Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 145 (2018) 564–569

Energy Procedia

www.elsevier.com/locate/procedia

Applied Energy Symposium and Forum, Renewable Energy Integration with Mini/Microgrids, REM 2017, 18–20 October 2017, Tianjin, China

Energy Flexibility through the Integrated Energy Supply System in Buildings: A Case Study in Sweden

Yang Zhang[a,*], Pietro Elia Campana[a,b], Ying Yang[b], Anders Lundblad[c], Jinyue Yan[a,b,†]

[a]*Division of Energy Processes, KTH-Royal Institute of Technology, SE-10044 Stockholm, Sweden*
[b]*School of Business, Society & Engineering, Mälardalen University, SE-72123 Västerås, Sweden*
[c]*Division Safety and Transport/Electronics, RISE Research Institutes of Sweden, SE-50462 Borås, Sweden*

Abstract

The increasing penetration level of renewable energies requires more flexibility measures at the consumption side. Flexible energy prices have been placed by energy providers to promote flexibility measures from energy users. However, because of the current energy supply system in buildings, these flexible energy prices haven't been fully taken advantage of. This study focuses on the integrated energy supply system in buildings. A Swedish office building is used as the case study. The integrated energy supply system is built by installing new components, including battery, heat pump and electrical heater, and hot water tank. Mixed Integer Linear Programming (MILP) problems are solved to determine the optimal component capacities and operation profiles. The results indicate that all the studied system configurations achieve lower net present cost (NPC) than the current system. It suggests that the integrated energy supply system can take advantage of the flexible energy prices and lower the overall energy cost in the building. Among the studied configurations, the combination of air source heat pump (ASHP) and electrical heater (EH) has the lowest investment cost. This combination also has the lowest NPC except in the scenario with low borehole cost.

Keywords: Heat Pump; District Heating; Photovoltaic; Energy Flexibility; MILP

* Corresponding author. Tel.: +46-8-7906529;
E-mail address: yaz@kth.se
* Corresponding author. Tel.: +46-8-7906529;
E-mail address: jinyue@kth.se

10.1016/j.egypro.2018.04.082

1. Introduction

The penetration level of renewable energies is increasing rapidly [1, 2]. More renewables energies are expected in future energy systems. However, the increasing capacities of intermittent solar and wind energies have negative effects on the stability and safety of energy systems. As the electricity production becomes more variable, flexibility measures at the consumption side are becoming more important [3]. Buildings consume about 40% of total energy in Europe [4]. Energy providers are encouraging building owners to adopt flexibility measures through flexible energy prices, including peak and off-peak prices, dynamic prices, seasonal prices and peak tariff. One of these flexibility measures is the demand side management (DSM), which is being extensively studied. Integrating the electricity and heat supplies can be another flexibility measure in buildings. The integration can lead to better control on the local energy system, and thus, building can switch to different energy carriers depending on the prices. To integrate the local energy supplies, different energy conversion and storage components need to be installed. These components can potentially lower the operation cost through coordinated operations [5, 6].

However, it remains unclear how to determine the appropriate component capacity to ensure the optimal system operation and the lowest cost. This problem can be formulated as an optimization problem, whose variables include the component capacities and the operation profile of each component.

Several relevant studies have been carried out. The integration of heat pumps (HP) and thermal energy storages (TES) was studied by Renaldi et al. [7]. A Photovoltaic (PV)-Battery system was studied by Khalilpour and Vassallo [8]. Dynamic programming was used by Salpakari et al. to determine the optimal operation of a PV-Battery-HP-TES system [9]. Beck et al. used the mixed integer linear programming (MILP) method to determine the optimal configuration and operation profiles of a residential PV-HP system [10]. However, a literature survey indicates that district heating, as a very important heat supply in Nordic countries, is seldom included.

This study focuses on the buildings that are connected to both the electrical grid and the district heating (DH) network. An office building is investigated as a representative case. Four components, including a battery, a heat pump (HP), an electrical heater (EH), and a hot water tank (HWT), are incorporated into the integrated energy supply system in the building. The investigation on whether the integrated energy supply system can take advantage of the flexible energy prices and lower the cost is carried out by using the MILP method.

2. Description of the studied building

The studied building is located at Västerås, Sweden. A 30 kW_p photovoltaic (PV) system was already installed. The recorded data in 2016 indicates that there was seasonal mismatch between production and consumption. The net electricity profile ($P_{Net.t} = P_{L.t} - P_{PV.t}$) is shown in Fig. 1 (a). The district heating profile is shown in Fig. 1 (b).

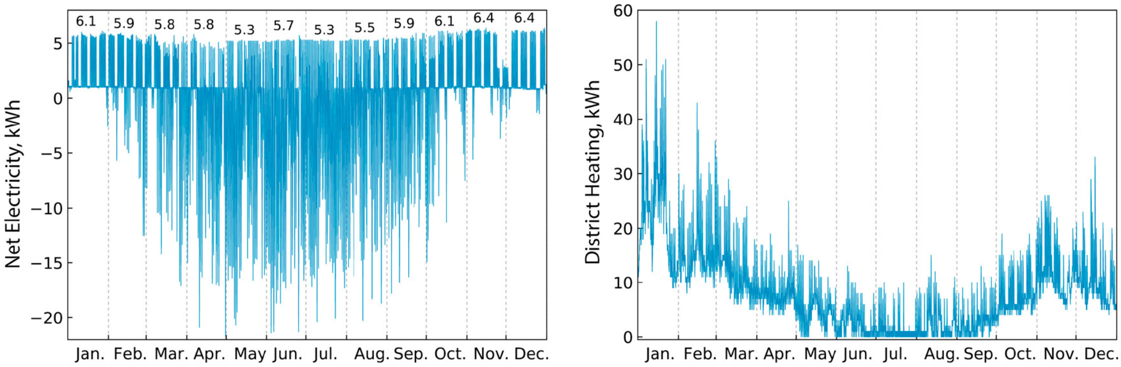

Fig. 1. (a) Net electricity and (b) district heating profiles of the reference system (Negative as exporting electricity)

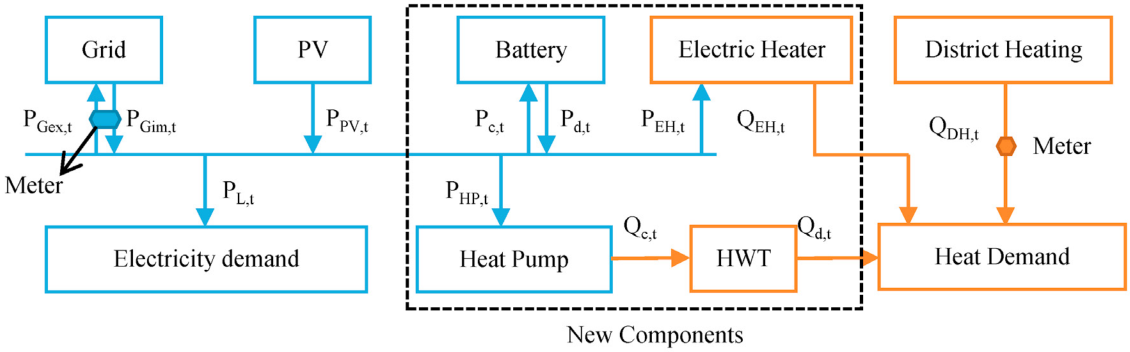

Fig. 2. New components and the integrated energy supplies in the building

In the current energy system (reference system), the electricity demand and the heat demands are supplied separately by the electrical grid (or PV) and the district heating network. As shown in Fig. 2, new components can be installed to form an integrated energy supply system. The heat demand can be provided by HP, DH and EH. In this study, the configuration is simplified that either DH or EH will be used together with HP for the heat supply. Moreover, the HP can be either Air Source Heat Pump (ASHP) or Ground Source Heat Pump (GSHP). In total, there are four system configurations: ASHP and DH (AS+DH); GSHP and DH (GS+DH); ASHP and EH (AS+EH); GSHP and EH (GS+EH).

The electricity costs are from the distribution system operator (DSO) and the retailer (RT). Depending on the peak electricity consumption, DSO cost can be calculated by Eqs. 1 or 2. The RT cost is calculated by Eq. 3. $P_{Gim,t}$ is the imported electricity. ELP_t is the electricity spot market price. The revenue ($R_{RT,y}$) from the exported electricity ($P_{Gex,t}$) is calculated with Eq. 4.

$$C_{DSO,y} = \left(5568 + \textstyle\sum_{t=1}^{8760} 0.176 \times P_{Gim,t}\right)(1 + VAT) \quad (1)$$

$$C_{DSO,y} = \left(5556 + \textstyle\sum_{m=1}^{12} 58.5 \times max\left(P_{Gim,t} | t \in Month_m\right) + \sum_{t=1}^{8760} 0.0535 \times P_{Gim,t}\right)(1 + VAT) \quad (2)$$

$$C_{RT,y} = \left(336 + \textstyle\sum_{t=1}^{8760} (ELP_t + 0.3879) \times P_{Gim,t}\right)(1 + VAT) \quad (3)$$

$$R_{RT,y} = \textstyle\sum_{t=1}^{8760} ELP_t \times P_{Gex,t} \quad (4)$$

The district heating cost is obtained through Eq. 5. Seasonal prices (WS: Warm season; MS: Middle season; CS: Cold season) are employed. C_{fix} and C_{peak} are cost parameters that are further dependent on the yearly peak of the district heating profile [11].

$$C_{DH,y} = \left(C_{fix} + C_{peak} \times Max(P_{DH,t}) + 0.236 \times \sum Q_{DH,t} | t \in WS + 0.44 \times \sum Q_{DH,t} | t \in MS + 0.5 \times \sum Q_{DH,t} | t \in CS\right)(1 + VAT) \quad (5)$$

3. Methodology

For each of the four system configurations, the component capacities and the operation profiles are determined simultaneously in an optimization problem. The system is linearized, and the optimization problem is solved as a Mixed Integer Linear Programming (MILP) problem using CPLEX solver.

3.1. Optimization objective

The optimization objective is to minimize the Net Present Cost (NPC) over the project lifetime (30 years). NPC is obtained in Eq. 6. It includes the investment cost (*Inv*), operation & maintenance cost ($C_{O\&M,y}$), replacement cost ($C_{R,y}$), electricity cost ($C_{DSO,y}$ and $C_{RT,y}$), electricity revenue ($R_{RT,y}$), and the district heating cost ($C_{DH,y}$).

$$\min\left\{\sum_{y=1}^{30} \frac{(C_{DH,y} + C_{DSO,y} + C_{RT,y} - R_{RT,y} + C_{O\&M,y} + C_{R,y})}{(1+d_r)^y} + Inv\right\} \quad (6)$$

3.2. Optimization constraints

The constraints for the optimization problem are shown in Eqs. 7-17. The constraints include energy balances (Eqs. 7-8), battery and HP power limit (Eqs. 9-11) and storage state limits (Eqs. 12-15). The performance of HP is dependent on the lift temperature (T_L) and is represented by the coefficient of performance (COP_t) [12]. T_L is the temperature difference between the source and the outlet. The outlet temperature is assumed as 50 °C. For the ASHP, the source temperature is the ambient temperature; for the GSHP, the source temperature is fixed as 6 °C [13].

$$P_{PV,t} - P_{c,t} + \eta \cdot P_{d,t} + P_{Gim,t} - P_{Gex,t} = P_{L,t} + P_{HP,t} + P_{EH,t} \quad (7)$$

$$Q_{d,t} \cdot \eta_d + Q_{DH,t} + Q_{EH,t} = Q_{D,t} \quad (8)$$

$$Q_{c,t} = P_{HP,t} \times COP_t \quad (9)$$

$$P_d, P_c \leq 0.37 \cdot Cap_{Batt} \quad (10)$$

$$Q_{c,t} \leq Cap_{HP} \quad (11)$$

$$SOC_t = SOC_{t-1} + \left(P_{c,t} - P_{d,t}\right)/Cap_B \quad (12)$$

$$20\% \leq SOC_t \leq 100\% \quad (13)$$

$$Q_{TS,t} = Q_{TS,t-1} + Q_{c,t} - Q_{d,t} \quad (14)$$

$$0 \leq Q_{TS,t} \leq \frac{V_{TES} \times \rho_w \times c_p \times \Delta T_{TES}}{3600} \quad (15)$$

$$COP_{ASHP,t} = 6.81 - 0.121 * T_L + 0.000630 * T_L^2 \quad (16)$$

$$COP_{GSHP,t} = 8.77 - 0.15 * T_L + 0.000734 * T_L^2 \quad (17)$$

3.3. Investment cost

The relationships between the capacity of each component and its investment cost are linearly correlated in Eq. 18. The parameters a_i *and* b_i are listed in Table 1.

$$Inv_i = a_i \times Cap_i + b_i \quad (18)$$

Table 1. Lifetime and investment costs for different components

Component (Abbreviation)/ Capacity Unit	Lifetime (Year)	a_i (SEK/Unit Capacity)	b_i (SEK)	References
Battery (Batt)/ kWh	15	4009	0	[14]
Heat Pump (HP)/ kW	15	1761.4	32245	[15]
Borehole (BH)/ kW	30	10000	0	[12]
Electrical Heater (EH)	15	200	0	
Hot Water Tank (HWT) / L	15	24.8	11553.9	[7]

Two additional scenarios are studied. In the low BH cost scenario, a_{BH} is decreased by 50%. In the high HP cost scenario, a_{HP} was increased by 50%.

4. Results and discussion

Accumulated cash flow and NPC of the reference system and four configurations are shown in Fig. 3. All the studied configurations have lower NPC than the reference system. It indicates that the integrated energy supply system can reduce the overall cost. Among different configurations, the ASHP and EH configuration has the lowest investment and lowest NPC. In all the configurations, battery is not selected by the optimization algorithm. It suggests that the battery cost is still high for being economically implemented in the studied case. Moreover, the combination of HP and EH has lower NPC than the combination of HP and DH. It suggests that EH is more economically favorable than DH as the supplement of HP in providing heating.

The investment, the yearly operation cost, and net present costs of these four system configurations are shown in Fig. 4. The “base case” refers to the results obtained under original economic assumptions. The “Low BH cost” and “High HP cost” refer to the results obtained in the two additional scenarios that are presented in Section 3.1.

The systems with ASHP have lower investment cost than these with GSHP. The lowest yearly operation cost is achieved by the combination of GSHP and EH. The GSHP and DH configuration always have the highest NPC. The ASHP and EH configuration usually achieve the lowest NPC except in the low BH cost scenario.

All the studied configurations can have lower NPC than the reference system. It indicates that the integrated energy supply system can be economically implemented in buildings. However, it should be noted the optimization results are achieved under the assumption of perfect forecasting in energy demands and supplies. Future works are needed in developing a real-time energy management system.

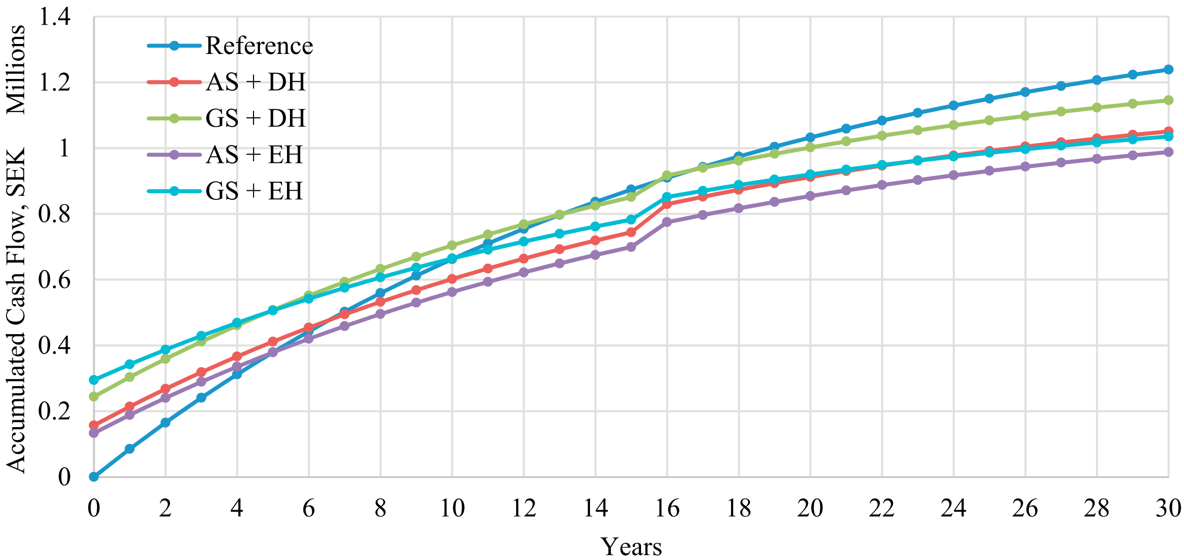

Fig. 3. Accumulated cash flows and NPCs of the reference system and four configurations

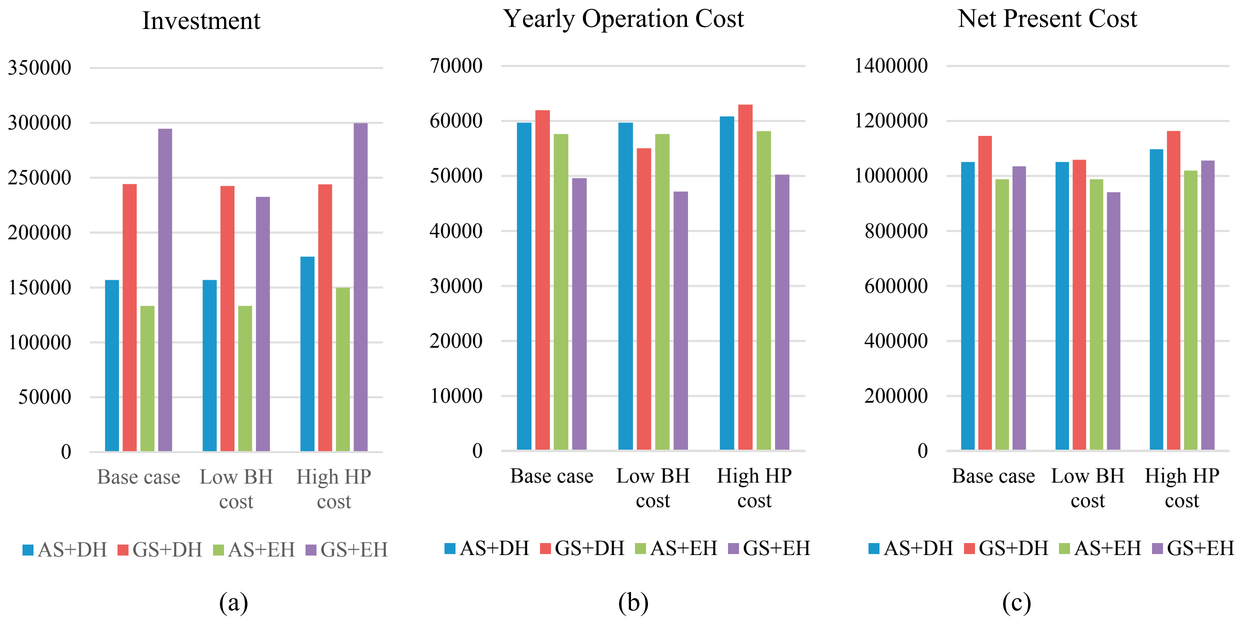

Fig. 4 (a) Investments, (b) Yearly operation costs, and (c) Net present costs of four configurations in different scenarios

5. Conclusions

The integrated energy supply system in an office building was studied. Four components, including a battery, a heat pump, an electrical heater, and a hot water tank, can be incorporated in the system. The component capacities and operation profiles are determined by solving a mixed integer linear programming problem. Four system configurations are studied. The results indicate all these configurations can achieve lower net present cost (NPC) than the current system. Two investment cost parameters are varied in different scenarios. In these scenarios, the combination of ASHP and EH always has the lowest investment. This combination usually achieves lower NPC than other combinations expect in the low borehole cost scenario. The combination of ground source heat pump and electrical heater has the lowest yearly operation cost. These results indicate that the integrated energy supply system can be employed to lower the total energy costs of the studied building.

Acknowledgements

This work has received funding from KKS Future Energy Profile through the project iREST, European Union's Horizon 2020 (No. 646529). Yang Zhang acknowledges the financial support from China Scholarship Council (CSC).

References

[1] IEA-PVPS. Snapshot of global PV markets. 2016 <http://www.iea-pvps.org/>.
[2] IRENA. Renewable Energy Statistics 2016. The International Renewable Energy Agency, Abu Dhabi, 2016.
[3] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sust Energy Rev 2015; 45: 785-807.
[4] Zhao H-X, Magoulès F. A review on the prediction of building energy consumption. Renew Sust Energy Rev 2012; 16: 3586-92.
[5] Zhang Y, Campana PE, Lundblad A, Yan J. Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation. Appl Energy 2017; 201: 397-411.
[6] Zhang Y, Lundblad A, Campana PE, Benavente F, Yan J. Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in Sweden. Energy Convers Manage 2017; 133: 249-63.
[7] Renaldi R, Kiprakis A, Friedrich D. An optimisation framework for thermal energy storage integration in a residential heat pump heating system. Appl Energy 2017; 186, Part 3: 520-9.
[8] Khalilpour R, Vassallo A. Planning and operation scheduling of PV-battery systems: A novel methodology. Renew Sust Energy Rev 2016; 53: 194-208.
[9] Salpakari J, Lund P. Optimal and rule-based control strategies for energy flexibility in buildings with PV. Appl Energy 2016; 161: 425-36.
[10] Beck T, Kondziella H, Huard G, Bruckner T. Optimal operation, configuration and sizing of generation and storage technologies for residential heat pump systems in the spotlight of self-consumption of photovoltaic electricity. Appl Energy 2017; 188: 604-19.
[11] Priser fjärrvärme. <https://www.malarenergi.se/foretag/fjarrvarme-foretag/prislistor-och-prismodeller/priser-fjarrvarme/> [assessed 01.06.2017].
[12] Staffell I, Brett D, Brandon N, Hawkes A. A review of domestic heat pumps. Energy Environ Sci 2012; 5: 9291-306.
[13] Björk E, Acuña J, Granryd E, Mogensen P, Nowacki J-E, Palm B, et al. Bergvärme på djupet2013.
[14] Tesla Powerwall. <https://www.tesla.com/powerwall> [assessed 01.06.2017].
[15] Fakta & priser IVT AirSplit. <https://www.ivt.se/produkter/luftvattenvarme/airsplit/fakta--priser/> [assessed 01.06.2017].