Techno-economic optimization of a multimodal energy system for a fully renewable energy-supplied Danish island

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Abstract:

Accelerating the green energy transition is of great importance in fighting global climate change. Currently, the Danish island Aero utilizes a large amount of fossil fuel-based energy resources in the electricity, heating, and transport sectors. In line with the holistic green transition initiatives in Denmark and the holistic goal of the fossil-fuel free Danish energy sector by 2050, this study aims to find a feasible solution for the island to be fully sustainable relying solely on renewable energy sources, operating in island mode. To that end, different approaches are investigated including the electrification of the transport sector, installing energy storage systems, increasing renewable energy production capacities, energy production planning, and demand side management. Using linear programming, a hybrid scenario combining these energy approaches is developed and an hourly optimization is conducted to balance the island's energy production and demand. The proposed hybrid scenario is compared to the island's current energy system operation (base scenario) via a techno-economic approach, where dimensioning of the technologies is evaluated and the overall system cost is projected. The results showed that the hybrid scenario achieves higher renewable energy contribution (100%) and lower system cost (1625.9 DKK/month/person) compared to that of the base scenario (55.77% and 1689.6 DKK/month/person respectively). In connection to the hybrid scenario, a sensitivity analysis is carried out to investigate the impact of specific modifications to the hybrid scenario on the system's technical and economic performance. The results showed that installing an additional ferry is the most beneficial approach to improve the hybrid scenario's performance.

Keywords:

Energy planning, sector coupling, island mode, optimization, demand side management

1. Background and motivation

To mitigate climate change and global warming, Denmark has set an ambitious goal to phase out fossil fuels and achieve CO_2 neutrality by 2050 [1]. Complying with the holistic goal of this fossil-fuel free Danish energy sector, Danish island Aero aims to be CO_2 neutral and self-sufficient in renewable energy by 2025 [2]. Aero has long been stepping towards green energy transition and the CO_2 emissions have been reduced by 38% in the period from the year 2008-2019. However, the current energy systems in Aero still rely on a large amount of fossil fuel-based energy resources in the three main sectors, i.e. the electricity, heating, and transport sectors.

Aero has already equipped wind turbines and PVs for green electricity production, the transport and heating sectors are responsible for the major CO_2 emissions on Aero. This is largely due to the use of fossil fuel-based cars and buses for transportation as well as oil burners for individual heating. To make it sustainable, the transport sector will be completely electrified by substituting fossil fuel-based vehicles with electric vehicles, and the oil burner will be replaced by district heating and electric water heating. However, these measures will lead to an increase in electricity demand. In addition, Aero aims to operate in island mode in the future without importing or exporting electricity, which poses a big challenge for the energy balance between supply and production. To address this issue, the current Aero energy systems need upgrades to be fully sustainable relying solely on renewable energy sources and operating in island mode.

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Possible solutions for the energy system upgrading encompass electricity generation expansion and electricity storage. In this paper, several different green energy technologies suitable for the conditions of the island have been selected. However, there are remaining questions to be answered in order to find the most feasible solution for a green energy system operation for the island of Aero:

- What is the optimal capacity of the energy system?
- How to optimally operate the energy systems to balance energy production and supply?

The multi-energy systems characterize energy systems on Aero as an energy hub where energy production, storage and usage by end-users are involved. Many studies in the literature apply mathematical optimization to find the optimal design and operation of energy systems.

Pazouki et al. [3] investigated the optimal planning and scheduling of an energy hub consisting of CHP, boiler, wind turbine, and electric and thermal energy storage systems. They formulated a mixed-integer linear programming (MILP) strategy for optimizing the energy hub under different season scenarios and analyzed the functionality of each subsystem in the energy hub in terms of delivering electricity and heat demand. Wang et al. [4] developed the energy hub model consisting of PV, CHP, boiler, HP, battery, and thermal energy storage systems. The proposed MILP optimization achieves a significant reduction of energy cost and CO_2 emissions as compared to the system without optimization. Some other similar works on the mathematical modeling and optimization of multi-energy systems can be found in [5]–[7]. An optimization study was done before for the Danish island of Bornholm, where the energy system was simulated both on an hourly basis and then from second to second [8]. Apart from optimizing energy system operation, some studies also apply mathematical optimization to optimize the capacity of different kinds of production [9]–[11].

The objective of the paper is to achieve self-sufficiency in renewable energy and operate in island mode on Aero by 2025. In this regard, this paper proposed a hybrid scenario devising a roadmap for upgrading the current energy system. The proposed hybrid scenario combines different approaches ranging from the electrification of the transport sector, installing energy storage systems, increasing renewable energy production capacities, energy production planning, to demand-side management. Furthermore, a mathematical optimization model for hour-to-hour balancing energy supply and demand is developed to find the optimal capacities for renewable energy production units and optimal dispatching schedules for various energy systems.

The rest of the paper is structured as follows: Section 2 describes the methodology and formulation of the optimization problem. Section 3 presents and discusses the optimization results for different scenarios. Lastly, the conclusions and contributions of the work are highlighted in Section 4.

2. Methodology and problem formulation

In this section, we present the formulation of the hourly optimization problem for a one-year simulation, which is applied to the energy system on Aero to find the most feasible solution for a green energy system operation by 2025. The mathematical models of the energy system associated with their operational constraints are described first, followed by objective functions for different scenarios and collected data for simulation. The energy system models described below contain both current existing energy systems and perspective energy systems to be installed in the hybrid scenario. The selection of the perspective energy systems relies on the preliminary study carried out in [12].

2.1. Model constraints

Energy balance

The balance between electricity production and demand is constrained in Eq.(1). Likewise, the balance between heating production and demand is constrained in Eq.(2),

$$P_{T,EL}^{t} = D_{T,EL}^{t}\ ,\forall t \tag{1}$$

$$P_{T,H}^{t} = D_{T,H}^{t}\ ,\forall t \tag{2}$$

2.1.1. Electricity sector

Interconnection to the main grid

The electricity interconnection to the island today has a limited capacity of 100 MW. This constraint only applied to the current energy systems while the future energy systems operating in island mode will not involve the use of the interconnection.

$$-I_C \le I^t \le I_C\ ,\forall t \tag{3}$$

Where the value I^t is positive during import, and negative during export.

Wind turbine

$$0 \le P_W^t \le P_{Wmax}^t \cdot F_W\ ,\forall t \tag{4}$$

$$1 \le F_W \tag{5}$$

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Where F_W is the scaling factor of the current wind capacity, allowing optimize wind turbine capacity suitable for the future energy system.

Photovoltaics (PV)

$$0 \leq P_{PV}^t \leq P_{PVmax}^t \cdot F_{PV}, \forall t \tag{6}$$

$$1 \leq F_{PV} \tag{7}$$

Where F_{PV} is the scaling factor of the current PV capacity, allowing optimize PV capacity.

Organic Rankine cycle (ORC)

The ORC has a certain capacity for heat and power, which are constrained in Eq.(8) and Eq.(9) respectively. Eq.(10) defines the maximum ratio between power and heat production.

$$0 \leq P_{ORCEl}^t \leq P_{ORCElmax}, \forall t \tag{8}$$

$$0 \leq P_{ORCH}^t \leq P_{ORCHmax}, \forall t \tag{9}$$

$$P_{ORCEl}^t \leq P_{ORCH}^t \cdot ORC\eta_{El/H}, \forall t \tag{10}$$

Biogas

Biogas turbine is the potential energy generation system to be installed, which makes use of biomass on Aero to produce electricity. Additionally, this requires installing a biogas plant that converts biomass to biogas first. In Eq.(11), the model is constrained so the model only uses the manure available on the island, and thus emissions in connection with the transport of biomass from outside the island are also avoided.

$$\frac{\sum_{n=1}^{8760} P_{Bio}^t}{\eta_{Bio}} \leq C_{Bio}, \forall t \tag{11}$$

$$0 \leq P_{Bio}^t \leq C_{Bio,C}, \forall t \tag{12}$$

The space heating, electric water heating and refrigerator described below are demand response unit that integrates consumers into the electricity system.

Space heating

An air-to-water heat pump is used for space heating. Eq.(13) is the model for indoor temperature dynamics, while Eq. (14) represents the constraint of the electric power of the heat pump. Eq. (15) is the indoor temperature constraint.

$$\theta_i^{t+1} = \theta_i^t - \frac{1}{C \cdot R}\left(\theta_i^t - \theta_0^t + R \cdot D_{Sp}^t \cdot COP^t\right), \forall t \tag{13}$$

$$0 \leq D_{Sp}^t \leq D_{Sp,C}, \forall t \tag{14}$$

$$\theta_{i,min}^t \leq \theta_i^t \leq \theta_{i,max}^t, \forall t \tag{15}$$

Electric water heating

Similarly, Eq.(13) is the model of water temperature in the tank.

$$\theta_{EWH}^{t+1} = \theta^t + \frac{1}{C}(-\alpha(\theta_{EWH}^t - \theta_i^t) - \upsilon^t + COP^t \cdot D_{EWH}^t), \forall t \tag{16}$$

$$0 \leq D_{EWH}^t \leq D_{EWH,C}, \forall t \tag{17}$$

$$\theta_{EWH,min}^t \leq \theta_{EWH}^t \leq \theta_{EWH,max}^t, \forall t \tag{18}$$

Refrigerator

The electricity is used in the refrigerator of each household to main favorable temperatures for food storage. The temperature inside the refrigerator has to satisfy the constraints in Eq.(19) and Eq.(21). The maximum electrical power of the refrigerator is constrained in Eq (20).

$$\theta_{ref}^{t+1} = \epsilon \cdot \theta_{ref}^t + (1-\epsilon)\left(\theta_i^t - R \cdot D_{ref}^t \cdot \eta\right), where\ \epsilon = e^{-\frac{\Delta t}{R \cdot C}},\ \forall t \tag{19}$$

$$0 \leq D_{ref}^t \leq D_{ref,C}, \forall t \tag{20}$$

$$\theta_{ref,min}^t \leq \theta_{ref}^t \leq \theta_{ref,max}^t, \forall t \tag{21}$$

There is no electricity storage available on Aero currently, the potential electricity storage considered are Li-ion battery, high temperature thermal storage and hydrogen storage. As the constraints are similar for the three storage systems, here only the constraints for Li-ion battery storage are elaborated in detail.

Li-ion battery storage

In a battery, the state of charge (SOC) must be kept consistent with the in- and outputs, which is constrained in Eq.(22). The charge and discharge are constrained in Eq.(25) and Eq.(26) to ensure the battery does not charge or discharge too quickly. In Eq.(23) the SOC is constrained between 0 and the maximum value.

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Constraint in Eq.(24) is to ensure the SOC at the first hour of the year and last hour of the year is consistent, enabling running the storage for multiple years.

$$SOC_b^{t+1} = SOC_b^t + Ch_b^t - Dis_b^t \text{ },\forall t \quad (22)$$

$$0 \leq SOC_b^t \leq SOC_{b,C} \text{ },\forall t \quad (23)$$

$$SOC_b^1 = SOC_b^{8760} \quad (24)$$

$$0 \leq Ch_b^t \leq Ch_{b,C} \text{ },\forall t \quad (25)$$

$$0 \leq Dis_b^t \leq Dis_{b,C} \text{ },\forall t \quad (26)$$

High-temperature thermal storage

High temperature thermal storage (HTTS) belongs to both the electricity and heating sectors. It is charged with electricity, which is used to heat rocks or minerals to very high temperatures, as high as 600 °C. The heat is then used to generate steam, which runs through a turbine to produce electricity and heat.

$$SOC_{HTTS}^{t+1} = SOC_{HTTS}^t + Ch_{HTTS}^t - Dis_{HTTS}^t \text{ },\forall t \quad (27)$$

$$0 \leq SOC_{HTTS}^t \leq SOC_{HTTS,C} \text{ },\forall t \quad (28)$$

$$SOC_{HTTS}^1 = SOC_{HTTS}^{8760} \quad (29)$$

$$0 \leq Ch_{HTTS}^t \leq Ch_{HTTS,C} \text{ },\forall t \quad (30)$$

$$0 \leq Dis_{HTTS}^t \leq Dis_{HTTS,C} \text{ },\forall t \quad (31)$$

Hydrogen storage

Hydrogen storage consists of three parts, an electrolyzer, a hydrogen tank and a fuel cell. The surplus electricity production can be stored in the form of hydrogen via electrolyzing water. The stored hydrogen can be used to produce electricity in need through fuel cells.

$$SOC_{Hyd}^{t+1} = SOC_{Hyd}^t + D_{Elec}^t \cdot \eta_{Elec} - D_{FC}^t \text{ },\forall t \quad (32)$$

$$0 \leq SOC_{Hyd}^t \leq SOC_{Hyd,C} \text{ },\forall t \quad (33)$$

$$0 \leq D_{Elec}^t \leq D_{Elec,C} \text{ },\forall t \quad (34)$$

$$0 \leq D_{FC}^t \leq D_{FC,C} \text{ },\forall t \quad (35)$$

$$SOC_{Hyd}^1 = SOC_{Hyd}^{8760} \quad (36)$$

$$D_{FC}^t = P_{FC}^t / \eta_{FC}, \forall t \quad (37)$$

2.1.2. Heating sector

On Aero, approximately a third of the households are heated with individual heating, while the rest are heated with district heating.

Solar collector

Solar collectors are very similar to wind turbines and PVs in that they are limited by the solar flux and the installed capacity. However, for solar collectors, the amount of installed capacity cannot be changed, as there are already a lot of solar collectors on Aero.

$$0 \leq P_{SC}^t \leq P_{SC,C}^t \text{ },\forall t \quad (38)$$

Straw boiler

$$0 \leq P_{DHB}^t \leq P_{DHB,C}^t \text{ },\forall t \quad (39)$$

District heating heat pump

$$0 \leq P_{DHHP}^t \leq P_{DHHP,C}^t \text{ },\forall t \quad (40)$$

$$D_{DHHP}^t \cdot COP_{DHHP}^t = P_{DHHP,}^t \text{ },\forall t \quad (41)$$

Seasonal heat storage

Aero currently equips a pit thermal storage for seasonal heat storage. The pit storage is a water reservoir and it uses a heat pump to discharge the heat. The maximum state of charge ($SOC_{SS,C}$) of the seasonal heat storage is 6.638 MWh.

$$SOC_{SS}^{t+1} = SOC_{SS}^t + Ch_{SS}^t - Dis_{SS}^t - H_L, \forall t \quad (42)$$

$$0 \leq SOC_{SS}^t \leq SOC_{SS,C} \text{ },\forall t \quad (43)$$

$$SOC_{SS}^1 = SOC_{SS}^{8760} \quad (44)$$

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$$0 \le Ch_{SS}^{t} \le Ch_{SS,C}, \forall t \tag{45}$$

$$0 \le Dis_{SS}^{t} \le Dis_{SS,C}, \forall t \tag{46}$$

2.1.3. Transport sector

Passenger electric vehicles and electric buses are not installed in Aero currently, while E-ferry is already running. They all serve as electric batteries with specific charging and discharging patterns.

Passenger electric vehicles

The specific electric car "Renoult Zoe" is used, which has a 53 kWh battery and a 400 km driving distance. All cars are assumed to be in use every morning at 7 am, when people go to work, and ready for charging again from 5 pm when they get home, until the next morning. It is assumed that 20% of cars drive 5 km twice every day and the owners have a charging box at home, with a capacity of 11 kW.

$$SOC_{AllEV}^{t+1} = SOC_{AllEV}^{t} + D_{AllEV}^{t} - Dis_{AllEV}^{t}, \forall t \tag{47}$$

$$0 \le D_{AllEV}^{t} \le D_{AllEV,C}, \forall t \tag{48}$$

$$0 \le SOC_{AllEV}^{t} \le SOC_{AllEV,C}, \forall t \tag{49}$$

Buses

Two public buses on Aero run the same route but from mirrored starting points. Each route takes approximately one hour and there is time for the buses to charge for 5 minutes after the completion of each route. The buses can charge completely during the night.

$$SOC_{bus}^{t+1} = SOC_{bus}^{t} + D_{bus}^{t} - Dis_{bus}^{t}, \forall t \tag{50}$$

$$0 \le D_{bus}^{t} \le D_{bus,C}, \forall t \tag{51}$$

$$0 \le SOC_{bus}^{t} \le SOC_{bus,C}, \forall t \tag{52}$$

Electric ferry (E-ferry)

The ferry starts at 6 in the morning, makes six round trips per day, and has 32 mins in Aeroskoebing between trips to charge if needed, returning to Aeroskoebing at midnight. The e-ferry has a large battery of 4.3 MWh. The charger in Aeroskoebing has a capacity of 4.2667 MW.

$$SOC_{EF}^{t+1} = SOC_{EF}^{t} + D_{EF}^{t} - Dis_{EF}^{t}, \forall t \tag{53}$$

$$0 \le D_{EF}^{t} \le D_{EF,C}, \forall t \tag{54}$$

$$0 \le SOC_{EF}^{t} \le SOC_{EF,C}, \forall t \tag{55}$$

2.2. Objective functions

This section details objective functions for various scenarios investigated in this paper. Overall, the objective functions are the same targeting minimizing the cost, enabling comparison of different scenarios. But they are subject to different constraints in accordance with the considered technologies for a specific scenario.

Business as usual (BAU) scenario

In order to compare the proposed hybrid scenario with the current energy systems on Aero, a business as usual (BAU) scenario was created resembling the current system, which will be the reference scenario for performance evaluation. The objective function of the BAU scenario is to minimize the costs consisting of variable costs, fixed operational costs and investment costs.

$$minimize \sum_{n=1}^{N} (C_V^n \cdot U^n) + \sum_{n=1}^{N} (C_I^n + C_F^n) \cdot C^n$$

$$s.t.\ Eq. (1-4), (6), (8-10), (13-21), (38-46), (53-55)$$

Where *n* denotes different technology, the variable costs (C_V^n) for each technology are multiplied by the use (U^n) of that technology. The fixed operational costs (C_F^n) and investment costs (C_I^n) for each technology are multiplied by the capacity (C^n) of that technology.

Hybrid scenario

As compared to BAU scenario, hybrid scenario has expanded wind turbines and PVs capacity, installed biogas turbines, electrified all buses and personal vehicles, eliminate the use of cable for connection to the mainland grid, added new energy storage systems including Li-ion battery storage, high temperature thermal storage and hydrogen storage. The objective function of hybrid scenario is to minimize the costs as well, which is the same as that of BAU scenario.

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$$minimize \sum_{n=1}^{N}(C_V^n \cdot U^n) + \sum_{n=1}^{N}(C_I^n + C_F^n) \cdot C^n$$

$$s.t.\ Eq.(1-2), (4-55)$$

Furthermore, extensions of the hybrid scenario were also investigated to see how the system changes under different conditions. Among them, the second ferry, exporting surplus electricity, and PtL technology are investigated.

Hybrid+2Ferry scenario

Currently, Aero has several ferry routes to the mainland and other islands, but there is only one electric ferry available between Soeby and Fynshavn. Therefore, it is interesting to investigate the possibility of replacing more of them with e-ferries. In hybrid+2Ferry scenario, the objective function is still minimizing the costs, subject to the same constraints in hybrid scenario, except that additional constraints for the second ferry are added.

Hybrid+Export scenario

Though Aero aims to operate energy systems in island mode, it is still worth investigating the potential economic benefits of selling surplus renewable electricity production to the mainland grid. In hybrid+Export scenario, the objective function is the same as that of the hybrid scenario, and the constraint for interconnection is included, allowing the export of electricity.

Hybrid+PtL scenario

The hybrid scenario does not consider green fuels for heavy transport since it is not yet the goal for the municipality by 2025. In continuation of this, complete sustainability is the aim for 2030, where elements like heavy transport must be considered through the Power-to-Liquid process. Hybrid+PtL share the same objective function as that of the hybrid scenario, but is subject to additional constraints for jet fuel and methanol production as shown in Eq. (56-63):

$$D_{FT}^t \cdot \eta_{FT} = P_{FT}^t \ , \ \forall t \quad (56)$$

$$\sum_{t=1}^{T} P_{FT}^t = D_{jet}^{Annual} \quad (57)$$

$$0 \le P_{FT}^t \le P_{FT}^{max}, \ \forall t \quad (58)$$

$$0 \le P_{FT}^{max} \quad (59)$$

$$D_{MeOH}^t \cdot \eta_{MeOH} = P_{MeOH}^t, \ \forall t \quad (60)$$

$$\sum_{t=1}^{T} P_{MeOH}^t = D_{MeOH}^{Annual} \quad (61)$$

$$0 \le P_{MeOH}^t \le P_{MeOH}^{max}, \ \forall t \quad (62)$$

$$0 \le P_{MeOH}^{max} \quad (63)$$

2.3. Data collection and implementation

To perform optimization, some essential data needs to be collected apart from the data for technology size and operating limitations. These data are outdoor temperature, solar irradiance, wind data profile, the electricity spot price, electricity demand and heating demand. One-year data (in the year 2018) is collected in a resolution of an hour. Note that the hourly electricity demand and heating demand for Aero cannot be found specifically. Hence, the electricity demand was estimated by scaling down the total electricity demand for Denmark to fit the size of Aero, and the heating demand was estimated by scaling down the total heating demand for Odense to fit the size of Aero. Figure 1 illustrates the derived electricity and heating demand.

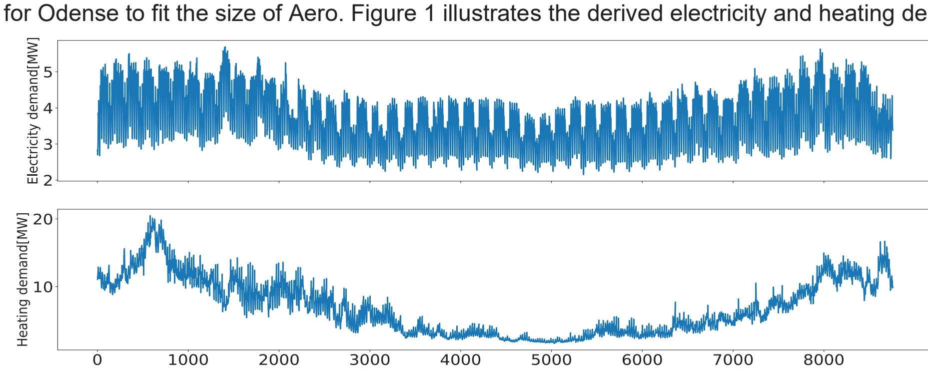

Figure. 1. Electricity and heating demand for Aero.

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The optimization was implemented in Matlab [13] using the package Yalmip [14], and the optimization problem was solved using “Linprog” solver for linear programming.

The expected outcomes of the optimization are the optimal capacity for existing PV and wind turbine expansion, the optimal capacity of the potential energy units, and the optimal dispatching schedule for each energy system involved.

3. Results and discussions

In this section, the optimization results of different scenarios are presented. Table 1 summarizes the main capacities of different energy systems in the investigated scenarios. As shown in the BAU scenario, the current wind turbine and PV capacities are 12 MW and 1.232 MW, respectively, while their capacities increase in the other four scenarios due to the increasing electricity demand. To better visualize the energy flows from the production side to the storage and end-user side, the corresponding Sankey diagram for each scenario is provided and discussed.

Table 1. Capacity overview of different scenarios

Capacity	Unit	BAU	Hybrid	Hybrid+2Ferry	Hybrid+Export	Hybrid+PtL
Interconnection (Import/Export)	[MWh]	11273/16305	/	/	Export: 519814.8	/
Wind capacity	[MW]	12	15.8	18.7	153.2	37.1
Wind production	[MWh]	38499	28568.4	30771.1	386351.0	115051.1
PV capacity	[MW]	1.232	15.4	18.9	164.0	34.7
PV production	[MWh]	1642.9	13813.4	16228.6	178797.1	39673.5
Li-ion capacity	[MWh]	/	4.4	5.6	0.28	0.20
HTTS capacity	[MWh]	/	0	0	0	0
Hydrogen capacity	[MWh]	/	0	0.45	0	0
Biogas turbine	[MW]	/	3.9	4.1	4.3	4.5
Jet fuel production capacity	[MW]	/	/	/	/	2.22
Methanol Production capacity	[MW]	/	/	/	/	5.99

3.1. BAU scenario

As shown in Figure 2, the current energy systems in Aero consume a large amount of fossil fuels for personal vehicles and household heating. The heating sector in Aero consists of around 1/3 individual heating and 2/3 district heating. The straw boiler, solar collector, ORC unit and seasonal storage supply a lot of district heating. District heating is close to using 100% renewable energy sources, depending on whether the electricity consumed in the heat pump comes from renewable energy sources or the mainland grid.

In BAU scenario, the importing and exporting of electricity happen frequently throughout the year to secure an hour-to-hour balancing of electricity demand and production. The total exporting electricity is higher than the total importing electricity, indicating there are many situations of having excess renewable electricity production, which necessity electricity storage for flexibility.

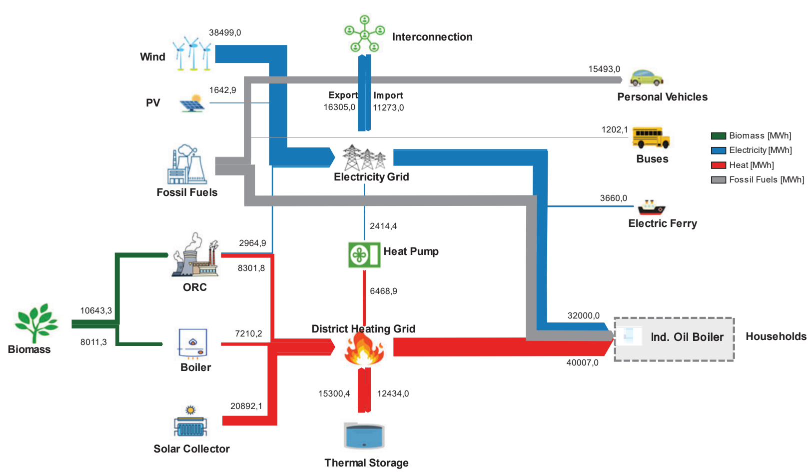

Figure. 2. Energy flows in BAU scenario.

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3.2. Hybrid scenario

Figure 2 illustrates the energy flow in hybrid scenario. As compared to BAU scenario, the interconnection is no longer available in hybrid scenario. The wind turbine capacity increases slightly, while the PV capacity increases more than 10 times. Hybrid scenario recommends installing a biogas turbine with a capacity of 3.9 MW. Concerning storage, a 4.4 MW Li-ion battery is included while the HTTS and hydrogen storage are not used. To run primarily on RES and storage, a very large amount of storage is needed for long periods when production is needed. However, this can be done far more easily with controllable production, in this case, the biogas turbine. This is far better since the storage of biogas or manure is far easier than storing hydrogen or electricity in a battery.
The demand for vehicles and individual heating is lower in hybrid scenario than that of BAU scenario. This is because the efficiencies of combustion engines and boilers used in BAU scenario are much lower than electric motors and heat pumps used in hybrid scenario, resulting in larger fuel demand.

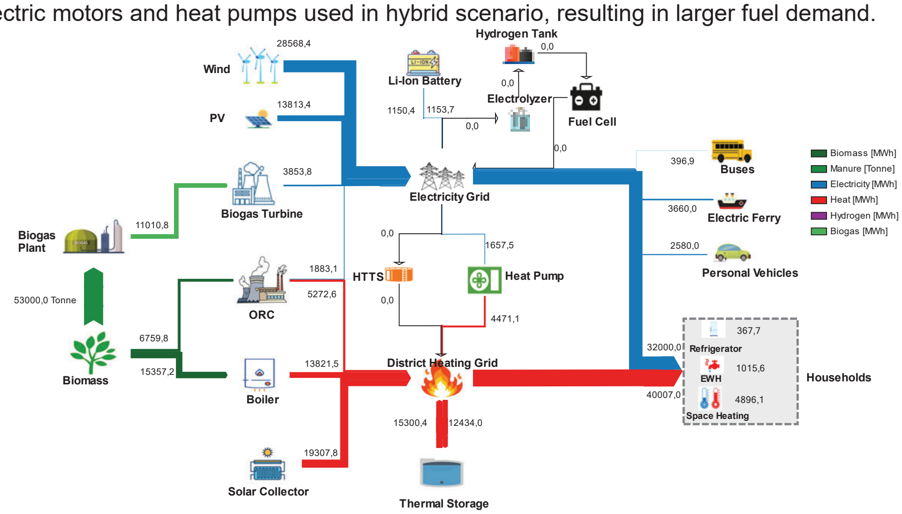

Figure. 3. Energy flows in hybrid scenario.

3.3. Hybrid+2Ferry scenario

The energy flow in the scenario with an additional e-ferry is seen in Figure 4, and the capacities can be seen in Table 1. The new ferry requires some extra electricity demand, leading to an increase in the capacity and production from renewable energy sources (RES) as compared to hybrid scenario. Furthermore, this increased demand also means that more long-term storage is suddenly needed, which means that hydrogen storage is included in a small capacity (0.45MWh). It is the only scenario that hydrogen storage is used among the investigated five scenarios and the Li-ion storage capacity also increases slightly compared to hybrid scenario. The barely used hydrogen storage in most scenarios is due to the high investment and operational cost, which is economically cost-ineffective.

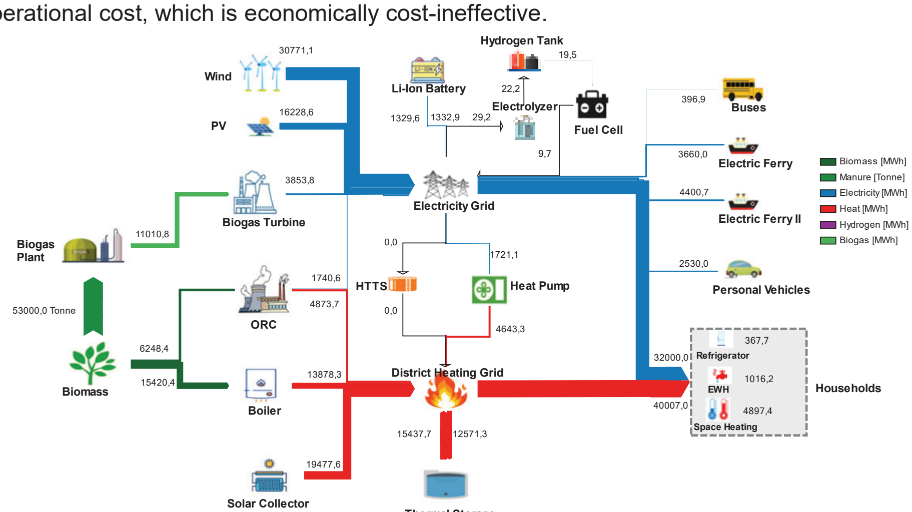

Figure. 4. Energy flows in hybrid+2Ferry scenario.

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3.4. Hybrid+Export scenario

It is clear from Table 1 and Figure 5 that allowing exporting surplus electricity changes the system significantly, and that making money from selling excess production to the grid is very much possible for most of the hours of the year. The RES capacities can be extremely high because production can be exported, and they can cover most of the demand. However there are still hours without wind or sun, therefore the battery, ORC unit and biogas turbine are necessary. The battery storage is used less than in other scenarios as the system prioritizes selling the surplus electricity for profits, resulting in a very small battery capacity (0.28MWh).

Hybrid+export scenario seems good as it benefits from selling electricity, but the model is based on current electricity prices. In the future, there will be an increasing amount of RES in the Danish system, which will most likely decrease the possibilities for profits from selling it. Furthermore, Aero is a small island with attractive nature and vacation homes, which creates a lot of resistance to building objects that damage the view, it is, therefore, infeasible to build that much wind turbine and PV capacity.

The hybrid+Export does not comply with the goal of island mode operation on Aero by 2025. But in the case that the demand on the island is met and there is still potential to produce a lot of green electricity, it would be ideal to export this electricity. In this way, the national main grid will benefit from the green electricity that would otherwise have been lost.

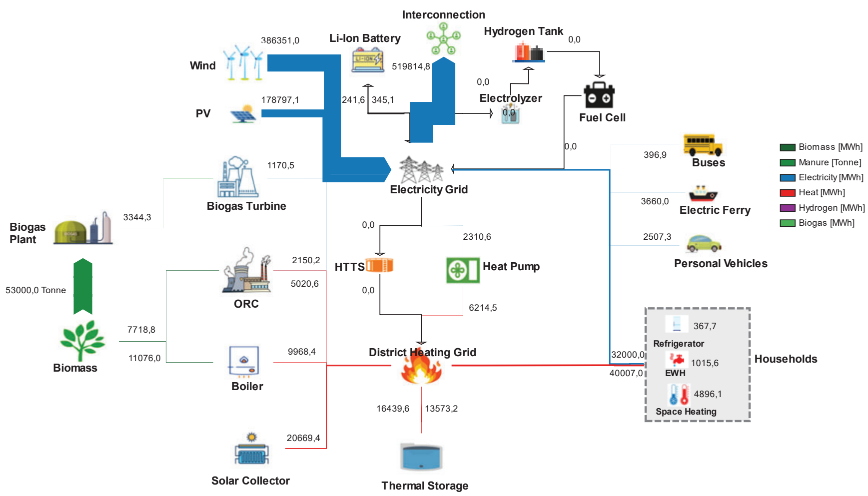

Figure. 5. Energy flows in hybrid+Export scenario.

3.5. Hybrid+PtL scenario

As shown in Figure 6 and Table 1, involving Power to Liquid in the system changes the system considerably as compared to hybrid scenario, though the changes are not as significant as hybrid+Export scenario. Since the efficiency of PtL process is low, the demand for electricity increases substantially. The RES production needs to fit the high demand. Therefore, a huge capacity of RES is needed in this scenario.

Hybrid+PtL scenario has no HTTS, no hydrogen storage, and a small Li-ion battery storage (0.2MWh), indicating the RES capacities in this scenario are almost fully utilized by end-users. This is because the PtL can almost always use the produced electricity. The PtL capacities are also relatively large. The results show that the PtL is not only an extra demand but is very useful for balancing the system.

3.6. Techno-economic evaluations

To quantitatively evaluate the technical feasibility and economic benefits of each scenario before real implementation in practice, the two key performance indicators (KPIs) are calculated and presented in Table 2. The metric of renewability is defined in Eq. (64), which reflects the share of renewable energy production over the total energy input for the island. It is assumed that the imported electricity is 100% based on fossil fuels. For Hybrid, Hybrid+2Ferry, Hybrid+Export, and Hybrid+PtL scenarios, the term "$I_{Imp} + P_{fossil}$" is zero, resulting in 100% renewability. However, only 55.77% of energy demand is supplied by renewable energy sources for the BAU scenario, which justifies applying a hybrid scenario to realize self-sufficiency in renewable energy.

$$Renewability\ \% = 1 - \frac{I_{Imp}+P_{Fossil}}{I_{Imp}+P_{Fossil}+P_{Wind}+P_{Bio}+P_{PV}+P_{ORCel}+P_{ORCheat}+P_{Boiler}+P_{SC}} \quad (64)$$

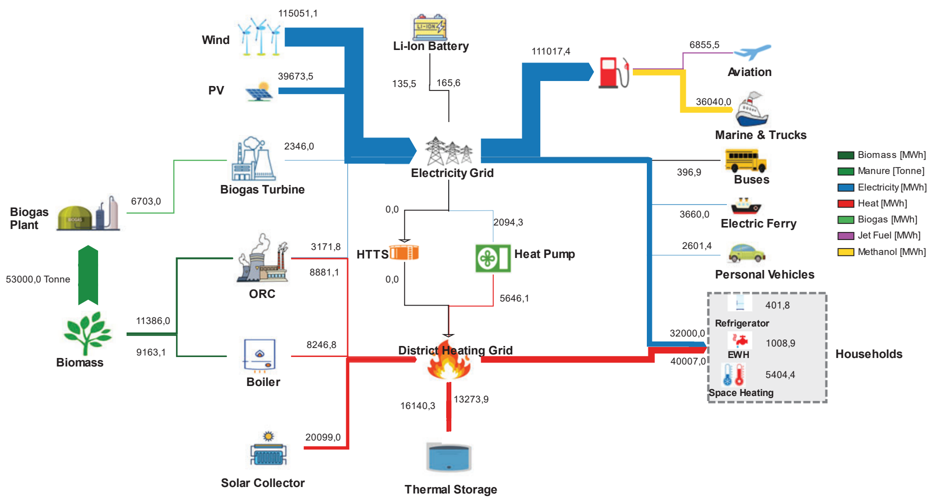

Figure. 6. Energy flows in hybrid+PtL scenario.

The total cost is calculated based on the annualized investment costs considering its lifetime, variable costs, and fixed operational costs. Then, the individual cost [DKK/month/person] is calculated and presented in the table, corresponding to what each citizen on Aero must pay to run the system.

As shown in Table 2, the lowest cost is achieved in the hybrid scenario, while hybrid+PtL exhibits the highest cost due to the expensive Power-to-Liquid unit. Therefore, the hybrid scenario is the final recommended scenario for the energy system upgrade roadmap for Aero by 2025 considering both technical feasibility and economic benefits.

Figure 7 shows the cost breakdown for each system. It can be seen that infrastructure cost accounts for the major part of total cost in all investigated scenarios except for the hybrid+Export scenario, where cost by renewable energy production predominates. This is because hybrid+Export scenario encourages selling electricity to the mainland grid for earnings, resulting in higher RES production and high cost for RES facility expansion. Note that infrastructure is an aggregate item consisting of several elements such as expenses for electric vehicles, buses, ferry, individual heating, and demand response units.

The results show that installing an additional ferry is the most beneficial approach to improve the hybrid scenario's performance among hybrid+2Ferry, hybrid+Export, and Hybrid+PtL scenarios. Even though hybrid+Export results in less cost, it is not advised as it violates the goal of island mode operation.

Table 2. Summary of the KPIs for different scenarios

KPIs	Unit	BAU	Hybrid	Hybrid+2Ferry	Hybrid+Export	Hybrid+PtL
Renewability	[%]	55.77	100	100	100	100
Cost	[DKK/month/person]	1689.6	1625.9	2035.6	1680.3	2430.3

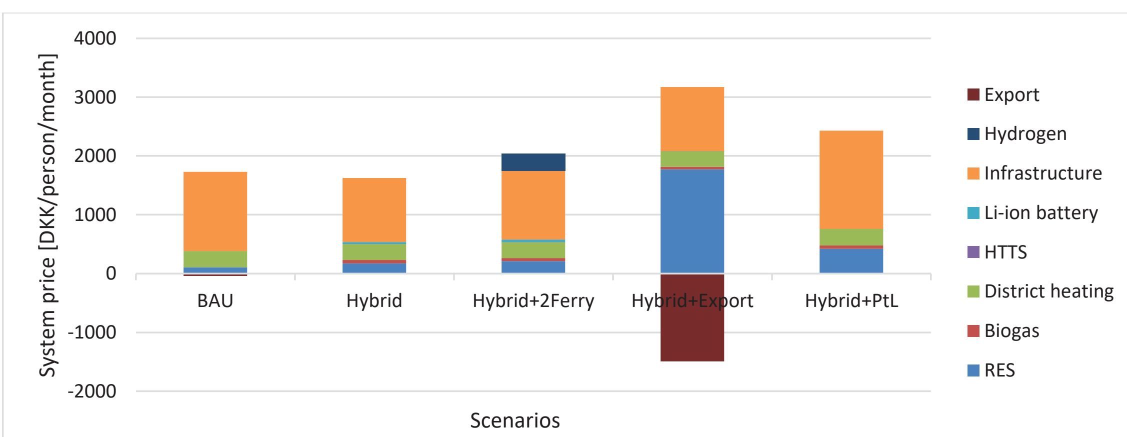

Figure. 7. Cost breakdown for all scenarios

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4. Conclusion

This paper aims to find a feasible solution for a Danish island Aero to be fully sustainable relying solely on renewable energy sources and operating in island mode by 2025. To that end, a hybrid scenario, as a combination of different technologies including electrification of the transport sector, installing energy storage systems, expanding renewable energy production capacities, energy production planning, and demand-side management, is proposed. A linear programming optimization problem is formulated in accordance with the hybrid scenario to optimize the energy system capacity and energy system operation.

The proposed hybrid scenario performance is analysed and compared to a business-as-usual (BAU) scenario, where the energy system remains unchanged but the energy system operation is optimized. A techno-economic approach is used to quantitatively evaluate the system's performance in terms of renewability and costs. The hybrid scenario yields 100% renewability and 1625.9 DKK/month/person, while the BAU scenario achieves 55.77% renewability with a higher cost of 1689.6 DKK/month/person. Thus, the established hybrid scenario should be seen as an achievable green energy system for the island in 2025, with various options for development. Among them, extensions of the hybrid scenario by including the second ferry, exporting excess electricity, and installing Power-to-Liquid units are investigated and compared, the results show that including the second ferry is the most beneficial approach to improve the hybrid scenario’s performance, with a cost of 2035.6 DKK/month/person.

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Nomenclature

P	energy production, MW
D	energy demand, MW
I	interconnection to the main grid, MW
F	scaling factor, -
SOC	state of charge, -
COP	coefficient of performance, -
ORC	the Organic Rankine Cycle unit
C	thermal capacitance, J/K
R	thermal resistance, K/W
υ	hot water consumption, MW
Ch	charge power, MW
Dis	discharge power, MW

Greek symbols

η	efficiency, -
θ	temperature, °C

Subscripts and superscripts

t	number of hours during a year
i	indoor air
W	wind turbine
C	maximum capacity
PV	photovoltaics
Sp	space heating
EWH	electric water heating
ref	refrigerator

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$ORCEL$	electricity output of the Organic Rankine Cycle
$ORCH$	heat output of the Organic Rankine Cycle
Bio	biogas turbine
b	li-ion battery
$HTTS$	high temperature thermal storage
Hyd	hydrogen storage
FC	fuel cell
$Elec$	electricity demand of the electrolyzer
SC	solar collector
DHB	district heating straw boiler
$DHHP$	district heating heat pump
SS	seasonal heat storage
EF	electric ferry

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