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List of Abbreviations

RES	Renewable Energy Sources
TFEC	Total Final Energy Consumption
P2G	Power to Gas
H2G	Hydrogen to Gas
HRES	Hybrid Renewable Energy Sources
SES	Smart Energy System
SEH	Smart Energy Hub
IET	Integrated Energy Systems
DRP	Demand Response Programs
MILP	Mixed-Integer Linear Programming
IEMS	Integrated Energy Management System
HTHPS	High-Temperature Heat and Power Storage

1 Lab-Access User Project Information

1.1 Overview

The summery of the information regarding the title, acronym, host laboratory, access period, and user group members are listed as follows:

Table 1. The summery of general information of the project

User Project Acronym	SES-MGES
User Project Title	Stochastic Multi-objective Scheduling of Smart Energy System considering Multi-generation Energy Storage
Project Keywords	Sector coupling, smart energy system, multi-generation energy storage, uncertainty analysis, multi-objective optimization
Host Laboratory	SESA-Lab (OFFIS)
Access Period	09/01/2022 -> 09/02/2022
User Group Members	Mohammad Ali Lasemi, PhD. Student at Aalborg University
	Ahmad Arabkoohsar, Associate professor at Aalborg University
	Amin Hajizadeh, Associate professor at Aalborg University

1.2 Research Motivation, Objectives, and Scope

Recent reports represent that the share of renewable energy sources (RESs) has consistently grown in the newly installed electricity production sources as well as the major portion of this share is related to wind power generation. This growth of generation share has led to increasing power systems uncertainty and getting harder conventional power plant operation. Therefore, the uncertainties and fluctuations of RESs have become a significant challenge to the operation and control of the power system and they cause that we're not able to utilize these resources more than a certain extent. For instance, renewable energy share in Total Final Energy Consumption (TFEC) has increased from 10.7 to 33.1 in Denmark since 2000 until 2015 [1]. Although Denmark has always been one of the pioneers in the use of renewable resources, yet, fossil fuel is a high share in TFEC. This issue occurred due to low access to dispatch-able renewable energy in Denmark. Wind power today provides more than 40% of the electricity energy generated in Denmark. Regarding heat, Denmark is already switching from coal to biomass in district heating and favoring renewables over oil and natural gas in individual heating [2]. Integrating variable renewable energy into the electricity system and making the heating sector more sustainable are two special focus areas of the Danish government. These two areas are critical for advancing decarburization in Denmark and they also offer attractive potential for energy system integration. Moreover, the natural gas network can also play a key role in energy system integration by considering the development of Power to Gas (P2G) and Hydrogen to Gas process (H2G) technologies in the future [3].

Integration of different energy infrastructures creates a great potential to better operate energy sources, reduce energy losses and cost as well as apply a higher share of renewables and lower environmental impact [4]. Traditionally, the primary energy networks such as natural gas network and power grid were operated separately. But, nowadays, with the technologies developing in the field of energy conversion, the existing energy carrier systems became closer together and their correlation and interaction have increased. This issue causes to increase the unified management significance of these networks. Energy management for integrated energy systems (IESs) is a so important and complex subject, especially when the competitive environment for an integrated energy market is considered.

In this project, our focus is on energy management of a local energy system, which supplies local energy demands by hybrid renewable energy sources (HRES) generation as well as energy trading through upstream energy networks. In this regard, we will seek a comprehensive model for the simulation of Smart Energy System (SES) infrastructures and Smart Energy Hub (SEH) facilities. The proposed SEH accesses to different energy conversion and storage units and through them can participate in the demand response programming and energy market as a prosumer.

1.3 Structure of the Document

The rest of this report is summarized into 5 sections. In the next section, state-of -the- art and state-of-technology regarding the proposed project are given. Then, executed tests and experiments haven discussed in section 3. first, the test plan, standards, procedures, and methodology have been presented and then, the test set-up for the proposed project has been given. In the section 4, we discuss bout the simulation and results obtained by testing the proposed problem of the project. Finally in the last section, the open issues and suggestions are given.

2 State-of-the-Art/State-of-Technology

With economic development in the world, the demand for energy consumption is growing. This consumption growth has caused that governments develop different energy networks to supply these demands based on their country's nature. On the other hand, integration of the different energy systems with multiple energy carriers has been implemented as a central principle for addressing energy challenges. The integrated energy management idea has caused to extend different models of energy policy [5]. IESs can increase total system efficiency and improve energy system's reliability. In addition, it can provide significant opportunities, such as increasing the penetration RESs and preparing a suitable basis for the efficiency enhancement of the mechanical energy storages, with the aim of developing the environmental and economic performance of the energy systems compared to the conventional energy systems [6].

The tendency to integrate the energy networks from the conceptual point of view, as well as the development of the required equipment for this integration from the industrial point of view, have caused that researchers have pursued novel concepts and frameworks to deal with optimal energy management of IESs [7]. In this context, SES and SEH have been presented as a promising paradigm to model and manage multi-energy systems [8]. Many numbers of researchers have done these two concepts to operate the IESs and shown that this new framework can lead to better performance than the traditional framework. Therefore, all of this achievement can smooth the way to reach sustainability in future energy systems. Gu et al. [9] have been designed an IES optimization method to improve the utilization of wind power energy by considering the thermal inertia of the building and the regional heat network. Kholardi et al. [10] have investigated the optimal energy management of the IES consists of a power, gas, and hydrogen network considering a hub energy concept. Ren et al. [11] have presented a multi-objective optimization problem to achieve the optimal configuration and performance of a hybrid combined cooling, heating, and power system driven by different energy resources such as natural gas, solar and geothermal energy.

Investigation of RESs and smart grid technologies such as Demand Response Programs (DRP) with the energy hub concept has created a new concept which is named SEH. Considering these issues to deregulated energy systems increases the reality of these researches and makes them practical. In this regard, Rakipour et al. [12] have presented a probabilistic optimal operation of an energy hub, with the participation of DRP in the electrical power and cooling sector. In another study, electrical and thermal DRP is given in [13] by the implementation of the price-based DRP through the distribution system operator. Also, with the aim of DRP implementation, tri-objective optimal EHM is investigated in [14], in which, the objective functions include operation cost, emission pollution, and the deviation of the electrical load profile from its desired value.

Energy systems in the real case have faced many uncertainties. The uncertain parameters could be increased by implementing the integration of the energy system due to raising energy interaction between different energy sectors [15]. Nevertheless, this integration basis can facilitate to find better solutions to deal with uncertainty, considering a correct management. Therefore, uncertainty analysis as the main concern for decision-makers should be considered a key point in the decision process of SES energy management to give confidence levels for decision-makers. The three novel operational scheduling approaches based on Mixed-Integer Linear Programming (MILP), Conditional Value at Risk (CVaR), and robust optimization are investigated in [16] for Integrated Energy Management System (IEMS) in the presence the hydrocarbon natural gas system, aiming to mitigate the renewable generation uncertainties. With considering the uncertainties of electrical demand and price, photovoltaic generation, and also electrical vehicles, the day-ahead bidding strategy is proposed for managing energy hub as a two-stage stochastic optimization problem in [17]. In [18], a bi-level stochastic programming problem model is presented for operating energy hub. Energy hub connected to power grid and gas network and energy hub manager follow to maximize its profit by offering electricity and heat prices to the clients. Model uncertainty is given in electricity demands, pool prices, and the electricity prices offered by the rival managers. Also, the proposed bi-level nonlinear stochastic program is transformed into an equivalent linear single-level one, using the KKT optimality conditions and the strong duality condition.

On the other hand, mechanical energy storage systems have been more taken attention to a large number of energy-storing applications, due to cost-effective and friendly environment. In this context, Zhang et al. [19] optimized the operating strategy of a hybrid energy storage system, comprising an adiabatic compressed air energy storage system, combined with a wind turbine and thereby, increased the successful wind power delivery to the local grid to over 93%. Meyer et al. [20] optimized the energy operating strategy of a solar concentrating plant with a thermal storage unit under partial-load operation and increased the efficiency and benefits of the power plant. Zhao et al. [21] employed nonlinear modeling approached to find a flexible yet optimal operation framework for pumped hydropower electricity storage systems and proved the effectiveness of their developed framework under severe operating conditions. In Ref. [22], a multi-objective energy management approach has been presented to obtain the optimum performance of the solar-powered CCHP system connected with a thermal storage unit.

Multi-generation energy storage systems as modern mechanical energy storages, offering multi-generation as output, are new technical solutions to increase total energy efficiency and reliability of an IES with improving integration between different energy networks. High-temperature heat and power storage (HTHPS) is a new generation of electricity storage technology that has received special interest from the leading energy companies in Northern Europe [23]. A steam-based configuration of this technology was designed, simulated, and tested in a pilot-scale by energy specialists of Siemens, Alphabet, etc. in Germany [24]. The idea of such an energy storage system is the store the surplus power of renewable power plants as heat at high temperatures (charging process) and use this heat to drive a Rankine cycle to cogenerates heat and electricity just in the form of a conventional steam-based CHP plant (discharging mode) [25]. Inspired by this innovation, Arabkoohsar et al. [26] launched the idea of an air-based design of this technology (i.e. the power block comes in a regular multi-stage gas turbine plant). The advantage of air-based HTHPS compared to its steam-based design is that owing to the fast start-up time an air-based system can be used as a real energy storage system while for the steam-based in which the start-up time is in the order of a couple of hours, the application is different. Moreover, a dynamic market analysis of a novel tri-generation CAES coupled with a wind farm in the Danish electricity system has been presented in [27]. In this reference, to improve the system performance, energy storage system has been proposed as a multi-stage turbine and compressor for the cogeneration of heat, cooling, as well as electricity. Arabkoohsar and Andresen [28] have optimized the operation strategy of an electricity-cold generation energy storage technology parallelized with large-scale solar assisted absorption chiller by the use of non-linear optimization techniques.

3 Executed Tests and Experiments

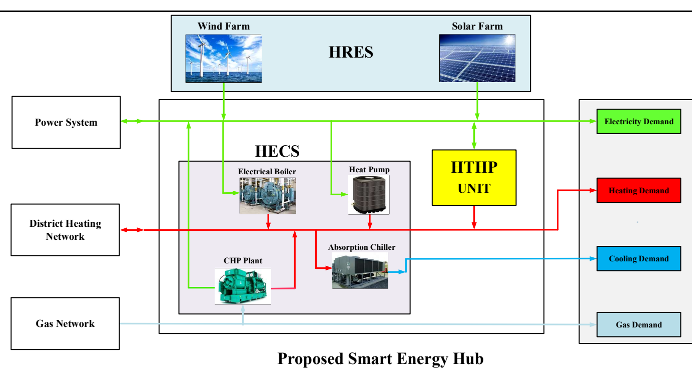
3.1 Test Plan, Standards, Procedures, and Methodology

Based on the proposed project definition, the test plan has been considered as follows:

1- **System components modeling:** This experiment has been carried out for all components of the proposed SES and their performance have been checked separately at the first, with the aim of obtaining exact modeling.
2- **Deterministic optimal operation:** In this experiment, we have been tested different scenarios contains finding the best topology of the proposed SES and detecting optimal sizing for the proposed multi-generation energy storage as well as investigating the effect of the proposed multi-generation energy storage system on the proposed energy hub performance.
3- **Stochastic optimal operation:** In this experiment, uncertainty analysis and proposing a stochastic multi-objective programming framework to reach a unified optimal operation scheme of the proposed SES has been carried out. First, the uncertain parameters of the system are modeled and then different stochastic optimization methods are carried out to reach the optimal operation.
4- **Energy market analyses:** Two main scenarios are considered in this experiment for testing. The first one is the proposed local SES modeling as a prosumer in a competitive environment of the energy market and investigating its participation in the energy market. Investigating DRP for different energy carriers to increase the energy management flexibility with participating in the system's demands in the energy management of the proposed SHE is also the second scenario for this experiment.

3.1.1 Test Specification SES-MGES-TC2.TS2

Table 2. The test specifications items

Reference to Test Case	SES-MGES-TC2
Title of Test	Co-simulation of SES-MGES-TC2
Test Rationale	Running the proposed SHE based on different models including static and dynamic model gives for HTHP storage unit.
Specific Test System (graphical)	

Target measures	• The amount of power exchange between SEH with power system. • The amount of Heat exchange between SEH with District Heating Network. • The amount of gas purchased from gas network. • The amount of energy exchange between energy conversion systems. • The amount of energy exchange for storage system.
Input and output parameters	Input: • The parameters belong to different part of system. • Forecasted generation of renewable energy resources. • Forecasted energy price for upstream energy networks. • Forecasted energy demand. Output: • The amount of energy exchange between SEH and upstream energy networks • The amount of energy exchange between energy conversion systems. • The amount of energy exchange for storage system.
Test Design	*1)* Insert input data *2)* Running the optimization problem for static model *3)* Saving the result *4)* Running the optimization problem for dynamic model *5)* Saving the result
Initial system state	Baseline scenario.
Suspension criteria / Stopping criteria	*Maximum number of iterations for optimization algorithm*

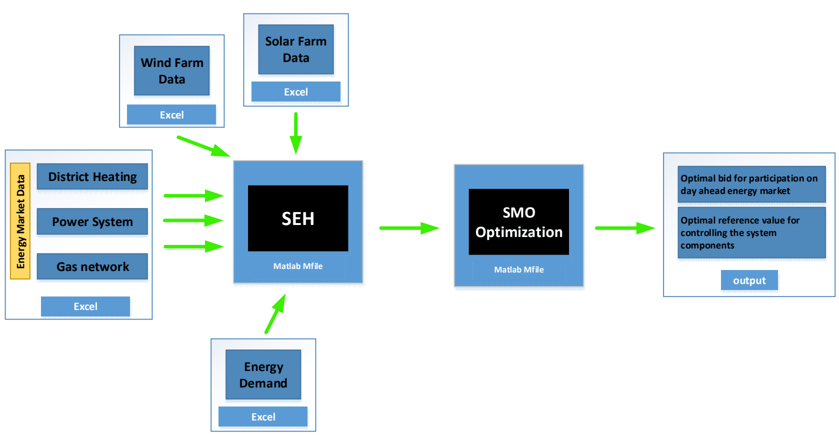


Figure 1. The test set-up configuration

3.2 Test Set-up(s)

Offline optimization has been investigated for the proposed project by using MATLAB software and EXCEL and the test setup is figured at Figure 1. In this test, optimal day-ahead scheduling of the proposed SEH, containing HTHPS system and local renewable energy system has been studied. The proposed SEH was considered as a prosumer and its participation on the day ahead energy market has been investigated. The study of this case is carried out as offline optimal operation for day ahead scheduling to find the best bidding strategy and charging and discharging modes. Optimization problem was applied to reach the best plan for next day by considering a quarterly planning horizon for upcoming uncertainty parameters including wind, solar, energy price, and load.

4 Results and Conclusions

4.1 Discussion of Results

To achieve a precise analysis and investigate the proposed energy hub model advantages, in this paper, three different scenarios have been assumed by considering 50%, 75%, and 100% penetration factors for renewable resources. Moreover, four cases are also studied according to Table 3. The sign √ demonstrates that the proposed energy hub of a case contains which types of equipment as well as the prosumer role, on the contrary, the symbol × shows that it does not include the equipment or prosumer role in this case.

Table 3. Classifications of case studies

Case studies	HECS	HRES	HTHPS	Prosumer
Case 1	√	×	×	×
Case 2	√	×	×	√
Case 3	√	√	×	√
Case 4	√	√	√	√

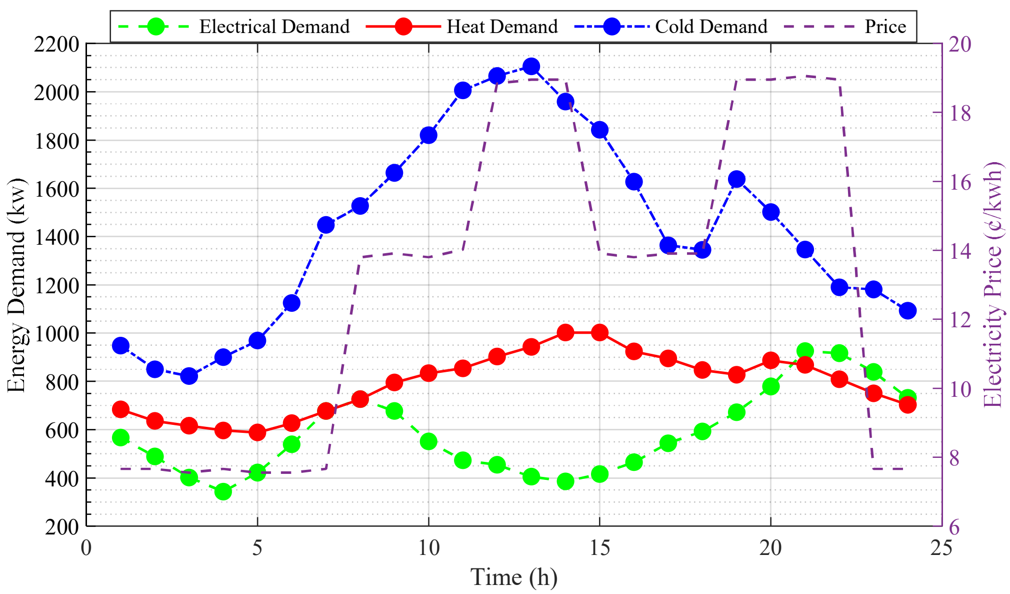


Figure 2. Energy demand and electricity price for the proposed Smart Energy Hub

The parameters regarding the energy converter devices, the energy demand of the proposed hub, energy prices, and carbon emission coefficient, as well as carbon emission management coefficient, have been considered according to [29]. Figure 2 demonstrates the energy demand of the case study. Moreover, the data for energy conversion systems has been considered according to [30]. The 3-stages HTHPS unit is employed for the case study, and physical and its technical parameters have been considered according to [6]. The tariff regime of the bonus and penalty coefficients are set based on the time-of-use electricity pricing regime as follows:

- $\beta_1 = 1.3\ \ \forall t\ \in$ 19:00–22:00, 12:00–14:00. (Peak hours)
- $\beta_2 = 1.0\ \ \forall t\ \in$ 8:00–11:00, 15:00–18:00. (Flat hours)
- $\beta_3 = -1\ \ \forall t\ \in$ 0:00–7:00, 23:00–24:00. (Bottom hours)

Table 4. Daily operation and emission cost ($) for cases 3 and 4 in different scenarios

Scenario #	***First Cost Function***		***Second Cost Function***	
	Case 3	**Case 4**	**Case 3**	**Case 4**
S1	-3.1187e+05	-3.5021e+05	1.0286e+04	1.0162e+04
S2	-5.3422e+05	-6.5440e+05	9.8002e+03	7.8421e+03
S3	-7.3679e+05	-8.3152e+05	9.5190e+03	7.6350e+03

The results obtained for different scenarios of cases 3 and 4 regarding the economic and environmental objectives are listed in Table 4. These results show the most optimal solution for the single objective decisions when the energy hub operator only considers one of the objectives of the proposed operation problem. As can be seen from these results, the proposed system can properly support the increment of renewable energy penetration. Respectively, 12.29%, 22.50%, and 12.86% decrement on operation cost is acquired by applying HTHPS unit for scenarios 1, 2, and 3. Moreover, the improvement in the emission cost is observed by reducing 1.21%, 19.98%, and 19.79% for the second cost function in different scenarios for case 4. It is worth mentioning that the negative value obtained for operation cost means the energy hub reaches profit.

Table 5 demonstrates the results obtained for different cases considering different weighting coefficients for the objective functions. By comparing the results obtained for cases 1 and 2, the energy hub owner, respectively, decreases by 39.5% and 5.0% its operation and environmental cost by participating in the energy market as a prosumer. However, regarding the results obtained for cases 1 and 2 with considering w_1=0 and w_2=1, the prosumer role cannot be effective when the hub doesn't utilize any renewable sources (i.e., case 2).

Based on the obtained results for cases 3 and 4, it can be seen that renewable resources can bring profit, which has been calculated as a negative cost, for the hub owner. HTHPS system also improves the system performance by increasing the system profit by 817.8 $ than case 3.

Table 5. Total operation and emission cost ($) for different cases considering different weighting coefficients

Case #	w_1**=1,** w_2**=0**		w_1**=0.5,** w_2**=0.5**		w_1**=0,** w_2**=1**	
	F1	***F2***	***F1***	***F2***	***F1***	***F2***
C1	4654.8	766.5	5233.7	312.1	5353.0	210.1
C2	1183.3	798.9	3163.4	296.3	5353.0	210.1
C3	-7367.9	560.1	-5603.8	203.7	-3673.1	95.1
C4	-8315.2	554.11	-6421.6	197.4	-3779.8	76.3

Respectively, figures (3) and (4) demonstrate the results obtained for Scenario 3 in Case 4

(S3-C4), regarding electrical and heat energy balance. As seen in these figures, the energy balance has been meted for all grids of the energy hub. HTHPS system is on the charging mode from 1 am to 2 pm because of high renewable generation availability and on the discharging mode from 7 pm to 11 pm.

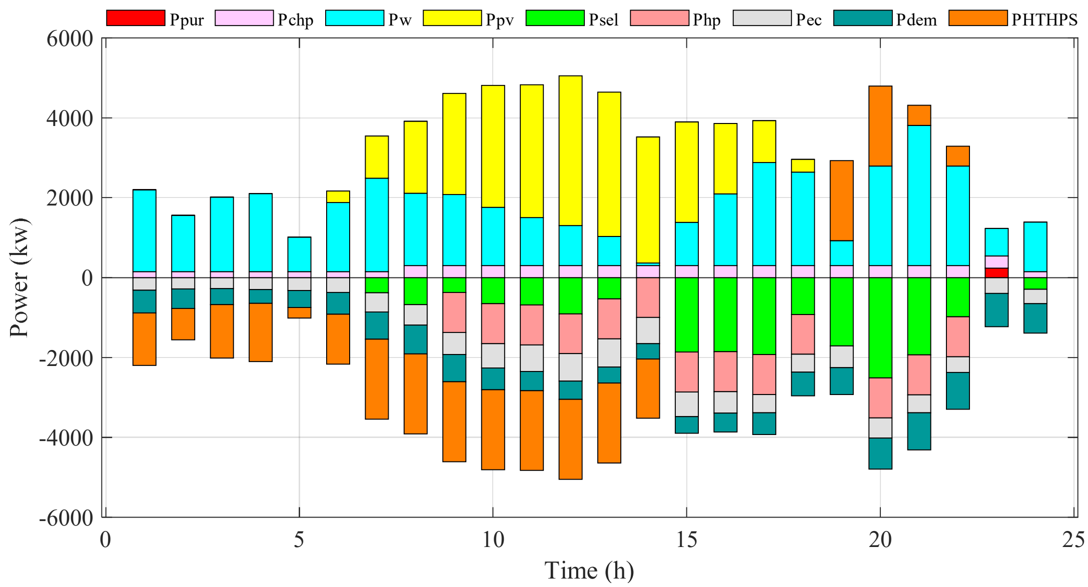


Figure 3. Results obtained for S3-C4 regarding electrical energy balance

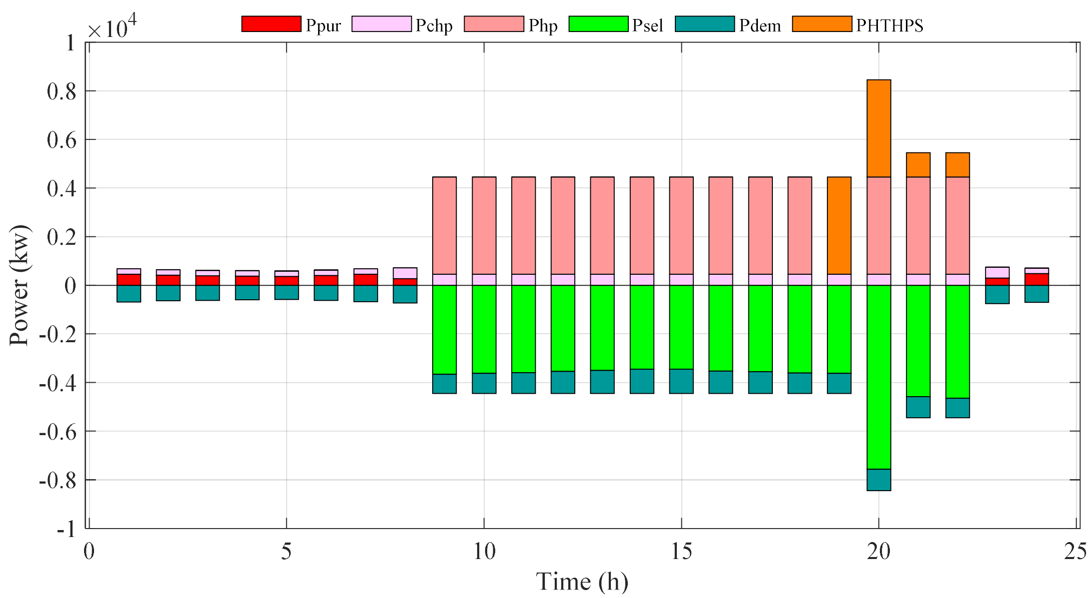


Figure 4. Results obtained for S3-C4 regarding heat energy balance

As can be seen from figures (3) and (4), except for bottom hours when the energy hub would be penalized for injecting energy to upstream networks, the heat pump is working on the maximum power for the rest of the hour, due to its high efficiency. Moreover, HTHPS unit supports the energy hub system to balance its energy transaction with upstream energy networks. Hence, the proposed SEH can properly participate in the energy market and manage the renewable energy generation fluctuations.

4.2 Conclusions

The ERIGrid 2.0 Lab Access program provided a pleasant opportunity for both User group and hosting organization for sharing their knowledge as well as it was a good opportunity for the researchers to improve their research to get practical based on the laboratory assessments. Therefore, we intend the results obtained from the proposed project provides context for larger projects, with the aim of more collaboration with SESA-Lab in the future. Moreover, with the collaboration created through this project, the partners can continue their relationship and propose a new solution in light of the European Union innovation program goals. The Holistic Test Description (HTD) also brings a clear structure to handle the project and It can help to define the scope of the experiment. Moreover, by applying that, it can start right away for the experiment because the lab environment for the use case has been defined. HTD can also be considered as the reference to reach the goal at the end of the experiment.

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