Electricity and Heat Sector Coupling for Domestic Energy Systems
Benefits of Integrated Energy System Modelling

Akhila Jambagi, Michael Kramer and Vicky Cheng
Energy Efficient and Smart Cities Research Group, Technical University of Munich
Boltzmannstrasse 17, 85748 Garching, Germany

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Abstract: A strong focus on reducing carbon emissions as well as the improvements in computing and control techniques for energy systems make it relevant to design energy systems in an integrated way. Coupling various energy sectors can offer many benefits in the way of flexibility and better utilisation of resources and infrastructures. To illustrate the benefits of coupling the heat and electricity sectors, a general model for a domestic energy system is developed, and two simulations are performed of domestic systems with sector coupling technologies. Further benefits can be gained by optimising the two systems together, implying that it can be advantageous to take an integrated optimisation approach for larger numbers of domestic systems.

1 INTRODUCTION

It is becoming important to study energy systems in an integrated way by coupling various energy sectors, because two recent developments are making it more relevant. The first trend is the importance of reducing carbon emissions, which has resulted in increased penetration of renewable energy generation. These are often intermittent in nature, thereby demanding more flexibility from the grid and demand side. Coupling the electricity and heat sector can be useful, as it has been shown that the intermittency can be combated by using Power-to-Heat technologies such as heat pumps (Vanhoudt et al., 2014).

Furthermore cogeneration has been shown to be a very efficient and low carbon energy source, providing another motivation for sector coupling (Houwing et al., 2011). This has particular relevance in the EU, since the Horizon 2020 calls have specifically promoted the use of renewables and cogeneration for residential buildings (Brenna et al., 2012).

The second trend is the movements towards smart energy systems, supported by improvements in computing and control techniques. An integrated control strategy for a multi-carrier energy system can offer much more flexibility, and could improve the utilisation of existing resources and infrastructure.

The aim of this study is to investigate the benefits that can be gained by sector coupling combined with optimisation techniques. This is shown through the modelling of two houses with different coupling technologies, and the further benefits gained by controlling them together. The focus for this study is the coupling of the heat and electricity sectors, and is part of a wider project aiming to develop a multi-energy carrier framework for the optimisation of energy systems at a district level.

A literature review on some published multi-energy carrier models is included in section 2. Section 3 describes the formulation of the model that has been developed for the study, and the three specific case studies, for which the results are discussed in section 4. Finally the conclusions and outlook are discussed in section 5.

2 LITERATURE REVIEW

There are several models that have been constructed with the purpose of analysing and optimising multi-carrier energy systems, of which some relevant ones will be discussed in this section. Firstly, the Energy Hubs model (Geidl et al., 2007), which formulates an Energy Hub as a unit where multiple energy carriers are converted and/ or stored. This model has been used for applications such as the conception of fuel cell systems (Hemmes, 2007). The model formulation

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in this study is based loosely on the Energy Hubs formulation.

A different approach is the Large Scale Virtual Power Plant (VPP) concept, as in (Giuntoli, 2013). This approach takes the popular VPP concept and distributes the various generation, storage and load resources over a larger territories, where ownership of the assets can be varied. The control and operation however is managed by a centralised scheduling coordinator that represents the common commercial interface. This is the control strategy that is used for the energy system framework developed in this project.

3 METHODS

3.1 General Optimisation Set up

The model describes each house as a collection of any number of the elements: Power Sources, Converters, Energy Storage Units, and Loads (Figure 1).

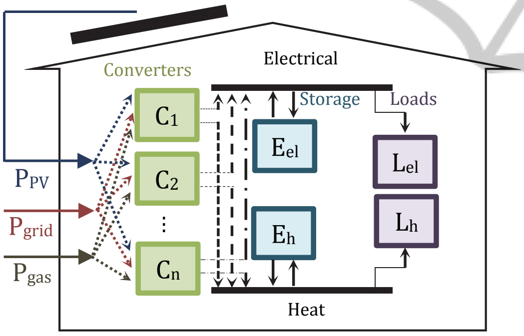

Figure 1: General Architecture for one domestic energy system, may contain any of the generation, conversion, storage or load elements.

Optimisation is performed on a 15 minute basis for 24 hours, and it is assumed that within the 15 minute intervals the power flows remain constant. The Loads and PV inputs are fixed time series, and therefore the controllable elements are the grid electricity and gas inputs, as well as the power flow in and out of the storage elements.

3.1.1 Model Dynamics

To ensure that the demand is met (1) is enforced, where C_{system} describes the dynamics of the converters of the specific house. Note that Δt refers to the duration of a time step (i.e. 15 minutes), and ΔE is the change in State of Charge of the storage unit during that time step. For simplicity and linearity the storage elements are considered ideal, and no cycle efficiency is included.

$$\begin{bmatrix} L_{el} \\ L_h \end{bmatrix} = C_{system} \begin{bmatrix} P_{grid} \\ P_{PV} \\ P_{gas} \end{bmatrix} - \frac{1}{\Delta t} \begin{bmatrix} \Delta E_{el} \\ \Delta E_h \end{bmatrix} \tag{1}$$

Furthermore various constraints will need to be met on the power inputs (2), storage energy levels (3) and the charging levels (4). Note that (1)- (4) have to be maintained for all time steps of the optimisation duration.

$$\begin{gathered} P_{\alpha,min} \leq P_\alpha \leq P_{\alpha,max} \\ \alpha \in \{grid, gas\} \end{gathered} \tag{2}$$

$$E_{\beta,min} \leq E_\beta \leq E_{\beta,max} \tag{3}$$

$$\begin{gathered} \Delta E_{\beta,min} \leq \Delta E_\beta \leq \Delta E_{\beta,max} \\ \beta \in \{el, h\} \end{gathered} \tag{4}$$

Finally a constraint is placed on the charge levels of the storage elements, that they should be the same at the beginning and end of the day (5).

$$E_\beta(t_0) = E_\beta(t_{end}) \tag{5}$$

3.1.2 Optimisation Problem

The developed modelling framework can be used to evaluate any objective function, however for this study a cost optimisation is performed. Other possible objectives could be minimising CO_2 emissions, or peak shaving. A linear programme is formulated where the objective function is as in (6), where p_{el}.and p_{gas} refer to the grid electricity and gas prices respectively.

$$f = \sum_{t=0}^{end} \left(p_{el} \times P_{grid}(t) + p_{gas} \times P_{gas}(t) \right) \tag{6}$$

A price ratio of 1:3 for gas to electricity is assumed in this study. It is possible to incorporate variable pricing schemes, however this is currently not particularly realistic for domestic consumption and was therefore left out. The optimisation problem therefore is to minimise (6), subject to (5) and (1)-(4) for every time step.

3.2 System Setup House 1

Single family house 1 is considered a refurbished old building with a three person household living on 150 m². A specific annual heat demand of 70 kWh/m² is assumed. The heat load is covered by a bivalent heating system consisting of a CHP and a furnace to cover the peak load. For simplicity of the problem

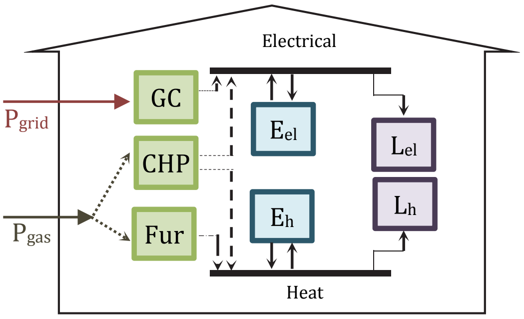

Figure 2: House 1 components - Grid Connection, CHP, Furnace, and thermal and electrical storage.

formulation the CHP is assumed to be perfectly modulating. The thermal and electrical efficiencies of the CHP are assumed to be constant for each operating point. A buffer functions as thermal storage and is connected to the heating system as in Figure 2.

The electrical demand of household appliances is covered either by electricity from the grid or the CHP. A battery serves as electrical storage and offers the possibility to decouple the generation and demand of electricity.

Both thermal and electrical storages are assumed to have no standby losses and no charging or discharging losses. This simplification is to keep the system dynamics linear. The properties of the devices in House 1 are summarized in Table 1.

Table 1: Parameters for the devices in house 1.

Device	Range/Value
P_{Grid}	0…30 kW
η_{grid}	1
P_{CHP}	0…12 kW
$\eta_{CHP,thermal}$	0.65
$\eta_{CHP,electrical}$	0.25
$E_{Battery}$	1…5 kWh
$P_{Battery,charge}$	0…0.8 kW
$P_{Battery,discharge}$	-0.5…0 kW
$E_{Buffer1}$	2…10 kWh
$P_{Buffer1,charge}$	0…6 kW
$P_{Buffer1,discharge}$	-6…0 kW

3.3 System Setup House 2

Single family house 2 is assumed to be a new build with a better energy standard leading to an annual heat demand of 50 kWh/m². Household size and living area are the same as in house 1. The heat demand is covered by a monovalent heat pump system connected to a buffer as shown in Figure 3. Heat pumps produce heat from low temperature sources as water, air or ground. The delivered heat flow $\dot{Q}_{th}$ is higher than the supplied power P_{el} to the compressor, since the heat pump uses the surrounding low temperature energy source. The coefficient of performance (COP) is defined by (7).

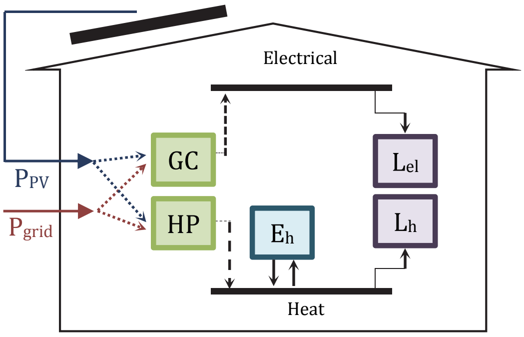

Figure 3: House 2 components - Grid connection, PV, Heat Pump, and Thermal Storage.

$$COP = \frac{\dot{Q}_{th}}{P_{el}} \tag{7}$$

The efficiency of a heat pump depends on the difference between the source and the output temperature (Quaschning, 2013). For simplicity a constant COP of 3 is assumed. Heat pumps are either available as on- and off-switching or modulating devices. Same as for the CHP in house 1, the heat pump is assumed to be perfectly modulating.

The buffer acts as thermal storage for the heating system in house 2.

A solar power installation of 5 kW on the roof top of the new build can cover the electrical demand of appliances and the heat pump. In this scenario, feed-in of excess electricity generation to the grid is not considered. The sizing of the devices in house 2 is summarized in Table 2.

Table 2: Parameters for the devices in house 2.

Device	Range/Value
P_{Grid}	0…30 kW
η_{grid}	1
$P_{HP,electrical}$	0…2 kW
COP	3
$E_{Buffer2}$	2…10 kWh
$P_{Buffer2,charge}$	0…6
	-6…0
$P_{PV,installed}$	5 kW

3.4 System Setup Combined Houses

The combined system of the two houses is defined by electrical interconnections between the CHP and battery in house 1 and the heat pump and PV in house

2. Thus the demand of appliances and the heat pump in house 2 can by supplied by the CHP and the battery in house 1. In addition, PV generation can supply the appliance demand of house 1 and feed the battery. There is no connection between thermal storages or the thermal output of the CHP or the heat pump.

3.5 Load Profiles

Demand profiles for electricity and heat are generated based on the reference load profiles for Germany of the VDI 4655. The guideline can be used to generate load profiles for single- and multi-family houses to support the optimal sizing of small scale cogeneration plants. The heat demand is calculated based on the buildings specific annual heat demand and its location in one of fifteen climatic regions of Germany. Furthermore, different demand profiles are available for combinations of the season of year, weekdays or Sundays and fine or cloudy weather conditions (VDI 4655, 2008).

Heat demand and PV generation coincide the most during the seasonal transition period (Brunner et al. 2014). To highlight the potential of sector coupling, the optimisation of the systems is calculated for a transition period weekday with a clear sky.

The electricity demand profiles are scaled by the number of household members. An annual consumption of 1750 kWh per person is assumed. The demand of domestic hot water is disregarded for simplicity.

The PV generation profile is based on measurements in April from a location in the south of Germany and scaled by the installed power. All profiles within the optimisation have a temporal resolution of fifteen minutes.

4 OPTIMISATION RESULTS AND DISCUSSION

4.1 House 1

Figure 4 shows the simulation results of demand and supply for electricity and heating, and the state of charge in the buffer and the battery.

House 1 can supply its heat demand from the CHP, the furnace and the buffer. Since the furnace only operates during peak load, on a transition period day the heat demand is covered by the CHP and the buffer i.e. the furnace is not operated at all.

The operation of the CHP and the buffer are determined by the heat demand. Electricity generated by the CHP is either used for the demand of appliances or to charge the battery.

Synergy effects are seen, as charging and discharging occur at opposite times for the battery and the buffer. The battery is charged during the early morning hours and kept constant throughout the day between 07:00 a.m. and 07:45 p.m. to later supply the relatively high electricity load during the late evening. Furthermore the CHP operates more during the evening hours, after 18:00, when electricity load is high, and since the heat demand does not match the buffer is charged instead. The storage devices

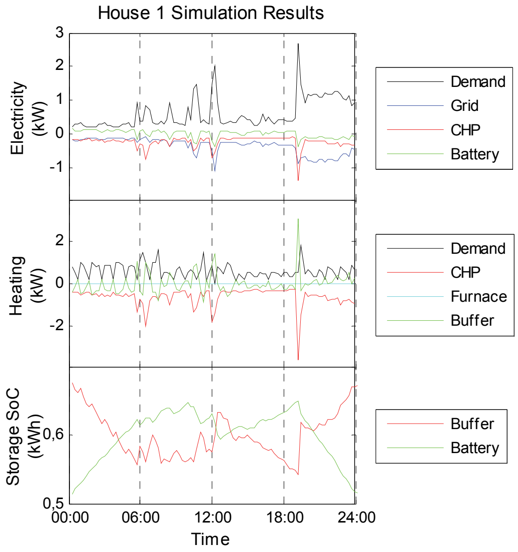

Figure 4: House 1 - Electricity, Heat and Storage time-series throughout the day.

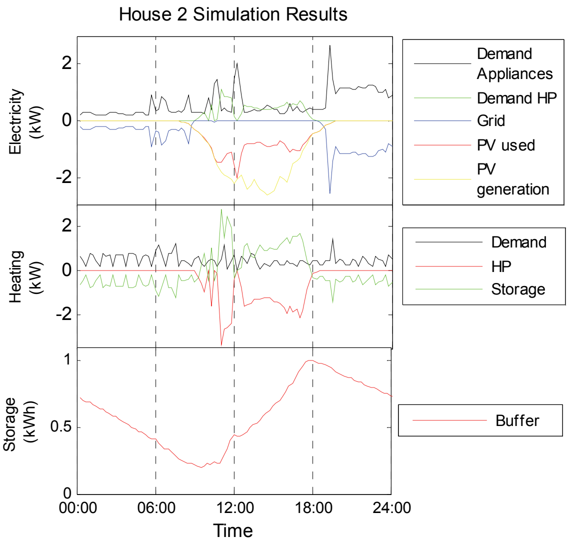

Figure 5: House 2 - Electricity, Heat and Storage time-series throughout the day.

discharge in most of the cases when peak demands for electricity and heat occur.

4.2 House 2

Figure 5 shows the simulation results for demand and supply for electricity and heat and the state of charge in the buffer for house 2.

The total electricity demand of house 2 is made up of the appliances and the HP demand. At times of no PV generation, all the electrical load has to be supplied by the grid. As the PV starts to generate electricity, it is preferred to buying electricity from the grid.

The example shows the potential of coupling the electricity and heating sectors with a heat pump. Between 09:15 a.m. and 18:00 p.m. the PV generation is mainly utilized to supply the heat pump and to charge the buffer. The heat demand occurring during the evening and morning hours is mainly covered by the buffer to avoid operating the heat pump with expensive electricity from the grid.

Even though the electricity demand in house 2 is mainly supplied by the solar power system during the day, still there is excess PV generation which cannot be utilized. Realistically this electricity would be sold back to the grid with a certain feed-in tariff, which would strongly vary by region. Note that to be able to compare various scenario's we have not considered this as part of the cost optimisation. As a consequence of the assumed setting, the excess generation has to be curtailed. This demonstrates the motivation of supplying the demand or battery in house 2 by interconnecting the two houses as described in Section 4.3.

4.3 Combined Houses

The results for the optimisation of the combined houses are shown in Figure 6.

There is now the possibility to use PV generation from house 2 in both houses replacing electricity from the grid whenever the solar power system feeds in. The amount of unused PV generation for the day is decreased from 42.6% to 4.1% in the combined system, illustrating a much better integration of the renewable energy source.

The battery is charged when PV generation is high, to later reduce the necessary supply of electricity from the grid by discharging from the evening to the early morning hours. Total energy discharged from the battery increases by almost factor 3 when the houses are combined, leading to a better utilization of the utilization of the storage device.

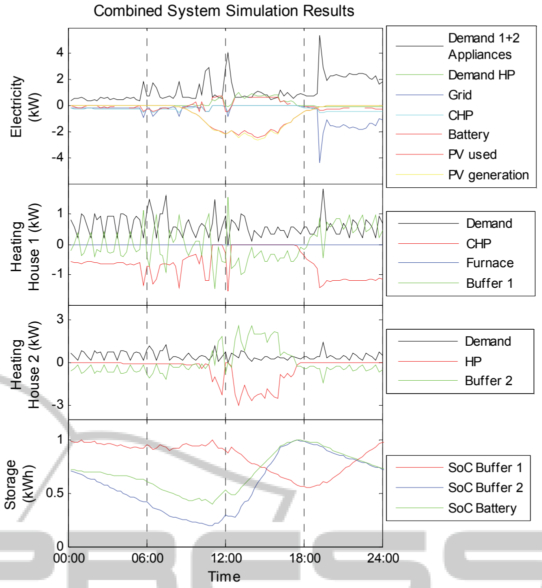

Figure 6: Combined System Electricity, Heat and Storage time-series throughout the day.

The only source of heating energy for House 1 is the CHP and the buffer which is also heated by the CHP. Therefore the total CHP production is restricted to the total heating demand of house 1. The CHP is not able to increase its overall production beyond that of the scenario in section 4.1, in order to supply more low cost electricity. The optimisation utilises the buffer for some time-shifting. As can be seen in the heating plot of house 1 in Figure 6, operation of the CHP is shut down between 12:15 p.m. and 17:15 p.m. during times of high PV generation. Buffer 1 is discharged simultaneously, leading to an increase of 46% in total daily discharged energy in comparison to the separated case. The operation of Buffer 2 has not changed from the scenario in 4.2, since it is still optimal to charge it during times of high PV generation.

Table 3: Objective function values of the compared systems.

System	Objective Function Value
House 1	194.11
House 2	108.26
House 1+House 2	302.37
Combined Optimisation	229.07 (-24.24%)

PV integration has an effect on the value of the objective function of the optimisation problem stated in section 3.1. Table 3 shows the objective function values for the separated houses and the combined houses. By interconnecting the houses the overall variable costs of the sum of the separate houses can be reduced by 24.24%. Cost are either caused by buying electricity from the grid or by burning gas for the CHP. With PV integrated in house 1, less electricity has to be purchased from the grid. Since the CHP generates the same amount of heat during the day in the separated and the combined cases, the effect of cost reduction is only caused by the enhanced integration of PV.

5 CONCLUSIONS AND OUTLOOK

The results of the three simulations have illustrated a number of benefits of coupling the heat and electricity systems of domestic buildings. House 1 results show the benefits of having both electrical and thermal storage to support a CHP plant by maximising its utilisation. House 2 showed the advantage of using a heat pump to better utilise the PV output. Finally the combined system shows the further benefits of the synergy by illustrating that greater benefits can be gained by optimising on a larger scale. The utilisation of PV increased, greatly reducing the cost of energy for both households.

Many simplifications have been made in this study, for example regarding the efficiency and linear operation of the energy storage characteristics, and constant efficiency characteristics for the CHP and heat pump. A better quantification of the advantages can be gained by more detailed modelling of the various components. This will result in non-linear system dynamics, and therefore more sophisticated optimisation techniques will be required.

Furthermore the results of this study suggest that it is worth optimising several domestic buildings or households together. This will also allow other technologies to be investigated such as CHP plants for entire building blocks.

These two components, more detailed modelling, and a wider scope of households, will guide the further work. As mentioned the wider project is to develop a framework for optimising energy systems at a city district or building block level. Another important factor that this study has not considered is the costing of various systems. Correct costing can allow the modelling framework developed in this paper to be extended and used for calculations such as optimal sizing of energy storage units and PV installations.

Besides sizing, a modelling framework will also allow for the evaluation of more sophisticated control techniques within a smart grid framework. Particularly the use of online control, where system measurements are used to re-optimise the operation at every time step has shown to bring cost benefits.

REFERENCES

Brenna, M., Falvo, M.C., Foiadelli, F., Martirano, L., Massaro, F., Poli, D., Vaccaro, A., 2012. Challenges in Energy Systems for the Smart Cities of the Future. In *Energy Conference and Exhibition (ENERGYCON),* Florence, p. 755-762.

Brunner, M., Schäfer, I., Rudion, K., Tenbohlen, S., 2014. Impacts of different seasons on the contribution of heat pumps to voltage stability. In *VDE-Congress 2014 Smart Cities Proceedings,* Frankfurt am Main, no. 46.

Geidl, M., Koeppel, G. Favre-Perrod, P., Klockl, B., Andersson, G., Frohlich, K ., 2007. Energy hubs for the future. In *IEEE Power and Energy Magazine*, vol. 5, no. 1, pp. 24–30.

Giuntoli, M., Poli, D., 2013. Optimized Thermal and Electrical Scheduling of a Large Scale Virtual Power Plant in the Presence of Energy Storages. *IEEE Transactions on Smart Grid.* vol. 4, no. 2, p. 942-955.

Hemmes, K., Zachariah-Wolf, J.L., Geidl, M., Andersson, G., 2007. Towards multi-source multi-product energy systems, *International Journal of Hydrogen Energy*, Vol 32, Issues 10–11, p. 1332-1338.

Houwing, M., Negenborn, R.R., De Schutter, B., 2011. Demand Response With Micro-CHP Systems. *Proceedings of the IEEE*, 99(1), 200-213.

Quaschning, V., 2013. *Regenerative Energiesysteme,* Hanser Verlag. München, 8th edition.

Vanhoudt, D., Geysen, D., Claessens, B., Leemans, F., Jespers, L., Van Bael, J., 2014. An actively controlled residential heat pump: Potential on peak shaving and maximization of self-consumption of renewable energy, *Renewable Energy*, vol. 63, p. 531-543.

VDI 4655, 2008. Reference load profiles of single-family and multi-family houses for the use of CHP systems. Beuth Verlag, Berlin.