POTENTIAL OF DEMAND AND PRODUCTION SHIFTING IN RESIDENTIAL BUILDINGS BY USING HOME ENERGY MANAGEMENT SYSTEMS

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ABSTRACT

A home energy management system (HEMS) for residential buildings is investigated regarding its load shifting potential. A photovoltaic system, temporally shiftable electrical devices, different heat producers (heat pump, condensing boiler), electrical and thermal storages and an electric car as well as varying building configurations are considered. In order to calculate this system simulations are carried out using SimulationX to emulate the residential environment and its devices as well as Matlab and GAMS to implement the optimization with the focus of minimizing costs and grid purchases. The simulation results show an increase of degree of autarky and self-consumption and a reduction of costs at the same time.

INTRODUCTION

The German energy supply will face huge structural changes within the transformation of the German energy system. Decentralized power units on a renewable basis will steadily replace centralized energy production in power plants. However, renewable energy supply deals with uncertainties due to its intermittent character. In order to ensure equality between electrical supply and consumption at all time further potential helping this equation to balance is needed. This capacity is especially to be found on the consumer side of the energy system, as the concept of energy production being a result of consumption has to be adapted so that demand follows production. Applying this principle, called Demand Side Management, on a smaller scale, e.g. on private households, offers a huge potential with its multitude of appliances that can be time shifted.

This environment is electrically characterized by frequent and fast load changes. Furthermore, decentralized on-site energy production, i.e. by photovoltaic systems, does not compulsorily match demand throughout a day. Usually the external grid balances supply and load exclusively. But a home energy management system (HEMS) is capable of reducing this discrepancy by shifting loads into times of energy surplus. Therefore, it simultaneously improves the integration of renewable energy into the grid of residential buildings and allows benefiting from variable electricity prices.

The HEMS introduced in this paper minimizes the overall energy costs whilst orientating its functionality to electricity price and weather forecast, e.g. prognosis of photovoltaic energy generation. Thus, all electrical loads, i.e. a washing machine or an electric vehicle, and any electrical storage are arranged in a cost optimal schedule. In addition, in residential buildings where the electrical and thermal sector are combined via electric heat generators not only electrical load but likewise thermal production shifting is facilitated. As thermal storages are available in these building configurations this coupling allows variations of the thermal load.

All studies are carried out within the project „e-MOBILie – energy autonomous electro mobility in a smart-micro-grid", which is one of about 50 projects within the "Schaufenster Elektromobilität"-initiative financed by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety by about 4.5 million €.

SIMULATION

Considered devices and scenario configuration

Figure 1 demonstrates the components included in the building simulation. It has to be distinguished between electrical (grey arrows) and thermal (blue arrows) power flow and producers, consumers and storages.

A decentralized electric energy supply is represented by the photovoltaic system. Its power output to the in-house grid depends on weather data (temperature, solar radiation), its location [ITI, 2014] and efficiency of the DC/AC Converter. In addition, a connection to the public electricity grid is available in order to obtain or feed back electric energy.

The following electrical consumers are taken into account: Demand side management (DSM) devices, electrical base load (BL), an electric vehicle (EV), an air-to-water heat pump (HP), and an immersion heater (IH). The DSM-devices feature the possibility of load shifting inside a timeframe selected by the inhabitants. Their load profiles are predefined and not interruptible. In this simulation a dishwasher, washing machine and dryer are considered as such. The electrical base load comprises every (non-DSM) consumer in residential buildings besides those demonstrated in Figure 1. Its data is derived from a

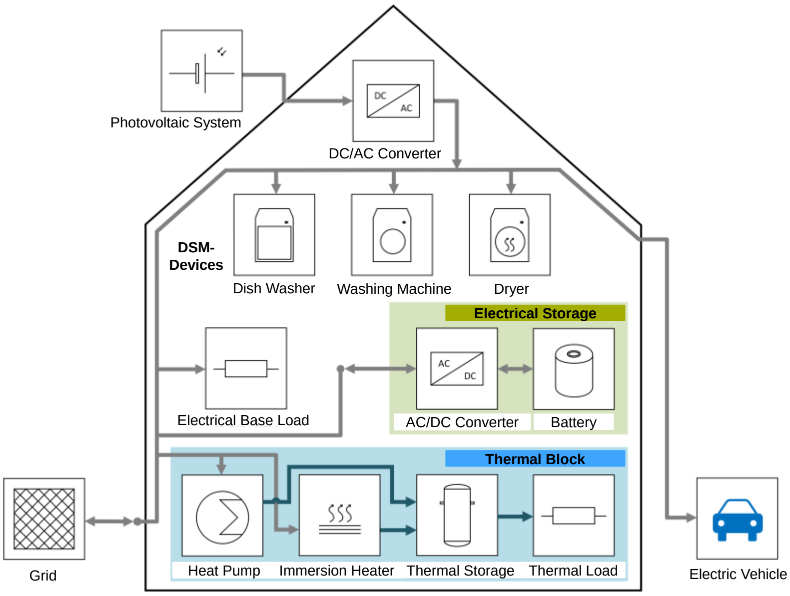

Figure 1: Overview of components [Tonn, 2014]

time budget survey data based stochastic simulation of inhabitants behaviour [Kandler et al., 2015a]. This simulation generates also all electrical load time series and the driving profile of the electric vehicle used in this paper. In order to satisfy the EV's driving consumption and air conditioning demand the EV is able to be charged whilst being plugged to the in-house grid. Charging at other locations and bidirectional charging (vehicle-to-grid) is not contemplated. Power of charging is limited to 3.68 kW and two charging modes are available, controlled, e.g. charging is interruptible and processed at low price times, and uncontrolled charging, e.g. charging cycle starts at moment of plugging the EV. Additionally, prior to every trip the EV is preconditioned, so that the internal temperature is comfortable.

A heat pump and an immersion heater represent the interface between electrical and thermal sector. Both devices generate heat out of electricity and therefore can be characterized as consumers and producers. Both supply thermal loads. In detail, the produced heat flows via two different thermal storages, satisfying the demands of the heating system (HS) and domestic warm water (DWW). The HP is connected to both thermal circuits, whereas the IH only supports the heat generation for the DWW. Moreover, the heat pump is non-modulating with an input power of 2 kW and works at a nominal flow temperature of 43 °C.

Finally, a battery allows storing electric energy from either the photovoltaic system or the grid. Both electrical and thermal storages help to increase the possibility of shifting these different loads.

All mentioned components are implemented within a single-family house that is designed as one zone model with 120 m². Shading depending on solar radiation, inner masses and heat inputs and losses through windows and walls are considered. Together with heat yields derived from presence of persons and electrical loads this results in the thermal demand that needs to be supplied.

The potential of the HEMS is evaluated in three scenario cases: minimal (MC), standard (SC) and best (BC) case. Every case refers to a special building configuration in order to reflect the main

Table 1: Scenario configuration

Components	**MC**	**SC**	**BC**
Building configuration	~1970 not refurbished	EnEV2009	EnEV 2012
Heat Generation	x (CB)	x (HP)	x (HP)
Electric Vehicle	x	x	x
Battery [kWh]	-	5	10
PV [kWp]	1	3	5
DSM-Devices	x	x	x
Immersion Heater	-	x	x
Thermal Storage HS [l]	-	700	700
Thermal Storage DWW [l]	300	300	300
not optimized in HEMS, optimized in HEMS			

types of the German building stock; a not refurbished old building and two buildings complying each with the German energy saving law (EnEV) of 2009 and 2012. Furthermore, depending on the scenario dimensioning of the components varies as shown in Table 1. Values were assumed within the project e-MOBILie so that the scenario range for applying HEMS is as wide as possible; from an old building with almost no potential of load shifting (MC) to a modern one with huge DSM capacities (BC). An “x” symbolizes if a certain component exists in this case. In MC Figure 1 is changed, such that the heat producer is a condensing boiler without thermal storage in the heating circuit and no electrical storage is installed.

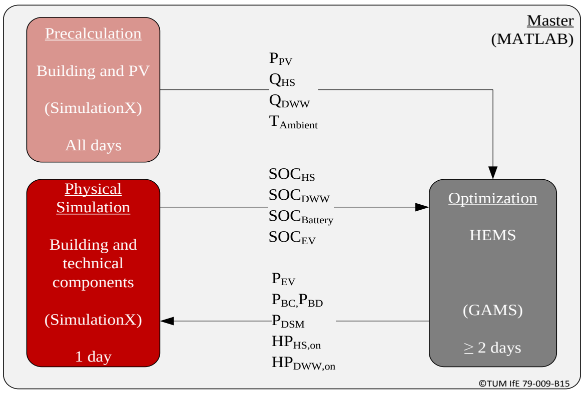

Figure 2 Simulation routine

Simulation routine

Figure 2 demonstrates the simulation routine. It consists of three main parts implemented in three different programs in order to exploit each particular advantage of the programs. The program master is realized with MATLAB, which controls the temporal sequence of the whole simulation and offers comfortable data handling. Embedded in this master are the precalculation and physical simulation carried out in SimulationX (Modelica based simulation tool; physical properties of all components can easily be represented and simulated in high detail), and the optimization computed in GAMS (General Algebraic Modeling System) with CPLEX solver, which allows to solve the occurring mixed integer optimization problem.

The precalculation simulates the building with its heating system and the photovoltaic system within the whole period considered in advance to the other simulation parts. Therefore, it serves to forecast the feed-in power of the PV (P_{PV}), the ambient temperature ($T_{Ambient}$), the heat demand of the heating system (Q_{HS}) and the domestic warm water (Q_{DWW}) based on [Kandler et al., 2015a] and weather data input. In order to calculate reasonable values for Q_{HS} in BC, the heat pump controller possesses predictive and adaptive properties [Kandler et al., 2015b].

These time series feed the optimization that represents the HEMS. According to the scenario case the manipulating variables calculated by the HEMS and inserted in the representation of the household are the charging power for the EV and the battery (P_{EV}, P_{BC}), discharging of battery (P_{BD}), the demand caused by DSM devices (P_{DSM}) and the switch-on signals for the HP ($HP_{HS,on}$ and $HP_{DWW,on}$). Based on these inputs the model of the building and the technical components is simulated. After the SimulationX run the latest values of the SOCs of all storages and the EV are extracted (SOC_{HS}, SOC_{DWW}, $SOC_{Battery}$ and SOC_{EV}) and returned to the HEMS. Transferring these state variables ensures that the optimization is synchronized to the actual processes in the real world simulation. Thus, the loop between physical simulation and optimization is closed and the HEMS starts a new run.

With the help of this loop a rolling horizon procedure is realized. The building simulation always comprises a time horizon of one day. Therefore, at each loop pass only the first 24 hours of the optimization results are extracted and put into the physical simulation. In order to avoid boundary effects at the end of the calculated timetable the minimal foresight of the HEMS should exceed one day. For example, if the planning interval equals the time interval of the simulation, e.g. it is only one day, the process of charging and discharging the battery would only consider the next day and the SOC is not optimized with regard to the following day. Likewise the other components would show a lack of optimal planning.

All simulations in this paper are conducted with a planning interval of two days. The realized time resolution is one respectively five minutes in SimulationX and optimization.

Home energy management system

The optimization problem is formulated as a mixed integer linear program (MILP) and takes production, consumption and storing of electrical and thermal energy at discrete time steps into account. Goal of the optimization is to minimize the operational energy costs in the residential building, e.g. costs (C_{Import}) arise from importing electricity from the grid, whereas revenues (C_{Export}) are generated for feeding energy back into the grid (see Equation 1). Consequently, the considered optimization is a dispatch and not an expansion problem. Therefore, it is assumed that all components already exist in the household and no purchase costs accrue to the system. Moreover, various restrictions are considered as follows: technical parameters as i.e. the maximum capacity of a storage or efficiency of processes, weather data, electricity price tariffs and time budget survey data affecting possible charging times for EV or switch-on times of DSM-devices. In order to reach the goal of minimal costs subject to these constraints whilst supplying the electrical and thermal demands (see Equation 2 and 3) the optimization is capable of shifting switch-on and charging times of devices and varying (dis-)charging powers of storages. [Honold et al., 2015]

$$\min \left[\sum_{\forall t} E_{Import} \cdot C_{Import} - E_{Export} \cdot C_{Export} \right] \quad (1)$$

Electrical: $\forall t$: $$P_{Import} + P_{PV} + P_{BD} = P_{BL} + P_{HP} + P_{IH} + P_{EV} + P_{DSM} + P_{BC} + P_{Export} \quad (2)$$

Thermal, HSS: $\forall t$: $Q_{HP} = Q_{Storage,HS,in}$ $\quad Q_{Storage,HS,out} \geq Q_{HS}$

Thermal, DWW $\forall t$: $Q_{HP} + Q_{IH} = Q_{Storage,DWW,in}$ $\quad Q_{Storage,DWW,out} \geq Q_{DWW}$ (3)

Table 1 demonstrates the components that are represented in the optimization depending on the scenario case. All devices in black color are either not represented in HEMS at all or if they are integrated in HEMS, they are not optimized. I.e. the PV is involved in the calculation but functions only as fixed energy supply. Devices in red color offer the possibility to optimize their schedule. In BC the HEMS operates the HP in times, when the electricity price is low or the coefficient of performance (COP) is high. This operation mode is facilitated by the existence of the thermal storages in the optimization. However, in SC the HP runs, when the SOCs of the thermal storages drop below the lower level of a hysteresis control. Hence, in SC the HP is not considered by the HEMS and therefore does not operate in a cost optimized mode. For the HP and the DSM devices only the time schedule is optimized, as the HP is non-modulating and DSM devices run programs with fixed power demand. In contrast, the EV and the battery also offer the potential of regulating the charging power. Furthermore, the HEMS always charges the EV in controlled charging mode. The building is indirectly represented in the optimization by the thermal demand for the heating system.

Physical simulation

In order to simulate the HEMS in an environment as realistic as possible, the physical simulation is modelled in a much more detailed level of abstraction compared to the optimization, because the model can be described more accurately in Modelica. Figure 3 demonstrates the model of the building and its technical components implemented in SimulationX. Its system configuration follows the values in Table 1. The manipulating variables from the HEMS are included appropriately. Only in BC two points have to be adjusted as there are two possible deviations from the optimized timetable that have to be considered: first, the HP controller may overrule the intended heat generation plan in both ways, either turn HP on or off if the thermal storages are empty or respectively fully charged, although $HP_{HS,on}$ or $HP_{DWW,on}$ are different. This behavior especially occurs when the forecasted heat demand differs from the actual one and ensures to keep comfort conditions within the building zone. As a consequence, the electric system either has free energy, because the HP does not run as scheduled, or additional energy is needed by the HP. In those cases the battery tries to balance this disparity depending on its SOC. Everything beyond this is compensated by the grid.

DISCUSSION AND RESULT ANALYSIS

All simulations comprise one year and are carried out in two versions: on the one hand the whole system of the residential building with optimized dispatch by the HEMS. On the other hand the system is investigated without HEMS as a reference case (REF) what facilitates to see the impact of the HEMS. In this reference case none of the devices follows an optimized schedule. The DSM devices always start at the first possible moment depending on user input. The EV is instantly charged as soon as it is plugged to the in-house grid. The battery is charged or discharged in moments of energy surplus respectively shortage in the in-house grid. Finally, the heat pump runs in hysteresis control. Referring to Figure 2, the simulation routine only consists of the physical simulation in SimulationX.

The following values are evaluated: electrical energy supplies and demands, operational costs and the degrees of self-consumption and autarky.

The energy supplies and demands represent the energy balances of each consumer and producer in

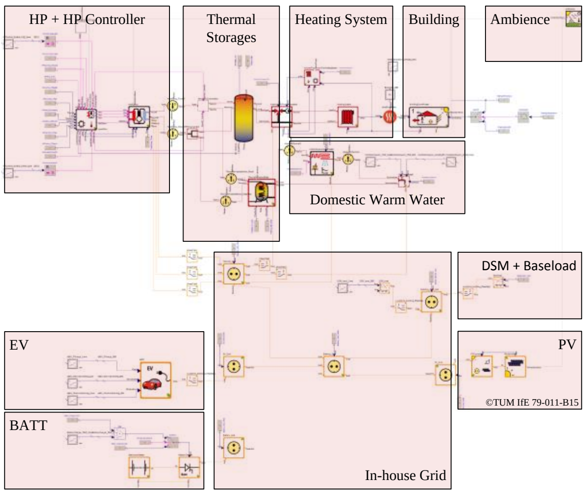

Figure 3 Model of building and technical components in SimulationX

the residential house system. The balanced values arise as the following demanded input time series have to be matched: driving consumption pre-conditioning of EV driven by a commuting full time employee, the electrical base load, the demand of DSM devices, the consumption of domestic warm water and of heating system resulting from influences like weather or presence of persons in the house. The resulting energy values are distinguished between quarters of a year and a whole year.

Operational energy costs are derived from electricity and gas prices. Thereby, a time-variable and a constant electricity price tariff are compared. The variable tariff is adopted from an existing one on the market, which fluctuates during the day between 20 and 31 €ct/kWh$_{el}$ [Stadtwerke Bielefeld, 2013]. The constant tariff persists at all time at 28.81 €ct/kWh$_{el}$ [Bundesnetzagentur, 2014b]. Furthermore, feeding back of electric energy into the grid is refunded by 12.5 €ct/kWh$_{el}$ (March 2015, according to the German EEG law 2014 [Bundesgesetzblatt, 2014]). Gas prices for the condensing boiler in MC are steady as well at 7.2 €ct/kWh$_{gas}$. [Bundesnetzagentur, 2014a]

The degree of self-consumption (sc) equals the rate of electrical energy from PV that can be used in the residential home simultaneously to production. The directly consumed power (P_{DC}) results from the synchrony of produced PV power (P_{PV}) and electrical demand (P_C). (see Equation 4) All power variables refer to one time step. [Weniger et al., 2013]

$$\forall t: \; P_{DC} = min(P_{PV}, P_C) \quad (4)$$

As there is a battery in the introduced system, PV power can not only be consumed directly but also be stored in the battery. Therefore, the self-consumption has to consider P_{DC} as well as the power $P_{BC,PV}$ used to charge the battery with PV power (Equation 5). It is important to notice that $P_{BC,PV}$ may only include power from PV as it is allowed to charge the battery with electricity from the grid ($P_{BC,Grid}$) as well as from PV (Figure 4). The number of time steps is called n. [Weniger et al., 2013]

$$\forall t: \; sc = \frac{\sum \frac{P_{DC} + P_{BC,PV}}{P_{PV}}}{n} \quad (5)$$

The degree of autarky (a) is another value to evaluate PV and battery systems in residential home contexts. Autarky describes the rate of electrical demand, which is supplied by PV and battery at the same time. As shown in Figure 4, it is derived from the directly consumed power (P_{DC}), electrical demand (P_C) and the power discharged from the battery ($P_{BD,PV}$), that has its origin in PV power [Weniger et al., 2013]:

$$\forall t: \; a = \frac{\sum \frac{P_{DC} + P_{BD,PV}}{P_C}}{n} \quad (6)$$

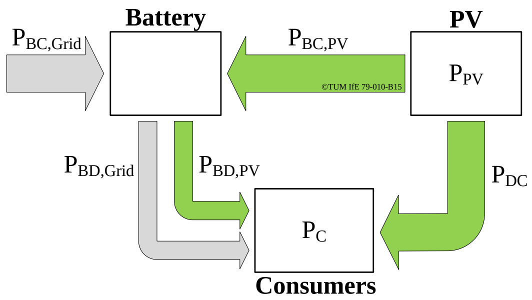

Figure 4: Power flow between PV, battery and consumers

Annual results

Figure 5 demonstrates the annual values of electrical energy demand and supply of each component as well as the degrees of autarky and self-consumption for all scenario and reference cases. Demands are displayed positive, supplies negative. The configuration of components and house are set as in Table 1, the electricity price tariff is time-variable.

As described before HEMS has the goal of minimizing costs, e.g. either it reduces electrical energy purchase from the grid (indicated in Figure 5) or devices are shifted into cost optimal (electricity price, PV generation) periods.

The diagram shows that yearly demands of base load, DSM devices and EV are equal in every instance, as base load is a fixed input time series and DSM devices and EV have to follow the restrictions of user behavior and driving consumption. In doing so, the temporal characteristic of charging the EV and switching on DSM devices is still optimized by HEMS, whereas in REF uncontrolled charging is used to charge EV and DSM devices follow a fixed time series. Values for PV align with the installed peak power, i.e. 5 kWp accord to approximately 5 MWh/a. Battery losses occur when battery is (dis-)charged. Together with demands of circulation pumps and immersion heater, they are in the same dimension as DSM devices.

Actual differences appear in the energy demand of the HP. In BC this value is reduced by HEMS by more than 1.7 MWh compared to reference case, as HP is shifted into COP optimal times in order to produce the same amount of heat (~6.3 MWh HS, ~2.5 MWh DWW) with less electrical energy using temperature of ambience air as energy source. In SC HP energy does not vary as HP run is not optimized by HEMS. In comparison to BC, thermal demand of the building and therefore electrical load of HP is higher according to an older construction standard. In MC heat is produced while burning gas in a condensing boiler, so no electrical energy is requested. All demands and PV energy result in the displayed imported, respectively exported current from or to the public electricity grid. HEMS purchases energy in moments when electricity prices are low and both PV generation and discharged energy from battery are not sufficient. Current is fed back into grid when Battery is fully charged and no consumer can be shifted into this period in order to absorb PV energy.

Overall, HP (if existing), EV and base load are the main loads. In MC energy demand is the lowest as heat production does not work on an electric basis. In BC the superior construction standard and the optimized schedule of HP lead to a lower energy demand and less imported energy than in SC, which is comparable in matters of component configuration. Furthermore, the restrictions described cause that HEMS is not capable of decreasing energy demand significantly in SC and MC.

Figure 5 also shows the degree of autarky and self-consumption. Autarky generally grows from MC to BC as a consequence of an increased PV system. Comparing HEMS and REF in each scenario, the gain in autarky results from the fact, that HEMS minimizes the energy demand. The greater the reduction of energy demand by HEMS is the more the autarky grows. Self-consumption mostly shows the same behavior. Values for BC and SC are rather high (around 90 % and 95 %) as a Battery is available to absorb surplus PV energy and as the overall consumption (11.7 MWh respectively 14.7 MWh) exceeds PV generation by far. Thereby the value of SC surpasses those of BC due to less installed PV power. As results imply, in a configuration like BC and SC high self-consumption rates are also possible without HEMS. In MC self-consumption does not reach a level that high because of the lack of an electric battery.

The only exception in the characteristic of self-consumption is BC. In this case self-consumption is slightly diminished. This results from the formula that calculates self-consumption. Reference value is PV generation P_{PV} which is the same in both instances HEMS and REF. The difference is the overall energy demand that is decreased in HEMS following from the reduced HP demand in the optimized case. Therefore, less power is consumed directly, the rate of self-consumption sinks. At the same time, the optimized schedule of HEMS counteracts this decrease. That is the reason why the rate of self-consumption drops only by approximately one percent.

As a consequence, in cases of significant differences in energy consumption between reference and optimized case the self-consumption rate does not clearly show the impact of HEMS, especially not in cases of high total energy demands. Whereas the degree of autarky, which refers to overall consumed energy, is a more distinct indicator of the effect of HEMS.

Characteristic quarterly behavior of results

Figure 6 illustrates the quarterly values of electrical energy demand and supply of each component as well as the degrees of autarky and self-consumption for HEMS in BC. Its characteristic trend is representative for all scenarios.

Demand of DSM devices, battery losses and immersion heater stay almost equal throughout one year, whereas the other components and their energy demands indicate a huge dependency of the season. EV charging demand decreases during summer (Q2, Q3) as less demand for air conditioning is needed and the EV is used fewer times due to vacation periods in

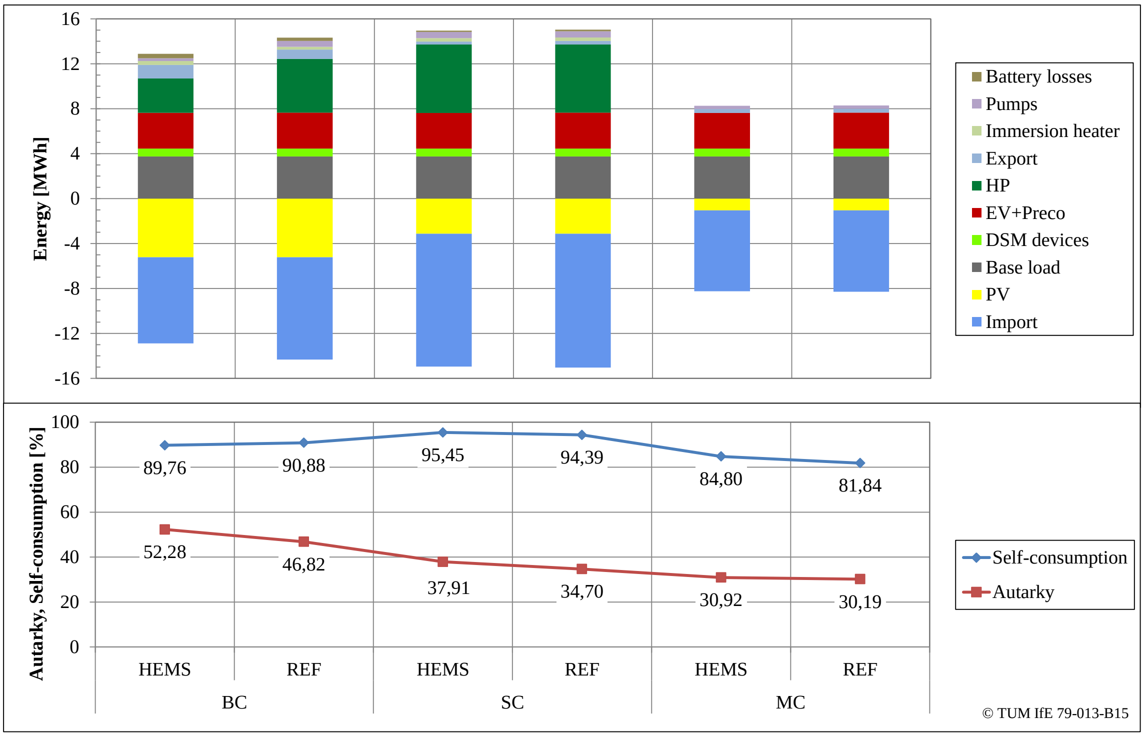

Figure 5: Electrical energies, autarky and self-consumption for all cases (annual values)

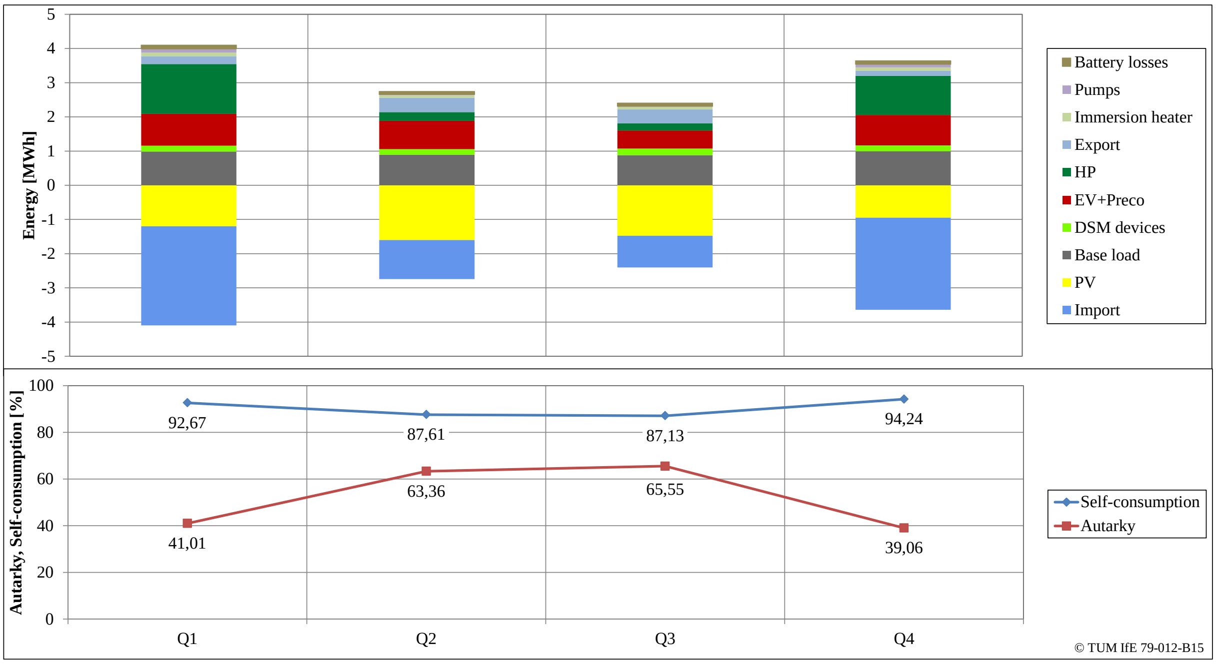

Figure 6: Electrical energies, autarky and self-consumption for BC (values on quarterly basis)

driving profile. As a result of increased PV production in Q2 and Q3 energy feed back into grid rises at the same time. In the same time period heat load mostly consist only of DWW, while in winter its main share results from the heating system. Consequently, import of electrical energy during winter exceeds summer times significantly.

Autarky and self-consumption correspond to these energy supplies and demands in two different ways. The more PV power is generated and the less energy is consumed in total the higher the autarky rate. Furthermore autarky reveals a distinct difference between summer and winter. The behavior of self-consumption is inverted to autarky: the less PV generation and the higher the demand, the greater the self-consumption.

Savings of costs

Figure 7 demonstrates savings of costs per year when using HEMS compared to REF case (without HEMS) for each scenario case. Costs include prices for consumed electricity and gas. Values are absolute savings in euro referring to cost in REF. Moreover, results for variable and constant electricity price tariffs are investigated.

In general, HEMS always reduces the operational energy costs of the household on the basis of the described assumptions and restrictions (Figure 7). In all cases HEMS has the goal to exploit as much PV energy as possible. Therefore, HEMS shifts devices into periods of PV generation or stores PV energy in a battery as this energy is for free. This minimizes purchase of electric energy from the grid and costs. Moreover, in scenarios with a variable electricity price tariff HEMS is capable of capitalizing on periods of low energy prices, whereas constant tariffs do not allow this. Hence, the difference in savings of costs between variable and constant tariff scenarios expresses this additional margin HEMS can generate in conjunction with variable tariffs, i.e. in BC this margin accounts for 44 € per year.

Saving of costs in BC exceeds the values of SC and MC by more than 400 €/a due to the fact that HP energy demand is reduced significantly in BC (see Figure 5). Furthermore, the less possibilities of intervention HEMS has, especially if HP or battery are not available or part of the optimization, the less economic benefit HEMS has. Consequently, saving of costs decreases steadily from BC over SC to MC as MC offers the least potential of load shifting. Additionally, MC with constant tariff demonstrates, that DSM devices and an EV as only shiftable components do not offer noteworthy savings of cost. On the one hand, DSM devices only consume 0.7 MWh per year, what is clearly less than an EV or HP (~3 MWh). Besides that, the small timeframes, in which switching on time of DSM devices can be postponed, explain its minor potential. On the other hand an EV represents a main consumer, but its commuting driving profile is characterized by limited presence especially during day hours when PV energy is generated. Compared to MC, in SC the Battery is the only further component that is controllable by HEMS. The saving of costs with constant tariff are significantly higher (90 €/a) than in MC, what indicates that a battery is an important component in conjunction with HEMS.

Finally, it has to be noted, that all components (PV, HP, HEMS…) are assumed to be depreciated. Thus, asset costs for these devices have to be considered when estimating the amortization period of a special house component configuration on basis of the illustrated yearly savings of costs.

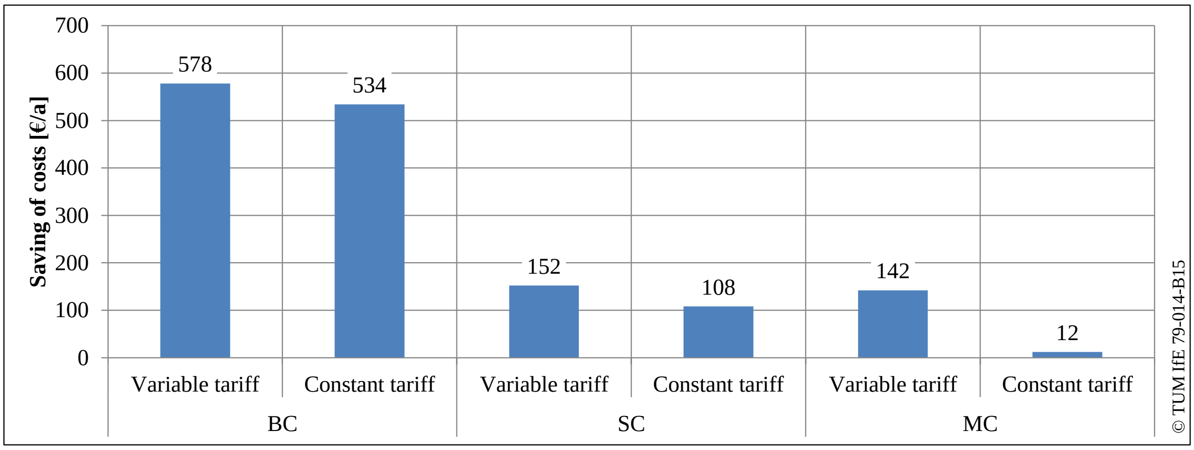

Figure 7: Savings of costs per year for all cases and for variable and constant electricity tariff

CONCLUSION

The simulations show that a smart energy management system utilizes the existing load shifting potential in a residential building for generating significant benefits regarding yearly energy costs. However, the amount of savings of costs strongly depends on the installed house component configuration. HEMS reaches the highest profits in combination with a battery and a controllable heat pump. Especially running the HP on an anticipatory schedule can distinctly reduce its electric energy demand. In contrast, a minor load shifting potential can be assigned to DSM devices and the EV, whose potential is very reliant on its driving profile. Furthermore HEMS is capable of capitalizing on variable tariffs if existing.

For all conducted scenarios the considered HEMS increases the degree of autarky and self-consumption. Particularly, the autarky rate indicates the effect of HEMS. On basis of its optimization goal to minimize operational energy costs, HEMS achieves to exploit the generated PV energy optimally and to reduce the purchase of energy from the grid at the same time.

NOMENCLATURE

HEMS = Home Energy Management System
HS = Heating System
DWW = Domestic Warm Water
DSM = Demand Side Management
BL = Base Load
HP = Heat Pump
IH = Immersion Heater
CB = Condensing Boiler
EV = Electric Vehicle
BC = Best Case
SC = Standard Case
MC = Minimal Case
REF = Reference Case
sc = Self-consumption
a = Autarky
P = Electrical Power
E = Electrical Energy
Q = Thermal Power
C = Costs / Revenues

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