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Developing an Energy Management System for Optimizing the Interaction of a Residential Building with the Electrical and Thermal Grids

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Abstract

The cost of locally installed renewable electrical and thermal systems in residential buildings is dropping rapidly and it has become increasingly common to invest in multiple-energy technologies such as PV, wind turbines and heat pumps. With the higher number of options, it is feasible to include more intelligent systems than basic low-level control in a residential building, especially with grid-connected local storage of heat and electricity. This article describes a proposed method and a prototype for an energy management system (EMS) for residential buildings. The energy management system applies a planning algorithm based on constrained non-linear programming using a successive linear programming (SLP) approach. The EMS can be quite easily customized for different system configurations. The system behavior is encoded into optimization constraints as a simplified energy flow-based model, but is robust enough to represent multiple connections to a state-of-the-art stratified heat storage tank. Experiments of the energy management methodology using simulation models for three case studies have shown promising results. The EMS is able to consistently adapt the operation of the system to changes in the optimization criteria.

Keywords: Energy Management System, optimizing building interactions with grids, energy cost minimization, primary energy consumption minimization

Introduction

The EU Energy Performance of Buildings Directive (EPBD- Directive 2010/31/EU) requires all new buildings to be nearly zero-energy buildings by the end of 2020 and the required low amount of energy should be covered to a very significant extent by energy from renewable sources produced on-site or nearby. At the same time, the cost of small-scale on-site energy generation is dropping, in particular the cost of PV panels, which has been

dropping in an almost exponential rate and is expected to be so in the near future [1], [2]. Besides, the cost of electricity storage, which is an important factor in the overall feasibility of solar installations, has been also decreasing [3]. Another important factor in the popularity of small-scale system adoption is the advancement in the field of inverter technology, which has reached a reasonable technical and economical level for small-scale installations. It is becoming increasingly feasible to include multiple energy technology options in a single residential energy system. With diverse local energy generations, it is therefore needed to practically manage the system's operation beyond the typical low-level control that is currently present in residential installations.

The goal of this paper is to present an approach for the operation of a proposed energy management system (EMS) for small-scale thermal and electrical systems in a single family building that include multiple energy-related components. The example building has a wind turbine, PV panels, solar-thermal collectors, Ground-Source Heat Pump (GSHP), hot-water storage tank and electrical batteries, and is connected to both electrical and thermal grids. The EMS focuses on the planning stage of the energy system with a high number of free parameters and non-linear interaction.

There is a lot of existing work on on-line planning of the behavior of a relatively small number of units with heuristic or combinatorial methods [4]–[6]. Non-linear programming and mixed integer linear/non-linear programming have been widely applied to off-line planning of the operation of larger scale micro-grids [7], [8]. In this work, it is to create an efficient method for on-line planning of a system with a high number of degrees of freedom. The computational efficiency is important in order to be able to simulate the system's operation in a significantly higher than the real time.

1. Description of the Building and the Energy Systems

The simulated building is located in Helsinki-Finland. It is a one-storey single family house with a net floor area of 150 m^2. The height of the first floor is 2.5 m. It is assumed that there are four occupants in the building. The building insulations, service systems, and internal gains comply with the Finnish Building Regulation D3 2012 [9]. The space heating utilizes a 40/30 °C hydronic radiator heating system. The hydronic heating system for the air handling unit utilizes a counter-flow heat recovery system with an annual heat recovery efficiency of 70%. The annual simulated space heating, air-handling unit heating, and domestic hot water heating demands are 39.9, 2.5, and 35.0 kWh/m^{2}a, respectively, while the annual simulated electrical demand of the non-heating household equipment is 30.2 kWh/m^{2}a.

The proposed energy management system (EMS) is tested using a simulated model of a system, part of which is also implemented in a hardware emulator installed at the HVAC laboratory, Aalto University, Finland. Figure 1 shows the components of the energy system. It is consisted

of the following elements: Stratified hot-water storage tank (0.5 m^3), Electric battery (20 kWh), Ground source heat pump with a rated heat output of 6 kW and COP of 3, Electric heating element with a rated output of 10 kW and efficiency of 0.95, PV panels (30.26 m^2) with a nominal operating power of 3.268 kW, Small-scale wind turbine with a nominal output power of 4 kW, Solar thermal collectors (8.6 m^2), Battery connection to the grid (maximum power of 6 kW), Heat pump for exporting heat with a rated heat output of 6 kW and COP of 2, and Connections to both electrical and thermal grids.

The EMS algorithm creates a plan for the operational states of each device and the routing of energy. The water tank is divided into two distinct nodes. The GSHP produces heat that can raise the water temperature in the lower node to a maximum temperature of 60 °C, while the electric heating element heats up the upper node for the purpose of keeping the domestic-hot water (DHW) at 60 °C. A plate divides the tank into two compartments and reduces the heat transfer from the upper node to the lower node. Heat for space heating is extracted from the lower part of the tank.

The DHW flows inside two heat exchangers connected on series, first into the lower part of the tank and next in the upper part. This series-connection of the heat exchangers creates a complex dependency on the relative temperatures of the two nodes of the tank. The solar-thermal collector is connected to the lower part of the tank via a heat exchanger. The heat losses from the tank surface are calculated. Heat for space heating and DHW can also be taken from the thermal grid through a bypass valve depending on the preference at each time-step. Both the house thermal demand and the renewable energy production were calculated by the simulation program TRNSYS 17.1.

The EMS method operates by creating a plan for different actions for the next 24 hours with 0.1 hour time steps. This operation planning is updated at each 0.1 hour interval using new data of the actual state of the simulated system. Inputs to the plan are formed by the current state of the system and the forecasted energy production and consumption boundary conditions. The plan is constrained by the maximum and minimum states of the energy storage systems and the maximum output powers of the operating devices.

The planning method builds a constrained optimization problem model for the system based on a simple description with three tables: one for the energy sources/storages, one for the active devices, and one for the production and consumption boundary conditions. The optimization problem describes the system using energy flow balances. It does not distinguish the roles of flow rate and temperature differential for heat flows. The states of the energy storage units are represented as constraints based on first-order integrations of the energy flows. Depending on the case, the target of the planning is minimization of either the energy cost or the net primary energy consumption.

This paper is a pure modeling exercise, however, the EMS is planned to be used in an emulator platform that includes real on-site renewable energy generations and connections with the electrical and thermal grids while the house is simulated in the computer with online interaction between the performance of the real and simulated parts.
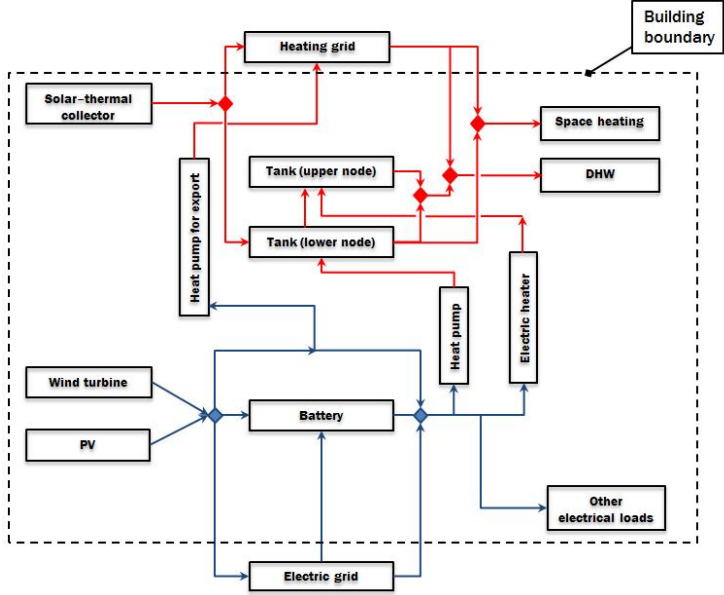

Fig. 1 Energy system components and energy flow.

2. Mathematical Methods

The planning methodology is based on a constrained non-linear optimization, in which the goal function is linear, a product of grid flows with prices. The constraints of the optimization problem describe the progression of the states of the energy storage units using first-order Euler integration of the corresponding energy flows.

$$C\Delta t(s_t - s_{t-1}) = \sum_i q_i \qquad (1)$$

Here s_t represents the state of an energy storage system at time t, C is a given constant that represents the energy capacity of the system, i.e. the rate of change of the state variable (such as temperature or state-of-charge) per unit of energy input/output. The quantities q_i represent energy flows into and out of the storage unit.

Each flow rate is connected between two entities in the system, and both entities create constraints on the flow rates. If flows q_i are the alternative

inputs to a device, the state of a device is given by $0 < p < 1$, and the outflows of the device are given by r_j, a set of constraints are created that specifies that the combined flows in the input and output connections should match the power state of the device, multiplied by the corresponding nominal rates:

$$\sum_i q_i = P_{in} p \qquad (2)$$

$$\sum_j r_j = P_{out} p \qquad (3)$$

For each boundary condition on the system, the sum of the connected flows is constrained to equal the value provided for the boundary. Cost factors are specified for the grid connections in the system. These cost factors are applied to the flow rates as optimization goal weights. All other parameters in the optimization have zero weights.

Very simple set-ups can be described by fully linear constraints. Such an approach was applied in an off-line study of a micro-CHP system by Alahäivälä et al. [10], utilizing mixed integer-linear programming (MILP). However, MILP is too slow for the purpose of an on-line planning system with the necessary number of degrees of freedom in this problem. In addition, the studied system cannot be adequately described by a linear system, due to the non-linear nature of the state-dependent interactions of the flows into the hot-water storage tank. Thus, it becomes necessary to introduce non-linear state-dependent coefficients into the constraint equations, while the overall equations remain mostly linear.

Due to the infeasibility of the computational cost of mixed-integer programming, the plan is made using the assumption that all devices can be progressively controlled at a range between zero and full power. This creates a considerable amount of differences between the actual (or simulated) performance of the system and the planned operation. However, the presence of energy storage alleviates the differences between the assumed continuous operation and the actual pulsed operation. Such a problem with mostly linear constraints and some state-dependent coefficients can be efficiently solved by a successive linear programming (SLP) approach [11]. Although successive linear programming is considered an inferior method for non-linear programming in general, in this class of problems it can be applied efficiently. The SLP approach substitutes linear models for the non-linear coefficients in the vicinity of the current best estimate of the energy storage states and performs a linear program on the generated linear sub-problem. Optimization of the sub-problems is iterated until reaching a stable solution.

The convergence of the problem is improved by using under-relaxation and an adaptive rectangular trust region that prevents the solution from stepping too far from the region of validity for the linearized coefficients. The under-relaxation takes care of most of the flickering around the stable

solution, while the remaining small oscillations are eliminated by shrinking the trust region when successive iterations produce updates in opposite directions. This under-relaxation approach has been successfully applied to the problem of short-term scheduling of the output of a chain of hydro power stations along a single water-way [12].

Additional slack variables with high cost factors are used in order to guarantee the feasibility of the individual sub-problems in the presence of possible infeasibilities created by the linear approximations. When the solution of the previous planning operation is used as a starting point, the necessary number of iterations is usually less than 5, and the planning if efficient enough to allow simulation of a year's worth of the system's operation in less than four days of CPU time, leaving plenty of room to expand the complexity of the planning operations in real-time operation. For real time operation, the possibility of using a similarly constrained mixed integer programming approach should be investigated.

3. Case studies

The EMS has been tested with a number of scenarios of which three cases are presented in this paper. Cases 1 and 2 involve optimization for the minimization of energy cost while in Case 3 the optimization is for the minimization of the net primary energy consumption.

Table 1. Time series in the simulation experimental cases.

Series No.	Case 1	Case 2	Case 3	Units	Type	Mean	Std. Dev.	Min	Max
1 Cost	elect. import	elect. import export		cent/kWh	hourly dynamic	11.14	1.44	6.21	32.08
2 Cost	elect. export			cent/kWh	hourly dynamic	4.12	1.16	0.14	21.00
3 Cost	heat import	heat import export		cent/kWh	seasonal	3.99	1.00	3.00	5.00
4 Cost	heat export			cent/kWh	seasonal	3.19	0.80	2.40	4.00
5 PEF			elect. import export	kWhPE/ kWhEnd	hourly dynamic	1.78	0.14	1.44	2.06
6 PEF			heat import export	kWhPE/ kWhEnd	hourly dynamic	0.73	0.056	0.59	0.85

In Cases 1 and 2, an hourly dynamic series for the electrical grid customer price from Helsingin Energia's database 2013 is used [13]. In Case 1, the electricity export price is assumed to only include the spot price, while

in Case 2 it is assumed equal to the import price as an assumption of an incentive scenario since no feed-in tariff has been in use in Finland. Prices for the thermal grid are assumed to be seasonal dependent: 5 cent/kWh in the winter period and 3 cent/kWh in the summer period. In Case 1, there is 20% discount for the heat export price from the building to the heating grid while in Case 2 they are assumed equal.

In Case 3, an assumed non-renewable primary energy factor (PEF) time series for the electrical grid is used. The same time series is scaled-down and used for the thermal grid. Same PEFs are used for energy imports and exports. For the three cases, an assumed 90% efficiency for the exported energy to the thermal and electrical grids is assumed. The time series used in each case along with some of their statistical data are presented in Table 1.

The results of the simulation cases are presented in Table 2. There is a major difference in the behavior of the EMS system between Cases 1 and 2. In Case 1, electricity will be exported only when the electricity price is greater than double the price available for exported heat. In this case, and due to the low export price, therefore electricity exports only happens occasionally as shown in Figure 2, which presents the rate of electricity exports according to the price levels.

In Case 2, electricity is not used for exporting heat at all due to the higher price differential. In addition, use of battery power is avoided during low prices, and battery charging is avoided during high price levels. This results in an almost equal increase in the quantity of energy imports and exports, but the considerable price differences result in a net monetary gain.

In Table 2, the first column for each case presents the energy flow to/from the grid in kilowatt-hours. The second column shows the optimization criterion, in terms of euros or kilowatt-hours of primary energy. An interesting aspect in the cost-based cases is that, while Case 1 is net-positive in site-energy balance, it has a monetary deficit due to the low export price levels. Case 2, on the other hand, is energy deficient, but has a monetary surplus. The main difference between these two cases is the export of electrically-generated heat, which only happens in Case 1, where the electricity export price is low enough to warrant it.

Case 3 is also net-positive in site-energy balance. For the optimization criterion, it is a net-positive primary energy case. Due to a lower level of fluctuations in the primary energy factors, compared to the price levels in Case 2, the time-shifting of electricity consumption is less aggressive.

Differences in solar heat export quantities between the cases are quite small. In Case 2, significantly more heat is imported from the heating grid for the DHW consumption in order to avoid inefficient use of electricity that could instead be exported.

Table 2. Case results.

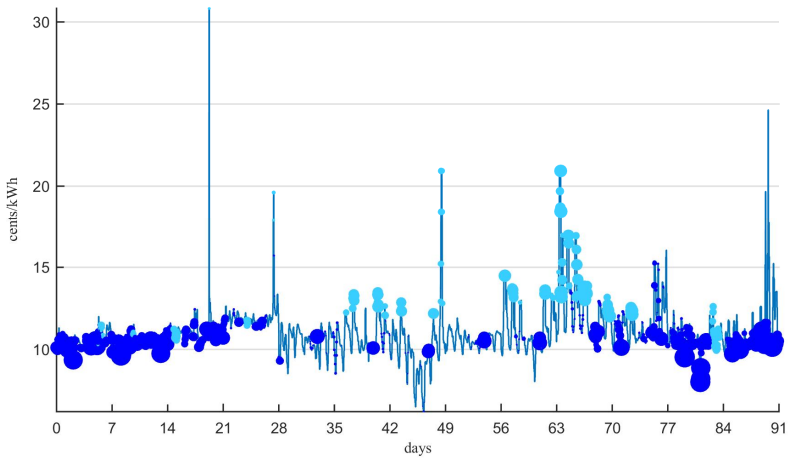|	Case 1		Case 2		Case 3	
	kWh	€	kWh	€	kWh	kWhPE
Electricity import	−2402	−249	−3676	−369	−2606	−4484
Electricity export	1018	57	5832	609	4604	7238
Space heating- heat import	−209	−6	−346	−10	−3	−2
DHW- heat import	−2908	−126	−4576	−188	−4310	−3128
Solar thermal export	2671	69	2705	69	2561	1613
HP thermal export	4755	133	0	0	0	0
Total	2924	−122	−613	110	246	1237

Fig. 2 Electricity imports (dark) and exports (light) on the electricity price graph, Case 1.

Figure 2 presents the rate of electricity imports and exports as a function of the import price level in Case 1. The areas of the dots reflect the rate of flow from or into the electric grid. The studied duration on the x-axis is one week per each month for one year. Exportable electricity is only present in the summer time, but even then, it is directly exported only when the electricity price reaches a high enough peak. When the price is lower, the energy is used for operating the export heat pump.
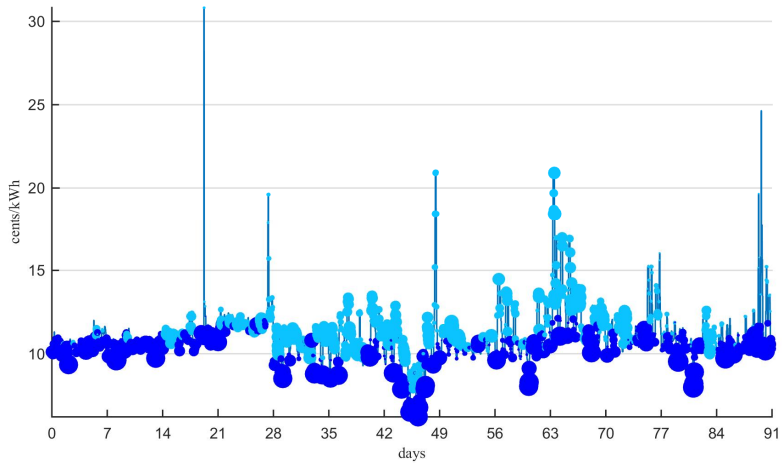
Fig. 3 Electricity imports (dark) and exports (light) on the electricity price graph, Case 2.

Figure 3 presents the same information in Case 2. In this case, the export heat pump is not operated, and electricity imports are used with price troughs even in the summer time in order to increase the potential for electricity exports during price peaks. Flows in both directions in the electric grid are increased during summer time, but only at the opposite extremes of the price curve, thus creating a net economic benefit compared to a system that only maximizes energy matching.

4.   Conclusions

The presented optimization methodology is shown to be a successful approach to the optimal management of a small-scale energy production and consumption system. The methodology makes many simplifying assumptions about the operation of the systems, but still manages to gainfully adapt the performance of a simulated system in many different scenarios. The methodology is able to make practical use of forward knowledge of price levels in order to control the external energy flows. It does not require any manual specification of heuristic rules, but can make informed choices irrespective of the particulars of the system configuration or its operating conditions. The performance of the EMS methodology has yet to be fully established with actual hardware systems, but the decisions that were made with simulated systems are logically sound, even in the presence of considerable degrees of freedom.

In the sense of computational efficiency, the methodology has room for extension into significantly wider-scale systems that could include shared

energy consumption of multiple residential buildings, for example. It can be incorporated into long-scale simulation studies of the optimal behavior of energy production and consumption systems.

5. Acknowledgements

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