Chapter 4
Solar Thermal Energy Storage for Residential Sector

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4.1 Introduction

An energy hub system is a multi-generation system where multiple energy carriers are converted, stored [1], and distributed to meet heat and electrical demand [2]. Converter devices can be solar thermal storage, CHP, and boiler. Solar thermal storage is used to convert solar irradiation to heat. Other technologies such as CHP and boiler are also suggested to convert natural gas to electricity and heat.

4.1.1 Literature Review

In this chapter, energy management system inside a residential energy hub system has been investigated. In order to minimize discomfort and operation costs, a new efficient algorithm for energy management system inside a residential energy hub system is presented in [3]. Stochastic programming is implemented in [4] for modeling optimal scheduling of energy hub systems. To minimize energy cost based on availability of each expected demand, resources, and prices, a new optimal management algorithm for optimal management of distributed energy resources in facilities with energy hub systems is provided in [5]. A day-ahead dynamic optimal

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B. Mohammadi-Ivatloo, F. Jabari (eds.), *Operation, Planning, and Analysis of Energy Storage Systems in Smart Energy Hubs*,
https://doi.org/10.1007/978-3-319-75097-2_4

operation and dispatch strategies of energy hub systems are presented in [6] to minimize daily operation cost. A stochastic scheduling for wind integrated smart energy hub system problem is presented in [7].

Energy management systems inside smart home have been investigated as follows: In [8], prioritizing operation of controllable appliances from the customer's viewpoint has been investigated to minimize customer energy costs. An energy management solution is presented in [9] to combine and describe advantages and features of both energy hub system framework and demand side management methods. In order to tackle the household load scheduling problem with uncertain ambient temperature and hot water demand, an interval number optimization method is provided in [10]. An optimization problem is proposed in [11] which simultaneously selects, sizes, and determines optimal operation of residential heating systems. In order to reduce electricity price of smart buildings and manage battery storage and temperature of thermal appliances, a new control algorithm is presented in [12]. In [13], various optimization techniques applied to demand side management system have been reviewed.

Literature review about solar thermal storage can be expressed as follows: Performance of a liquid thermocline and a packed bed are compared with each other in [14] for an off-shore wind-TP system. To reduce heat pumps operational temperature differences, application of hybrid pumped thermal electricity storage is studied and provided in [15]. To determine operational state of power generation unit based on thermal and electric demand, a new thermal storage strategy is provided in [16]. Economic impact of designing thermal energy storage system is analyzed and provided in [17]. Technologies about high temperature solar receivers associated with power tower systems and power dish are compared and provided in [18]. A new distributed energy resources customer adoption model of thermal energy storage is provided in [19] to improve tracking of losses based on temperature of ambient and storage. Summary of different thermal energy storage systems and solar thermal storage materials is provided and compared in [20].

4.1.2 Novelty and Contributions of This Research

According to our knowledge, there is no research available about optimal energy consumption scheduling of a residential energy hub system in the presence of solar thermal storage system. So, in this chapter, a residential hub energy system model containing CHP generator, boiler, electrical storage, solar thermal storage, and smart appliance is proposed. Two cases studied are used to assess the impacts of solar thermal energy storage on operation cost of residential energy hub system. According to the above information, the novelty and contributions of this paper are presented below:

- Energy management of a residential hub energy systems is proposed in the presence of solar thermal energy storage.

- Scheduling optimal performance of all equipment within the residential hub energy systems.
- Scheduling and prioritizing performance of smart appliances in the presence of distributed energy sources with the aim of minimizing total operation cost of residential hub energy systems.
- Employing mixed-integer programming (MIP) to guarantee global optimal.

4.1.3 *Chapter Organization*

The rest of the proposed chapter is categorized as follows: The mathematical model has been presented in Sect. 4.2. Input data, case study, and the results are provided in Sect. 4.3. Discussion and conclusions are presented in Sect. 4.4.

4.2 Problem Formulation

As shown in Fig. 4.1, the proposed residential hub energy system model contains CHP generator, boiler, battery storage system, solar thermal storage, and smart appliances. Optimal energy consumption scheduling of a residential energy hub system has been formulated in this section. The objective function includes operation cost of equipment in a residential energy hub system which can be presented as:

$$\mathrm{OBJ}=\left\{\begin{array}{l}\sum_{j=1}^{J}\sum_{t=1}^{T}\frac{\left(\lambda^{\mathrm{Gas}}\times P_{j,t}^{\mathrm{CHP}}\right)}{\eta^{\mathrm{CHP}}}+\sum_{j=1}^{J}\sum_{t=1}^{T}\frac{\left(\lambda^{\mathrm{Gas}}\times P_{j,t}^{\mathrm{Boiler}}\right)}{\eta^{\mathrm{Boiler}}}\\ +\sum_{j=1}^{J}\sum_{t=1}^{T}\mathrm{MC}^{\mathrm{elec}}\times\mathrm{DR}^{\mathrm{elec}}+\sum_{j=1}^{J}\sum_{t=1}^{T}\lambda_{t}^{\mathrm{Grid}}\times P_{j,t}^{\mathrm{Import}}\\ -\sum_{j=1}^{J}\sum_{t=1}^{T}P_{j,t}^{\mathrm{export}}\times\lambda^{\mathrm{export}}\end{array}\right\}\times\Delta t \tag{4.1}$$

The objective function includes operation cost of CHP, boiler, battery storage system, cost of purchased power from grid, and profit of selling power to grid.

4.2.1 *Combined Heat and Power (CHP) Generator*

The output power of CHP generator should not exceed its designed capacity which is presented as [21]:

$$P_{j,t}^{\mathrm{CHP}}\leq\mathrm{CAP}^{\mathrm{CHP}} \tag{4.2}$$

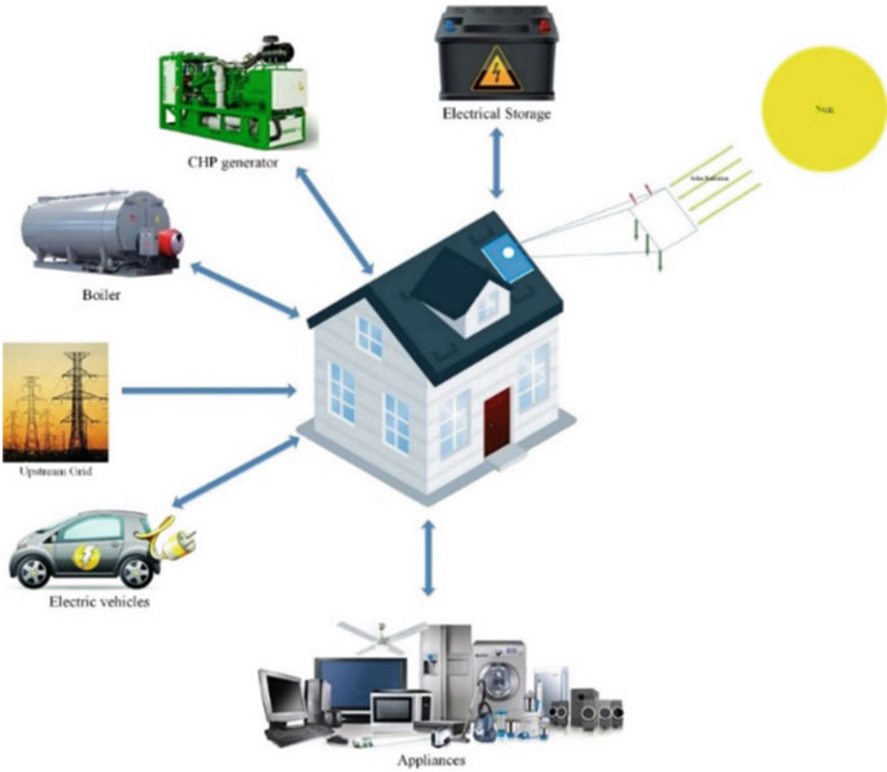

Fig. 4.1 Schematic diagram of proposed residential hub energy system model

4.2.2 Boiler

The output power of boiler as well as CHP generator should not exceed its designed capacity. In this regard, Eq. (4.3) is presented [21].

$$P_{j,t}^{\text{Boiler}} \leq \text{CAP}^{\text{boiler}} \tag{4.3}$$

4.2.3 Battery Storage System

The model of central battery storage system which is available for all residential hub energy system sector is obtained from [21]. The technical constraints related to battery storage system are described as follows:

The output power of battery storage system as well as other equipment should not exceed its designed capacity and therefore Eq. (4.4) is presented.

$$\sum_{j=1}^{J} \mathrm{SOC}_{j,t}^{\mathrm{elec}} \le \mathrm{CAP}^{\mathrm{elec}} \tag{4.4}$$

The state of charge of battery storage system at time t is equal to the state of charge of battery storage system at time $t-1$ plus the charged amount at time t minus the discharge power at time t. Also, discharge rate of battery storage at time t should not exceed state of charge of battery storage at time $t-1$. Mathematical formulation of mentioned statements is provided as follows:

$$\mathrm{SOC}_{j,t}^{\mathrm{elec}} = \mathrm{SOC}_{j,t+1}^{\mathrm{elec}} + \left(\mathrm{CR}_{j,t}^{\mathrm{elec}} \times \eta^{\mathrm{elec}} \times \Delta t\right) - \left(\frac{\mathrm{DR}_{j,t}^{\mathrm{elec}} \times \Delta t}{\eta^{\mathrm{elec}}}\right) \tag{4.5}$$

$$\frac{\mathrm{DR}_{j,t}^{\mathrm{elec}} \times \Delta t}{\eta^{\mathrm{elec}}} \le \mathrm{SOC}_{j,t-1}^{\mathrm{elec}} \tag{4.6}$$

The charge and discharge rate of battery storage system should not exceed charge and discharge limits of battery storage:

$$\mathrm{CR}_{j,t}^{\mathrm{elec}} \le M^{\mathrm{elec}} \times B_{j,t}^{\mathrm{elec}} \tag{4.7}$$

$$\mathrm{DR}_{j,t}^{\mathrm{elec}} \le M^{\mathrm{elec}} \times \left(1 - B_{j,t}^{\mathrm{elec}}\right) \tag{4.8}$$

The total state of charge of the battery storage system at each time period is equal to the sum of state of charge of sub-batteries storage system at each residential hub energy system sector:

$$\mathrm{SOC}_{t}^{\mathrm{Totalelec}} = \sum_{j=1}^{J} \mathrm{SOC}_{j,t}^{t} \tag{4.9}$$

In order to avoid net accumulation, state of charge of the battery storage system at the end of the each sample day should be equal to the initial value of battery storage. In the proposed model, the initial state of charge of battery is set as variable to determine the best initial state of charge for one day utilization [21]. Otherwise, it can be set as parameter which is obtained from the end of previous day.

$$\mathrm{SOC}_{1}^{\mathrm{Totalelec}} = \mathrm{SOC}_{48}^{\mathrm{Totalelec}} = S^{\mathrm{elec}} \tag{4.10}$$

The charge and discharge rate of battery storage system should not exceed the charge and discharge limits of battery storage which are defined by the battery manufacturer. For this reason, Eqs. (4.11) and (4.12) are presented.

$$\sum_{j=1}^{J} \mathrm{CR}_{j,t}^{\mathrm{elec}} \leq \mathrm{CRL}^{\mathrm{elec}} \tag{4.11}$$

$$\sum_{j=1}^{J} \mathrm{DR}_{j,t}^{\mathrm{elec}} \leq \mathrm{DRL}^{\mathrm{elec}} \tag{4.12}$$

4.2.4 Exchanged Power Between the Residential Energy Hub System and Upstream Grid

The imported/exported power from/to grid at each period of time is calculated as follows:

$$P_{j,t}^{\mathrm{Import}} \leq M^{\mathrm{Grid}} \times B_{j,t}^{\mathrm{Grid}} \tag{4.13}$$

$$P_{j,t}^{\mathrm{export}} \leq M^{\mathrm{Grid}} \times \left(1 - B_{j,t}^{\mathrm{Grid}}\right) \tag{4.14}$$

4.2.5 Appliances

Household appliances can be noted as fridge, washing machine, dishwasher, etc. The appliances should be ON between the specific time periods which is determined by the owner of residential energy hub system. Also, each appliance must be active continuously (θ) based on the predefined length of time ($P_{j,\,i}$) within the determined time period which is determined by the owner of residential energy hub system and for this reason, Eq. (4.15) which is obtained from [21] is provided as follows:

$$\sum_{t=T_{j,i}^{\mathrm{Start}}}^{T_{j,i}^{\mathrm{Finish}}-P_{j,i}} \omega_{j,i,t-\theta} \tag{4.15}$$

4.2.6 Solar Thermal Storage

The model of solar thermal storage is obtained from [19]. Solar thermal storage converts solar irradiation to thermal which is used directly or stored in the thermal storage system to be used in other periods. The technical constraints related to thermal storage are described as follows:

The state of charge of solar thermal storage at time t is equal to the state of charge of solar thermal storage at time $t-1$ plus the charged heat minus the discharged heat and loss of heat at time t. Also, state of charge of solar thermal storage should not exceed its designed capacity. In this regard, Eqs. (4.16) and (4.17) are presented.

$$H_t^{\text{stored}} = H_{t-1}^{\text{stored}} + \eta^{\text{ch,Ther}} \times H_t^{\text{ch,Ther}} - \sum_j^J \frac{H_{j,t}^{\text{dch,Ther}}}{\eta^{\text{dch,Ther}}} - H_t^{\text{loss,Ther}} \tag{4.16}$$

$$H_t^{\text{stored}} \le \text{CAP}^{\text{Ther}} \tag{4.17}$$

The imported/exported power from/to solar thermal storage at each period of time is limited by discharge/charge rate. For this reason Eqs. (4.18) and (4.19) are presented.

$$H_t^{\text{ch,Ther}} \le B_t^{\text{ch,ther}} \times \text{CAP}^{\text{Ther}} \times H^{\text{ch,Ther,max}} \tag{4.18}$$

$$H_{j,t}^{\text{dch,Ther}} \le B_{j,t}^{\text{dch,ther}} \times \text{CAP}^{\text{Ther}} \times H^{\text{dch,Ther,max}} \tag{4.19}$$

Heat losses of solar thermal storage depend on the capacity of solar thermal storage, ambient temperature, and amount of stored energy in the solar thermal storage. So, the heat losses can be formulated as follows:

$$H_t^{\text{loss,Ther}} = H_{t-1}^{\text{stored}} \times \theta^{\text{storage}} + \theta^{\text{static}} \times E_t^{\text{unuse}} \tag{4.20}$$

The unused energy of solar thermal storage system can be calculated based on the minimum/maximum temperature of solar thermal storage, ambient temperature, and the capacity of solar thermal storage as follows:

$$E_t^{\text{unuse}} = \text{CAP}^{\text{Ther}} \times \frac{T^{\min} - T_t^{\text{amb}}}{T^{\max} - T^{\min}} \tag{4.21}$$

The amount of converted solar irradiation to the heat at each period of time depends on the solar irradiation, efficiency, and the surface area of thermal energy storage panel. Also, the charge rate of solar thermal storage at each period is limited by the converted amount of solar irradiation to heat. For this reason, Eqs. (4.22) and (4.23) are presented.

$$Q_t = \varphi_t^{\text{solar}} \times A^{\text{app}} \times \gamma^{\text{Ther}} \tag{4.22}$$

$$Q_t \ge H_t^{\text{ch,Ther}} \tag{4.23}$$

4.2.7 Energy Balances

Energy balance constraint between the production and consumption power can be written as:

$$\begin{aligned}&\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{\theta=1}^{P_{j,i}-1} P_i^{\text{Consump}} \times \omega_{j,i,t-\theta}\\&= P_{j,t}^{\text{CHP}} + \text{DR}_{j,t}^{\text{elec}} - \text{CR}_{j,t}^{\text{elec}} + P_{j,t}^{\text{Import}} - P_{j,t}^{\text{export}}\end{aligned} \tag{4.24}$$

4.2.8 Thermal Balances

The heat balance constraint between producers and consumers can be written as:

$$H_{j,t}^{\text{Demand}} = \alpha^{\text{CHP}} \times P_{j,t}^{\text{CHP}} + P_{j,t}^{\text{Boiler}} \tag{4.25a}$$

With considering the solar thermal storage, Eq. (4.25a) will be updated as:

$$H_{j,t}^{\text{Demand}} = \alpha^{\text{CHP}} \times P_{j,t}^{\text{CHP}} + P_{j,t}^{\text{Boiler}} + H_{j,t}^{\text{dch,Ther}} \tag{4.25b}$$

4.3 Numerical Simulation

The proposed residential hub energy system model contains CHP generator, boiler, battery storage, solar thermal storage, and smart appliances. The entire time horizon of case study is 24 h with time interval of 30 min. The starting time of case study is from 8 AM and the ending time is 8 AM of the next morning. The proposed optimization problem has been studied in two case studies with and without considering the effect of solar thermal storage on total operation cost of residential hub energy system.

Case study 1 is related to the optimal scheduling of residential hub energy system consumption without considering the effect of solar thermal storage. In this case, the objective is to minimize total energy cost of residential hub energy system (4.1) subject to constraints (4.2)–(4.15) and (4.25a). In the second study, the effect of solar thermal storage is considered in which the objective is to minimize the total energy cost of residential hub energy system (4.1) subject to constraints (4.2)–(4.24) and (4.25b).

4.3.1 Input Data

Technical information of solar thermal storage is presented in Table 4.1 [19]. Consumption power and operation time length of each appliance are presented in Table 4.2 [21]. All appliances except the washing machine, dish washer, and tumble dryer have constant power consumption rate during the operation time while the electrical profiles for washing machine, dish washer, and tumble dryer are presented in Fig. 4.2 [22]. Technical information of CHP, boiler, and battery storage system are provided in Table 4.3 [21]. The earliest starting time of appliances and latest finishing time of appliances are presented in Tables 4.4 and 4.5, respectively. Market price and ambient temperature are presented in Figs. 4.3 and 4.4 [23, 24], respectively. Solar irradiation is presented in Fig. 4.5 [25]. Heat demands for each residential hub energy system sector are presented in Figs. 4.6 and 4.7, respectively [21]. Natural gas price is considered to be 2.7 p/kWh and the cost of selling power to the upstream grid is set to be 1 p/kWh$_e$ [21]. It should be mentioned that the developed MIP model is implemented using CPLEX [26] in GAMS software [27].

Table 4.1 Technical information of solar thermal storage [19]

Parameters	Value	Parameters	Value
A^{app}	50 m^2	$\theta^{storage}$	5.7%
γ^{Ther}	95%	θ^{static}	5.6%
CAP^{Ther}	100 kW	$H^{dch, Ther, max}$	25%
$\eta^{ch, Ther}$	95%	$H^{ch, Ther, max}$	25%
$\eta^{dch, Ther}$	95%	T^{max}	65 °C
T^{min}	36 °C		

Table 4.2 Power consumption and length of operation time of each appliance

Appliances	Power consumption (kW) [21]	Length of operation time (h) [21]
Washing machine	Fig. 4.2	2
Dish washer	Fig. 4.2	2
Tumble dryer	Fig. 4.2	1.5
Cooker hob	3	0.5
Cooker oven	5	0.5
Microwave	1.7	0.5
Interior lighting	0.84	6
Laptop	0.1	2
Desktop	0.3	3
Vacuum cleaner	1.2	0.5
Fridge	0.3	24
Electrical car	3.5	3

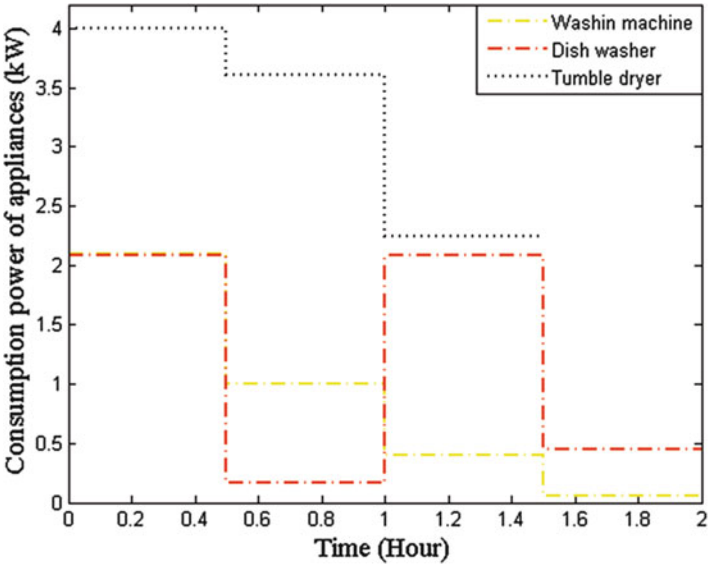

Fig. 4.2 Electricity utilization profiles of washing machine, dish washer, and tumble dryer

Table 4.3 Technical information of CHP, boiler, battery storage system, and thermal storage system

Parameter	Value
CHP	
η^{CHP}	35%
CAP^{CHP}	4 kW_e
α^{CHP}	1.3
Boiler	
η^{Boiler}	85%
CAP^{boiler}	24 kW_{th}
Battery storage system	
η^{elec}	95%
CAP^{elec}	4 kW_eh
MC^{elec}	0.005 p/kWh_e
M^{elec}	2 kW_e
CRL^{elec}	4 kW_e
DRL^{elec}	4 kW_e

4.3.2 Simulation Results

In this section the effect of solar thermal energy storage system has been investigated in two cases. In case 1, total operation cost of residential hub energy system without considering effect of solar thermal storage has been solved. In order to show the effect of solar thermal energy storage, the same problem is been solved in case 2 with considering the effect of solar thermal storage system. With comparing the results of cases 1 and 2, it can be seen that operation cost in case 2 is decreased

Table 4.4 Earliest starting time of appliances (h) [21]

Smart homes	1	2	3	4	5	6	7	8	9	10
Washing machine	12	11	–	13	–	18	14	16	11	–
Dish washer	16	14	–	11	–	22	22	20	16	–
Tumble dryer	19	17	–	14	–	1	1	23	19	–
Cooker hob	15	10	–	13	10	14	18	11	10	–
Cooker oven	11	15	–	20	13	13	–	–	19	20
Microwave	21	13	–	20	12	17	–	18	20	10
Interior lighting	18	–	20	20	22	19	–	17	20	21
Laptop	19	–	17	17	19	21	–	18	19	19
Desktop	17	–	16	–	14	19	20	22	20	–
Vacuum cleaner	18	–	19	–	20	16	22	21	21	21
Fridge	0	–	0	–	0	0	0	–	0	0
Electrical car	21	–	20	–	19	18	17	–	21	19

Table 4.5 Latest finishing time of appliances (h) [21]

Smart homes	1	2	3	4	5	6	7	8	9	10
Washing machine	20	18	–	19	–	23	18	20	15	–
Dish washer	19	16	–	14	–	1	24	22	18	–
Tumble dryer	24	21	–	17	–	6	3	1	20	–
Cooker hob	16	11	–	15	13	17	23	15	15	–
Cooker oven	12	16	–	22	16	16	–	–	24	1
Microwave	22	14	–	22	15	20	–	20	21	11
Interior lighting	24	–	2	2	4	1	–	23	2	3
Laptop	1	–	22	20	24	3	–	22	24	24
Desktop	23	–	20	–	19	1	1	1	24	–
Vacuum cleaner	2	–	23	–	1	22	4	4	4	5
Fridge	24	–	24	–	24	24	24	–	24	24
Electrical car	7	–	3	–	23	2	1	–	6	5

about 16.88%. In case 2, solar energy storage system is used to meet heat demand instead of boiler. So, the cost of gas consumption is reduced and this causes the reduction of operation cost of residential hub energy system. Comparison results of two cases related to the operation cost of residential hub energy system are studied and presented in Table 4.6.

Output power of CHP and boiler are presented in Figs. 4.8 and 4.9, respectively. In the second case study, the output power of CHP is decreased 33.60 kW. The produced heat by boiler after 12 PM has become zero and instead of boiler, heat produced by solar thermal storage is used to meet heat demand.

Charge and discharge rates and state of charge of battery storage system are provided in Figs. 4.10 and 4.11, respectively. Battery storage in the second case study is charged 6.77 kW more in comparison with case one. Also, battery storage system is discharged 6.33 kW more compared to case one. So, in the second case

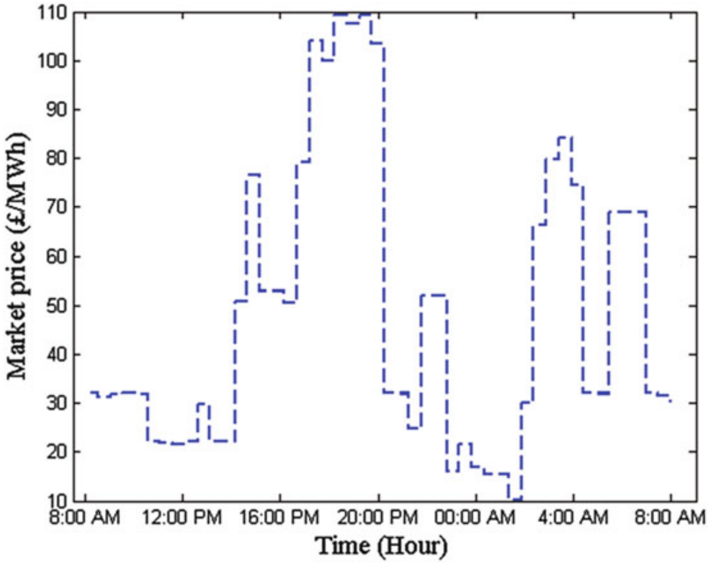

Fig. 4.3 Market price (£/MWh) [23]

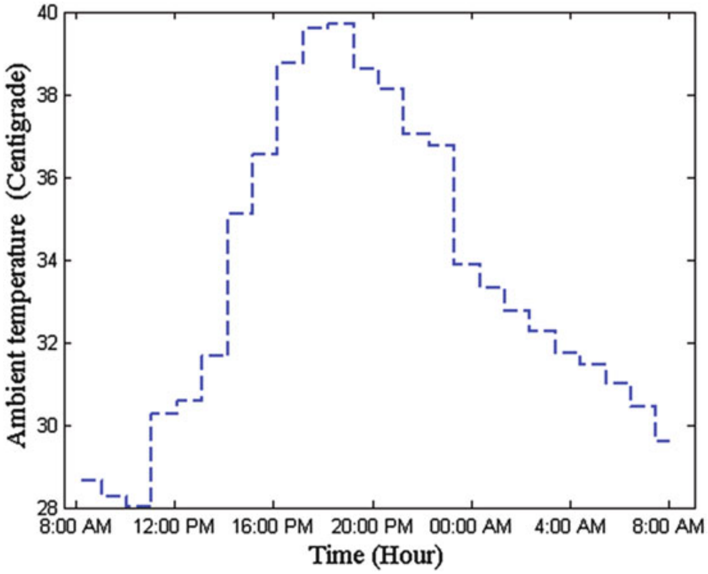

Fig. 4.4 Ambient temperature (°C) [24]

study, the state of charge of battery is 2.61 kW less in comparison with case one. Also, it can be observed that with considering the effect of solar thermal storage, battery storage system is charged and discharged more.

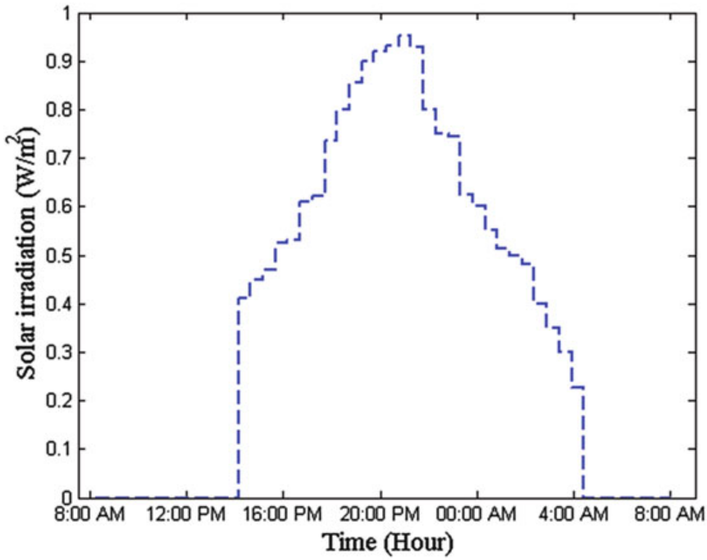

Fig. 4.5 Solar irradiation (W/m^2)

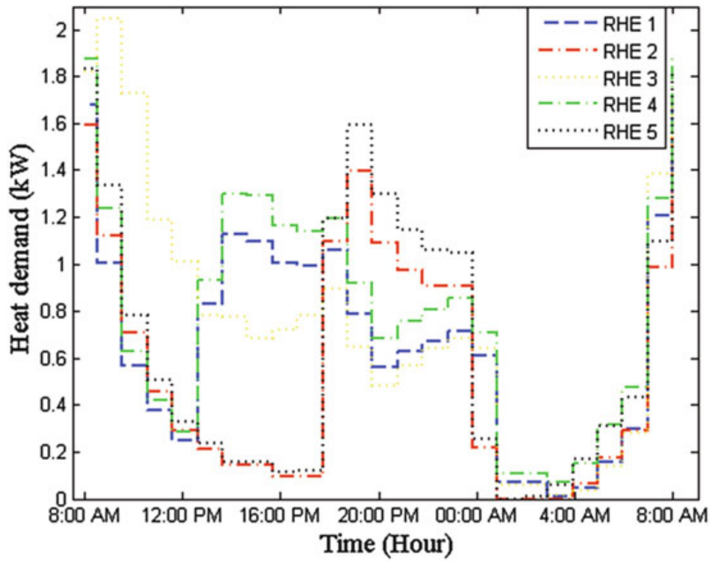

Fig. 4.6 Heat demand of sectors 1–5 in residential hub energy system [21]

The charge, discharge, state of charge, and thermal losses of solar thermal storage are presented in Fig. 4.12. It can be observed that the solar thermal storage produced 337.52 kW heat with converting the solar irradiation and discharged 164.61 kW to

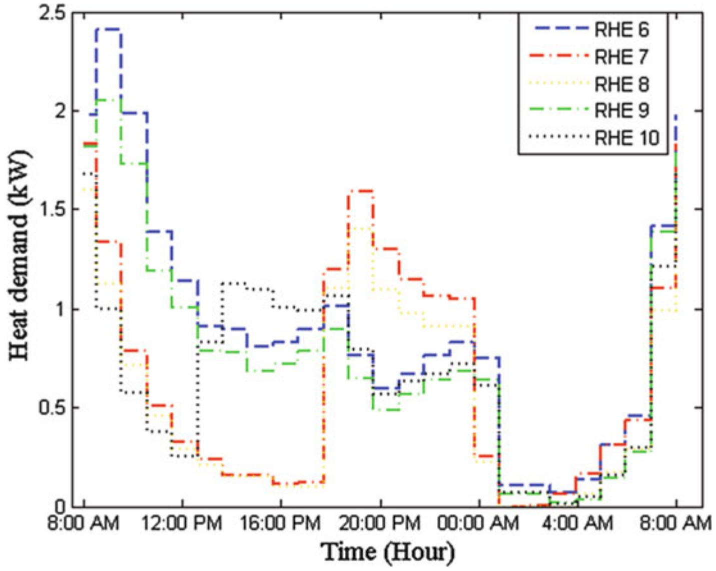

Fig. 4.7 Heat demand of sectors 6–10 in residential hub energy system [21]

Table 4.6 Total operation cost of residential hub energy system

Case 1:Without considering effect of solar thermal storage	13.9483 £
Case 2: With considering effect of solar thermal storage	11.5943 £
Cost reduction in comparison with case 1	16.88%

meet heat demand of residential hub energy system. Total losses of solar thermal storage are 147.38 kW during the 24 h study case.

Imported/exported power from/to the grid is presented in Fig. 4.13. In case 1, imported power from grid is 472.84 kW and exported power to grid is 1.9 kW. In case 2, imported power from grid is 506.89 kW. So, imported power from grid is increased 7.2% in comparison with case 1 and exported power remained constant in comparison with case 1.

The activation time of each appliance in each residential hub energy system sector for cases 1 and 2 is presented in Tables 4.7 and 4.8, respectively. It should be mentioned that each appliance is active continuously (θ) within the determined time period ($P_{j,i}$) by the owner of smart home. With comparing the obtained results from two case studies, it can be understood that the activation time of some appliances is only shifted in small time intervals.

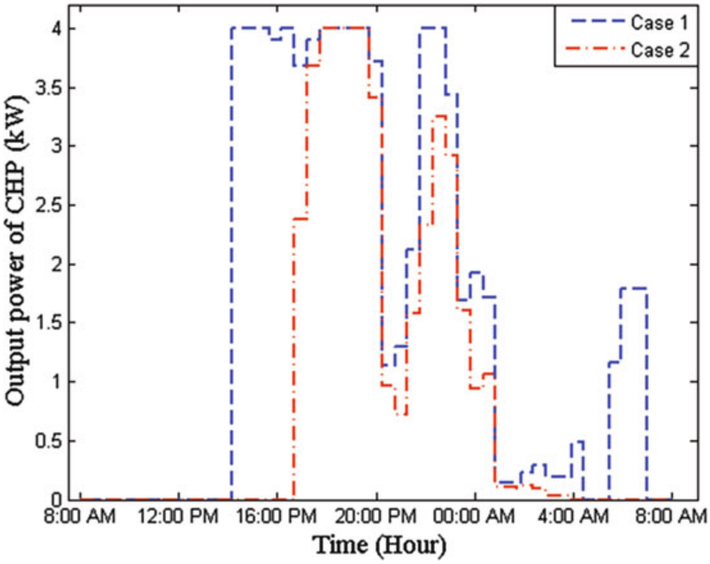

Fig. 4.8 Output power of CHP (kW)

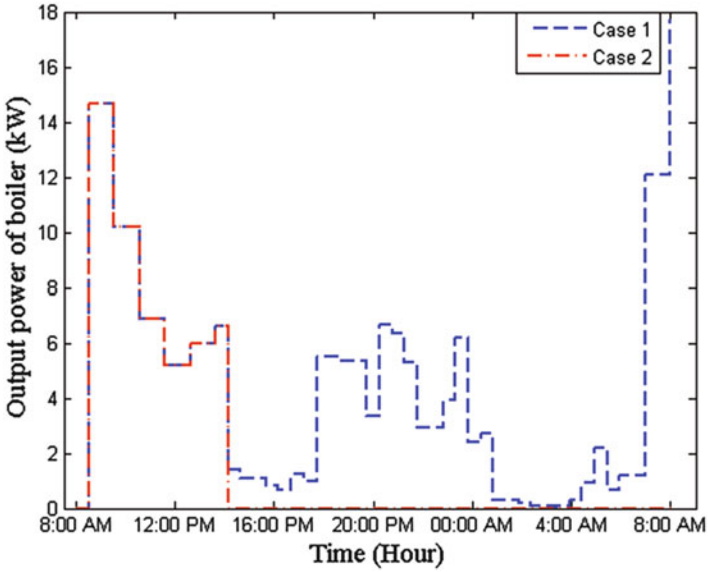

Fig. 4.9 Output power of boiler (kW)

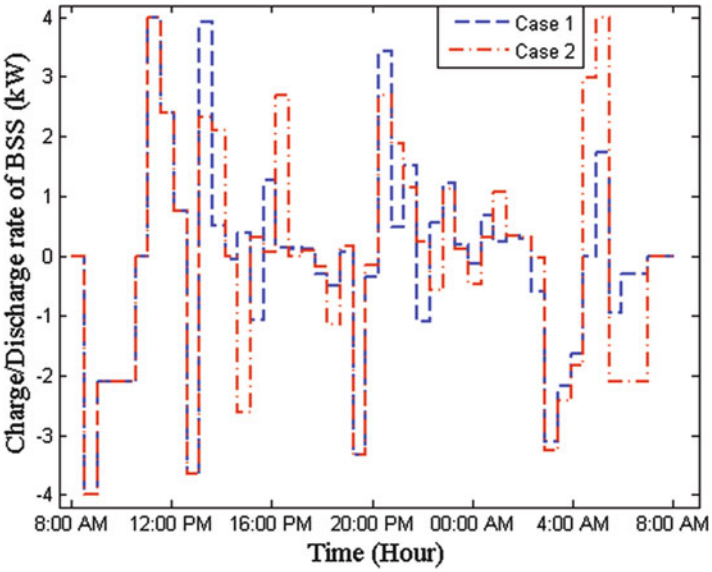

Fig. 4.10 Charge/discharge rate of battery storage system (kW)

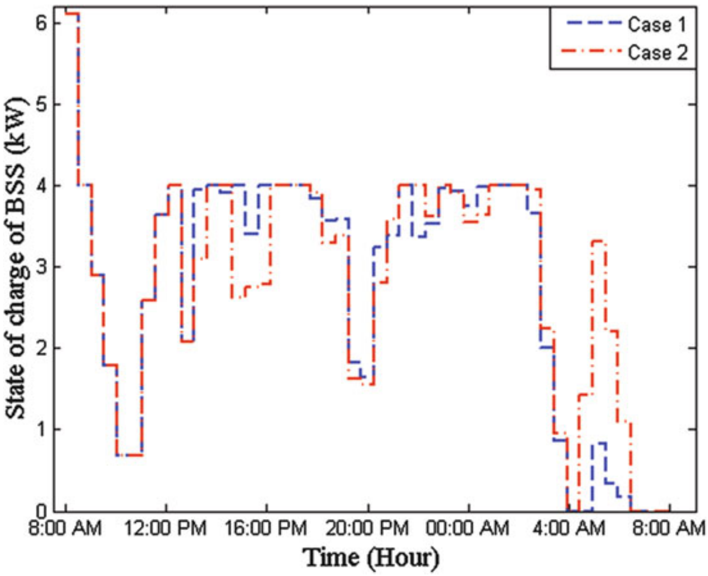

Fig. 4.11 State of charge of battery storage system (kW)

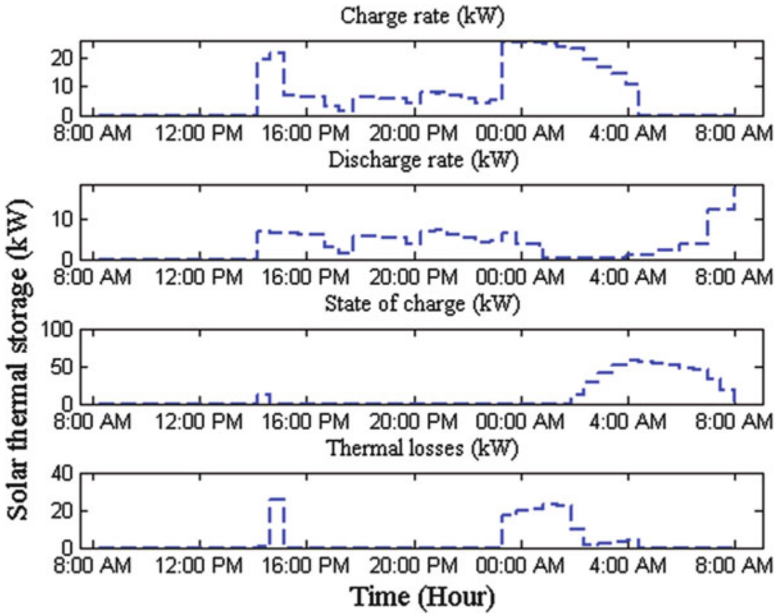

Fig. 4.12 Solar thermal storage (kW)

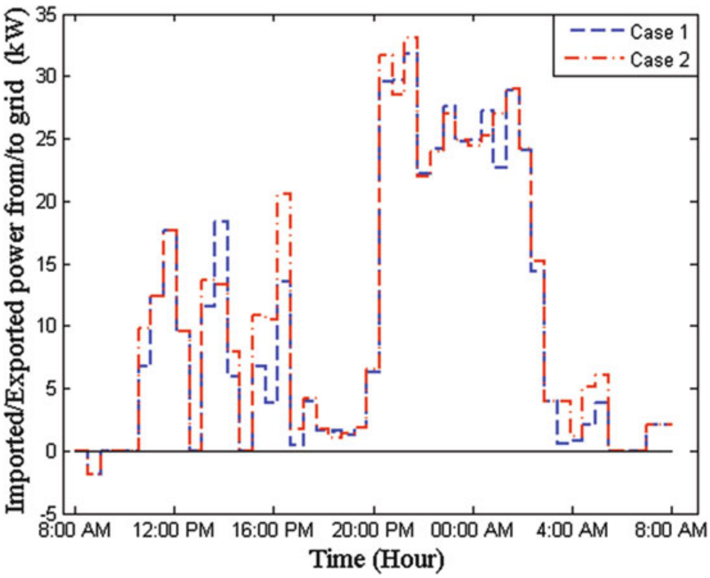

Fig. 4.13 Solar thermal storage (kW)

Table 4.7 Activation time of appliances without considering the effect of solar thermal storage (h)

Sectors	1	2	3	4	5	6	7	8	9	10
Washing machine	12–14	11–13	–	13–15	–	18–20	14–16	16–18	11–13	–
Dish washer	16–18	14–16	–	11–13	–	23–1	22:30–00:30	20–22	16–18	–
Tumble dryer	21:30–23	20–21:30	–	15–16:30	–	1–2:30	1–2:30	23:30–1	19–20:30	–
Cooker hob	15–15:30	10:30–11	–	13:30–14	11:30–12	14–14:30	23–23:30	11:30–12	13–13:30	–
Cooker oven	11:30–12	16–16:30	–	21–21:30	13:30–14	13:30–14	–	–	23–23:30	20:30–21
Microwave	21–21:30	13:30–14	–	20:30–21	12–12:30	17:30–18	–	19:30–20	21–21:30	10:30–11
Interior lighting	18–24	–	20–2	20–2	22–4	19–1	–	17–23	20–2	21–3
Laptop	20–22	–	19:30–21:30	18:30–20:30	19:30–21:30	23–1	–	20–22	20–22	19:30–21:30
Desktop	20–23	–	16–19	–	14–17	22–1	22–1	22:30–1:30	20–23	–
Vacuum cleaner	20:30–21	–	22:30–23	–	1–1:30	16–16:30	00:30–1	1–1:30	23:30–24	1–1:30
Fridge	1–24	–	1–24	–	1–24	1–24	1–24	–	1–24	1–24
Electrical car	23–2	–	23:30–2:30	–	20–23	20–23	20–23	–	24–3	21:30–00:30

Table 4.8 Activation time of appliances with considering the effect of solar thermal storage (h)

Sectors	1	2	3	4	5	6	7	8	9	10
Washing machine	12–14	11–13	–	13–15	–	18–20	15–17	16–18	11–13	–
Dish washer	16–18	14–16	–	11–13	–	23–1	22:30–00:30	20–22	16–18	–
Tumble dryer	21:30–23	20–21:30	–	15–16:30	–	1–2:30	1–2:30	23:30–1	19–20:30	–
Cooker hob	15:30–16	10:30–11	–	13:30–14	11:30–12	14–14:30	23–23:30	11:30–12	10:30–11	–
Cooker oven	11:30–12	16–16:30	–	21–21:30	13–13:30	13:30–14	–	–	23–23:30	20:30–21
Microwave	21–21:30	13–13:30	–	20–20:30	12–12:30	17:30–18	–	19:30–20	21–21:30	10:30–11
Interior lighting	18–23:30	–	20–2	20–2	22–4	19–1	–	17–23	20–2	21–2:30
Laptop	20–22	–	20–22	18:30–20:30	22–24	23–1	–	20–22	21–23	20–22
Desktop	20–23	–	16–19	–	14–17	22–1	22–1	22:30–1:30	20–22:30	–
Vacuum cleaner	20–20:30	–	21–21:30	–	1–1:30	16–16:30	00:30–1	1–1:30	24–00:30	1–1:30
Fridge	1–24	–	1–24	–	1–24	1–24	1–24	–	1–24	1–24
Electrical car	23–2	–	23:30–2:30	–	20–23	20–23	20–23	–	00:30–3:30	22–1

4.4 Conclusion

In this chapter, optimal energy consumption scheduling of a residential hub energy system containing CHP unit, boiler, battery storage, solar thermal storage, and smart appliances is proposed. In this chapter, effect of solar thermal storage has been analyzed in two cases. By comparing the obtained results, it can be found that operation cost of residential hub energy system with considering effect of solar thermal storage is decreased 16.88%, imported power from grid is increased 7.2%, and battery storage system is charged and discharged 28.8 and 21.17% more, respectively. Output power of boiler is decreased 43.28% and output power of CHP is decreased 55.13%. It should be mentioned that the developed MIP model is implemented using CPLEX in GAMS software. Finally, risk-based optimal energy consumption scheduling of a residential energy hub system in the presence of solar thermal storage system can be modeled using information gap decision theory framework and robust optimization approach as a future work.

Nomenclature

Index

j	Residential hub energy system sector
t	Time period index
i	Appliances index
θ	Operation period of appliances index

Parameter

CAP^{CHP}	Capacity of CHP generator (kW_e)
α^{CHP}	Heat to power ratio of CHP
CAP^{boiler}	Capacity of boiler (kW_{th})
CAP^{elec}	Capacity of battery storage system (kWh_e)
η^{elec}	Battery storage charge/discharge efficiency (%)
M^{elec}	Maximum capacity of battery storage system (kW_e)
DRL^{elec}	Discharge limit of battery storage system (kW_e)
CRL^{elec}	Charge limit of battery storage system (kW_e)
$P_{i,\theta}^{Consump}$	Consumption power of ith appliance at the operation period θ (kW_e)
$P_{j,i}$	Processing time of ith smart appliance at jth residential hub energy system sector (h)

$T_{j,i}^{\text{Start}}$	Latest finishing time of *i*th smart appliance at *j*th residential hub energy system sector (h)
$T_{j,i}^{\text{Finish}}$	Earliest starting time of *i*th smart appliance at *j*th residential hub energy system sector (h)
M^{Grid}	Maximum capacity of bought power from grid (kW_e)
$\eta^{\text{ch, Ther}}$	Charge efficiency of solar thermal storage system (%)
$\eta^{\text{dch, Ther}}$	Discharge efficiency of solar thermal storage system (%)
CAP^{Ther}	Capacity of solar thermal storage system (kWh_{th})
$T^{\max}$	Maximum operation temperature (°C)
$T^{\min}$	Minimum operation temperature (°C)
T_t^{amb}	Ambient temperature (°C)
$H^{\text{ch, Ther, max}}$	Maximum charge rate of solar thermal storage (kW_{th})
$H^{\text{dch, Ther, max}}$	Maximum discharge rate of solar thermal storage (kW_{th})
θ^{storage}	Coefficient of solar thermal storage loss (scalar number)
θ^{static}	Coefficient of static solar thermal storage loss (Scalar number)
E_t^{unuse}	Unusable energy due to temperature limitation (kWh)
φ_t^{solar}	Solar irradiation (W/m^2)
A^{app}	Surface of solar thermal panel (m^2)
γ^{Ther}	Efficiency of solar thermal panel (%)
$H_{j,t}^{\text{Demand}}$	Heat demand (kW_{th})
Δt	Time interval duration (h)
λ_t^{Grid}	Price of imported power from upstream grid (£/kWh_e)
λ^{export}	Cost of selling power to the upstream grid (£/kWh_e)
λ^{Gas}	Natural gas price (£/kWh)

Variables

$P_{j,t}^{\text{CHP}}$	Output power of CHP (kWe)
$P_{j,t}^{\text{Boiler}}$	Output power of boiler (kW_{th})
$\text{SOC}_{j,t}^{\text{elec}}$	State of charge of sub-batteries storage system (kWh_e)
$\text{SOC}_t^{\text{Totalelec}}$	Total state of charge of battery storage system (kWh_e)
$\text{CR}_{j,t}^{\text{elec}}$	Charge rate of battery storage system (kW_e)
DR^{elec}	Discharge rate of battery storage system (kW_e)
MC^{elec}	Maintenance cost of battery storage system (£/kWh_e)
$P_{j,t}^{\text{Import}}$	Imported power from grid (kW_e)
$P_{j,t}^{\text{export}}$	Exported power to grid (kW_e)
H_t^{stored}	State of charge of solar thermal storage (kWh_{th})
$H_t^{\text{ch,Ther}}$	Charge rate of solar thermal storage (kW_{th})
$H_{j,t}^{\text{dch,Ther}}$	Discharge rate of solar thermal storage (kW_{th})
$H_t^{\text{loss,Ther}}$	Heat loss rate of solar thermal storage (kW_{th})
Q_t	Amount of converted solar irradiation to heat (kW_{th})

Binary Variable

$B_{j,t}^{\text{elec}}$	Binary variable: equal to 1 if battery storage is charged at time *t*; otherwise 0
$\omega_{j,i,t}$	Binary variable: equal to 1 if *i*th appliances at *j*th residential hub energy system sector is ON at time *t*; otherwise 0
$B_{j,t}^{\text{Grid}}$	Binary variable: equal to 1 if power is bought from grid at time *t*; otherwise 0
$B_{t}^{\text{ch,ther}}$	Binary variable: equal to 1 if solar thermal storage is charged at time *t*; otherwise 0
$B_{j,t}^{\text{dch,ther}}$	Binary variable: equal to 1 if solar thermal storage is discharged at time *t*; otherwise 0

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