Modelling of Residential Hybrid Renewable Energy System

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Abstract: This project aims to evaluate the optimal investment decision regarding the implementation of cross-sectional LCTs such as photovoltaic systems, electrical boilers, gas boilers, heat pumps or storage systems, at different tariff options and for different household stereotypes (large or small dwelling areas). Two mathematical models, a basic and a optimal model, have been developed and implemented in GAMS to assess the electrical and thermal aspects, where different technologies and their capital and maintenance costs, as well as fuel and electricity prices have been taken into consideration. The objective is to minimize the total energy system costs while keeping up with the demand, over the lifetime, and the development of the model has been carried out step by step.The basic and Optimal model were compared and analysed. They were economically assessed and a social evaluation between high- and low-income households was done as well.

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Contents

1 Contributions

Table 1: Coding and Modelling Contributions

Coding and Modelling	Carlos Ramirez	Catarina Oliveira	Miguel Madeira	Sergio Espina
Basic Model			X	
Photovoltaic cell			X	X
Irradiance data			X	X
Heat Pump	X		X	
Heat Storage			X	
Battery			X	
Exported energy	X		X	
Optimal model			X	
Data validation			X	
Code testing and debugging			X	

Table 2: Poster Contributions

Poster	Carlos Ramirez	Catarina Oliveira	Miguel Madeira	Sergio Espina
Introduction		X	X	
Objectives		X	X	
Methodology			X	
System Configuration				X
Results	X		X	
Sensitivities			X	
Conclusion			X	
General Structure			X	

Table 3: Report Contributions

Report	Carlos Ramirez	Catarina Oliveira	Miguel Madeira	Sergio Espina
Abstract	X	X	X	
Nomenclature		X		
General Structure			X	
System Configuration				X
Research pages			X	

2 Nomenclature

Decision Variables

bat	Battery installed capacity in kW
bat_to_HP	Battery electricity to heat pump
$boilerC$	Boiler installed capacity in kW
$charge_{bat}$	Charge battery
$charge_{heat\_stor}$	Charge heat storage
$discharge_{bat}$	Discharge battery
$discharge_{heat\_stor}$	Discharge heat storage
$energy_{surplus}$	Exported electricity to the grid
$heat\_stor$	Heat storage installed unit capacity in kW
HPC	Heat pump installed capacity in kW
PV_to_HP	Electricity from solar cells to heat pump
$PVarea$	Installed Photovoltaic cells area
PVC	Photovoltaic cells installed capacity in KW
soc_{bat}	State of battery charge
soc_{heat_stor}	Heat storage state of charge
T_{bat}	Total annual battery costs
T_{boiler}	Total annual gas boiler costs
T_{grid}	Total annual grid electricity costs
T_{heat_stor}	Total annual heat storage costs
T_{HP}	Total annual heat pump costs
T_{PV}	Total annual photovoltaic cells costs
$T_{surplus}$	Total annual earnings from selling electricity
$x_{el_{grid}}$	Quantity of electricity coming from the grid
$x_{el_{HP}}$	Electrical consumption from heat pump
$x_{el_{PV}}$	Electricity from solar cells
$x_{th_{boil}}$	Output of heat boiler

Objective Function

Z	Energy purchase cost

Parameters

bat_{charge_eff}	Battery charging efficiency
bat_{charge_lim}	Battery charge limit

$bat_{discharge\_lim}$	Battery discharge limit
bat_{linear_loss}	Battery linear losses
$boiler_{CC}$	Boiler capital cost
CC_{bat}	Battery capital cost
CC_{heat_stor}	Heat storage capital cost
CC_{PV}	Photovoltaic cells capital cost
COP_{HP}	Efficiency of the heat pump
$cost_{gas}$	Cost of natural gas
$efficiency_{PV}$	Efficiency of the Photovoltaic cells
$electload_{P4\_i\_Aj}$	Electricity demand in each household
$fees_{electNetwork}$	Fees to access electricity network
$heat\_stor_{charge\_eff}$	Heat storage charging efficiency
$heat\_stor_{charge\_lim}$	Heat storage charge limit
$heat\_stor_{discharge\_eff}$	Heat storage discharging efficiency
$heat\_stor_{discharge\_lim}$	Heat storage discharge limit
$heat\_stor_{linear\_loss}$	Heat storage linear losses
$heatload_{Aj}$	Heat demand in each household
HP_{CC}	Heatpump capital cost
$irradiance$	Solar irradiance per timestep
$lifetime_{bat}$	Battery lifetime (years)
$lifetime_{boiler}$	Boiler's lifetime (years)
$lifetime_{heat\_stor}$	Heat storage lifetime (years)
$lifetime_{HP}$	Heatpump lifetime (years)
$lifetime_{PV}$	Photovoltaic cells lifetime (years)
OaM_cost_{bat}	Battery Operation and maintenance costs
OaM_cost_{boiler}	Operation and maintenance costs from boiler
$OaM\_cost_{heat\_stor}$	Heat storage Operation and maintenance costs
OaM_cost_{HP}	Operation and maintenance costs Heatpump
$soc_{initial}$	Initialisation state of battery
$spot\_price$	Grid electricity spot market price
$taxes_{electCons}$	Electricity consume taxes
$taxes_{electHeat}$	Heating electricity taxes
$taxes_{gasCons}$	Gas consumption taxes
tt	Time step

3 Research

3.1 Basic Model

In the basic model only one way of fulfilling the electricity and heat demand was considered. Electricity is provided by the grid and heat is provided by a gas boiler. It was assumed that all 4 studied households were already connected to the grid and, therefore, no capital cost was added on that regard. The gas boiler, however, was assumed to not be installed yet, thus capital costs were added. Another important assumption that was considered for both the basic model and the optimal model was that, if installed, the technologies are always installed at the start of the year and used the whole year. The basic model follows **equation 1** to **equation 6**.

$$Min. \quad Z = T_{grid} + T_{boiler} \tag{1}$$

Subject to:

$$T_{grid} = \sum_{tt=1}^{8760}(spot\_price(tt) \cdot x_{el_{grid}}(tt) + taxes_{electCons} \cdot x_{el_{grid}}(tt) + fees_{electNetwork} \cdot x_{el_{grid}}(tt)) \tag{2}$$

$$\begin{aligned} T_{boiler} = & \sum_{tt=1}^{8760}(cost_{gas} \cdot x_{th_{boil}}(tt) + taxes_{gasCons} \cdot x_{th_{boil}}(tt)) \\ & + boiler_{CC} \cdot \frac{boilerC}{lifetime_{boiler}} + OaM\_cost_{boiler} \cdot boilerC \end{aligned} \tag{3}$$

$$x_{el_{grid}}(tt) = electload_{P4\_i\_Aj}(tt) \quad \forall\, tt \tag{4}$$

$$x_{th_{boil}}(tt) = heatload_{Aj}(tt) \quad \forall\, tt \tag{5}$$

$$x_{th_{boil}}(tt) \leq boilerC \quad \forall\, tt \tag{6}$$

Where $P4\_i$ refers to the household income, i=1 for 33k€ income and i = 3 for 60k€ and Aj refers to the household area, j = 80 m^2 or j = 180 m^2.The same nomenclature will also be used in the optimal model equations.

The objective of this model is to minimize the cost of energy in different households, therefore it is natural that our objective function is the sum of all the possible costs of our energy system, **equation 1**. **Equation 2** is the sum of all grid related costs, the spot price, the taxes and the total network fees. **Equation 3** is similar, but now it is the gas cost and taxes that are taken into account plus the capital and maintenance costs. Equations **4** and **5** are the demand equations. Finally, **equation 6** dictates how much boiler capacity has to be bought in order to satisfy the heat consumption at all times, this equation is key in calculating the capital cost associated with the boiler. We have assumed that the installed capacity is an integer. This is so we do not get capacities that would never be available on the market. This might lead to an overestimation of the costs. Nonetheless, at all times, if we switch the definition of the capacity to be a positive variable and not an integer the model would work just as well.

3.2 Optimal Model

For the optimal model, six options were considered to fullfill heat and electricity demand. Other than the ones already considered in the basic model, four LCTs were added: a heat pump, photovoltaic cells, a battery and a heat storage. As before, the capacity of these devices was assumed to be an integer and the devices are always installed at the start of the year. The system configuration can be seen on **figure 2**. The optimal model follows **equation 7** to **equation 32**.

$$Min. \quad Z = T_{grid} + T_{boiler} + T_{HP} + T_{bat} + T_{heat\_stor} + T_{PV} - T_{surplus} \tag{7}$$

Subject to:

$$T_{grid} = \sum_{tt=1}^{8760} (spot\_price(tt) \cdot x_{el_{grid}}(tt) + taxes_{electCons} \cdot x_{el_{grid}}(tt) + fees_{electNetwork} \cdot x_{el_{grid}}(tt)) \tag{8}$$

$$\begin{aligned} T_{boiler} = & \sum_{tt=1}^{8760} (cost_{gas} \cdot x_{th_{boil}}(tt) + taxes_{gasCons} \cdot x_{th_{boil}}(tt)) \\ & + boiler_{CC} \cdot \frac{boilerC}{lifetime_{boiler}} + OaM\_cost_{boiler} \cdot boilerC \end{aligned} \tag{9}$$

$$\begin{aligned} T_{HP} = & \sum_{tt=1}^{8760} (x_{el_{HP}}(tt) \cdot spot\_price(tt) + taxes_{electHeat} \cdot x_{el_{HP}}(tt) + fees_{electNetwork} \cdot x_{el_{HP}}(tt)) \\ & + HP_{CC} \cdot \frac{HPC}{lifetime_{HP}} + OaM\_cost_{HP} \cdot HPC \end{aligned} \tag{10}$$

$$T_{PV} = CC_{PV} \cdot \frac{PVC}{lifetime_{PV}} \tag{11}$$

$$T_{bat} = CC_{bat} \cdot \frac{bat}{lifetime_{bat}} + OaM\_cost_{bat} \cdot bat \tag{12}$$

$$T_{heat\_stor} = CC_{heat\_stor} \cdot \frac{heat\_stor}{lifetime_{heat\_stor}} + OaM\_cost_{heat\_stor} \cdot heat\_stor \tag{13}$$

$$T_{surplus} = \sum_{tt=1}^{8760} (spot\_price(tt) \cdot energy_{surplus}(tt)) \tag{14}$$

$$x_{el_{grid}}(tt) + discharge_{bat}(tt) + x_{el_{PV}}(tt) - charge_{bat}(tt) - energy_{surplus}(tt) \geq electload_{P4\_i\_Aj}(tt) \quad \forall\, tt \tag{15}$$

$$x_{th_{boil}}(tt) + x_{th_{HP}}(tt) + discharge_{heat\_stor}(tt) - charge_{heat\_stor}(tt) \geq heatload_{Aj}(tt) \quad \forall\, tt \tag{16}$$

$$x_{th_{boil}}(tt) \leq boilerC \quad \forall tt \tag{17}$$

$$x_{th_{HP}}(tt) \leq HPC \quad \forall tt \tag{18}$$

$$COP_{HP} \cdot (x_{el_{HP}}(tt) + PV\_to\_HP(tt) + bat\_to\_HP(tt)) = x_{th_{HP}}(tt) \quad \forall tt \tag{19}$$

$$\begin{aligned} soc_{bat}(tt_0) = (1 - bat_{linear\_loss}) \cdot soc_{bat}(tt_0 - 1) + charge_{bat}(tt_0) \cdot bat_{charge\_eff} \\ - \frac{discharge_{bat}(tt_0) - bat\_to\_HP(tt_0)}{bat_{discharge\_eff}} \end{aligned} \tag{20}$$

$$soc_{bat}(tt_0) = soc_{initial}(tt_0) \tag{21}$$

$$soc_{bat}(tt) \leq bat \quad \forall tt \tag{22}$$

$$charge_{bat}(tt) \leq bat \cdot bat_{charge\_lim} \quad \forall tt \tag{23}$$

$$discharge_{bat}(tt) + bat\_to\_HP(tt) \leq bat_{discharge\_lim} \cdot bat \tag{24}$$

$$soc_{heat\_stor}(tt_0) = soc_{initial}(tt_0) \tag{25}$$

$$\begin{aligned} soc_{heat\_stor}(tt_0) = (1 - heat\_stor_{linear\_loss}) \cdot soc_{heat\_stor}(tt_0 - 1) \\ + charge_{heat\_stor}(tt_0) \cdot heat\_stor_{charge\_eff} - \frac{discharge_{heat\_stor}(tt_0)}{heat\_stor_{discharge\_eff}} \end{aligned} \tag{26}$$

$$soc_{heat\_stor}(tt) \leq heat\_stor \quad \forall tt \tag{27}$$

$$charge_{heat\_stor}(tt) \leq heat\_stor \cdot heat\_stor_{charge\_lim} \quad \forall tt \tag{28}$$

$$discharge_{heat\_stor}(tt) \leq heat\_stor_{discharge\_lim} \cdot heat\_stor \tag{29}$$

$$x_{el_{PV}}(tt) + PV\_to\_HP(tt) = irradiance(tt) \cdot PVarea \cdot efficiency_{PV} \tag{30}$$

$$x_{el_{PV}}(tt) + PV\_to\_HP(tt) \leq PVC \tag{31}$$

$$PVarea \leq Aj \cdot 0.8 \tag{32}$$

Equations **8**, **9** and **17** are the same as those for the basic model. Equations **10** to **13** account for the total costs associated with each of the technologies and are, in general, a sum of the capital costs, the maintenance costs and the costs of their respective resource (e.g gas for the boiler). Equation **14** calculates the total exported energy. Our objective function, **7**, is then the sum of the costs minus the sold electricity. Equation **15** is our electricity demand equation, the sold electricity and the change of the battery is added to the electricity demand but now there are also more sources, namely the discharge of the battery and the PV production.Equation **16** is our heat demand, the charging of the heat storage is added to the demand while the sources are now the boiler, the heat pump and the discharging of the heat storage. Equations **17**, **18**,

22, **23**, **24**, **27**, **28**, **29**, **31** all follow the same principle, the max production/storage of a device is limited by it's installed capacity.Solar cells are further limited by the total roof size of the household, **equation 32**. Equations **20** and **26** calculate the state of charge of the battery and the heat storage respectively by considering the soc in the last time period, the charging and discharging in this time period and the linear losses. The only difference between them is the bat_to_HP term which is the discharging of the battery to the heat pump. All of the electricity consumption of the heat pump, **equation 19**, had to be separated from the electricity demand due to the fact that the taxes for heat production are smaller. The initial state of the battery and the heat storage are defined in equations **21** and **25** respectively. Finally, the calculation of the electricity production from the PV is done in **equation 30**. The solar irradiance data was taken from [1]. It was assumed the solar cells were fixed at the optimal angle in Lyngby. The results and comparison between the 2 models are in **table 4** and **figure 1**.

Household	Optimal Model						Basic Model		Cost Savings (%)
	Boiler	Heat Pump	Battery	Heat Storage	PV	Z	Boiler	Z	
80 m2 area 66k€ income	1	1	4	0	12	1265.07	2	2090.80	39
180 m2 area 66k€ income	1	3	6	2	19	2041.98	4	3523.43	42
80 m2 area 33k€ income	1	1	4	0	11	1177.16	2	1959.51	40
180 m2 area 66k€ income	1	2	6	2	19	2060.37	4	3569.09	42

Table 4: Optimal and basic model results

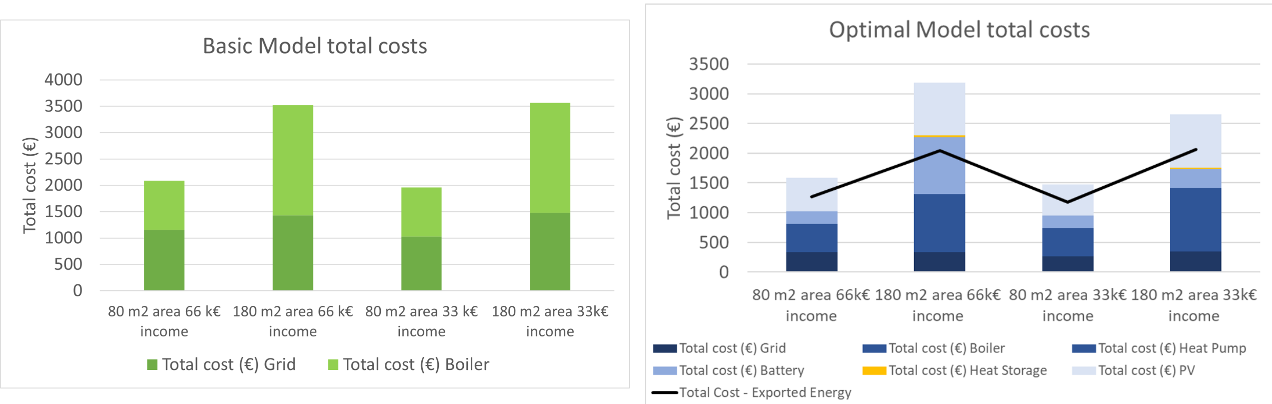

Figure 1: Optimal and basic model total costs

From these results we can conclude that the optimal model can develop energy system layouts that reduce the costs in about 40%. In the households with the biggest heat and electricity demands the optimal models invests in all technologies. The heat pump is, in general, more used than the gas boiler. The Optimal model highly invests in solar energy, so we can expect CO_2 emissions to go down even though this aspect was not considered in the model at all. The results are aligned with what was to be expected, the main surprise would be the big investment in solar cells, but this is mainly explained by the high electrical consumption taxes and network fees considered. The Optimal model can be used to explore all sorts of interesting scenarios such as the one considered on the poster.

4 System Configuration

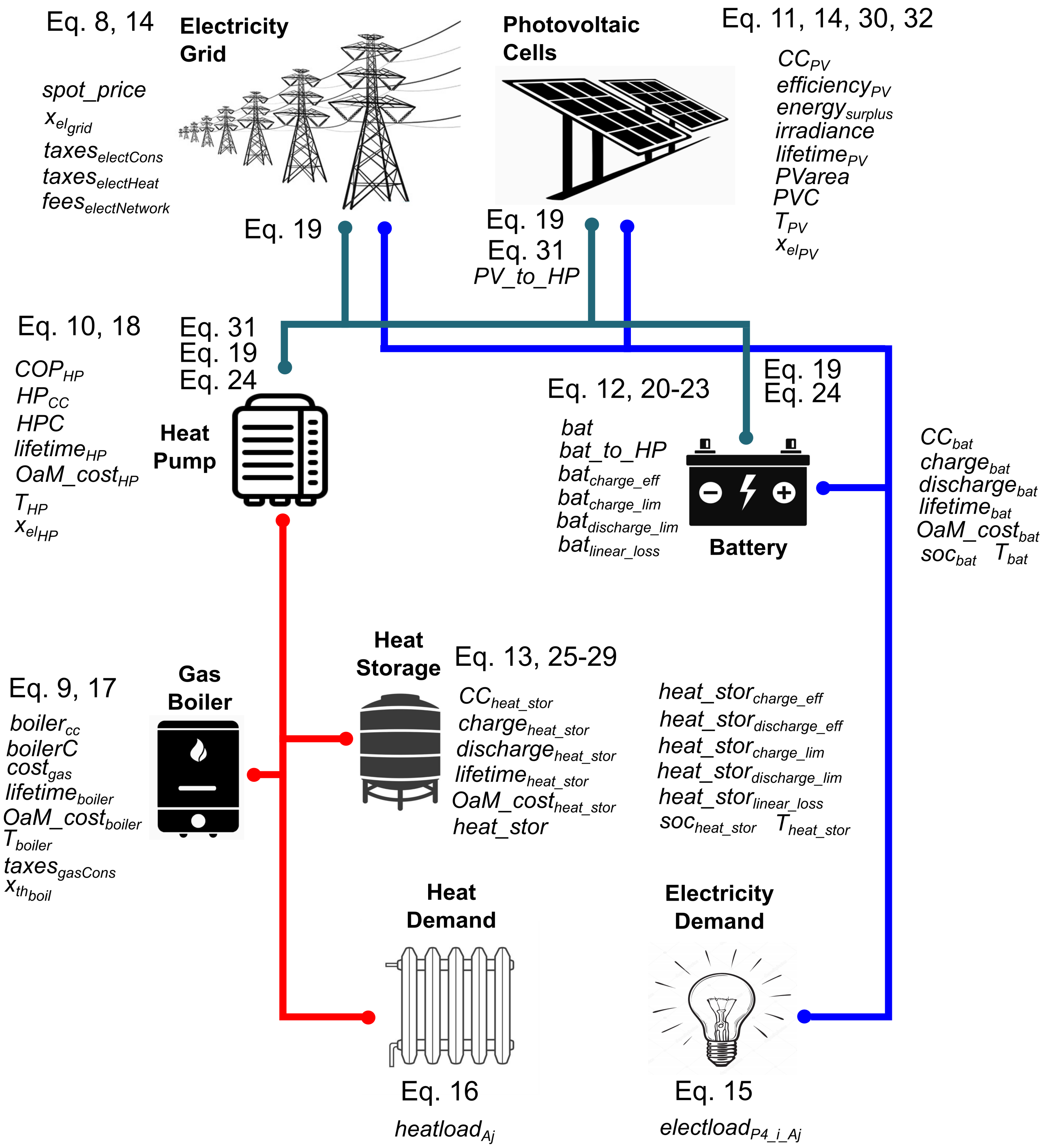

Figure 2: System configuration

References

[1] European Comission. *Photovoltaic Geographical Information System*. URL: https://re.jrc.ec.europa.eu/pvg_tools/en/#MR.

[2] Jonas Katz et al. "Household electricity consumers incentive to choose dynamic pricing under different taxation schemes". In: *WIREs Energy and Environment* 7.1 (2018), e270. DOI: https://doi.org/10.1002/wene.270. eprint: https://wires.onlinelibrary.wiley.com/doi/pdf/10.1002/wene.270. URL: https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.270.

[3] Lena Kitzing et al. *The residential electricity sector in Denmark: A description of current conditions*. Tech. rep. DTU Management Engineering, 2016.

[4] Wolf Fichtner Thomas Kaschub Patrick Jochem. "Solar energy storage in German households: profitability, load changes and flexibility". In: ().

[5] Wolf Fichtner Erik Merkel Russell McKenna. "Optimisation of the capacity and the dispatch of decentralised micro CHP systems: A case study for the UK". In: ().

[6] Wilhelm Kuckshinrichs Gianmarco Aniello Hawal Shamon. "Micro economic assessment of residential PV and battery systems: The underrated role of financial and fiscal aspects". In: ().