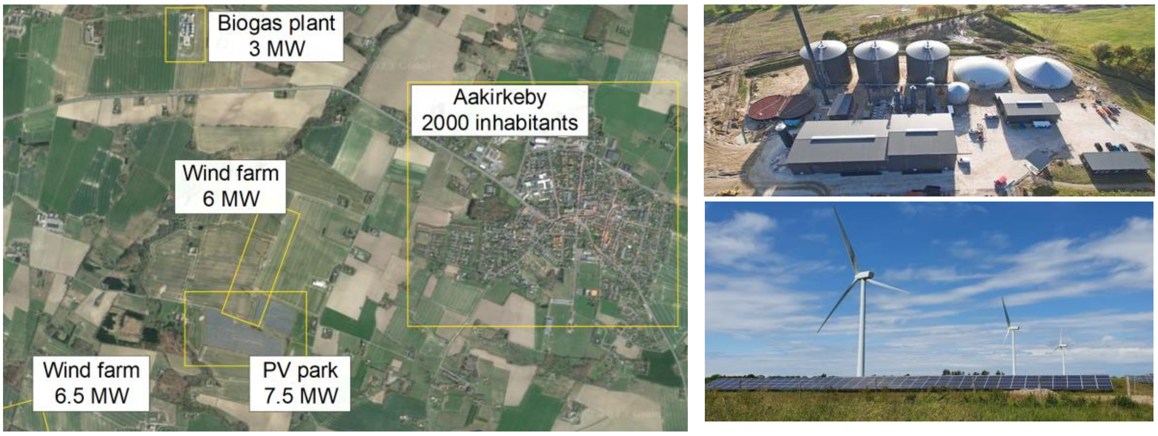


Figure 2: Location of distributed energy resources at the substation of Aakirkeby, Bornholm (left); Bornholms Bioenergi 3 MW biogas plant (top right); 6 MW wind farm and 7.5 MW PV park (bottom right).

2 Overview of key performance indicators for the Lighthouse Island Bornholm

In Section 2.1, the generic key performance indicators (KPIs) that were developed at a project level are presented, serving as a common evaluation tool for interventions in different locations. A subset of these KPIs is relevant for the demonstration on Bornholm which will be further assessed within this deliverable. To this end, Section 2.2 provides a selection based on which the work in UC4 and UC5 are further evaluated.

2.1 General key performance indicators at project level

The table contains a comprehensive list of key performance indicators (KPIs) used to measure various parameters at a project level. The KPIs are primarily focused on energy generation, demand, environmental impact, economic and societal factors, as well as demographic details. Power system specific measures comprise, for instance, renewable energy generation such as solar, wind, biogas, and hydroelectric power, while also involving factors related to electricity demand, greenhouse gas emissions per capita, interconnection and battery storage capacities, among others. Demographic and societal factors cover population statistics, the number of vehicles and in particular electric vehicles per 1000 inhabitants, and the unemployment rate. Economic and geographic measures include GDP per capita and other island-specific factors like total area.

These KPIs cover a wide spectrum of factors relevant to energy, environment, economics, and society, offering a robust framework for analysing and evaluating the performance and impact of a project or certain interventions in a project on any island. The table further provides a common framework that individual island may use to assess the impact evolution of certain interventions or infrastructure projects. For the Lighthouse Island Bornholm, the specific situation for the reference year 2019 is detailed in Table 1. If individual KPIs are not applicable for the case of Bornholm, they are denoted as "*n.a.*".

Table 1: Project-wide key performance indicators for measuring the impact of individual interventions.

Parameter	Unit	Status 2019
Island annual electricity demand	GWh	243
Peak annual demand	MW	50
GHG emissions (definition missing)	tons per capita	8.75
Solar annual electricity generation	GWh	20.1
Wind annual electricity generation	GWh	96.7
Population	habitants	39,000
Biogas annual electricity generation	GWh	7.8

Energy provided through interconnection (import)	GWh	88.8
Energy provided through interconnection (export)	GWh	15.25
Interconnection capacity	MW	60
Battery storage capacity	MW	0
Battery storage capacity	MWh	0
GDP per capita	€	38,000
Area	km^2	588
Bioenergy annual electricity generation (woodchips)	GWh	28.3
Bioenergy annual heat generation (biogas, woodchips, straw)	GWh	289
Waste incineration annual heat generation	GWh	48
No. of vehicles per 1000hab	no./1000hab	450
No. of EVs per 1000hab (subset of above group)	no./1000hab	20
Hydroelectric annual generation	MWh	n.a.
Pumped hydro storage capacity	kW	n.a.
Pumped hydro storage capacity	KWh	n.a.
Other storage technologies capacity (hot water storage at heat plants and CHP)	kW	variable
Other storage technologies capacity (hot water storage at heat plants and CHP)	GWh	1.05
SAIDI-system avg interruption duration index	-	n.a.
Combined cycle annual generation (combined gas cycle)	MWh	n.a.
Global horizontal irradiation	KWh/m^2	990
Unemployment rate	%	3.9
Geothermal annual generation	MWh	n.a.
Renewable annual generation	GWh	170
HDD-heating degree days	no.	n.a.
CDD-cooling degree days	no.	n.a.
Average wind speed at the 10% of the windiest surface	m/s	7.09
Hydric stress	scale 1 to 5	n.a.
Global battery capacity of EVs with v2g capability factored down for usability	MWh	0.2

2.2 Selected key performance indicators for UCs 4 and 5

Table 1 details the KPIs on a project level, bringing together the specifics of all Lighthouse islands. For the investigations on Bornholm, the focus is set on a smaller subset of the listed KPIs, while these in addition differ between the UCs. Since the impact of UC-specific interventions on the whole island might be hard to quantify, the selection for assessment is based on Table 1, but might not cover all aspects. For UC4, which is studying the benefits of the HCS demonstrated at Campus Bornholm in Rønne, the following KPIs were assessed as part of the replication plan:

- Energy produced by the PV installation of one HCS (kWh)
- Energy delivered to EVs charging at one HCS (kWh)
- Energy imported from the grid at one HCS (kWh)
- Energy exported to the grid at one HCS (kWh)
- Self-sufficiency of one HCS (%)
- Self-consumption of one HCS (%)
- Operational CO_2 emissions of one HCS ($\mathrm{kg}_{\mathrm{CO}_2}$)
- Number of EVs on Bornholm (#)
- Number of HCSs on Bornholm (#)
- Total energy values (PV, EV, import, export) of all HCSs on Bornholm (kWh)
- Total CO2 emissions of the HCSs on Bornholm, and comparison to ICE cars ($\mathrm{kg}_{\mathrm{CO}_2}$)

Each of the listed KPIs will be addressed in detail in the Section 3.

For UC5, which is addressing the full energy system integration on Bornholm subject to future developments, the following KPIs will be discussed as part of the replication plans:

- Electricity production from renewable energy sources (MWh)
- Heat production from renewable energy sources (MWh)
- Electricity production capacity of renewable energy sources (MW)
- Heat production capacity of renewable energy sources (MW)
- Electricity demand from flexible and inflexible assets (MWh)
- Heat demand from flexible and inflexible assets (MWh)
- Curtailment of renewable energy sources (MWh)
- Operating hours of flexible assets (h/a)
- Import/export to/from the island from/to Sweden via the sea cable connection (MWh)
- Biogas generation on Bornholm (m^3 or MWh)
- Electrolyser capacity and hydrogen production (MW and MWh)
- Methane production and storage capacity (MWh)
- Waste heat re-utilisation from Baltic Energy Island (MWh)

Each of the listed KPIs will be addressed in detail in the Section 4.

3 REPLICATION ACTION PLAN FOR USE CASE #4 – TRANSITION TO DC GRIDS

The impact assessment for UC 4 is meticulously organized into three key sections. Initially, it offers a comprehensive system description. Subsequently, it presents the operational results derived from the demonstration period. Lastly, the document outlines a detailed replication plan extending until the year 2050. This plan incorporates an impact assessment grounded in the KPIs previously defined in Section 2.

3.1 Detailed system description

Figure 3 provides a schematic overview of the HCS, comprising a 312 kWh BESS, two 175 kW EV fast chargers, a 61 kWp PV system, and a 43 kW connection to the local AC low-voltage distribution grid. The BESS, as a power and energy buffer, facilitates full usage of the power capability of both the PV system and EV chargers, despite the grid capacity being lower rated than the system components [6]. The energy storage consists of three reconfigurable battery strings of 104 kWh each, which have the characteristic of changing their cell topology during operation. Besides offering advantages in cell balancing [7], this design provides the intrinsic capability to dynamically adapt the string voltage during operation [8][9]. This enables flexible management of the system through a busbar matrix, allowing to individually connect the strings to the other system components without any interfacing DC-DC converters [10][11].

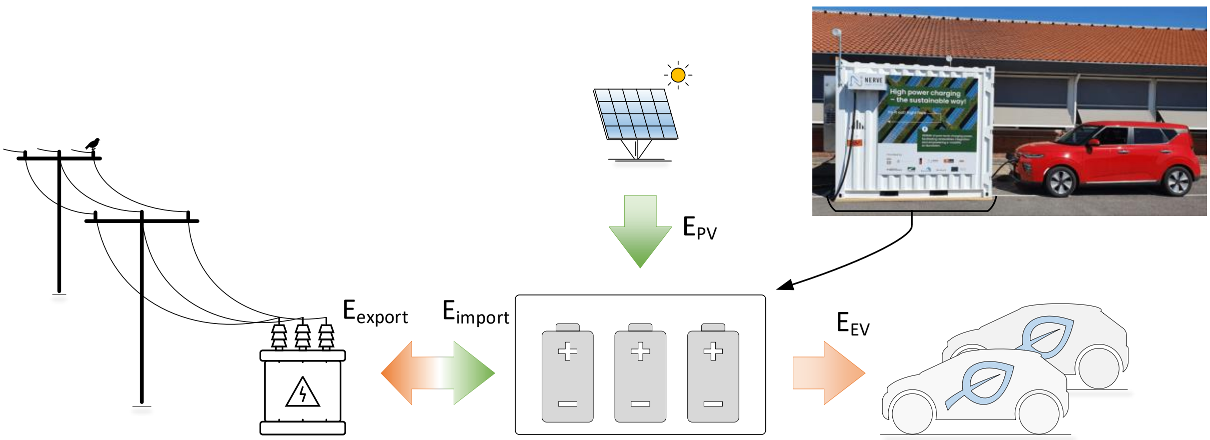


Figure 3: Overview of the hybrid EV fast charging system on the island of Bornholm. Adopted from [12].

For the demonstration phase of the prototype being in operation from July 2021 to September 2022, the HCS was monitored in high resolution with recorded measurements at all system components [13]. Specifically, the PV production was measured together with the solar irradiation at the site in second-based resolution. The power flowing from and to the battery system was measured together with the string connection to the individual units as well as the state-of-charge levels of the battery strings. This allowed for estimating the energy that was sent to the grid, imported from the grid, stored, or charged to the EVs. The EV charging data obtained at the demonstration site cover arrival and departure times as well as charging progressions of individual charging sessions [14]. Moreover, electricity meters were installed at the point of connection of the HCS monitoring the actual imported and exported energy to the grid and providing information on the system's auxiliary consumption for thermal management.

The acquired measurements were analyzed to assess the performance of the HCS with respect to several key performance indicators. The energy flows from and to the system components were examined, both in absolute numbers for the full demonstration period and average hourly progressions over a day. From these energy flows, the system's self-sufficiency and self-consumption can be calculated, describing how well the system is able to satisfy its own demand (EV charging) from own local production. These metrics are key for assessing such HCS solutions with own production unit and storage. In addition, the charging behavior at the HCS has been analyzed with respect to the distribution of charging sessions over the total demonstration period as well as during the day. The recorded data further allowed to determine the operational CO_2 emission reduction introduced by the HCS solution, compared with the similar energy requirement from gasoline cars as well as EVs charged solely from the grid with an average emission factor.

3.2 Key results from the demonstration activities

This section summarizes the key figures from the demonstration activities related to UC4. Firstly, an overview of key operational data acquired with the HCS throughout the demonstration is presented. Secondly, the self-sufficiency and self-consumption of the system is derived. The third part is dedicated to an emission estimation, comparing the HCS solution to fast chargers with direct grid connection and ICE vehicles. Finally, the performance of the system with one year of full operation is summarized based on previously defined KPIs.

3.2.1 Key operational data

The HCS was operational between July 2021 and September 2022. Table 2 gathers the overall operational results of the system operation by years. During this testing period, a total number of 2008 EVs was charged from the battery. The table summarizes the energy provided to the EVs, energy exported from the HCS to the grid, energy harvested from the local PV system, and energy imported from the grid. In the beginning of the demonstration phase, energy export to the grid as well as the capabilities of harvesting PV energy were not fully operational, leading to lower-than-expected values. Hence, more energy had to be relatively imported to substitute missing PV energy. In 2022, significantly more PV energy was utilized in the HCS. Similarly, the amount of energy charged to EVs increased in 2022 due to more charging sessions taking place, as more and more people became aware of the charging location.

Table 2: Overall energy inputs and outputs of the HCS prototype for the complete demonstration phase [12].

Year	E_{EV} (kWh)	E_{export} (kWh)	E_{PV} (kWh)	E_{import} (kWh)
2021	4,891	0	491	5,253
2022	16,899	2,418	9,260	10,861
Total	21,790	2,418	9,751	16,114

3.2.2 Self-sufficiency and self-consumption

For an HCS, self-sufficiency is an important metric detailing how much of the local consumption, i.e., in this case the EV charging, was met by the local PV system. Zepter et al. [15] derive how to calculate self-sufficiency in systems with energy storage. Applying the formula for the self-sufficiency ratio (SSR), as in (1), yields:

$$SSR = \frac{E_{\mathrm{PV}}}{E_{\mathrm{PV}} + E_{\mathrm{import}}} \cdot 100\% = 37.7\%, \qquad (1)$$

signifying that 37.7% of the local demand was met by the local PV system for the whole demonstration period. Besides self-sufficiency, the self-consumption ratio (SCR) determines the amount of PV energy that was utilized for local demand, and it calculates as

$$SCR = \frac{E_{\mathrm{EV}}}{E_{\mathrm{EV}} + E_{\mathrm{export}}} \cdot 100\% = 90.0\%. \qquad (2)$$

Thus, 90% of the local generation has been used for EV charging.

The overall roundtrip battery system efficiency has been calculated to be 93.5%, based on the difference between energy inputs and outputs of the battery strings.

3.2.3 Carbon emissions

This section establishes the reductions in carbon emissions from EVs powered by the battery system compared to vehicles with an ICE, and EVs powered by direct grid charge. The total EV demand from Table 2 is used to determine the total driving distance by EVs assuming an average consumption of 0.2 kWh/km [16]:

$$D_{EV} = \frac{E_{EV}}{r_{EV}} = \frac{21{,}790 \text{ kWh}}{0.2 \frac{\text{kWh}}{\text{km}}} = 108{,}950 \text{ km} \quad (3)$$

Considering an average consumption rate of 15 km/l, a vehicle with an ICE consumes 7,263 l of gasoline to cover 108.950 km:

$$C_{ICE,petrol} = \frac{D_{EV}}{r_{ice}} = \frac{108{,}950 \text{ km}}{15 \frac{\text{km}}{\text{l}}} = 7{,}263 \text{ l} \quad (4)$$

The emission rate from an ICE is estimated to be 2.43 kg_{co_2}/l [17], yielding total emissions of:

$$\Upsilon_{ICE} = C_{ICE,petrol} \cdot \epsilon_{petrol} = 7{,}263 \text{ l} \cdot 2.43 \frac{\text{kg}_{\text{CO}_2}}{\text{l}} = 17{,}649 \text{ kg}_{\text{CO}_2} \quad (5)$$

When taking into consideration the emission factor of the Danish electricity grid of 0.142 kg_{co_2}/kWh in 2021 [18], the total emissions if the grid was to cover the whole EV demand are:

$$\Upsilon_{grid} = E_{EV} \cdot \epsilon_{grid} = 21{,}790 \text{ kWh} \cdot 0.142 \frac{\text{kg}_{\text{CO}_2}}{\text{kWh}} = 3{,}094 \text{ kg}_{\text{CO}_2} \quad (6)$$

The HCS under investigation is also connected to a rooftop PV system. Assuming a CO_2 emission rate of 0.02 kg_{co_2}/kWh for the PV installation [19] and a SSR of 37.7% for the HCS, the combined emissions from using the local PV system and the Danish grid for the EV demand reduce even further:

$$\Upsilon_{battery} = E_{EV} \cdot [SSR \cdot \epsilon_{PV} + (1 - SSR) \cdot \epsilon_{grid}] = 2092 \text{ kg}_{\text{CO}_2} \quad (7)$$

The results above are derived using the values in Table 2 for PV production and imported energy during the operational demonstration. Comparing EV charging from grid to the ICE emissions, a reduction of approximately 14.5 tons CO_2 is achieved. An additional reduction of around 1000 kg CO_2 is achieved when PV energy is integrated into the HCS.

3.2.4 One year of full operation

Based on the measurements, a comprehensive simulation study was conducted to acquire data for 1 year of uninterrupted operation with full functionality. The simulations were based on the actual PV and EV data recorded at the demonstration site and executed with a time resolution of 1-minute intervals. The PV time series is based on measurements for a reference 61 kW PV system on the same rooftop (68.24 MWh per year), since the PV system connected to the prototype occasionally had to be curtailed when grid export was not approved yet. The EV consumption profile is based on August 2022 and repeated throughout the year, corresponding to a total EV consumption of 58 MWh/year. This month is chosen since it represents a period where all system functionalities were active. This allows for the reconstruction of the system operation with grid exports being enabled right after the deployment of the HCS. The simulation model also considers the battery roundtrip efficiency of 93.5%, as well as an average auxiliary consumption of 1.98 kW (17.4 MWh per year), which is based on the second-based power measurements for the prototype in August 2022. For more details the interested reader is referred to [5]. The simulation serves as the baseline scenario of one single HCS on Bornholm and provided the following values.

Table 3: KPIs for one year of continuous operation with the HCS solution.

KPI	
PV energy production	68.24 MWh
Energy provided for EVs	57.7 MWh
Energy imported from the grid	56.4 MWh
Energy exported to the grid	42.4 MWh
Self-sufficiency	54.7 %
Self-consumption	57.6 %

3.3 Replication plan for UC4

The replication plan for UC4 envisions the deployment of multiple HCSs on the island, comprising the same architecture tested within the Insulae project. To express the potential of the replication plan it is necessary to quantify the number of EVs and the corresponding number of required high-power chargers for Bornholm. The assumptions of our analysis are based on the Danish tool 'ChargePoint Calculator' [20].The online tool projects the expected number of EVs and required number of chargers (different types) for all Danish municipalities, including Bornholm, from now until the year 2050. Figure 4 presents the projected values for EVs and high-power chargers.

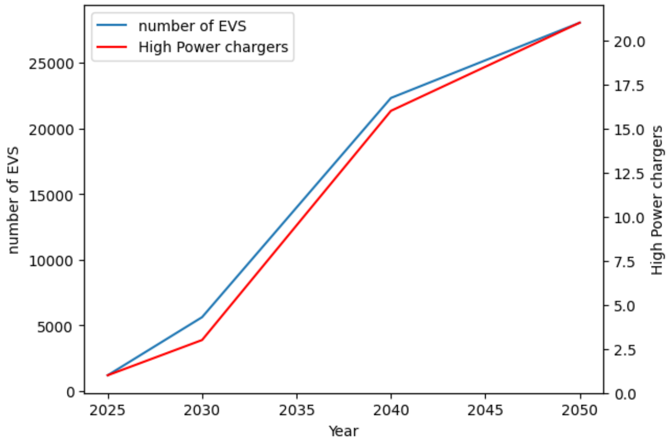


Figure 4: Projected development of the numbers of EVs and high-power chargers on Bornholm.

Assuming the fast charging infrastructure will be provided by the same architecture as the HCS tested as part of the demonstration activities, the installed battery and PV capacity will increase accordingly. Following the same control principles as applied in Section 3.2, the projections until the year 2050 are summarized in the following table.

Table 4: Projection of EVs, number of HCSs, installed capacities, and corresponding energy values.

KPI	2025	2030	2040	2050
Number of EVs	1206	5631	22319	28051
Number of required high power chargers	1	3	16	21
Installed PV power (kW)	61	183	976	1281
Installed battery (kWh)	312	936	4992	6552
Annual energy from PV (MWh)	68.24	204.72	1091.84	1433.04
Annual energy for EVs (MWh)	57.7	173.1	923.2	1211.7
Annual grid import (MWh)	56.4	169.2	902.4	1184.4
Annual grid export (MWh)	42.4	127.2	678.4	890.4

These parameters serve as the basis for assessing the large-scale impact of UC 4. To complement the numbers, assumptions regarding emission values for grid and PV system are to be made. The assumptions for the Danish electricity grid CO_2 content is based on European estimation for CO_2 grid content for the time horizon 2020 to 2050 [21], scaled by the ratio of European CO2 content of 2020 and the Danish grid CO2 emissions content of 2020 [22]. Assuming a fixed ratio, the projections for the CO2 emissions in the Danish grid are provided by the following table.

Table 5: Projection of carbon emissions in the electric grid in Denmark.

Year	2025	2030	2040	2050
Grid CO2 factor (gCO2/kWh)	133.80	79.26	40.59	21.56

Furthermore, the estimated CO_2 content of energy provided by PV systems was examined. Assuming a CO2 factor for energy from PV systems of 20 g/kWh [19], and an expected decrease to 13.2 g/kWh in 2050 [23], the following table provides a projection of the CO_2 factor, considering a linear dependency.

Table 6: Projection of carbon emissions of PV energy.

Year	2025	2030	2040	2050
PV CO2 factor (gCO2/kWh)	19.06	17.89	15.54	13.20

According to the presented tables, the CO_2 values are following a downward trend for both PV and grid, with the associated emissions from PV energy being significantly lower than the grid value.

Based on these assumptions, the emissions of three main scenarios are estimated. The first scenario describes the emissions that would be caused if the range (in km) provided by the HCSs across the island would have been covered with ICE vehicles. The second scenario considers high-power chargers with direct grid connections, i.e., without local battery and PV system. The third scenario considers the HCS tested as part of the demonstration activities, i.e., with local battery and PV system. To this end, the equations introduced in Section 3.2 are applied to estimate the emissions for all three scenarios.

Table 7: Overview of replication plan for UC4 including the impact on the island.

Parameter	2025	2030	2040	2050
Number of EVs (#)	1206	5631	22319	28051
Number of high power chargers (#)	1	3	16	21
Installed PV power (kW)	61	183	976	1281
Installed battery capacity (kWh)	312	936	4992	6552
Annual energy from PV (MWh)	68.24	204.72	1091.84	1433.04
Annual energy for EVs (MWh)	57.7	173.1	923.2	1211.7
Annual grid import (MWh)	56.4	169.2	902.4	1184.4
Annual grid export (MWh)	42.4	127.2	678.4	890.4
Grid CO2 content (gCo2/kWh)	133.80	79.27	40.59	21.56
PV CO2 content (gCo2/kWh)	19.06	17.89	15.54	13.20
Distance driven with ICE cars (km)	288,500	865,500	4,616,000	6,058,500
Gasoline used for ICE cars (l)	19,233	57,700	307,733	403,900
CO2 emissions with ICE (t)	46.74	140.21	747.79	981.48
CO2 emissions without BESS & PV (t)	7.72	13.72	37.47	26.13
CO2 emissions with BESS & PV (t)	4.10	7.91	24.82	20.58

The results show that EVs significantly reduce CO2 emissions compared to ICE vehicles. This effect is drastically enhanced with increased deployment of renewable energy sources, due to the reduced CO2 emissions of electricity production. In case of fast chargers with direct grid connection (without local BESS and PV), in 2030 the associated CO2 emissions are reduced to around 10% of ICE emissions. In 2050, this value is expected to drop to 2%. When deploying fast chargers with local battery and PV system, the emissions can be further reduced. In 2030, the HCS solution has 42.35% lower operational CO2 emissions compared to fast chargers with direct grid connection. In 2050, the reduction is only 21%, due to the improved CO2 content of the grid. In comparison with conventional gas stations for ICE vehicles, the HCS solution substantially reduces CO2 emissions by 94 % in the year 2030, and by 98 % in the year 2050. Hence, the HCS demonstrated in UC4 emerges as a key solution on the journey to sustainable transportation on Bornholm. Future demonstration activities may also explore the potential application in logistic use cases [24]. Moreover, the deployed battery systems may support Bornholm's electricity system by providing ancillary grid services [25][26]. As high market potentials for frequency control tend to coincide with low utilization levels at fast chargers, this service may present an interesting income potential for battery-buffered EV fast charging systems [27].

4 Replication action plan for use case #5 – Local bio-based economies supporting the electrical, thermal and transport systems integrated management

This section details the replication action plans based on UC5. After a detailed system description of the VPP and the future developments of the energy system for the whole island in Section 4.1, the key results from the demonstration activities in UC5 are presented in Section 4.2. A more extensive description of these results is provided in the (confidential) deliverable D6.4 that aims at reporting the operating results from the demonstrations on the Lighthouse Island Bornholm [5]. In Section 4.3, the replication action plans are described in detail and four scenarios for interventions are defined. Section 4.4 reports the simulation results of these scenarios conducted with the established *Bornholm Energy System Model,* while Section 4.5 reports the results obtained with the Investment Planning Tool (IPT) that has been developed in this INSULAE project.

4.1 Detailed system description

Being a pioneer in the green transition, Bornholm aims at 100% CO2-neutral energy production by the year 2025 and is currently pushing towards coordinated integrated energy systems for further reducing its carbon footprint. Gabderakhmanova et al. [28] provide a detailed overview of the research activities within the H2020 Insulae project, one of them is the virtual power plant (VPP) at the 60/10 kV substation of Aakirkeby. Figure 5 presents the single-line diagram of the investigated VPP including its control architecture. The VPP integrates several electrical generation and consumption feeders, connected on the 10 kV side of the substation, among others two wind parks, a large-scale PV installation and the township of Aakirkeby. A detailed description of individual units and an overview of simulation studies centred around the VPP is provided in deliverable D4.9 [29].

The idea of coordinating all units together in a substation level has been investigated in [30] and [31]. For this task, the VPP thinking has been expanded to the whole island of Bornholm based on the learnings and outcomes of the demonstration activities in UC5.

The *Bornholm Energy System Model* constitutes the whole energy system of Bornholm, including production and consumption of among other things heat and electricity and energy required for transportation. The model has been extended by BEOF as part of the INSULAE activities by adding atoms for electrolysis and e-fuel production, as well as electric vehicles and offshore wind generation. The representation of the district heating system has been enhanced as well.

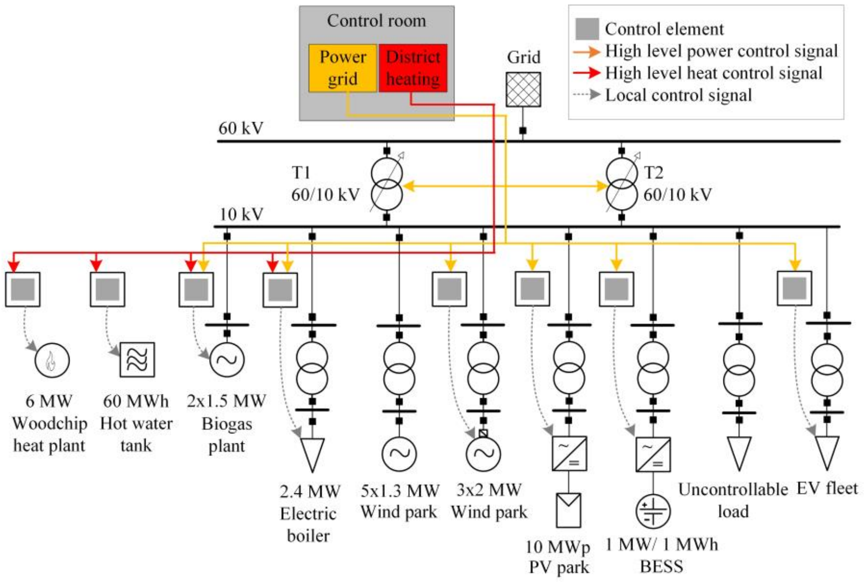


Figure 5: Single line diagram with included control architecture based on [28].

Figure 6 gives an overview of future developments of the island of Bornholm until 2050. Some of these developments are represented by the following analyses both with the Bornholm System Model and the Investment Planning Tool (IPT) of the Insulae project. The main interest of these simulations is how different developments will interact with each other and how they will impact the energy system balance on the island.

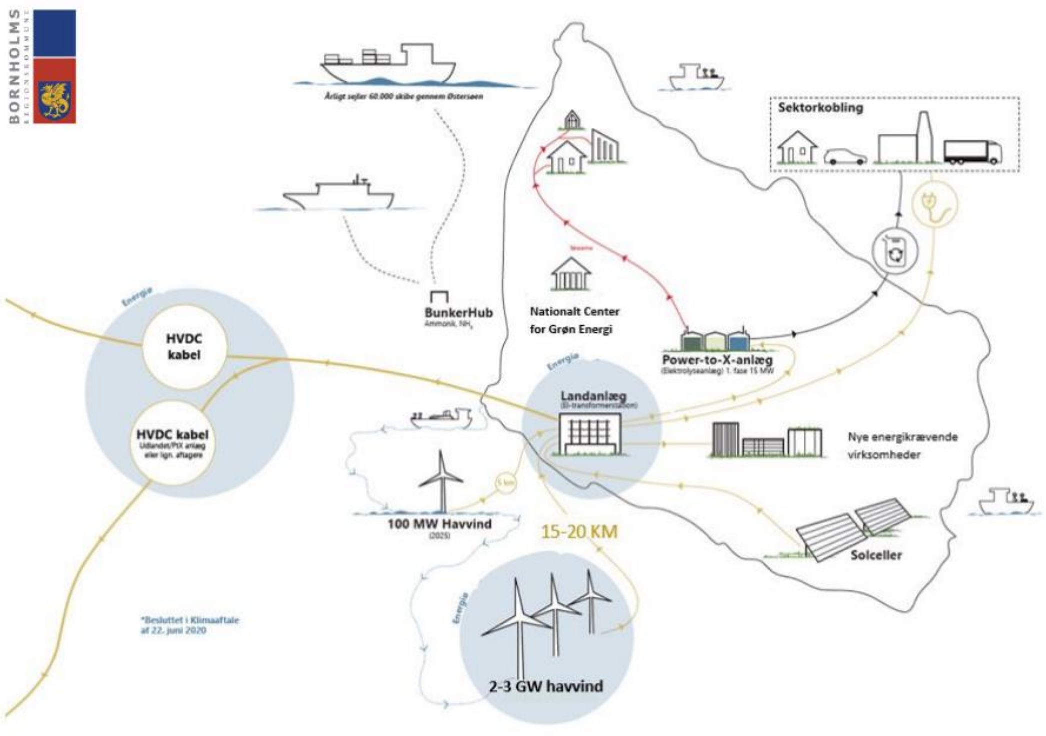


Figure 6: Overview of future energy system developments on the island of Bornholm [32].

4.2 Key results from the demonstration activities in UC5

Deliverable D6.4 discusses the key results from the demonstration activities in UCs 4 and 5 of the Lighthouse Island Bornholm. With respect to UC5, the following main results and conclusions are drawn:

Operational flexibility of distributed generation units:

- Based on experimental tests, we analysed in [33] the operational flexibility of three key technologies: a 6 MW wind farm, 10 MWp and 116 kWp photovoltaic (PV) installations, and a 3 MW biogas plant.
- **Performance:**
    - The wind turbines respond well to power limitations but show occasional overshoots above set limits. The response accuracy averages at 5.46 % including spikes and 0.01 % when excluding spikes. The turbines take 10-11 seconds to activate and have ramp rates of 44.4 kW/s for downregulation and 60 kW/s for upregulation.
    - The PV systems react nearly instantaneously to power limitations, reducing from 85 kW to 60 within 8 seconds after receiving a setpoint change order.
    - The biogas plant operates with good precision in maintaining power profiles, although it shows slower ramp rates (7-8 kW/s) than the specified grid code requirements (10-300 kW/s). However, adjustments in the generator control settings might enable compliance with the grid code.
- **Conclusions:** The tested renewable distributed generation units on Bornholm display satisfactory performance concerning their operational flexibility, but there are specific areas such as overshoots in wind turbines and slower ramp rates in the biogas plant that might need further optimization to align with grid code requirements. Overall, these renewable energy units showcase potential for integrating into a low-carbon energy system, but some technical refinements might be necessary for precise compliance with grid standards.

Biogas and methanol production:

- With insights from the biogas plant operator, we gathered in [34] and [35] info from the biogas production process of the biogas plant in Aakirkeby, while investigating the possibility of biogas upgrading to either synthetic natural gas or methanol.
- **Insights:**
    - The island of Bornholm has a significant feedstock potential, but the biogas plant is currently only permitted to treat 120,000 tons per year out of an estimated 741,425 tons [35]. The biogas plant receives organic wastes from local farmers around 60 times a week with on average 36 tons of slurry.

- The substrate composition of the biogas plant is approx. 70 % of cow slurry, 20 % pig slurry, 6 % of slaughterhouse waste, and the remaining 4 % corn and fish waste. The average percentage of total solids in the feedings is 12-14 %.
- The daily biogas production is around 25,000 m³ (750,000 m³ per month). Converting this biogas to synthetic natural gas (SNG) would require 121 tons of hydrogen (9 MW electrolyser) and 67 MWh of electricity for the complete monthly biogas generation. This results in an energy efficiency of 45.6 %. When upgrading the carbon content of the biogas generation to methanol instead, it is assumed that 63.4 % of the CO_2 could be captured from the combustion and enriched with 120 tons of hydrogen (as above). Then, 625 tons of methanol can be produced (holding an energy content of approx. 53 % of the input energy), which could cover a share of 29 % of the energy demand of the local ferries leaving from Bornholm.

- **Conclusions:** The biogas plant on Bornholm has significant untapped potential for waste conversion into biogas. However, its current operational capacity is limited. Furthermore, the possibility of upgrading biogas to synthetic natural gas (SNG) or methanol (MeOH) for various applications has been explored, particularly in the transportation sector. The studies emphasise the energy requirements and efficiency challenges associated with these conversion processes, signalling the need for integration with renewable energy sources and the importance of technological advancements for optimal utilisation of waste resources [31].

Multi-energy coordination at substation level:

- In [30], we investigated the potential for hydrogen production at the substation of Aakirkeby for the use in seaborne passenger transportation which is one of the biggest emission sources of the island Bornholm [31]. A model-based analysis considers the investment in hydrogen assets on Bornholm, focusing on sizing of hydrogen assets (electrolyser + hydrogen storage) and their integration into the local VPP.
- **Insights:**
  - Based on an investment optimisation model, a specific size of 9.6 MW of for an electrolyser system has been determined as cost optimal. The electrolyser acts as flexible asset and captures efficiently the overproduction at the substation to produce hydrogen. On top, the waste heat of the electrolyser supplements the district heating system by supplying 21 % of the thermal demand.
  - The results show that an annual average yearly production of 820 tons of hydrogen is feasible with the fluctuating production of wind and solar PV at the substation of Aakirkeby. The hydrogen production shows certain variability with high production during spring months due to complementary wind and solar power, while it decreases in winter when wind power is low.
  - The analysis further compares the CO2 emissions for diesel and hydrogen as fuel sources for the seaborne ferry transportation from and to the island of Bornholm.

Our results show the potential reductions in emissions with hydrogen, in particular *green* hydrogen, emphasising the need to transition to a sustainable green hydrogen production.

- **Conclusions:** Hydrogen is a potential cleaner fuel source for seaborne passenger transportation, considering the significant emission reduction it can offer when produced sustainably. The corresponding hydrogen assets can provide benefits to the island power system by acting as a flexible load for the island power system, while serving excess process heat to the district heating system.

To sum up, the following three lessons are learnt from the demonstration activities in UC5:

1. RES units show satisfactory performance in responding to power limitations, despite room for improvement with respect to the grid standards, and thus allow for a flexible operation.
2. The biogas plant has untapped potential for waste conversion, but current treatment capacity is limited. Exploring SNG and MeOH production highlight the need for higher renewable penetration levels and technological advancements.
3. Hydrogen assets could be valuable flexibility assets in island power system, demonstrating potential for renewable-based hydrogen production for use in different applications (e.g. ferry transportation), while serving the electrical and district heating system.

Based on these lessons learnt, this deliverable will in the following explore replication action plans that aim at expanding the analyses towards an island level. The assessment is done based on previously defined Bornholm-specific KPIs.

4.3 Replication action plans for the Lighthouse Island Bornholm

In the following, the replication action plan with respect to UC5 addresses the simulation studies conducted in various stages, primarily focusing on the expansion of the VPP to encompass Bornholm's entire energy system. It outlines the strategic integration of renewable energy sources, technological upgrades in biogas production, and the impact of currently under development offshore wind parks. Furthermore, the simulations introduce considerations for the ambitious transformation of Bornholm into an energy island, establishing key connections to Denmark's mainland and neighbouring countries.

In the upcoming simulation scenarios, the *VPP strategy*, i.e., high coordination of different energy assets, will encompass Bornholm's entire energy system to satisfy island electricity demand and manage energy import/export from/to Sweden via a submarine cable. The upgraded biogas plant continues to play a decisive role either through combined heat and power generation, or through the production of biofuels during renewable surplus periods, aimed at high self-sufficiency values for the island energy system [15]. The focus of the studies is on the further integration of volatile renewable sources. Simulation **#5** described deliverables D4.9 [29] and D6.1 [13] is serving as a reference for the subsequent simulations, representing the current renewable and EV penetration level on the island plus an electrolyser system of 6 MW. Figure 7 visualises the changes to be implemented through to 2050 on the island. These developments are in the following integrated into five additional scenarios, denoted as **#20** – **#24** in addition to the scenarios presented in D6.1 [13]. These scenarios are computed on an energy level with thssse *Bornholm Energy System Model* in an hourly resolution. In all cases, 2019 is the reference year for weather conditions and demand.

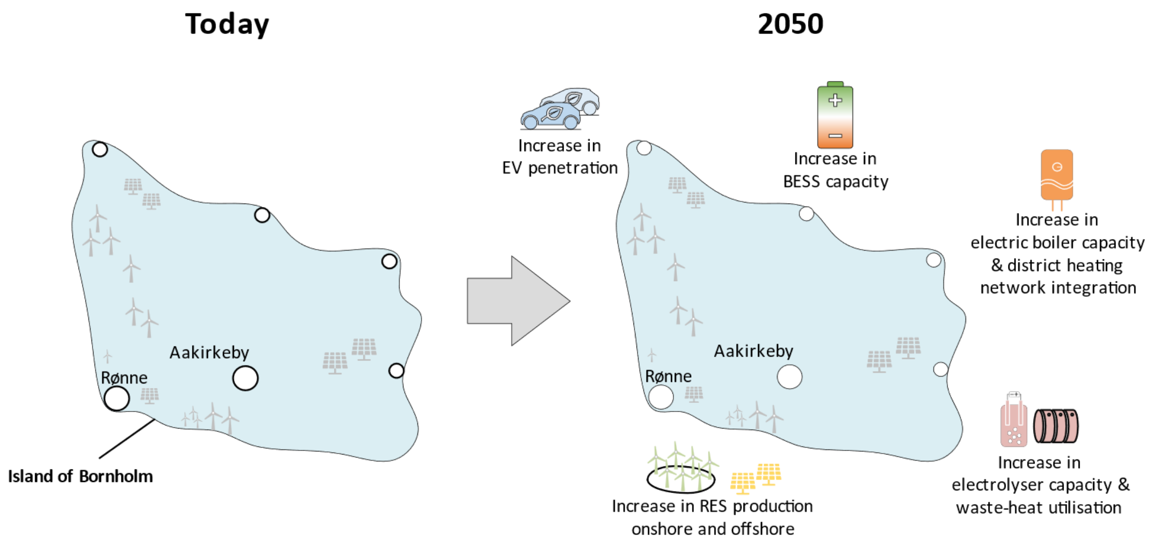


Figure 7: Overview of the energy system development on Bornholm until 2050.

The rationale of the *Bornholm Energy System Model* is as follows: Electricity generation in the VPP comes primarily from volatile RES (wind and solar PV). The CHP units of the biogas plant and the utility DH plant are only activated in times when RES generation is low, and the BESS cannot provide missing electrical energy. If RES production exceeds demand and the capacity of BESS, EV charging and the electrolysis process, then electricity is exported to Sweden. If the CHP units of the biogas plant and the district heating plant are unable to fulfill demand, then electricity is imported from Sweden. The utility CHP unit is producing heat and electricity on woodchips, primarily with the goal of satisfying the district heating demand in Rønne. The start-up time of the utility CHP unit can be approx. 6 hours in the worst case, and the model anticipate that import will take place until the utility can cover the demand. Remaining heat demand is expected to be covered by renewable sources. Electrolysis and subsequent methanization processes at the biogas plant enhance the amount of synthetic natural gas (methane) available, that can substitute fossil fuels for process-energy in industry and diesel for heavy transportation.

In the simulations presented in deliverable D4.9 [29], the impact of electrolysis and methanization (production of e-methane) was significant in the local VPP, both to absorb excess electricity production and to produce more fossil-free fuels. When expanding the VPP to the whole Island of Bornholm, the impact on the whole energy system is significantly smaller. However, the owner of the biogas plant (*Bigadan A/S*) has published in 2022 a plan for increasing the biogas production by up to four times[1], primarily aiming at using large amounts of straw in the process, which corresponds to our initial findings from 2020 [35].

Table 8 summarizes the assumptions made for reference scenario **#5** (coming from D4.9) and outlines additional scenarios explored within the scope of scaling up the examined solutions for implementation across the whole of Bornholm.

Table 8: Replication scenarios of the VPP mode for whole Bornholm with several development plans.

Scenario	#5	#20	#21	#22	#23	#24
Area	Aakirkeby	Bornholm	Bornholm	Bornholm	Bornholm	Bornholm
Weather data	2019	2019	2019	2019	2019	2019
Submarine cable CO2 emission factor 2020 + DH plant Aakirkeby incl. grid and customers	2019	2019	2019	2019	2019	2019
Onshore wind turbines [MW]	12.5	37	37	37	37	37
Nearshore wind turbines [MW]	–	–	100	100	100	100
Photovoltaics [MW]	7.5	23	73	73	73	73
Biogas CHP [MW]	3	3	3	3	3	3
Stationary BESS [MW/MWh]	1 / 1	10 / 10	10 / 10	10 / 10	10 / 10	10 / 10
Electrolyzer + Methanization [MW]	6	6	6	6	6	6
Electric vehicles [#]	–	112	9000	19,000	19,000	19,000
EV charging	Uncontrolled	Uncontrolled	Uncontrolled	Uncontrolled	Uncontrolled	Uncontrolled
Electric boiler [MW]	2.4	2.4	2.4	2.4	2.4	2.4
Electric boiler at Utility [MW]	–	–	25	25	25	25
Electrolysis at Utility [MW]	–	–	–	25	25	25
DHN Rønne – Hasle interconnector	–	–	–	–	–	✓
Energy Island Waste Heat [MW]	–	–	–	–	12	12

[1] https://energiwatch.dk/Energinyt/Renewables/article14778378.ece

Overview of the simulation scenarios

Scenario **#20** reflects the current energy system on Bornholm with 37 MW onshore wind capacity and 23 MW PV capacity, and a small penetration of EVs. The only change is that the stationary battery capacity is set to 10 MWh / 10 MW. All units and energy flows are coordinated for the whole island to satisfy the multi-energy demand in an optimal way.

Scenario **#21 (*RES upscaling*)** considers the construction of a 100 MW nearshore wind park (as currently planned through a local initiative) as well as an additional 50 MW of PV capacity on the island (goal of the municipal *Energy Strategy for Bornholm*). This is expected to contribute a substantial increase in renewable energy surplus and subsequently increased biofuel production. It is further anticipated that by 2025 – 2030, additional EVs are most likely to be adopted increasing the share of EVs to around 50 % of the car fleet. Due to high and relatively stable wind production from the offshore wind farm, an electric boiler at the utility is introduced replacing the decommissioned incineration plant at BOFA (as planned by 2032).

Scenario **#22 (*100% EV penetration*)** increases the consumption of EVs to a 100% electrified road transportation level, assuming every car (ICE) is converted to an electric version. This will increase electricity demand and it is further assumed in the simulations that the demand for EVs is inflexible. To accommodate the high amount of RES production, a 25 MW electrolysis plant at the utility is added to the model representation of Bornholm for producing hydrogen and different subsequent fuel derivatives.

Scenario **#23 (*Waste heat utilization from Baltic Energy Island*)** adds the option of recovering waste heat from the onshore transformer/converter station which will be built in relation to the 3 GW Baltic Energy Island. The Danish parliament has decided to build this Energy Island near Bornholm, while the island serves as a transformer station. The electricity from the offshore wind farm will be transmitted to Zealand and Germany. Yet, waste heat from the onshore transformers/converters is anticipated in our simulations to be fed into the district heating systems. As the TSO *Energinet* is still in the designing process, it is a pragmatic approach to assume that 0.6 % of a 2 GW heat pump with a COP of ~6 can be utilized for use in the district heating network, adding a thermal source of 12 MW.

Scenario **#24 (*District heating network integration*)** simulates the interconnection of the local district heating networks between Rønne and Hasle with the goal of maximizing the use of the waste heat from the Energy Island facility.

4.4 Simulation results from the Bornholm Energy System Model

The following sections present the results for each of the scenarios described sequentially, starting with Scenario **#21**. The comparison to Scenario **#20** will be made at the end of this part of the deliverable in Section 4.4.5.

4.4.1 Scenario #21 – RES upscaling

In scenario **#21**, immediate changes involve the introduction of a 100 MW offshore wind park, an additional 50 MW of photovoltaic capacity, a 25 MW electrical boiler at the Rønne power plant, and approximately 9,000 EVs, constituting about half of the island's traditional internal combustion engine (ICE) cars. The deployment of this renewable capacity results in a substantial increase of (mainly volatile) renewable production from 153 GWh to 748 GWh, while the demand rises by almost 40% to 333 GWh. Hence, the annual production on the island is now more than twice the electricity demand, and the island is thereby depending on the existing electrical connection to Sweden of 60 MW for both import and export. Yet, when production surpasses demand and the connection capacity, renewable electricity production needs to be curtailed. With this massive expansion without the build-out of flexible demand resources, the result of this scenario is a large curtailment of 20.5% of the annual renewable availability. Large quantities of renewable electricity cannot be utilized as the connection to Sweden is too small to transmit the electricity in peak production hours, despite the already substantial export to Sweden of approx. 40% of the total electricity production.

The surge in demand is primarily due to the electrical boiler, operating for about 1140 full load hours, methanization at the biogas plant, and the increase in EVs. The electrical boiler helps reduce curtailment by switching between combined heat and power (CHP) when electricity is scarce and stand-alone boiler production when there is an excess of renewable electricity, additionally utilizing a heat accumulator (storage) for balancing/shifting heat production. The import of electricity to the island accounts for about 4% of demand.

The increase in electrical vehicles is in the simulation is "uncontrolled" which means that charging is performed in a fixed timeslot each afternoon. This limits the EVs' ability to balance excess renewable production. As their demand falls in the periods with already high demand, optimizing the charging of EVs could significantly reduce curtailment. Moreover, changes in the biogas plant from CHP to methanization yield a considerable methane quantity, potentially useful in agriculture or heavy transport.

This scenario indicates the necessity to enhance flexibility on the demand side and optimize CHP production to accommodate increased wind and PV capacity. It is not optimal to integrate large quantities of wind and PV on the island without extending the flexibility on the demand side. Introducing new electricity demand resources, assuming that they are flexible, can prosper on the excess of electricity in peak hours and thereby run efficiently relatively few hours. Although export possibilities exist, significant curtailment may devalue wind and PV energy commercially.

Figure 8 shows an excerpt of the model output for the month of September, based on the weather and demand data from the year 2019. The upper part of the plot (positive y-axis) shows the vast amounts of wind production (light blue), while solar PV (yellow) and grid imports take lesser shares.

On the demand side (negative y-axis), the main demand sinks are the island demand (dark blue), the export to Sweden via the interconnector (green) and curtailment (dark blue).

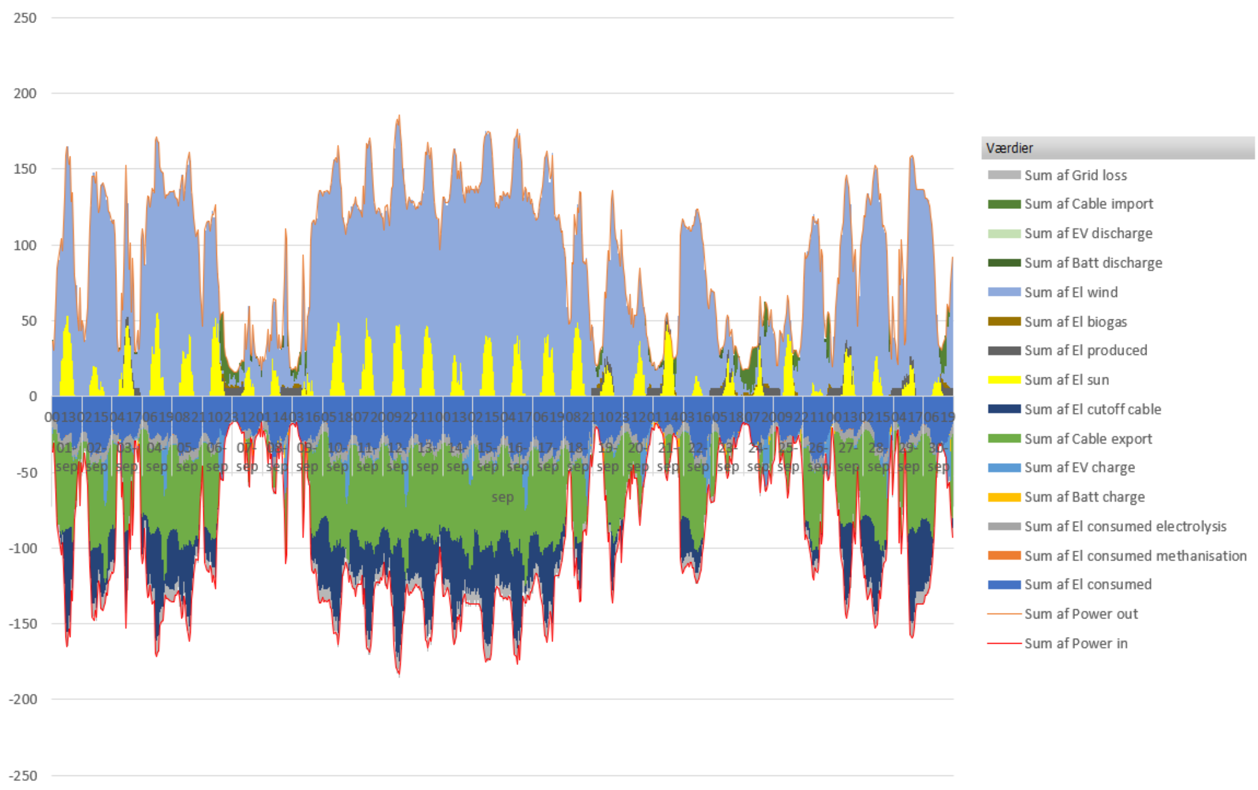


Figure 8: Scenario - #21: Electricity production and demand in the month of September.

4.4.2 Scenario #22 – 100% EV penetration

In scenario **#22**, the demand for electricity from EVs increased significantly from 9000 to 19,000 vehicles if each traditional car (ICE) is replaced with an electric version. Additionally, a 25 MW electrolysis plant was integrated at the local utility, located in Rønne.

The added flexible demand from the 25 MW electrolysis process that can be coordinated in accordance with renewable production, and the demand from the EVs substantially reduce the amount of curtailment on the island. This is even the case despite the assumed inflexibility of the electricity demand from the EVs. In this scenario, curtailment can be reduced to around 4% of the total production on the island. Implementing a smarter way of handling the large amount of EV demand will assumedly further reduce the amount of curtailment.

At the Rønne CHP plant, there has been a 20% decrease in electricity production. This reduction happened because the 25 MW electric boiler is now producing more of the necessary heat.

The newly introduced electrolyser at the power plant consumes around 160 GWh which means it operates for approx. 6400 full load hours (73% of the year). This suggests that further exploration is needed to find the most suitable size for this capacity.

Although there is still substantial amount of electricity being exported, it is less than in scenario **#21**. The import is even further to a marginal amount.

Figure 9 visualizes the supply and demand operations for a small excerpt in March (7th – 10th). Compared to the previous visualization in Scenario **#21**, the picture changes on the demand side. The amount of electricity used in the electrolysis process (grey) as well as the energy charged to the EVs (blue) is taking a large share of the local production. Export to Sweden is significantly lowered, while curtailment is also occurring in peak times with production level of over 120 - 130 MW. As a reference, inflexible residential peak demand is around 60 MW.

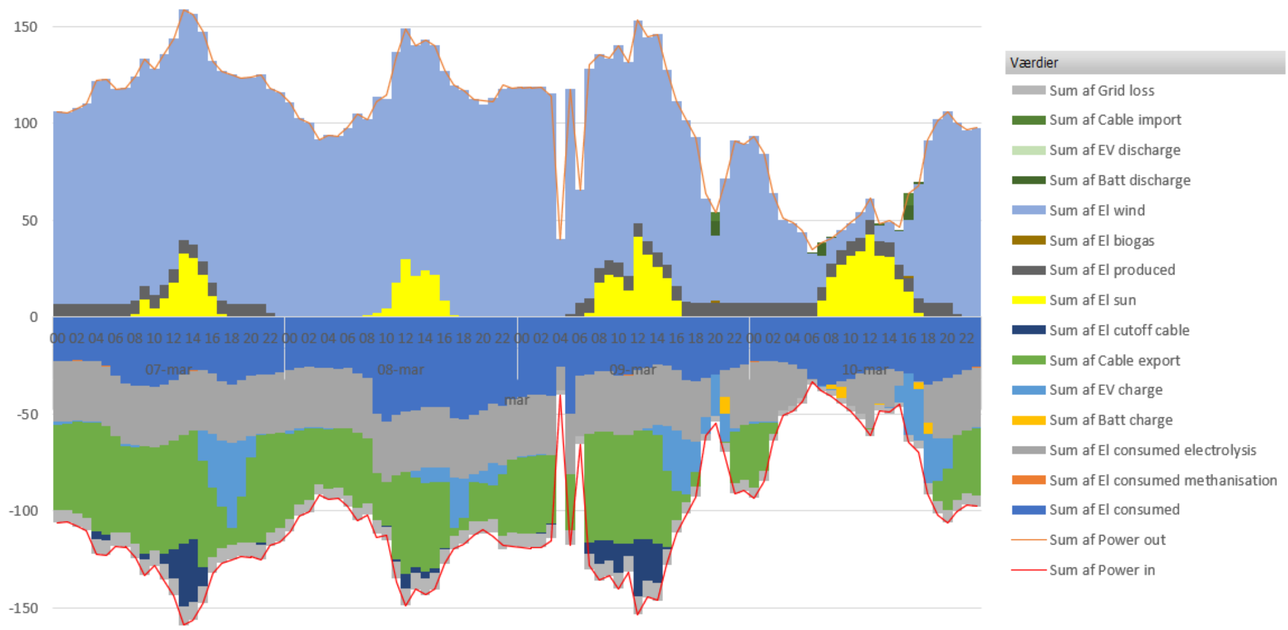


Figure 9: Scenario #22: Electricity production and demand from 7th - 10th of March.

Furthermore, in Scenario **#22**, there is an opportunity to improve the way heat and electricity are generated at the Rønne CHP plant (dark grey). It seems that the electric boiler and the CHP do not run efficiently with respect to available electricity production from wind and solar PV. The CHP produces even when there is export of electricity from Bornholm to Sweden and large amounts of wind and solar production. This increases the level of curtailment, as can be seen in Figure 9. It can be assumed that the price of electricity is lower when there is a surplus of electricity from wind and that the boiler can replace the heat production of the Rønne CHP during certain hours, in particular when there is excess electricity that would otherwise be curtailed.

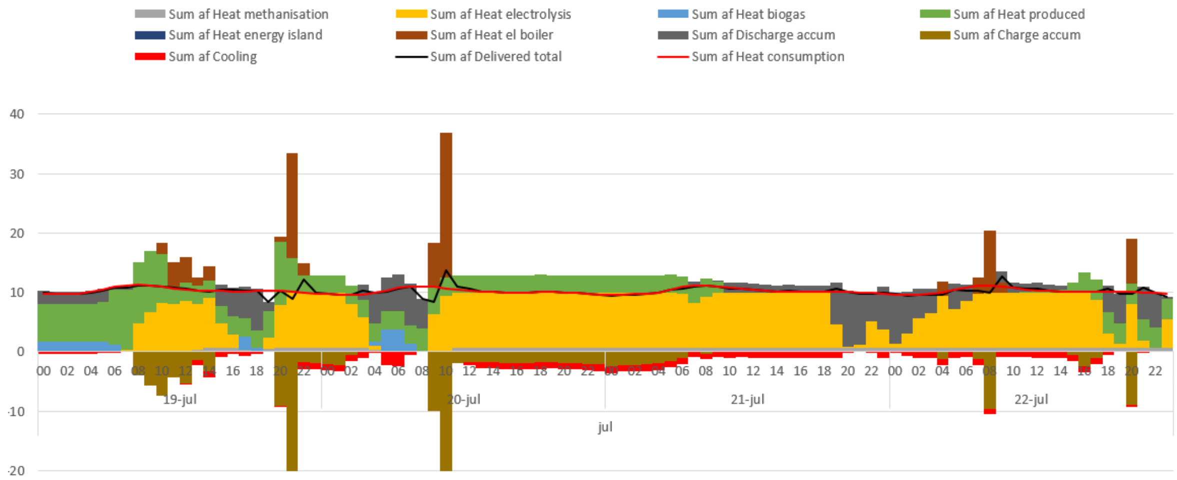


Figure 10: Scenario #22: Heat production and heat demand from 19th – 22nd of July.

Figure 10 visualizes the heat supply and demand balance. The red line signifies the heat demand in an hourly resolution for four days in July. It can be noticed that a large share of heat is supplied by the electrolysis process of the 25 MW electrolyser (orange). The remaining heat is supplied by the CHP in Rønne (green) and the biogas plant (blue). The heat accumulator (storage) either discharges in times of less heat production (grey) or charges in times of more heat production (brown).

There are more detailed features of the scenario that needs to be further investigated. One example is that heat is cooled of at the same time as the heat accumulator (storage) is charged. This happens at times when there is large electricity production from both wind and PV. It is assumed this will not take place in reality.

Here, it would also be interesting to further investigate the optimal size of batteries as this is a possibility to both store electricity produced and to deliver other services to the electricity network such as balance and frequency stabilization.

4.4.3 Scenario #23 – Waste heat utilization from Baltic Energy Island

In Scenario **#23**, 12 MW maximum waste heat from the onshore converter station which will be built in relation to the 3 GW Baltic Energy Island is included in the following simulation. The heat production from this station is estimated based on assumptions (as the planning process from the side of Energinet is not finally concluded) and the waste heat production is integrated into the *Bornholm Energy System Model*.

The heat from the converter station reduces the electricity production from the Rønne CHP (utility), while at the same time reducing the use of the electric boiler substantially as well as decreasing the electricity consumption from the 25 MW electrolyser facility at the utility. As a result, some of the flexible demand introduced in the previous scenarios is activated and the total effect of this is that curtailment is further reduced to 12.7 GWh annually.

The heat production from the Energy Island is substantial, and it reduces the production at the Rønne CHP by 50%, while the electric boiler has fewer operating hours. There is quite a large quantity of heat being cooled from the Baltic Energy Island in the summer season, and the total ability to produce heat from different units is probably larger than would be optimal. The investment into a 25 MW electric boiler could become a stranded asset when the waste heat of the converter station can be recovered to this extent. The flexibility in the heating production is delivered by the CHP plan in Rønne that takes the load in winter as well as spring and autumn.

Figure 11 visualizes the electrical supply and demand balance in Scenario **#23** for the 6th – 11th of March. It can be noted that the district heating plant in Rønne is needed to a lesser extent compared to previous scenarios, while wind and solar PV still contribute the largest share of production. On the demand side, the three main sinks of electricity are again residential demand, electrolysis, EV charging, and export to Sweden. The amount of curtailment is further reduced compared to Scenario **#22**.

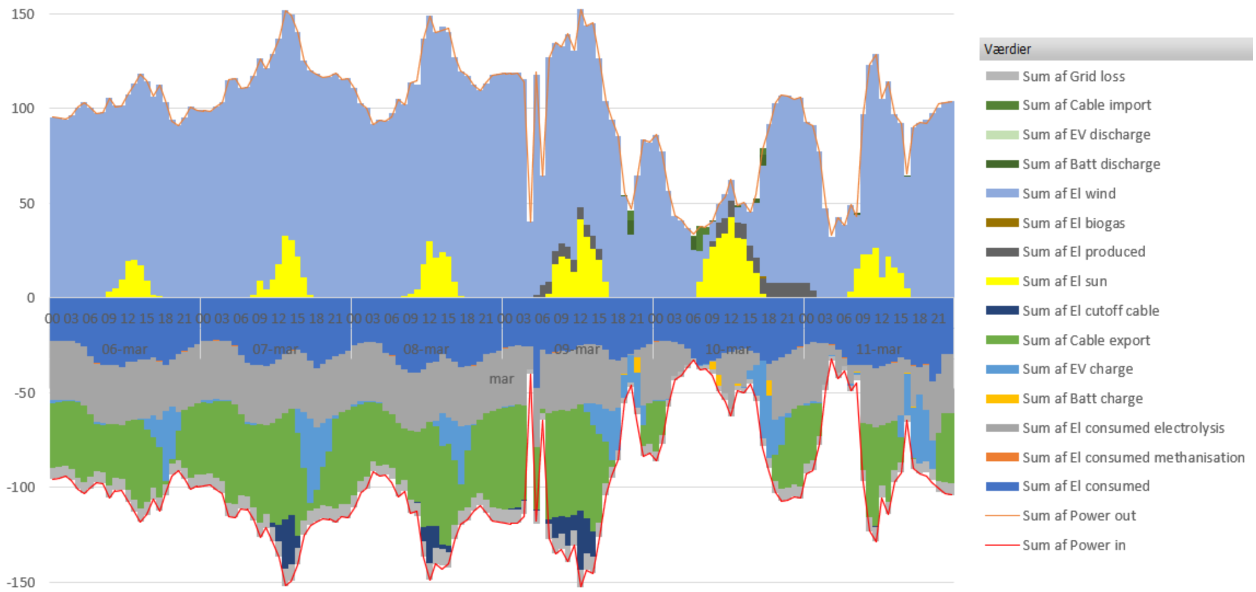


Figure 11: Scenario #23: Electricity production and demand from the 6th - 11th of March.

Figure 12 plots the heat and demand supply balance in Scenario **#23**.

The annual heat production from the CHP in Rønne is reduced from 101 GWh to 41 GWh, and the heat production from the electrical boiler decreased from 22 GWh to 3 GWh. Waste heat from the converter station makes the most significant contribution as base load to the heat supply. The biomass-fired heat CHPs secure the heat demand and run more flexibly than in the present system today. The heat accumulators (storages) are loaded by running the CHP plant when the prognosis for wind production is low and thereby the expectation for excess heat from the Baltic Energy Island is expected to be reduced. This allows an optimal use of the excess heat, the electricity production from the wind turbines and the use of the CHP producing combined heat and power, while having the possibility of storing thermal energy in the accumulator (storage).

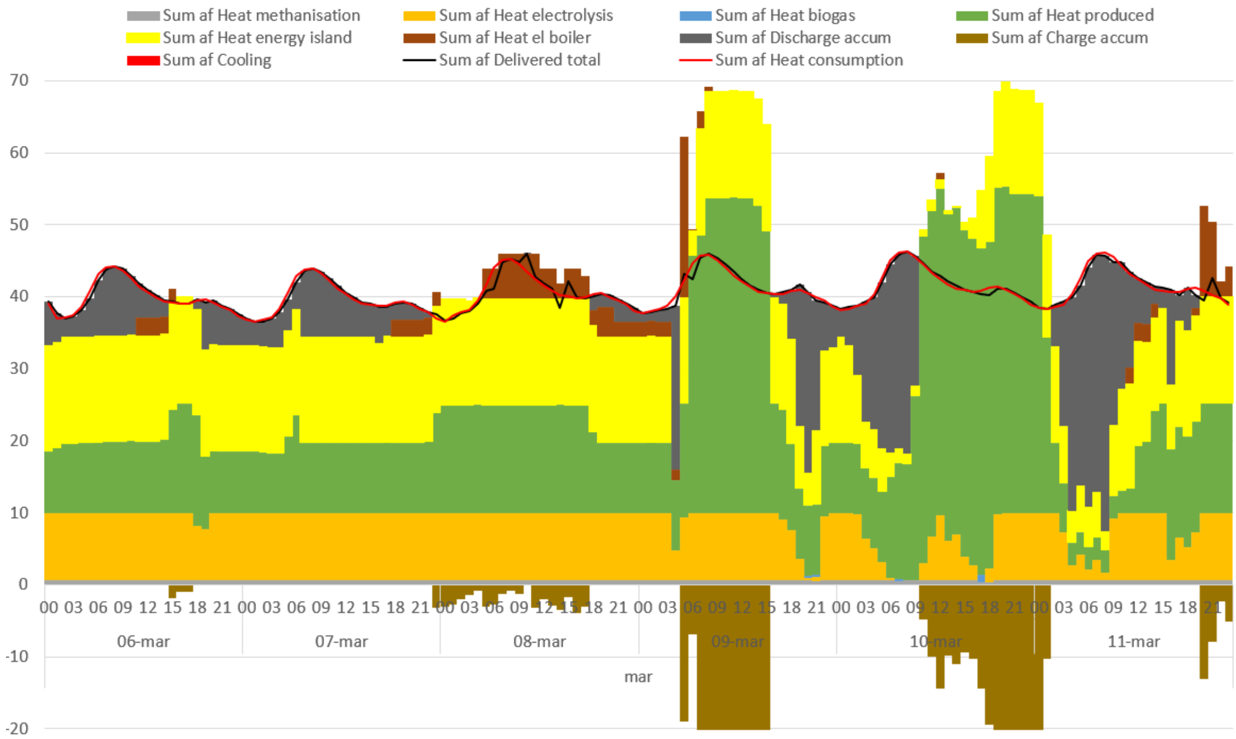


Figure 12: Scenario #23: Heat production and demand from the 6th - 11th of March.

4.4.4 Scenario #24 – District heating network interconnection

In Scenario **#24**, an interconnection from the district heating network (DHN) in Rønne and Hasle is created, enabling the absorption of additional heat from the Baltic Energy Island facilities. As can be seen from Figure 13, this translates into the CHP in Rønne having increased production as it must supplement a larger DHN, and that the Hasle DHN faces a substantially reduced residual load. All in all, the heat loss by cooling the converter station will be reduced by almost 10 GWh.

The electric boiler will operate again for longer durations as compared to the previous scenario, adding to, and stabilizing the heating system whenever renewable electricity is accessible. Given the substantial amounts of renewable electricity and surplus heat from the converter station and electrolysis, the significance of the heat accumulation tank (thermal storage) becomes considerable. When combined with the electric boiler, it will help in stabilizing and harmonizing the heating system. In general, for the demand side the main insights stay the same as for the previous scenario.

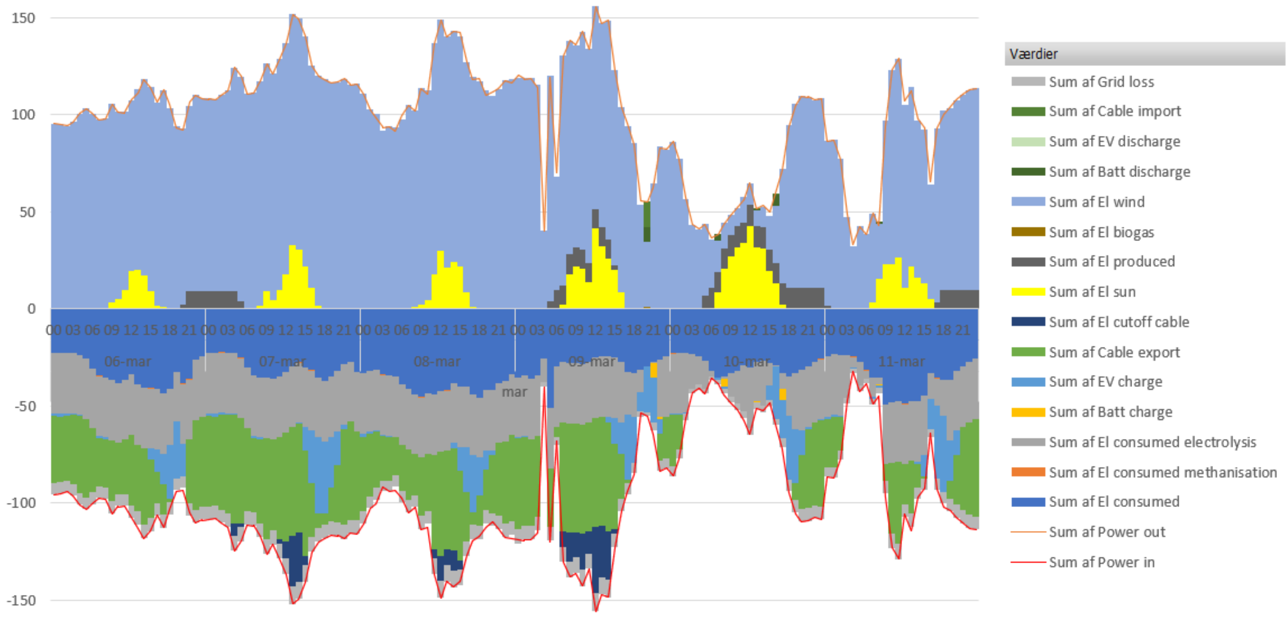


Figure 13: Scenario #24: Electricity production and demand from the 6th - 11th of March.

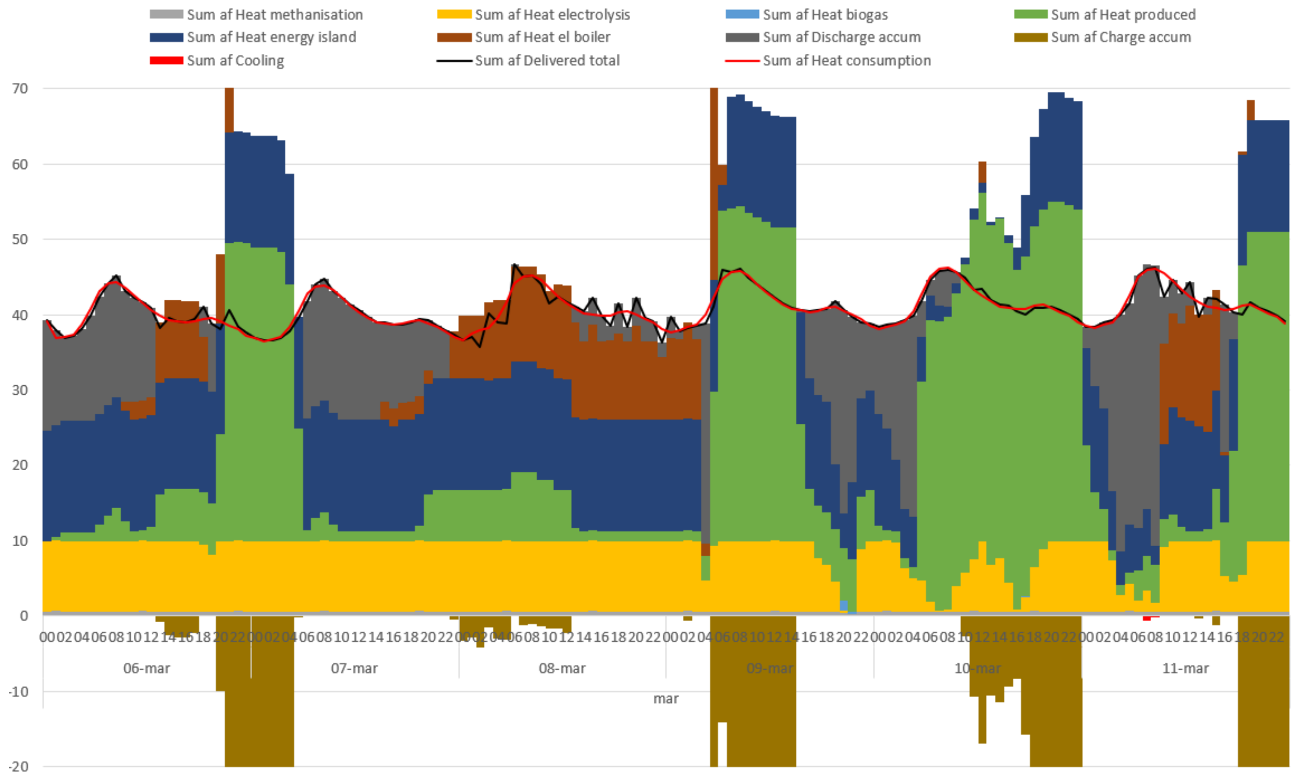


Figure 14: Scenario #24: Heat production and consumption from the 6th - 11th of March.

The heat production from the CHP in Rønne will mainly be used to load the heat storage in the cold winter season and thereby deliver both stability and flexibility to the heat system (Figure 14). The operation pattern of the CHP in Rønne will have to be investigated further. It will be interesting to investigate other means of heat production, e.g., a larger electric boiler or a heat pump based in wastewater plants.

Figure 15 shows the heat production and consumption balance for six days in July. The baseload heat in summertime is covered by excess heat from the converter station (blue) and the electrolyser (orange). This is also where there at times it is necessary to cool off heat at the converter station (red).

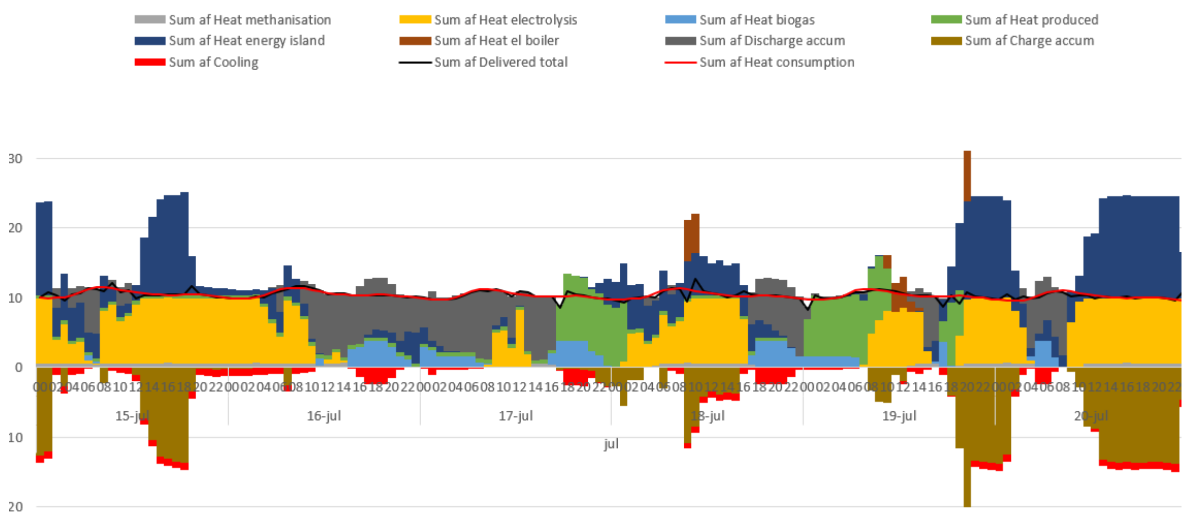


Figure 15: Scenario #24: Heat production and consumption from the 15th - 20th of July.

Further work must be done regarding the actual excess heat from the converter station in relation to the wind production profile and the trading and transmission pattern over the transmission lines to Zealand (Greater Copenhagen area) and Germany. This will affect the load in the heat system, and it is assumed there will be gains in optimizing the total heat production assets.

4.4.5 Summary and comparison between the simulated scenarios

When integrating substantial amounts of renewable sources like wind and solar PV, it is important to look at the potential for incorporating flexible demand. This flexibility can exist in various forms such as utilizing an electrolyser to produce hydrogen, leading to the development of PtX facilities and sustainable fuel production. It will also be important to look at possibilities to charge EVs flexibly, e.g., by using smart chargers and price signals to customers. As electricity demand in the transportation sector increases, flexibility becomes incredibly valuable.

The integration of the electricity and heating systems is also a strong point, especially in absorbing the considerable output variations from volatile renewable production units. Simulating the Bornholm energy system is a continuing task that includes evaluating different technologies and the optimal mix between them. There are some of the existing assets that will have rather few operation hours and therefore it will be important to optimize the total economy of the energy system and value their flexibility they can bring to the system. This will avoid stranded investment into bridging technologies.

Larger batteries seem to be a rather expensive option to store and shift large quantities of electricity. Their main purpose and value lie more likely in balancing the electricity system providing ancillary services such as frequency control. The long-term use of biogas production on the island may not involve generating electricity and heat. Instead, its value lies in PtX-applications or in the direct use in industries and transportation, offering more significant benefits.

The 5% curtailment in scenarios **#22**, **#23** and **#24** might be possible to be further reduces by increasing flexibility in demand, enhanced sector coupling and additional storage option, thus strengthening both the island economy and that of individual assets.

Table 9 provides an overview of the hydrogen and methane production and the need for hydrogen and methane storage in the different scenarios. Both hydrogen and methane production are peaking in scenarios **#21** or **#22** as there are not sufficient flexible demand side assets in these scenarios. When adding more interconnections and considering the waste heat from the *Baltic Energy Island*, less heat from the electrolysis process is needed to satisfy the district heating demand, driving down the operating hours of the electrolysers and methanisation processes.

Table 9: Hydrogen and methane production in the different scenarios.

Scenarios	#20	#21	#22	#23	#24
Hydrogen production [tons / GWh]	105 / 4.15	726 / 28.6	3396 / 133.8	3160 / 124.5	3188 / 125.6
Hydrogen storage [tons / GWh]	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Methane production [1000 m^3 / GWh]	731.1 / 8.0	3363.4 / 37	3272.9 / 36	3151.6 / 34.7	3193.8 / 35.1
Methane storage [1000 m^3 / GWh]	0 / 0	18.9 / 209	18 / 198	16.7 / 183	17.1 / 188

Table 10 provides an overview of the annual electricity production and consumption values obtained in the different scenarios, summarising the insights from the previous section on the specific scenarios. Adding the RES sources (near shore wind park and PV installations) increases the total electricity production massively on the island, and only through the introduction of flexible demand-side assets (higher EV charging, electric boiler for heat production, and electrolysis processes for hydrogen production), the curtailment can be reduced to acceptable levels.

Table 10: Annual electricity production and consumption overview in the different scenarios.

		#20	**#21**	**#22**	**#23**	**#24**
Biogas CHP	[MWh]	9.033	1.852	2.101	2.434	2.318
BEOF	[MWh]	27.140	33.234	21.765	11.372	18.498
Vindmøller [Sose - 5x1,3MW]	[MWh]	15.156	15.156	15.156	15.156	15.156
Vindmøller [Kalby - 3x2MW]	[MWh]	13.990	13.990	13.990	13.990	13.990
Landvindmøller	[MWh]	45.874	45.874	45.874	45.874	45.874
Landvindmøller 2	[MWh]	22.148	22.148	22.148	22.148	22.148
NearshoreWindfarm	[MWh]	0	573.865	573.865	470.569	470.569
SunCells VPP	[MWh]	0	0	0	0	0
SunCells Bornholm	[MWh]	28.051	28.051	28.051	28.051	28.051
New SunCells Bornholm	[MWh]	0	59.873	59.873	59.873	59.873
BESS (cent,batteri)	[MWh]	1.588	1.589	1.808	2.109	2.059
EV discharge	[MWh]	0	0	0	0	0
Powergrid loss (6%)	[MWh]	-9.684	-47.643	-46.969	-40.168	-40.589
El, total production	**[MWh]**	**153.297**	**747.990**	**737.661**	**631.409**	**637.948**
Elforbrug til varmeproduktion (nærvarme)	[MWh]	**38.779**	**38.779**	**38.779**	38.779	**38.779**
BESS (cent,batteri)	[MWh]	1.761	1.770	2.012	2.346	2.291
EV - charge	[MWh]	292	23.719	50.080	50.076	50.075
Elforbrug_private	[MWh]	54.256	54.256	54.256	54.256	54.256
Elforbrug_øvrig	[MWh]	139.835	139.835	139.835	139.835	139.835
ElectricBoiler Østerlars	[MWh]	110	2.269	1.345	1.157	1.076
ElectricBoiler Utility	[MWh]	0	28.555	22.015	3.252	9.019
Elektrolyse	[MWh]	6.327	43.543	42.700	40.720	41.069
Elektrolyse_utility	[MWh]	0	0	161.070	148.891	150.223
Metanisering	[MWh]	69	317	308	297	301
Total el demand	**[MWh]**	**241.429**	**333.042**	**512.400**	**479.610**	**486.923**
	DIFF	-102	84	111	102	101
ElectricityMarket -Import	[MWh]	93.553	13.918	20.557	24.737	22.881
ElectricityMarket -Eksport	[MWh]	5.523	314.638	213.918	163.744	161.147
Netto import	[MWh]	88.030	-300.721	-193.361	-139.007	-138.266
Cut-off (el)	[MWh]	0	114.143	31.789	12.689	12.659

Similarly, Table 11 provides an overview of the annual heat production and consumption in the different scenarios. Here, it can be notices that especially the heat production of the CHP in Rønne and Hasle reduced significantly in scenarios **#23** and **#24**, through the waste heat recovery from the transformer station of the *Baltic Energy Island*, and the interconnection between the district heating networks which are nowadays operated stand-alone. The waste heat from the electrolysis processes and the heat production from electric boiler supplement the supply of the heat demand significantly.

Table 11: Annual heat production and consumption overview in the different scenarios.

		#20	#21	#22	#23	#24
Production Unit BOFA	[MWh]	49.434	0	0	0	0
BEOF	[MWh]	101.320	122.282	80.156	41.596	66.022
Production Unit RVV	[MWh]	1.715	1.692	2.159	165	4.854
Production Unit HSL	[MWh]	45.418	45.438	45.438	45.438	1.310
Production Unit KLM	[MWh]	7.523	7.523	7.523	7.523	7.523
Biogas CHP	[MWh]	11.379	2.013	2.301	2.682	2.539
Production Unit AAK	[MWh]	18.726	12.601	13.559	14.006	14.087
Production Unit LOB	[MWh]	0	0	0	0	0
Production Unit NEX	[MWh]	66.643	66.643	66.643	66.643	66.643
Production Unit OSL	[MWh]	19.210	19.210	19.210	19.210	19.210
Production Unit - DC	[MWh]	0	0	0	0	0
Production Unit CTRLVRM	[MWh]	115.787	115.787	115.787	115.787	115.787
Production Unit VRMPMP	[MWh]	31.029	31.029	31.029	31.029	31.029
Production Unit BIOM	[MWh]	13.451	13.451	13.451	13.451	13.451
Production Unit EL	[MWh]	21.646	21.646	21.646	21.646	21.646
Production Unit SEK	[MWh]	42.947	42.947	42.947	42.947	42.947
Heat from Heat units and CHP total	[MWh]	546.228	502.262	461.849	422.122	407.047
Acc. Heatstorage		295	190	150	0	346
Elektrolyse	[MWh]	1.898	13.063	12.810	12.216	12.321
Elektrolyse_utility	[MWh]	0	0	48.321	44.667	45.067
Metanisering	[MWh]	954	4.391	4.272	4.114	4.169
ElectricBoiler Østerlars	[MWh]	110	2.269	1.345	1.157	1.076
ElectricBoiler Utility	[MWh]	0	28.555	22.015	3.252	9.019
EnergyWasteIsland_heat	[MWh]	0	0	0	84.703	84.703
Cooling total (surplus heat)	[MWh]	-455	-1.717	-1.779	-23.519	-14.983
Cooling plants	[MWh]	-350	-364	-396	-444	-617
Cooling Energy Island	[MWh]	0	0	0	-21.549	-13.157
Cooling elektrolyzer	[MWh]	-103	-1.333	-1.364	-1.509	-1.192
Cooling methanization	[MWh]	-1	-20	-19	-18	-18
Heat, total delivered		**549.030**	**549.013**	**548.982**	**548.713**	**548.764**
Heat Loss Grid		82.782	82.782	82.782	82.782	82.782
Varmeforbrug	[MWh]	466.650	466.650	466.650	466.650	466.650
Heat, total consumed	**[MWh]**	**549.432**	**549.432**	**549.432**	**549.432**	**549.432**
Diff heat		**-403**	**-419**	**-450**	**-720**	**-668**

4.5 Simulation results from the Investment Planning Tool

The scenarios previously run on the established *Bornholm Energy Simulation Model* have been replicated in the Integrated Planning Tool (IPT) developed in INSULAE. This replication allows us to compare outcomes, gaining a more comprehensive understanding of upcoming challenges. It also opens opportunities to identify deviations and potential improvements in both the existing model and the IPT. The examination primarily focused on Scenarios **#21** and **#22**, since scenarios **#23** and **#24** deal with surplus heat from the onshore converter/transformer station associated with the 3 GW *Energy Island* and new connections between district heating areas on Bornholm which have yet to be completely determined.

The differences in results from the Bornholm model and the IPT serve as a valuable reference for further investigations and analysis concerning a strategy for decarbonisation the energy system on Bornholm. Each model possesses distinct characteristics that highlight different areas of interest. In addition, the comparison of the two tools may help finetuning both models by completing them with missing features.

BEOFs limited experience with the IPT will have to be expanded to get the full value out of the IPT. The model is working and gives indications on challenges and issues to be explored. The IPT is a large model for the rather complex energy system on Bornholm (production and consumption of both electricity and district heating), and therefore it is estimated that the IPT must be a part of planning and analysis over a longer period before the full value of the IPT can be accomplished.

4.5.1 Scenario #20 – VPP Bornholm

Scenario **#20** constitutes the base case for the simulations in the IPT with data of the year 2019 and no new generation or consumption capacity added. In the following the main insights from the model are gathered here. The import of electricity in this scenario is found to be substantial when using the IPT.

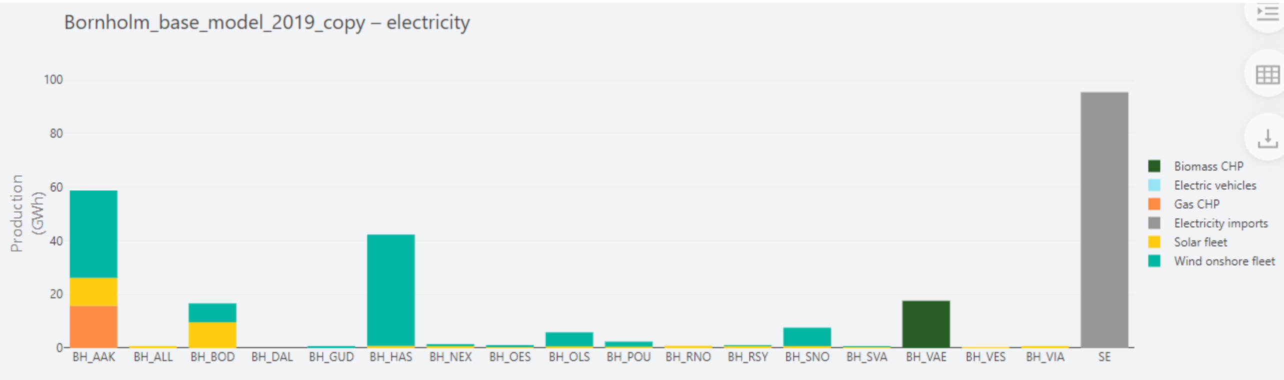


Figure 16: Scenario #20 (IPT): Electricity production per node in the network on the island.

Electricity demand is a total of 248 GWh and this is marginally higher than in the Bornholm model.

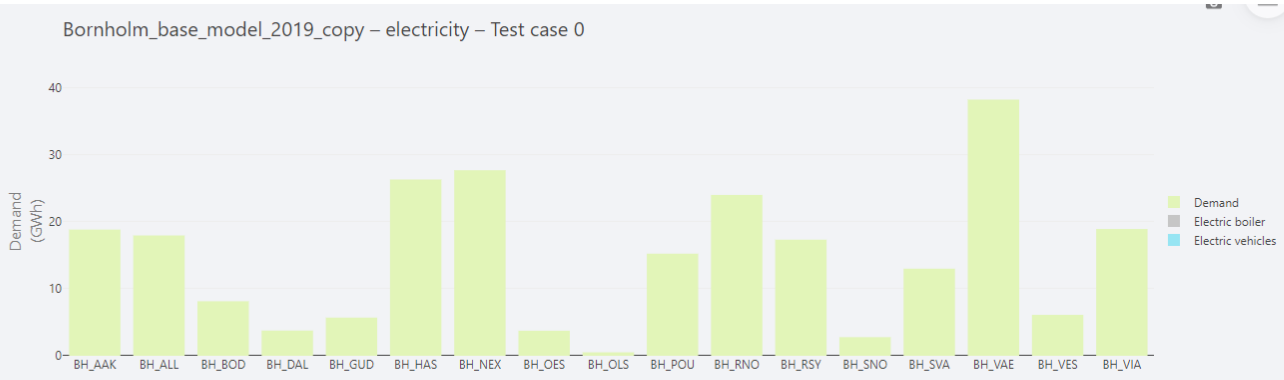


Figure 17: Scenario #20 (IPT): Electricity demand per node in the network on the island.

The heat production is based on woodchips, straw, waste, and biogas.

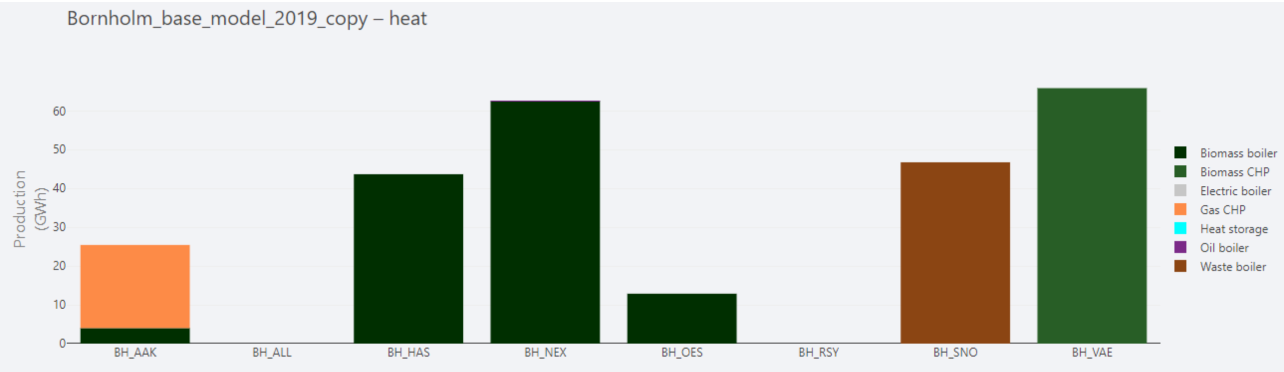


Figure 18: Scenario #20 (IPT): Heat production per district heating system on the island.

4.5.2 Scenario #21 – RES upscaling

In Scenario **#21**, immediate changes include the establishment of a 100 MW offshore wind park, an additional 50 MW in photovoltaic installations, a 25 MW electrical boiler at the CHP in Rønne, and the introduction of 9,000 electric vehicles, accounting for approximately 50% of all cars (ICE) on the island.

The total electricity production is around 650.6 GWh in the IPT simulation, which is approximately 100 GWh lower than in the Bornholm model.

While onshore wind production remains consistent between the two models, there is a significant discrepancy in forecasting the nearshore wind farm's production. The IPT predicts 133 GWh less in production compared to the Bornholm model. The IPT model demonstrates a more accurate forecast of production at 4400 full-load hours, while the Bornholm model suggested an unexpectedly high figure of 5740 full-load hours.

Figure 19: Scenario #21 (IPT): Annual electricity production by source.

Figure 19 plots the annual electricity production by source in Scenario **#21** with the IPT. The biomass CHP produces 12.6 GWh, while the biogas CHP supplies 15.8 GWh. The largest production stems from the wind offshore fleet contributing 442.3 GWh, while solar PV provides 83.3 GWh and wind onshore fleet 95.6 GWh.

The Electricity consumption is a bit higher mostly due to the electric boiler at the CHP plant but also by a different approach of including EVs.

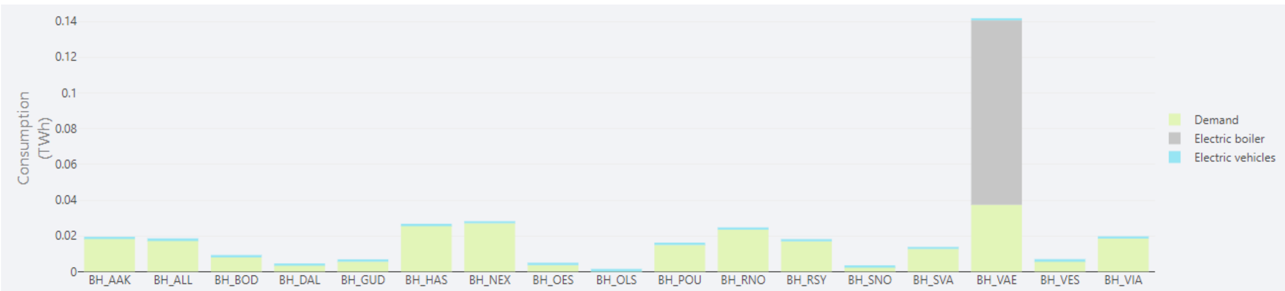


Figure 20: Scenario #21 (IPT): Electricity demand per node in the network and per source.

The initial annual electricity demand stands at 248 GWh, and this figure escalates with the incorporation of additional EVs and the electrical boiler at the CHP in Rønne. This demand rises by nearly 30 GWh - 17 GWh for EVs and 12 GWh for the electrical boiler.

The implementation of the 100 MW near-shore windfarm, along with expanded PV installations, leads to a curtailment of over 420 GWh per year. This curtailment essentially amounts to almost all the production from the near-shore windfarm being unutilized.

This issue likely stems from the fact that the total production costs from offshore wind are higher compared to both onshore wind and PV installations. Additionally, there might be limitations in the model's capacity to export electricity and efficiently manage production and demand. The overarching conclusion aligns with the outcomes derived from using the Bornholm model – a substantial increase in (renewable) electricity production, particularly from the offshore wind farm, leads to significant curtailment of renewable production. This situation either necessitates greater flexibility in managing demand or requires adjustments and optimization in determining the scale of additional investments in both solar and wind power.

The demand peak raises to 76.5 MW and the transmission capacity to Sweden is 60 MW, which indicates a need for future investments in transmission capacity to the mainland. The demand splits into the sectors residential demand, electric boiler, and electric vehicles.

The 100 MW offshore windfarm exceeds the capacity of the transmission system on the island, which has a maximum capacity of 60 MW. Consequently, there is not enough adequate consumption to fully utilize the production generated by the windfarm.

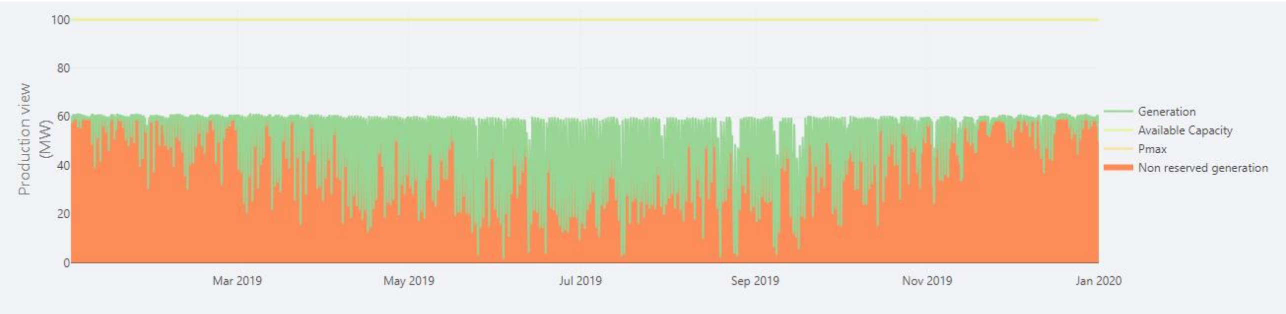


Figure 21: Scenario #21 (IPT): Electricity production from the 100 MW offshore windfarm.

The simulation shows that any surplus renewable production capacity is exported whenever feasible. However, as mentioned earlier, the existing capacity is significantly insufficient to minimize the level of curtailment to an acceptable or tolerable level.

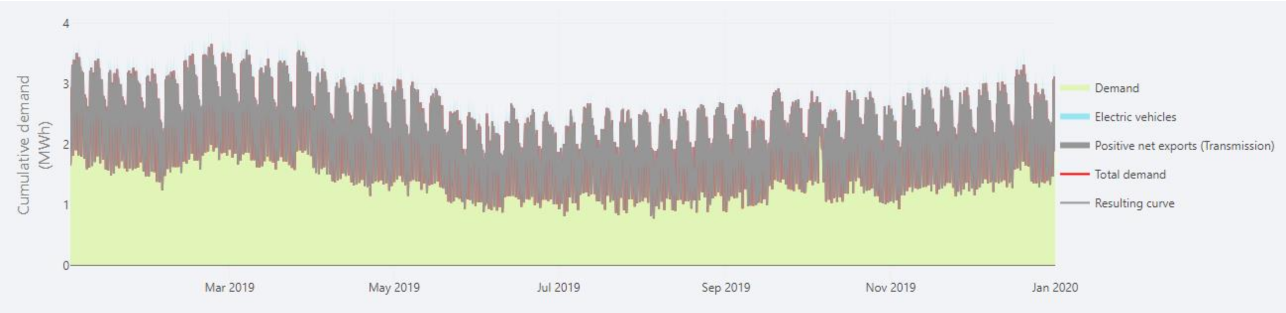
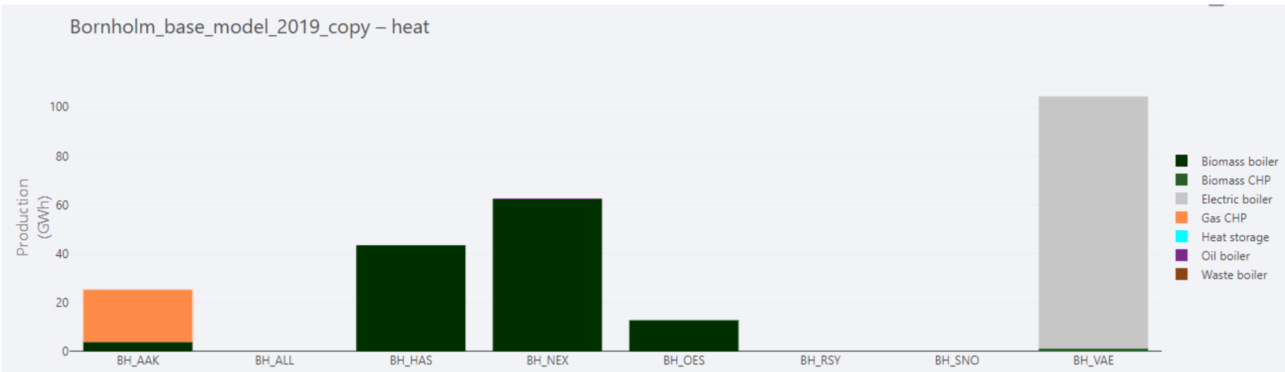


Figure 22: Scenario #21 (IPT): Electricity demand for the year 2019.

The most significant change in heat production is the decommissioning of the waste incineration plant, and that the surplus electricity derived from renewables substitutes the use of biomass at the Rønne CHP. However, a more detailed understanding might emerge if considerations regarding price optimization and the operational capabilities of the CHP are factored in. It is anticipated that the outcomes from the Bornholm model would better represent a real scenario wherein the Rønne CHP takes the place of incineration, and the utilization of the electrical boiler would likely be only partial. This outcome would be intricately tied to the costs of biomass and electricity.



Biomass boiler	Biomass CHP	Electric boiler	Gas CHP	Heat storage	Oil boiler	Waste boiler
122.59	78.47	25.92	21.43	0.00	0.02	0.00

Figure 23: Scenario #21 (IPT): Heat production by source per node.

Heat demand seems to be underestimated in the IPT and is total 260 GWh. The demand in Rønne is assessed to low in the model.

4.5.3 Scenario #22 – 100% EV penetration

In Scenario **#22** electricity demand from EVs increased from 9000 to 19,000 vehicles, assuming every car (ICE) is converted to an electric version. Furthermore, 25 MW electrolysis at the utility location in Rønne is integrated.

The electricity production is comparable to Scenario **#21** with small changes in the wind production and a rise in PV-to-grid production.

Figure 24: Scenario #22 (IPT): Annual electricity production by source.

Figure 24 plots the annual electricity production by source in Scenario **#22** with the IPT. The biomass CHP produces 22.7 GWh, while the biogas CHP supplies 15.8 GWh. The largest production stems from the wind offshore fleet contributing 452.6 GWh, while solar PV provides 82.5 GWh and wind onshore fleet 100.8 GWh.

The simulation with the IPT suggests that there is no import of electricity. Yet, as the *Bornholm Energy System Model shows*, there will likely be some import from Sweden when no local unit can satisfy the demand. But the IPT has a less strict integration of EVs, meaning that there might be more levels of flexibility compared to the Bornholm model.

The electricity demand is certainly affected by the introduction of 19,000 EVs and of the electrolyser in Aakirkeby. The consumption by EVs seems to be only half compared to the Bornholm Model. This would be interesting to analyse further.

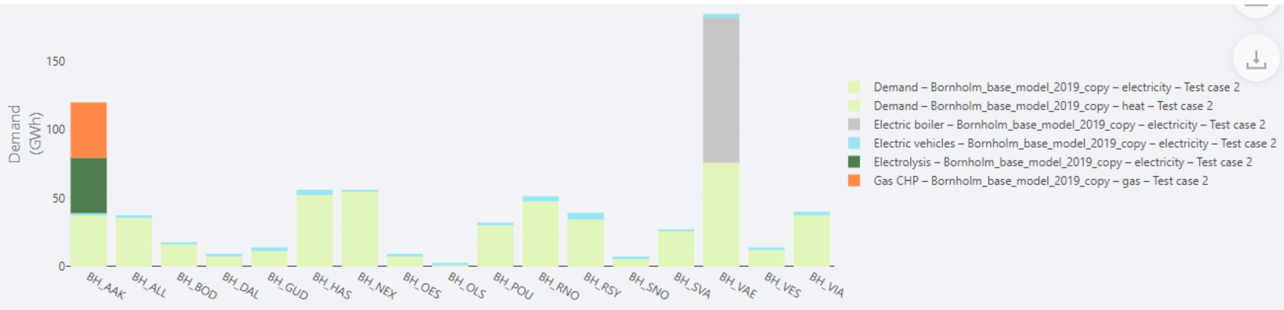


Figure 25: Scenario #22 (IPT): Electricity demand per node in the network and per source.

The curtailment of renewable energy is still at a high level in this Scenario **#22** and seems to be only marginally affected by the higher demand from the EVs. This stands in a clear contrast to the Bornholm model. The IPT finds that in **#22** the curtailment is at 420.7 GWh.

Visualising the *flexibility needs* is an interesting and helpful feature of the IPT. This measure provides an overview of the flexibility demand in the system in different spatial and temporal resolutions. Figure 26 suggests that the flexibility demand is largest daily and specifically at the substations in Nexø, Hasle, and Aakirkeby.

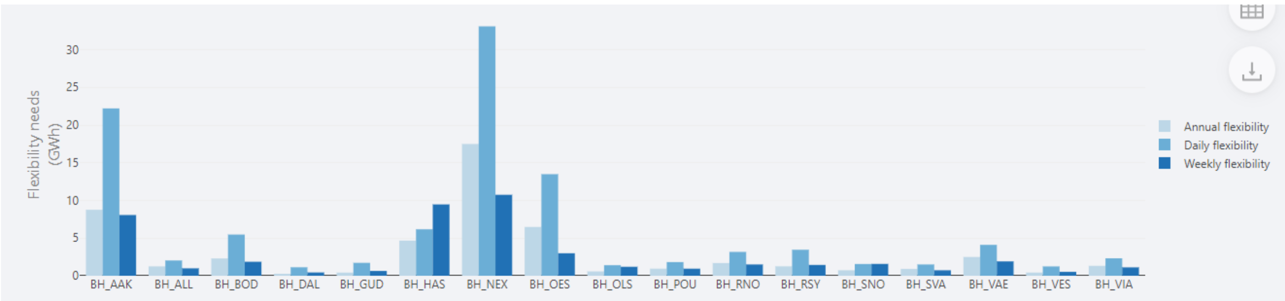
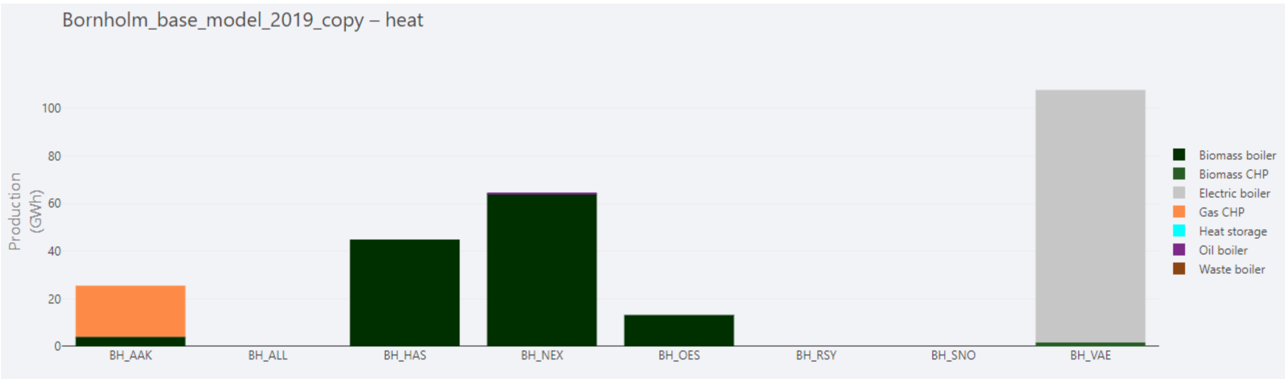


Figure 26: Scenario #22 (IPT): Flexibility needs at different nodes in the network and for different temporal resolutions.

The heat production in Scenario **#22** is similar to the one in Scenario **#21** and thereby the necessity to investigate this further is the same.



Biomass boiler	Biomass CHP	Electric boiler	Gas CHP	Heat storage	Oil boiler	Waste boiler
122.59	84.71	19.69	21.43	0.00	0.02	0.00

Figure 27: Scenario #22 (IPT): Heat production by source per node.

4.6 Insights and Considerations with the IPT

This section summarizes the key challenges and strengths associated with the IPT from the perspective of BEOF with respect to simulating the Bornholm energy system.

1. **Complexity:**
   The IPT provides a lot of functionalities and several functions, demanding experience and a nuanced understanding for an effective modelling procedure. Inexperienced handling increases the risk of malfunctions or incorrect outcomes.

2. **Strengths in Network Simulation:**

A notable strength lies in the IPT's capacity to consider bottlenecks in the electricity networks during simulations, enhancing its practicality. At the same time the complexity is rather large as basic data in the model as well as input of new assets are important for valid results.

3. **Variety of KPIs:**
   The model offers an extensive range of KPIs, strengthening its utility as a robust planning and decision-making tool.

4. **Integrated Sector Complexity:**
   The model integrates various sectors—electricity, district heating, transport, and gas—resulting in a complex framework. The primary focus on the electricity network requires an overall approach for handling other systems. This is reflected, e.g., in EVs representation where the EV load must be distributed to all nodes to reflect the load on the system. There is a variation here that is difficult to change between scenarios.

5. **Integration Challenges in Bornholm:**
   On Bornholm the electricity and district heating systems will be totally integrated. To reflect this the model would have to take the performance of the district heating system into account. That is the district heating network – production, network, and demand on a nodal and pipe level. This would make it eventually possible to run the simulation with a complete picture of both the electricity and the district heating systems.

5 Conclusions

The island of Bornholm anticipates a substantial increase in electric vehicles (EVs), projected to grow from the current 350 EVs (2022) to 5600 EVs by 2030, and 28,000 EVs by 2050. To meet the rising charging demand in the upcoming years, a sufficient network of public charging infrastructure is required.

While the demand for high-power chargers (> 100 kW) in Bornholm is comparatively lower than in other Danish municipalities, the island will still require three of these chargers by 2030, 16 by 2040, and 21 by 2050. The Hybrid Charging System (HCS) showcased in UC4 emerges as a pivotal solution to meet this demand. By utilizing local photovoltaic (PV) energy, the HCS actively contributes to the island's transportation decarbonization efforts.

The replication plan of UC4 will ultimately increase the PV capacity installed in Bornholm's HCSs by 1.3 MW by 2050, generating 1.4 GWh of clean energy annually. The integrated batteries in the HCSs play a crucial role, providing a total storage capacity of 6.6 MWh. This storage capacity enables the utilization of 58% of the PV energy directly for EV charging, with the surplus being exported to the grid. Furthermore, the batteries facilitate the seamless integration of high-power chargers into Bornholm's distribution network, eliminating the need for any upgrades to the existing grid infrastructure. In comparison with conventional gas stations for ICE vehicles, the HCS solution substantially reduces CO2 emissions by 94 % in the year 2030, and by 98 % in the year 2050. Hence, the HCS demonstrated in UC4 emerges as a key solution not just as a solution on the journey to sustainable transportation on Bornholm.

For UC5, the comprehensive exploration of the replication action plans based on multiple tools underscores the strategic initiatives aimed at transforming Bornholm in a sustainable energy island. Using the existing *Bornholm Energy System Model* and the IPT developed over the last four years in the INSULAE project, different scenarios of future energy system developments on Bornholm have been simulated and their impact on Bornholm-specific KPIs, for instance RES curtailment, e-fuel production as well as transport electrification, have been investigated. In all these simulations, the *VPP rationale,* which has been tested in a smaller setup at the substation of Aakirkeby, has been extended to the whole island allowing for full coordination between units and different sectors (electricity, heat, gas, transport).

The developed scenarios offer a roadmap for the expansion of the VPP and emphasises the importance of flexibility in demand, sector coupling, and storage options to optimise the island energy system. Furthermore, the comparison between the Bornholm Energy Simulation Model and the Integrated Planning Tool (IPT) in the context of Scenarios #21 and #22 not only reveals insights into upcoming challenges but also serves as a catalyst for continuous improvement and fine-tuning of both models, highlighting the complexity and importance of ongoing planning and analysis.

As we move forward, the exploration of PtX facilities, sustainable fuel production, and the optimization of assets with limited operation hours become crucial considerations. The strategic use of larger batteries for ancillary services and the reimagining of biogas production for PtX applications and direct use in industries and transportation further underscore the multifaceted approach required for Bornholm's decarbonization. The envisioned scenarios, particularly those with reduced curtailment through increased flexibility in demand and additional storage options, represent the clear action plan for a sustainable island economy, as well as a goal for both resilience and adaptability of its energy system. The journey towards a decarbonized energy future for Bornholm is ongoing, with the IPT emerging as a valuable tool that, with continued exploration, finetuning and further experience, may contribute significantly to the island's long-term energy planning and analysis.

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