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Co-Optimization of Electrical and District Heating Networks: Bornholm case study

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Abstract— **With the growing energy demands, the interdependence among multiple energy domains is increasing rapidly. The optimal dispatch of the different energy sources, storage systems, and flexible loads in a multi-energy system is a challenging problem. This paper focuses on the co-optimization of a multi-energy system consisting of electrical and district heating networks to address the challenge. The electric boilers and heaters act as interconnecting elements between the two systems. Utilizing the available flexibilities in both systems, the co-optimization focuses on energy management to achieve economical operation and reduction in renewable curtailment. The algorithm uses the day-ahead forecast of renewable generation as well as electrical and heating demands to determine the optimal schedule for the various generation, storage, and flexible loads in both systems. A case study based on the multi-energy system at Bornholm Island, Denmark is presented in this paper. The results show a significant reduction in renewable power curtailment and a reduction in CO_2 emissions achieved via the interconnected systems.**

I. INTRODUCTION

Increasing renewable energy penetration into the electrical grid helps to utilize more clean energy and reduce the carbon footprint. However, renewable sources pose multiple challenges like uncertain power generation and reliability issues. The electrical network faces multiple security issues with uncertain sources and the flexibility of the system is low when operated alone. In contrast, when an electrical system is operated along with a district heating system(DHS), the effect of uncertainties is reduced, and the flexibility of the overall system is increased. In recent years, an increasing interest in operating multiple energy systems with interconnecting elements can be observed [1].

Smart grids and smart cities have multiple energy vectors like solar, wind, heat, and gas on the source side and controllable heat, gas, and electricity vectors on the load side along with storage elements [2]. The optimal scheduling of sources, flexible loads, and storage elements of multiple energy domains i.e., co-optimization will increase the overall energy utilization of the system and help to overcome the renewable intermittency problem. Also, co-optimization helps in the efficient utilization of unused energy carriers and satisfies the demand optimally. The flexibility in multi-energy systems comes from storage, interconnecting elements, and flexible loads.

In the existing literature, various algorithms are available to operate multi-energy systems(MES) efficiently. Each of these works differs in the complexity of the MES models adopted and the objective of the optimization. Most of these papers are based on linear programming, mixed-integer formulations, dynamic programming, genetic algorithms, and Lagrangian relaxation methods [3]–[8]. One of the early works in MES [9] introduced the energy hub model with multiport inputs and outputs from various energy domains. Different energy conversions happen inside the hub and the optimal dispatch algorithms decide the levels of energy conversions. In [10], a nonlinear formulation of the scheduling problem with integrated electricity and district heating systems is discussed. An optimal scheduling algorithm using subsidy strategies is developed in [11], which mainly focuses on obtaining the subsidy signals to control the heating system. In [12], a linear model of an electrical and nonlinear model of the natural gas system has been used to perform robust co-optimization. The majority of these works focus on the economical operation of the overall system and the effect of flexible loads and storage on co-optimization is not well addressed.

The main contribution of the paper is demonstrating the advantage of co-optimization to reduce renewable curtailment and flexible load utilization for the economical operation of MES with a practical application to the Bornholm demo site [13]. A linear optimization model is used to obtain the day-ahead schedule of multiple energy sources. The interconnecting elements between the electrical and heating systems are treated as flexible electrical loads and the same acts as flexible sources for the DHS. Flexible thermal loads which can be time-shifted are also considered in this work. The day-ahead forecasts of renewable generations and fixed load demands are the inputs to the algorithm. The advantage of the flexible loads and thermal storage is clearly shown in this work. Results show a significant reduction in renewable curtailment, reduction in CO_2 emissions, and cost savings of both systems.

The rest of the paper is organized as follows, Section II describes the modeling of electrical and district heating systems. Then, Section III describes the linear co-optimization model which optimizes both systems simultaneously. Finally, the simulation results of Bornholm Island and the conclusions of the work are discussed.

II. ELECTRICAL AND DHS MODEL

In this section, the system model of Bornholm Island is described. The island consists of an electrical power

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system (EPS) and a district heating system (DHS) that caters to electrical and heating demands. The EPS consists of conventional generation sources, renewable sources like solar and wind, fixed electrical loads, and flexible electrical loads. The DHS consists of a heating plant, where straw boilers, electric boilers, and hot water storage tanks are installed. The hot water from the DHS plant will be supplied to households, schools, and community swimming pools. Each house is also equipped with an electric heater to heat the water locally. The electric boilers at the DHS plant and household electric heaters are the interconnecting elements that connect both systems. Also, these interconnecting elements act as flexible loads for the EPS. On the other hand, community swimming pools and schools act as flexible heat loads for the DHS. These flexible loads can be time-shifted but they have a constraint on the consumed power at any given hour.

A. Electric Power System

The EPS consists of conventional sources and renewable sources which will balance the fixed and flexible electrical demands of the system. The power balance equation for EPS is given by (1).

$$P_t^{CG} + P_t^{RES} = D_t^B + D_t^{FL} + P_t^{RES\_curt} \tag{1}$$

Where, P_t^{CG} is the net conventional generation power, P_t^{RES} is the net power from renewable sources. D_t^B is the base electrical demand of the entire island, D_t^{FL} is the flexible electrical demand and $P_t^{RES\_curt}$ is the curtailed renewable power.

As discussed, the electrical demand of the island is classified into fixed and flexible demand. The fixed demand, D_t^B is the forecasted base demand of the complete island, and $D_t^{FL}$is the flexible demand which will be determined by the co-optimization. $P_t^{RES\_curt}$ is the curtailed renewable power, which will always be a positive quantity. The flexible demand includes the electric boilers demand, D_t^{EB} at the DHS plant, and the net electric heaters demand, D_t^H at the household level which is given by (3c).

$$D_t^{FL} = D_t^{EB} + D_t^H \tag{2}$$

Conventional generators are associated with constraints representing their capacity limits. The flexible loads will have limits on their consumption at any given hour. The subscripts min and max denote the minimum and maximum limits of each variable.

$$\begin{aligned} P_{min}^{CG} \leq P_t^{CG} \leq P_{max}^{CG} \\ D_{min}^{EB} \leq D_t^{EB} \leq D_{max}^{EB} \\ D_{min}^{H} \leq D_t^{H} \leq D_{max}^{H} \end{aligned} \tag{3}$$

The other constraints like the ramp-up and ramp-down time of the generators are not considered in this model since the implementation of the co-optimization does not consider the controlling of these generation sources. The forecast of PV and wind generation and the forecasted base demand are parameters that are known before the optimization. The rest of the variables which include the generation from conventional sources and the flexible demand and curtailment are optimized by the co-optimization algorithm.

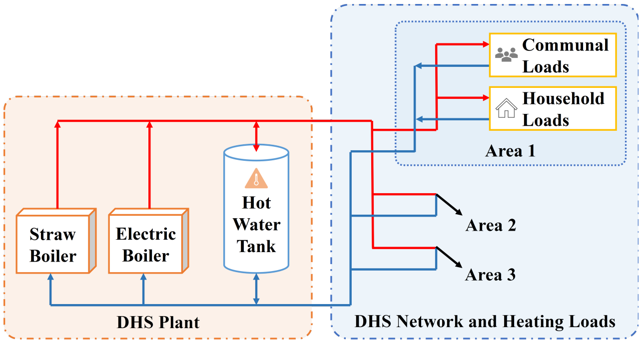


Fig. 1. DHS at Bornholm consisting of heating plant and consumers

B. District Heating System

The DHS consists of a hot water supply plant, flexible communal loads, and fixed household loads connected as shown in Fig 1. The DHS plant generates heat power from conventional boilers like straw boilers or wood-chip boilers, H_t^S, and also from electric boilers, H_t^{EB} which will be utilized to heat the water and cater the fixed demand, H_t^B, and flexible demand, H_t^{FL}. The hot water tank (HWT) is used to store or retrieve heat energy and constitutes the flexibility to serve the demand at a later stage during the period of high fuel cost or renewable intermittencies. $H_t^{HWT\_out}$ and $H_t^{HWT\_in}$ represent the output and input heat power of the HWT. At the household level, electric heaters will also heat the hot water. The aggregated net heat power of the electric heaters is denoted by H_t^H.

The heat power balance equation governing the DHS plant and the consumer loads is given by (4).

$$H_t^S + H_t^{EB} + H_t^H + H_t^{HWT\_out} - H_t^{HWT\_in} = H_t^B + H_t^{FL} \tag{4}$$

The heat energy of HWT is represented by E_t^{HWT}. HWT will have constraints on the maximum and minimum amounts of energy that it can store, as shown in (5). Δt represents the time step of the computation.

$$\begin{aligned} &E_t^{HWT} = E_0^{HWT} + (H_{HWT\_in} - H_{HWT\_out})\Delta t, t = 1 \\ &E_t^{HWT} = E_{t-1}^{HWT} + (H_{HWT\_in} - H_{HWT\_out}\Delta t), t \geq 1 \\ &E_{min}^{HWT} \leq E_t^{HWT} \leq E_max^{HWT} \end{aligned} \tag{5}$$

The heat generated from the straw boiler is limited by the rated capacity of the boiler. Apart from the maximum injection/retrieval rate of the HWT, it must be ensured that either the charging or discharging of the HWT takes place at any instant. Additional constraints are specified as given by (6). Here, $x_t^{HWT\_out}$ is a binary variable that equals 1, if extraction from the storage is active, otherwise, the

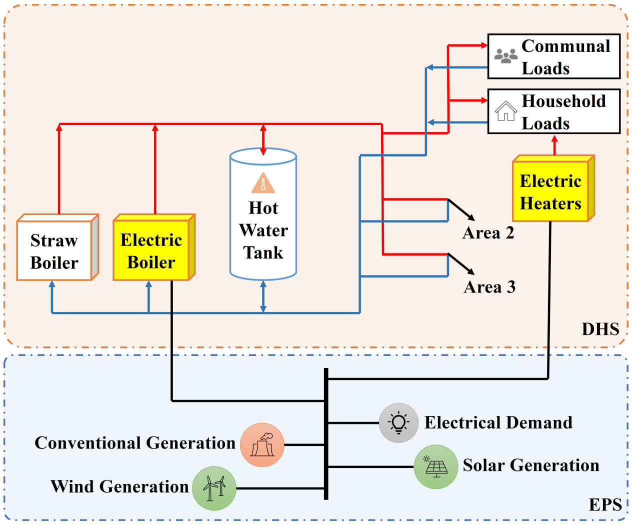


Fig. 2. Interconnection between EPS and DHS at Bornholm

variable equals 0, and $x_t^{HWT\_in}$ equals 1 if the injection in the storage is active or else equals to 0.

$$\begin{aligned} H^S_{min} &\leq H^S_t \leq H^S_{max} \\ H^{HWT}_{min} x_t^{HWT\_out} &\leq H_t^{HWT\_out} \leq H^{HWT}_{max} x_t^{HWT\_out} \\ H^{HWT}_{min} x_t^{HWT\_in} &\leq H_t^{HWT\_in} \leq H^{HWT}_{max} x_t^{HWT\_in} \\ x_t^{HWT\_out} + x_t^{HWT\_in} &\leq 1 \end{aligned} \tag{6}$$

Since the case study considered a large system where the losses in the DHN are very less compared to the heating demand, the nonlinear distribution model is not considered as part of the heat balance equation. The effects of circulating water pumps, water pressures, heat exchangers, temperature drop or losses in pipes, circulating water in boilers, stratification effect, and temperature mix were not taken into consideration in the modeling. Rather, the heat losses are added to the heating demand H_t^B as a small percentage of the demand.

The EPS and DHS are interconnected by the linking elements which are electric boilers and electric heaters, as shown in Fig. 2. The heat power and the electric power are related as shown in 7. Here, η^{EB} and η^{H} represent the conversion efficiencies of electric boiler and heater respectively.

$$\begin{aligned} H_t^{EB} &= \eta^{EB} D_t^{EB} \\ H_t^{H} &= \eta^{H} D_t^{H} \end{aligned} \tag{7}$$

III. CO-OPTIMIZATION PROBLEM

The main objective of the co-optimization algorithm is to utilize the flexibility from the DHS system in the EPS to avoid renewable curtailment and reduce the use of conventional generation and boilers. This is achieved by utilizing the electric boilers at the DHS plant to cater to the real-time heating demand and store the excess heat energy in the hot water tank. This reduces the use of conventional boilers of the DHS plant and maximizes the renewable utilization of the island. The co-optimization shall make sure that the electric boilers are utilized during the period of peak renewable generation. The HWT will ensure to store hot water when excess renewable power is available and discharge during the low renewable period and high heat demand periods. The heating demand can also be catered by the electric heater at the consumer premise which will help in further utilization of renewable energy.

A. Cost Function

The cost function reflects the objectives of co-optimization which are low operation cost, low renewable curtailment, and maximum utilization of HWT. The objective function, F consists of operating cost, C_O and penalty cost, C_P as given in (8)

$$F = C_O + C_P \tag{8}$$

The operational cost includes the cost of generation from various conventional generators in EPS and the straw boiler of DHS. C_O is given by (9),

$$C_O = \sum_{t=1}^{24} (c_{CG} P_t^{CG} + c_{straw} H_t^s) \tag{9}$$

Where, c_{CG}, represents the cost for electrical generation from various conventional generations like biogas, CHP, and fossil fuel power plants and c_{straw} is the cost of heat energy generated using the straw boiler.

The penalty is associated with renewable curtailment. The co-optimization tries to avoid any renewable curtailment and a penalty price, p_{RES} is assigned for the curtailed power to minimize that.

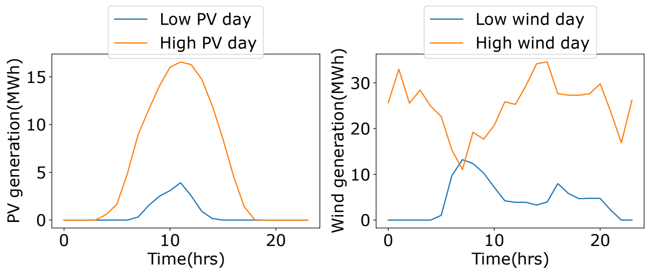
$$C_p = \sum_{t=1}^{24} (p_{RES} P_t^{RES\_curt}) \tag{10}$$

The optimization algorithm will minimize the cost function F subject to various constraints associated with the EPS and DHS. The entire co-optimization problem is described as follows (11)

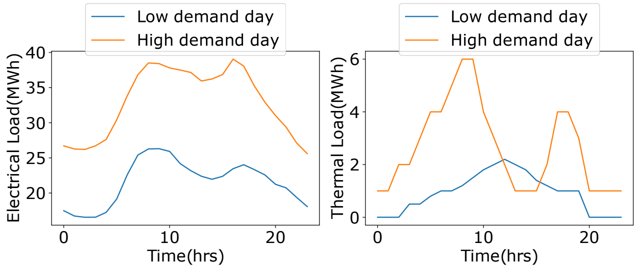
$$\begin{aligned} \min_{P_t^{CG}, H_t^s, P_t^{RES\_curt}} \quad & F \\ \text{subject to} \quad & (1) - (7) \end{aligned} \tag{11}$$

IV. SIMULATION RESULTS

The electrical sources considered for the simulation analysis are PV, wind, and conventional generation from CHP, Biomass, and fossil fuel generators. For analysis purposes, a single price for conventional generation sources is considered here. The electrical demand includes the total fixed electrical load of the island and flexible electric load power comprising electric boilers at the DHS plant and electric heaters at households. The DHS plant is equipped with straw and electrical boilers as shown in Fig. 1. The heating demand of the DHS network consists of the forecasted base heating demand of households and the flexible communal heating demand.



(a) PV generation (b) Wind Generation



(c) Electrical Load (d) Thermal Load

Fig. 3. Typical generation and load profiles for a day at Bornholm

The typical renewable generation and electrical demand profiles for the island are selected from historical data available in [14]. The curtailment cost is the penalty cost for curtailing renewable power. The power system operator should define this value depending on any agreements with RES plants, the energy market, and other policies. The PV generation, wind generation, and load profile of the island for two typical days are shown in Figure 3. The days are selected to take into consideration the two extreme cases of generation or load. Since the historical data on the heating demand of the DHS plant is not available, a fictitious variation is used for the simulation analysis which is shown in Fig. 3.

In the case of a high-demand day, it is assumed that the household heating loads will be higher during morning and evening time periods. A typical bell curve is considered in the case of a low-demand day. Various parameters for the simulation studies are listed in Table I. The communal loads act as flexible loads for the heating system. These flexible loads allow time-shifting and try to reduce the total operating cost. The communal loads are mostly catered by HWT or EB instead of the straw boiler source which increases the operating cost. Based on the different generation and demand profiles, three test cases are considered to analyze the outcome of the co-optimization algorithm. A comparison of co-optimization and individual system optimization is also presented here.

Case 1: High RES generation and high demand

In this scenario, high power generation from renewable sources and high fixed demand in both systems is considered. Generally, high renewable generation and high demand might not occur on the same day, but this fictitious case is considered to demonstrate the savings with the algorithm. The generation and demand profiles are shown in Fig. 3. The result of the co-optimization for this case is illustrated in Fig. 4.

TABLE I

Simulation Parameters

Parameter	**Value**	**Parameter**	**Value**
P^{CG}_{min}	0 MW	P^{CG}_{max}	96 MW
H^{S}_{min}	0 MW	H^{S}_{max}	4 MW
D^{EB}_{min}	0 MW	D^{EB}_{max}	2.2 MW
D^{H}_{min}	0 MW	D^{H}_{max}	0.2 MW
H^{HWT}_{min}	0 MW	H^{HWT}_{max}	5 MW
E^{HWT}_{min}	0 MWh	E^{HWT}_{max}	80 MWh
H^{FL}	3 MW	p_{RES}	537.85 €/MW
c_{CG}	141.2 €/MW	c_{straw}	26.89 €/MW

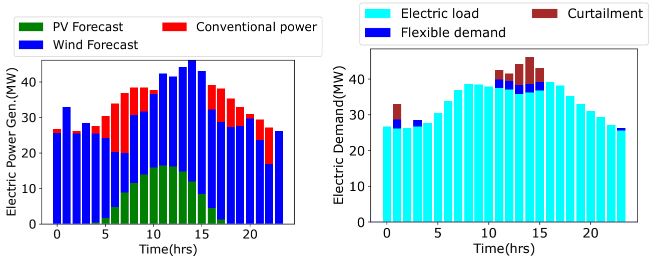
During the time instants when the demand is more than the renewable generation, conventional generators are used to generate additional power. For instants when the demand is less than the renewable generation, the excess power is used to cater to the flexible demand comprising of the electric boilers and electric heaters of the DHS. The flexible electric power in this scenario is as shown in Fig. 4b. In case the flexible power reaches the maximum limit, the excess renewable generation is curtailed. The flexible electric power is utilized to heat the hot water at DHS and/or at households using the heaters.

Straw boilers are operated in coordination with electric boilers to meet the heat demand of the island. The HWT charging and discharging is as shown in Fig. 4c. It can be observed that hot water is being stored during the hours when renewable power is curtailed i.e., during the excess renewable generation period. The time-shifting property of communal loads allows the load to be shifted to times when straw boilers are not operating and also during high RES availability times. It can be seen in Fig. 4d that the communal load is being catered by HWT instead of being catered by straw boilers. The use of a co-optimization algorithm and usage of electrical boilers during the instants of excess RES generation has resulted in the reduction of RES curtailment by 16.73 MWh. The use of electric boilers in the DHS plant also has reduced the usage of the straw boiler. The comparison of optimizing both the systems individually i.e., independent case and performing co-optimizing is summarized in Table II.

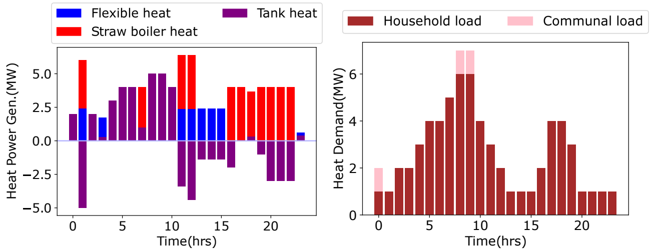
Case 2: High RES generation and low demand

In this scenario, high power generation from renewable sources and low fixed demand in both systems is considered. The result of the co-optimization for this case is illustrated in Fig. 5.

As the electrical demand in the EPS is low as shown in Fig. 5b compared to the RES generation in Fig. 5a, there is an excess of generation. The excess RES generation is utilized by the flexible boilers and heaters by turning



(a) Electrical power generated (b) Electrical power demand



(c) Heat power generated (d) Heat demand of the island

Fig. 4. Total electrical and heat power generation and demand in the Island

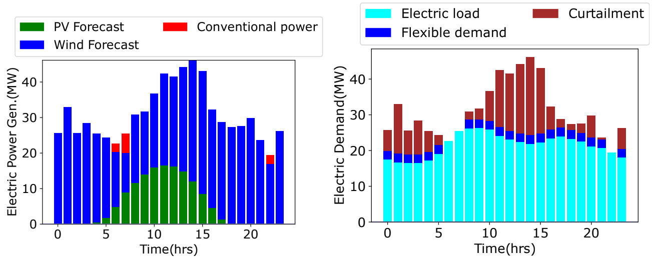
them on at the maximum capacity, thereby reducing the renewable curtailment. The electric boilers acting as the load of the EPS system during hours of excess RES are shown as the flexible power in Fig. 5b. The heat generated from the electric boilers is either used for catering to the heat demand of the island (both household and communal) or to charge the hot water tank. In Fig. 5c the flexible heat is at the maximum capacity and the hot water tank is getting charged during most of the hours indicated as a negative value in Fig.5.

During the period of renewable intermittencies, the electrical demand is catered by conventional generators. The heat generated by the electrical boiler is used to cater to the household and communal loads as well as charge the hot water tank. The hot water tank is charged within the limits of operation to utilize the RES generation. The excess heat energy stored in the hot water tank can be used during the subsequent schedule horizons thereby reducing the straw boiler usage.

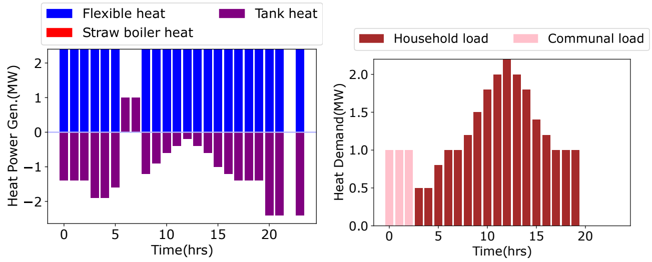
It can be seen in Fig. 5d that the communal loads are shifted to the time when high RES is available. This time-shifting property helps in reducing the overall operating cost of the system. The comparison of optimizing both the systems individually and performing co-optimizing is summarized in Table III. The co-optimization has resulted in the reduction of curtailment by 50.4 MWh which is a 22.4% reduction. Here, the electric boiler is not utilized when conventional electric power is being utilized. Also, the straw boiler is never turned on in this scenario using the co-optimization method and CO_2 emissions are zero.

Case 3: Low RES generation and high demand

This scenario considers a case in which the generation from renewable sources is low and the demand in both systems is high. The typical low PV day and low wind day profiles are considered for PV and wind generation. The typical high-demand profile is considered for electrical and heat loads which are shown in Fig. 3.



(a) Electrical power generated (b) Electrical power demand



(c) Heat power generated (d) Heat demand of the island

Fig. 5. Total electrical and heat power generation and demand in the Island

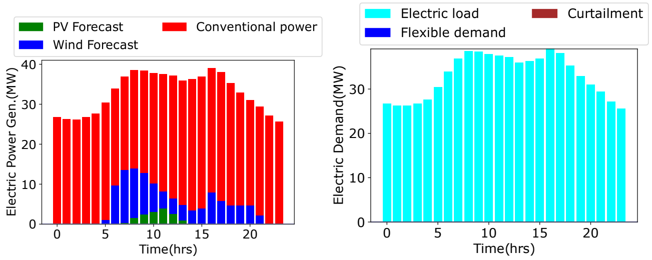
TABLE II

COMPARISON OF INDEPENDENT OPTIMIZATION AND CO-OPTIMIZATION

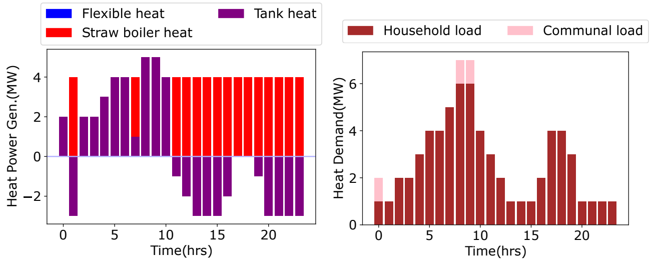
Case	Case 1		
	Independent	Co-optimization	Change
Renewable curtailment	42.7 MWh	25.9 MWh	39.2%
Fuel cost of straw boiler (EUR)	1146	846	26.2%
CO_2 emissions from straw boiler (ton)	23.04	17.01	6.03
Energy gain of the hot water tank (MWh)	0	0	

The result of the co-optimization is illustrated in Fig.6. As the electrical demand is not able to be met by the RES, the conventional generation units are used to cater to the demand. Since there is no excess generation from EPS, the DHS plant relies on the straw boiler to generate the heat power to cater to the various heating demands. The electric boiler does not take part in the DHS operation in this case. The communal loads are catered by HWT which are charged by straw boiler. As we cannot use any RES here, the time-shifting loads cannot provide much cost savings in this case.

Overall, from all the test cases, the co-optimization algorithm proves to provide better results in reducing the renewable curtailment, reducing the straw boiler utilization, and operating the MES economically.



(a) Electrical power generated (b) Electrical power demand



(c) Heat power generated (d) Heat demand of the island

Fig. 6. Total electrical and heat power generation and demand in the Island

TABLE III

COMPARISON OF INDEPENDENT OPTIMIZATION AND CO-OPTIMIZATION

Case	Case 2		
	Independent	Co-optimization	Change
Renewable curtailment	224.8 MWh	174.5 MWh	22.4%
Fuel cost of straw boiler (EUR)	902	0	100%
CO_2 emissions from straw boiler (ton)	18.14	0	18.14
Energy gain of the hot water tank (MWh)	0	23	23

V. Conclusions

A co-optimization algorithm for the optimal dispatch of generation sources, storages, and flexible loads in multi-energy systems is presented in this paper. Day-ahead forecasts of renewable generation as well as demands of different energy domains are the inputs for this algorithm. The developed algorithm is tested on Bornholm island, consisting of electrical and district heating networks. The obtained day-ahead optimal schedules show a significant reduction in renewable curtailment and efficient utilization of electric boilers and thermal storage. This is mainly achieved by proper time-shifting of the flexible loads. The co-optimization resulted in an overall reduction of the operating cost of both the systems and a reduction in CO_2 emissions.

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