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Energy Scheduling Model to Optimize Transition Routes Towards 100% Renewable Urban Districts

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ABSTRACT

The purpose of this paper is to develop a model to analyze options for 100% renewable urban districts which self-consume locally generated renewable energy as much as possible and import (or export) energy from (or to) external grids as little as possible. Energy scheduling algorithms are developed to prioritize energy generation and storage of local renewable energy. The model is applied in a Dutch case study in which three renewable energy system concepts are evaluated against the case reference. Optimal capacities are determined for minimal operational costs including a penalty on carbon dioxide production. Attractiveness of these concepts is discussed in relation to costs, environmental concerns and applicability within the Dutch context of the energy transition.

Keywords:

Urban energy;
District heating;
Renewable energy;
Smart grids;
Optimal capacity;
Energy priority scheduling;
Energy transition;

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1. Introduction

As in most North-Western European countries, approximately 40% of the total energy consumption of the Netherlands is related to heat demand. More than half of this consumption is for heating buildings and domestic hot water. Due to the natural gas reserves in the Northern part of the country and offshore, the Netherlands relies mostly on natural gas combustion for the supply of the heat demand in boilers, but besides that, also a large part of the electrical energy demand is fulfilled by large scale gas fired, co-generation plants. This ongoing situation gave Dutch industry a leading position worldwide in natural gas network and boiler technology. As combustion of natural gas leads to 50% less CO_2 emissions compared to combustion of coal, the Dutch energy system was relatively environmentally friendly in the past, in comparison with many countries which relied predominantly on coal combustion. However, global warming due to increasing CO_2 concentration in the atmosphere is recognized as a major threat to the population and environmental policies contain targets to out-phase the use of fossil fuels entirely. Recently, new agreements on climate change are adopted by the UNFCCC (United Nations Framework Convention on Climate Change) [1] with a treaty to limit global warming to 2.0 degrees and to strive for a limitation of 1.5 degrees. The treaty is signed by many governments in the world, including the Netherlands. The Dutch ministry of economic affairs, responsible for energy policies, has announced a shift of paradigm: initiatives towards integration of renewable energy in the heating sector will be encouraged in order to phase-out the use of natural gas completely by 2060 [2]. In [3], the Dutch government translates this vision into policy measures and proposals. Recent years

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show a growing number of district heating projects with integrated renewable energy sources and a growing number of so called all-electric buildings in which the thermal demand is electrified by heat pumps. The collective approach of district heating has advantages for the integration of renewable energy, especially for existing buildings in densely populated areas [4]. However, new low-energy houses require less energy for space heating which makes individual heating systems in many cases a more attractive option, although integration of renewable energy and a suitable thermal source for heat pumps are important drivers to consider low temperature district heating in this case [3]. Due to the natural gas heritage, many urban districts in the Netherlands lack the possibility to connect to larger district heating systems. Hence, there is a large potential for new urban energy concepts with local district heating solutions. The challenge for such concepts is to integrate local renewable energy in such a way that the energy supply-demand chain is optimized towards zero CO_2 emissions and with a positive business case.

This paper investigates options to integrate renewable energy within a recent local district heating project in the new district Nieuwveenselanden in Meppel [5] in such a way that the generated renewable energy is deployed by the district as much as possible. The analysis and results presented in this paper are to some extend relevant for many new and existing urban districts in the Netherlands, either having a collective or individual heating system. In many of our recent studies, the level of self consumption of renewable energy is an important quality aspect for citizens and energy utilities. The district in Meppel presently counts 106 occupied houses and a further 90 houses are built in 2016 and 2017. The houses are connected to a combined district heating and cooling system for two important reasons: (1) there is a wish to use locally available renewable fuel (biogas and wood chips) and cooling (aquifer, lake source) for which a collective approach is more suitable than individual heating, (2) the number of houses and the density of houses and heating or cooling demand per area is sufficiently large.

Due to an unforeseen decline in the building sector up to the year 2015, development of the area slowed down and investments into the generators for the district heating system were limited to natural gas boilers and electric compression coolers. For the present system and for future generations of the expanding district, the aim is to investigate possible routes towards integration of renewable energy.

Contributions: the paper presents an algorithmic model which schedules controllable renewable energy generation, thermal and electrical storage. The model uses profiles for thermal and electrical demand and uncontrollable renewable generation as input. For a Dutch new built urban district case, the model is applied to determine optimized capacities of renewable energy concepts and the possibility to reach 100% renewable energy supply.

The paper is structured as follows. Section 2 summarizes related work into fourth generation district heating systems, integration of renewable energy into existing networks and modeling frameworks for determining optimal configuration of energy systems. Section 3 outlines the methods used in this paper: (a) methods used to generate input data for the district's electric, heating and cooling demand, (b) the modeling framework to determine optimal sizes of generators and storage facilities, operational costs and environmental impact. Section 4 discusses case related results. Finally, conclusions and recommendations are given in Section 5.

2. Related work

The district heating system of Meppel is operated at 80 degrees supply temperature for heating and 15 degrees for cooling. The joined return ranges in temperature between 20 and 35 degrees. Following recent developments in Denmark, the so called fourth generation district heating (4DH) concept [6], the aim is to lower the supply temperature in order to reduce heat loss. In [7] we determine the optimal supply temperature at 60 degrees. At that temperature, the decrease of costs due to lower thermal losses are breaking even with higher costs due to increasing pumping energy. Besides that, in the case of Meppel, 60 degrees is also a safe minimum supply temperature to avoid legionella bacteria growth in the supply of domestic hot water through the home heat exchangers which are connected to the network. As a second step, the supply temperature can be reduced further if heat pumps are used to increase the temperature at the household level. This approach is part of an “all electric” concept which we investigate in this paper. In [8], a case for including low temperature geothermal heat into an existing district heating system is investigated which demonstrates the feasibility of using heat pumps for this purpose.

As future renewable energy systems are supplied predom-inantly by renewable energy from solar-PV, wind turbines, geothermal energy and biofuel, district heating systems can provide large amounts of cost effective flexibility to balance energy generation and demand [4] and [3], predominantly by "power to heat" technologies and large scale thermal storage. Dutch policies [9] and [3] however, are more aimed at reducing the heat loss of buildings and increasing the share of renewable energy within the power grid than to stimulate district heating. We believe the positive role that (district) heating systems can play in the energy transition is presently overlooked by national and regional policy makers in the Netherlands. Hence, this paper demonstrates the possibilities that arise when the (district) heating system plays a central role within an integrated, renewable energy system, in order to contribute to a better understanding of these possibilities.

Determination of optimal generation capacities of renewable generators for (district) heating systems is a recent investigation area. For larger area and district energy supply studies, the software "Energyplan" is suitable to analyze system capacities and energy flows [10]. For a case application see [8]. In Energyplan it is possible to configure renewable generators which are applicable for local, urban districts and to use fixed scheduling methods for least costs or least CO_2 production. However, the control of thermal and electrical generation and storage energy flows as part of a local energy system, determines the resulting capacities but also to which extend the generated renewable energy is effectively used for the local consumption, which is our main goal. We have no detailed insight of the scheduling methods of Energyplan for this purpose, which is why we develop our own model for this. Besides that, some of our future work involves renewable energy systems which contain a new type of seasonal thermal storage (Ecovat, see [11]) for which control of different temperature layers is important in relation to the thermal energy generation and demand. This new type of storage is not yet part of Energyplan. A model for control purposes of the storage is presently developed by the University of Twente. Therefore, this paper is a first step towards a model for the analysis of urban energy systems which contain the Ecovat seasonal thermal storage. As a second step and part of future work, we compare the results of this paper with Energyplan results of the same energy system and input data as discussed in this paper. As third step we implement the model for the Ecovat seasonal thermal storage.

Part of our earlier work involved the development of a method to determine optimal capacities of a biogas CHP and thermal storage in relation to the size of the district in [12]. The present paper has a much wider scope and aims to integrate different renewable energy generators in order to analyze different concepts. Optimal capacities of renewable energy generators depend on often contradicting objectives for a specific project, as many of the relations between capacity and costs are non-linear. Hence, this is a particularly difficult problem for mathematical optimization. In [13] genetic algorithms are used to find optimal capacities of heat pumps for a Swiss district heating system. In [14] a non linear programming model is used to design district heating networks which are minimized on total energy consumption and operational costs. In [15], optimal size of a residential micro CHP and storage in Japan is determined by applying a mixed integer nonlinear programming model. Finally, an example of a similar algorithmic energy priority scheduling approach is given in [16] for a case study which involves solar PV integration with power to heat and thermal storage for a district heating system in Italy. They use Multi-Objective Evolutionary Algorithms with a Pareto front to determine optimal capacities of solar PV generation with electrical and thermal storage. Their paper shows two methods of optimization. Our paper has a wider and thus more complex scope for the energy priority scheduling, and also provides a thorough discussion of the case results in terms of energy flow behavior and the achievable economic and environmental results.

Patterns for the aggregated heating and cooling demand and electrical energy demand of households are either based on measured data or simulation models. For the thermal demand, suitable methods based on measured data are treated in [17] and [18]. As data is often lacking, simulation methods are often used. In [19], [20] deterministic modeling approaches are given. In [21] we develop a modeling approach based on a general thermal network model of the Meppel houses. This method is also adopted in this paper for which we show the used parameters and results. As part of the heating demand, we show a simplified modeling approach for domestic hot water demand profiles. For the household electrical energy demand profile we use the method and python codes developed in [22].

3. Methods

3.1. Energy systems

As introduced in Section 1 we assume that 200 houses are connected to a district heating and cooling system and local electricity grid which is connected to the larger grid. The case reference energy system contains collective boilers with natural gas as fuel for heating, a small thermal storage to guarantee continuous temperature supply of hot water and electric cooling compressors for the supply of cold water. For the case reference, all household electrical demand is supplied by the larger grid which contains a mixture of generation sources.

To integrate renewable energy, the Meppel project considers to replace the fossil fuel (natural gas) consumption of the case reference system with a different combustion technology using locally available wood chips as biofuel for the supply of the district heating demand in two forms: with a biofuel boiler or with a biofuel co-generator. For the cooling demand, various renewable options are available. Often used in the Netherlands are natural sources with sufficient low temperatures of 8–12 °C. Most commonly used are underground aquifers. Close to the Meppel project is a deep lake formed by sand excavations. This lake can be used as cooling source and as source for heat pumps. Aquifer and lake source cooling have the advantage of low electrical energy consumption as they only require pumping energy. The main disadvantage is that initially, the investment is much higher than compression cooling [23] and [24]. Another option is power to heat. Local or regional renewable electricity generation is transformed into heat by using heat pumps. As source for renewable electricity generation we investigate a large Photo Voltaic (PV) facility and regional available wind energy. The latter is mainly introduced to investigate to which extend the production drop of solar PV energy in the winter period is sufficiently compensated by increased production of wind energy within the region. It is also interesting to investigate whether biofuel co-generation on a smaller scale may be valuable as a supplement to the power to heat option or not.

A global schematic which represents variants of these options (bio-source versus power to heat) is shown in Figure 1 for which the terms are explained in Table 1. The schematic does not include all possible renewable energy options, the most important being solar thermal energy, either as a decentral or central system. A decentral installation, i.e. rooftop solar collectors and household scale storage is difficult to integrate within a district heating system and involves substantial additional costs, while offering only fuel or electricity savings, depending on the district heating generation concept. A central solar thermal system (collector field and large scale storage) is often not a

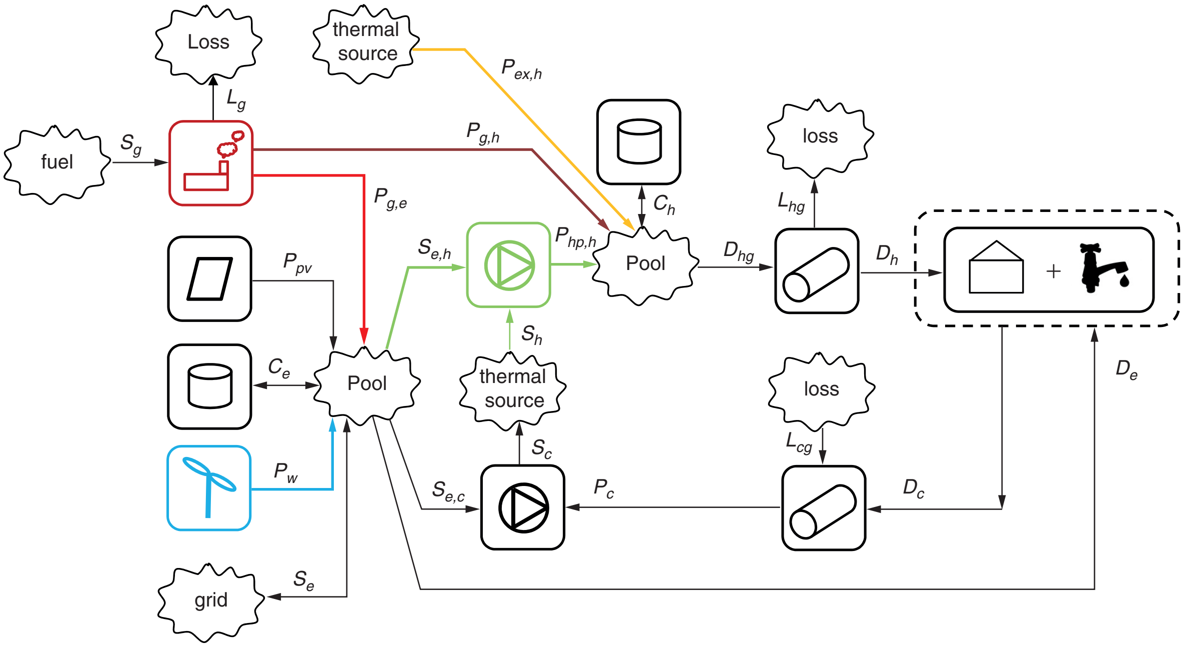


Figure 1: Global demand-supply schematic of modeling framework

Table 1: Energy model terms

Term	Signification	Group
S	energy from Source	supply chain elements
P	Produced energy by converter	
D	energy supplied to Demand	
C	energy Charged to/from storage	
L	Loss of energy	
h	heating	energy functions
c	cooling	
e	electricity	
g	generator (boiler/co-generator)	converters
cc	compression cooler	
pv	photo voltaic modules	
w	local wind turbines	
hp	heat pumps	
ex	external heating	
hg	heating grid	pipes or networks
cg	cooling grid	

feasible economic option in the Netherlands due to the required land space and associated property costs. This is the main reason why solar thermal energy is rejected by the Meppel district heating utility in an early stage of the project. However, our future work will include seasonal thermal storage and also solar thermal energy generation.

The schematic contains an "external" heat supply, which is in our case a natural gas boiler which is used to supply any residual heat demand which cannot be supplied by the configured renewable sources.

In the following subsections we develop a model for the schematic given in Figure 1. The main purpose of the model is to investigate energy flows, costs of energy supply and system component capacities which determine equipment investment costs. In [12] we show that daily energy consumption values are sufficient for generation capacity optimization. However, when the balance between energy generation, consumption and storage is investigated, an hourly timescale shows much more information to evaluate energy flows. Short term peak demand flows are only visible when minute or second time scales are used. However, such small time scales lead to large data arrays and a large computational effort during capacity optimization studies. We use an hourly time scale as a compromise. A limitation is that due to possible higher short term demand and supply loads, the model should not be used for final dimensioning of the electrical network (cables, transformers, power switches etc.).

3.2. Heating and cooling demand profile

As we lack historical data but require valid demand data which contains inertial effects of the houses, the district heating and cooling demand profile is determined by simulation, according to the procedure and equations given in Appendix A. The district heating demand also includes demand for domestic hot water. For this an approximation method is shown in Appendix B. The domestic hot water profile is added to the district space heating profile which results in a district heating profile, D_h. The profile is shown in Figure 2. The district cooling demand profile D_c is shown in Figure 3. Within these figures, the grey lines signify hourly demand, the black lines signify 24 hour average demand.

3.3. Household electrical energy demand profile

Also for the household electric demand, a simulation method is used to generate realistic data. For this we use the open source profile generator tool developed and validated with real data of a group of Dutch households in [22]. Within the tool, the following is configured

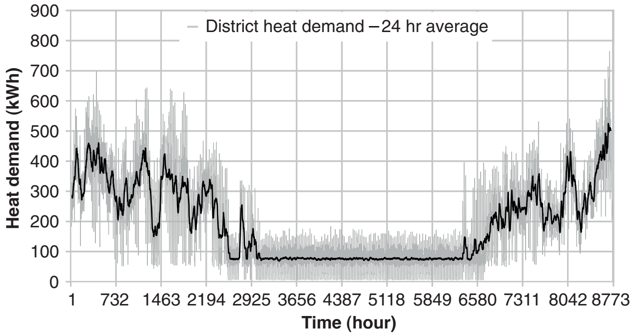


Figure 2: Aggregated district heating demand D_h

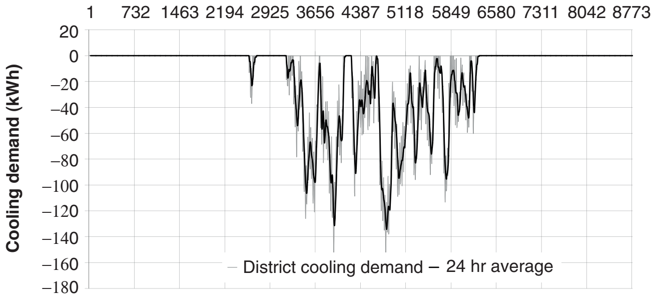


Figure 3: Aggregated district cooling demand D_c

according to the population composition of the Meppel district:

- power consumption of household electrical appliances such as: water kettle, washing machine, dishwasher, microwave, induction cooking, fridge, vacuum cleaner, etc.,
- occupancy related settings, and
- number of household types (estimated from project in formation): 18 single worker, 18 single retired, 20 dual worker, 20 dual with single worker, 20 dual retired, 36 family with dual worker, 68 family with single worker.

The profile generator outputs the hourly electricity consumption of each household excluding time shiftable devices such as a washing machine and dishwasher. For this, a standard device profile is given as output and starting times based on a random distribution. To include this consumption into the total electricity demand profile of all the households, a distribution function for the starting times is first determined. Then a total consumption profile for all the time shiftable devices is added to the total electricity demand profile. For the first week of the year, the resulting aggregated profile D_e is shown in Figure 4.

The average yearly consumption per household is 2882 kWh.This is similar as the present country average for two person households. The profile shape is approximately similar as the standard network profile shown in [25].

3.4. Solar PV and wind turbine generation

To calculate solar PV electricity production, the same relations are used as mentioned in Appendix A to translate global solar irradation into radiation on the plane of the PV panels, which are assumed to be placed due South with a 40 degrees tilting angle. Hourly PV production in kWh/m^2 unit is calculated by multiplying the solar radiation on the PV panel with a constant state-of-industry efficiency of 16% for a PV system including PV module efficiency, inverter efficiency and minor cable losses. For simplicity, the influence of module temperature on the electricity production is neglected. Solar PV is financially and juridically part of the local urban energy system as in most cases, home installations are payed for by the home owners or by the local energy utility.

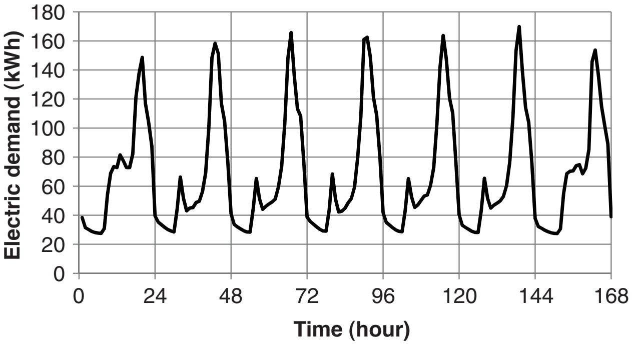


Figure 4: Aggregated household electrical energy demand D_e

Because larger wind turbines produce significantly more energy than required for 200 houses, wind turbines are financially and juridically assumed not to be part of the local urban energy system. In our model, wind energy is treated as a special form of grid electricity import. Priority is given to wind energy when it is available and an excess of wind energy is not stored in the electrical storage. The amount of available wind energy is determined by the production of a single wind turbine, for which we assume a state-of-industry 1.5 MW wind turbine with 80 meters axle height and 70 meters rotor diameter. The generation profile is determined in three steps, refer to Appendix C. The wind turbine produces a yearly amount of electrical energy equivalent to the yearly demand of 1000 households. Hence, for 200 houses, one fifth of the energy produced by the wind turbine is available when grid imports are required. Although the basic tariff for wind energy is somewhat higher than the basic tariff for "grey" electricity, there are no CO_2 costs involved for wind energy. Therefore, the total costs per unit (basic tariff plus CO_2 costs) are approximately equal to "grey" energy from the grid.

3.5. Biofuel boiler and CHP generation

For the biofuel boiler or CHP we assume that the hourly production can be varied in 10 equal increments between 0 and maximum power. To calculate the fuel requirement, we further introduce a constant thermal efficiency (0.95 for the boiler, 0.62 for the CHP) and additionally a constant electrical efficiency (0.33) for the CHP for all control steps. This is a simplification of the reality. Efficiency of industry-standard equipment usually drops for lower production rates.

3.6. Heat pump and cooling generation

For the heat pump a constant Coefficient Of Performance (COP) including source pumping energy of 3.8 is determined from thermodynamic heat pump cycle calculations with evaporator temperature of 5 degrees, condenser temperature of 65 degrees Celsius and compressor efficiency of 88%. The heat pump supplies thermal energy for the district heating demand directly and is not able to charge the thermal storage because the thermal storage is charged with a higher temperature up to 95 °C. Part of future work is to include the possibility to charge the thermal storage with the heat pump with a varying COP. For the generation of cooling energy, the COP of a lake source or aquifer is project-dependent. We estimate the COP of both options to be similar at 20. Practical performance of these options is reported in [23] and [24]. Cooling COP of the case reference which uses a compressor refrigeration cycle is determined at 2.5.

3.7. Thermal and electrical storage

A storage may have several functions within an urban energy system:

- Increase self-consumption: overcome the mismatch between production hours and consumption hours of energy produced locally by renewable energy generators like solar PV.
- Enable smaller generation capacities by storing energy to use at a later moment for peak demand.
- Increase profitability: store (electric) energy at times of low energy prices, sell (electric or thermal) energy for higher prices.

The present analysis is limited to storage of energy with a daily charge and discharge pattern. Energy losses from the storage are assumed negligible but will be included in the model as part of future work.

3.8. Electricity grid import and export

Throughout the paper we focus on self-consumption of locally generated renewable energy. The reasons for this are:

- In comparison to “grey” energy from the main grid, renewable energy is in general still more expensive to generate but has a lower market value when it is being exported to the main grid, i.e. it is financially often more attractive to self-consume the generated energy. However, the present situation for Dutch households is that by law an equivalent unit price is received for exports and levied for imports of electricity as long as the yearly exports don't exceed the imports. A yearly export surplus is multiplied with a much lower unit price and is therefore a less attractive situation.
- A capacity optimization on minimum energy costs which includes low prices for imports of “grey” energy from the main grid will lead to much less renewable energy generation and hence, counteract a greener energy supply.
- Self consumption within a neighborhood reduces energy transport losses on a larger scale.
- Many people like the idea to produce and consume their own energy.

To steer the optimization towards self-consumption, a higher constant price for grid imports is assumed and lower constant price for grid exports, which is realistic from the viewpoint of a utility who buys and sells electricity on the market. The values are based on present day average spot market price levels. Within the model, we did not introduce a pricing penalty on electricity peaks. However, the costs of transformers and cables within the model has a relation with the peak electricity values and these costs will increase with higher electricity peaks.

3.9. Optimization model

It is common practice in the design of Heating and Cooling equipment to determine capacities based on the maximum heating and cooling demand. However, if the demand is supplied by a combination of different generators and partly by a storage, a simulation is required to determine the capacities. With multiple supply sources, optimal capacity of each generator is related to the objective, e.g. minimal costs. An iterative optimization model is developed for which the general framework is shown in Figure 5. Initial capacities are input to the energy scheduling model (refer to Section 3.10) which has hourly demand as input and supply energy flows as output. The supply energy flows are translated by the cost optimization model into

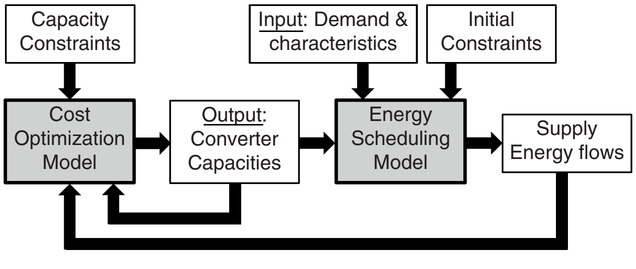


Figure 5: General framework of the optimization model

operational expenditures. Through multiple iterations with a suitable solving method, optimal generator capacities are determined in relation to a predefined objective. As objective for the optimization we propose to minimize the following cost function, Equation 1.

$$\begin{aligned} &\text{Minimize} \sum_{j\in J} C_{j,\,capex} + C_{j,\,opex} + C_{import,\,grid} + \\ &\qquad C_{CO2,grid} + C_{CO2,ngas} - B_{export,grid} \\ &\text{variable : } X_j \\ &\text{subject to : } X_{min,j} \le X_j \le X_{max,j} \end{aligned} \tag{1}$$

In which:

- X_j signifies capacity of equipment within set J.
- $J = \{$biofuel CHP, biofuel boiler, heat pump, refrigerator, heat pump/natural cooling source, solar PV, thermal storage, electrical storage, grid connection, external heat$\}$, i.e. J represents a set which constitutes energy converters, storage facilities and capacity dependent grid connection.
- A wind turbine is not part of set J. The model calculates as last step the required electricity import from the grid. Within this import, wind energy has priority before import of "grey" electricity from the grid.
- Yearly capital expenditures (CAPEX) of configured options from set J, consisting of the depreciation of investments, which is related to capacity by Equation 2. In this equation Y_{min} signifies the Investment Cost Per Unit Size or Capacity and X_{min} signifies the Capacity, both for the smallest considered unit. The parameter a is a power law factor which is determined from various project related information sources on equipment investments. Values for these parameters are given in table 2. Y_{max} and X_{max} signify investment cost per unit size and capacity of the largest considered unit.

$$C_{j,capex} = \frac{X_j \cdot Y_{min,j}}{LifeTime_j} \cdot \left(\frac{X_j}{X_{min,j}} \right)^{-a} \tag{2}$$

- Yearly operational expenditures (OPEX), consisting of two parts: (1) yearly maintenance costs expressed as fixed percentage of investments, (2) yearly costs of energy supply, e.g. fuel costs for which we write:

$$C_{fuel} = \sum_{t}^{\tau} C_{ngas,t} + C_{biogas,t} + C_{biomass,t} \tag{3}$$

- In which the following signification is used: $ngas$ is natural gas consumption (external heat in the model), $biogas$ is biogas consumption of the CHP and $biomass$ is biomass consumption by the boiler. For the summation, τ is the total number of hours, each hour signified by t. For cost parameters, refer to Table 2 and 3.
- Costs (C) and benefits (B) of grid imports and exports, evaluated with a similar expression as Equation 3. The applied costs per unit energy are specified in Table 3. For simplicity reasons, yearly totals of the grid import and export are multiplied by fixed prices. In reality, dynamic electricity market prices could apply, e.g. varying hourly average prices, but this depends on the case circumstances. Refer to Table 3 for tariffs.

Table 2: CAPEX, lifetime and maintenance parameters

Equipment	Unit	Y_{min} €/unit	Y_{max} €/unit	X_{min} unit	X_{max} unit	a	Life Time years	Maintenance %
biofuel CHP	kW_e	2000	1400	50	1000	0.125	15	4
external heat supply	kW_th	60	40	50	1000	0.132	15	4
biofuel boiler	kW_th	1200	800	50	1000	0.129	30	4
solar PV	kW_p	1600	900	10	1000	0.125	25	1
heat pump/refrigerator	kW_th	500	360	50	500	0.148	20	4
heat pump/cooling source	kW_th	1200	750	5	3,333	0.065	50	2
thermal storage	kWh	70	40	10	2500	0.096	50	1
electrical storage	kWh	300	150	10	2000	0.145	10	2
grid connection cables & transformers	kW	140	26	100	1000	0.780	25	3

Table 3: Energy price parameters

Equipment/process	Fuel type	Cost (€/kWh)
biofuel CHP	biogas	0.045
external heat supply	natural gas	0.028
biofuel boiler	wood chips	0.023
wind energy	—	0.11
grid imports	—	0.07
grid exports	—	–0.04

- A penalty for CO_2 production applicable only for combustion of natural gas and imports of "grey" electricity. To steer the optimization more towards self-consumption, there is no CO_2 benefit within the objective for exporting renewable electricity to the grid. We introduce an artificial high price as the present average European trading price for CO_2 emissions of approximately 7 €/ton is by far not high enough to play a decisive role during the optimization. In [26] the effects of CO_2 trading prices on reducing emissions worldwide are investigated. To be an effective instrument for the world climate targets, a price in the range of $40-50$ €/ton is concluded as a tipping point for large scale integration of green electricity production and storage. However, for heat generation within urban energy systems, we find with the model that 60 €/ton is the minimum CO_2 price level for which systems based on renewable energy are starting to be feasible as outcome of the optimization. The Dutch energy tax for household energy consumption can also be interpreted as a CO_2 tax. Presently, the energy tax is €0.25/m^3 natural gas and €0.10/kWh electricity. For natural gas combustion into heat, a ratio of 52 kg CO_2/GJ or 0.187 kg CO_2/kWh_{th} is accounted for. For grid electricity, the ratio is deduced from [27] which states that the Dutch energy production sector emitted 53 MTon CO_2 in 2015 and according to [28] the production was 97 TWh in 2015. This leads to 0.558 kg CO_2/kWh_e. When the Dutch energy tax for households is interpreted as CO_2 tax, the present price is calculated at a minimum of €134/ton. Part of future work is to further investigate the relation between renewable energy system capacities and the price of CO_2 emissions.

The optimization problem is non-linear and convex. The convexity is dominated by the decrease of unit price with size, i.e. $f_j(\alpha x) \leq \alpha f_j(x)$ which applies to all CAPEX and OPEX terms related to the use of equipment in set J. We used Excel's built in non-linear solver. The process involves some art to manually determine size constraint boundaries and then to apply local optimization with a randomized algorithm to increase the probability of finding the optimum solution out of many candidate solutions. The process is time consuming but successful for all investigations considered in this paper.

We should note that the results depend on the CAPEX and OPEX parameters given in Tables 2 and 3. Although these parameters are the result of an investigation into cost information from projects across Europe, quotation information is subject to interpretation. Besides that, prices change in time and prices differ between countries, projects and suppliers. The given parameters are also limited within a certain size range, applicable for urban districts ranging in size from only a few houses up to approximately 2000 houses. Hence, Table 2 and 3 should be applied with great care or altered according to more recent or specific insights.

3.10. Energy scheduling model and algorithms

In this section we develop a model for the global system shown in Figure 1, in the form of algorithms which express the scheduling order and the magnitude of energy generation and storage.

The main algorithm is given in D.1, Appendix D and contains the following 6 steps which are evaluated in consecutive order for each time step:

1) In the first step, the electrical energy balance is calculated, taking solar PV generation and the demand into account. It is then verified whether it is the best decision to charge or discharge the electrical storage and to what amount, refer to Algorithm D.2. For this, the heat demand and the possibility to use electrical energy for the heat pump is taken into account through control variable $CE_{1,t}$ (value: 0 or 1). In case of surplus renewable electricity production, priority is given to heat production, $CE_{1,t} = 1$ (if possible and required) or to electrical storage, $CE_{1,t} = 0$.
2) In the second step, the heat pump production from the surplus renewable electricity production is calculated when applicable, refer to Algorithm D.3.
3) The third step involves a more complicated consideration for charging or discharging the thermal storage, depending on storage status and

thermal demand. Also, the storage or demand can be charged or supplied by either a biofuel boiler or CHP. In case of a CHP, a heat pump may consume the generated electricity and become a co-producer of heat. Heat production of the CHP is split into two parts: a part which generates heat for charging the thermal storage, $PT_{g,h,t}$, and a part which generates heat for the heat grid demand, $PHG_{g,h,t}$. The possible heat production of a heat pump, $P_{hp,3,t}$ is during this step limited by the total generated electrical energy by the CHP, but the CHP may produce more heat and electricity when required, refer to Algorithm D.5. The decision to charge or discharge the thermal storage is expressed by control variable $CT_{3,t}$ (value: 0 or 1) which is determined by Algorithm D.4. The decision is determined by the thermal storage state (Q_{t-1}), a safe minimum thermal storage state which is related to the seasonal heat demand (Q_{min}) and the maximum storage state (Q_{max}). Once the heat generation of the biofuel generators and heat pump are determined, the charging or discharging energy of the thermal storage is calculated by Algorithm D.6.

4) In the fourth step, the thermal and electrical energy balances are calculated to determine if charging of the electrical storage is possible and to what amount, refer to Algorithm D.7.
5) The fifth step evaluates the remaining heat grid demand and determines the possibility and amount of heat production by the heat pump, for which electricity from the grid is imported in case the electricity energy balance is negative (shortage), refer to Algorithm D.8 in which the required import from or export to the electricity grid is calculated. In this algorithm, priority is given to wind energy and if this is insufficient, then additionally, “grey” electricity is imported.
6) In the sixth step the remaining heat demand is calculated. To balance this, generation by the external heat supply is calculated in Algorithm D.9.

4. Results

Results of the model are discussed for 3 renewable energy system concepts:

1) Bio-heat: biofuel boiler, solar PV, wind energy, thermal and electrical storage, natural cooling source.
2) All-electric: heat pump, solar PV, wind energy, aquifer thermal source and electrical storage.
3) Mixed: biofuel CHP, heat pump, solar PV, wind energy, aquifer thermal source, thermal and electrical storage.

4.1. Equipment size

For the reference case, the peak capacity of the boiler is determined by the peak heat demand. For the 3 renewable energy system concepts, generation capacities are determined by optimization and the results are shown in Table 4. The last concept shown (near autonomous) is explained further onwards.

4.2. Sensitivity analysis

The global optimal solution is investigated by varying the capacities around the obtained optimal values. The result is shown in Figure 6 for Concept 3 (other concepts show similar results). 5 lines are shown of which (horizontal axis) 4 concern capacity variation of a single generator (heat pump, CHP, solar PV) and the thermal storage. The fifth line concerns a simultaneous variation of all these together. The vertical axis shows the percentage increase of the objective function, relative to the optimal value shown in Table 4. The following is observed:

Table 4: Production unit capacities for the case reference and 3 renewable energy concepts

Concept	External heat supply kW	Heat pump kW	Biofuel boiler CHP thermal kW	CHP electric kW	Solar PV m^2	Thermal storage kWh	Electric storage kWh	Objective function €/y
Reference	752							161,073
1	511		241		1570	250	200	146,861
2	532	500			2140	0	180	143,613
3	501	161	90	48	1400	150	0	141,982
Near autonomous	265	169	309	164	2004	1410	1220	172,134

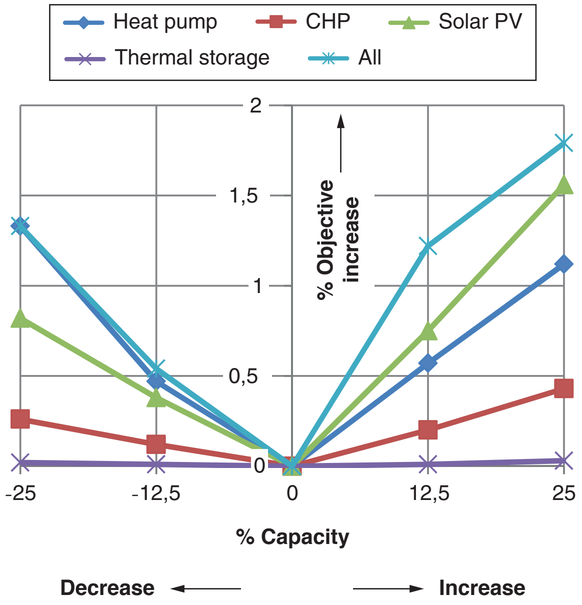


Figure 6: Convergence for Concept 3

- a relatively large variation of the capacities (25%) results in a relatively small increase of the objective function, especially for the size of the thermal storage,
- the relation between capacity variation and the objective function is non-linear,
- all variations show that the objective increases, which is an indication that the solution is likely to be the global optimum, and
- the size of the thermal storage has an insignificant influence.

4.3. Energy flows

In Tables 5 and 7, the yearly electrical and thermal production and consumption total for the case reference and the 3 renewable concepts are given. In Table 6 the total grid imports and exports are given and the highest hourly peak values. For the case reference, the total electrical energy for cooling is higher than for the 3 renewable concepts because the reference uses a

Table 5: Yearly total electrical production and consumption (kWh/y)

Concept	Household electric demand	Cooling electric demand	Wind turbine production	Solar PV production	Direct power to heat	CHP electric production	Heat pump consumption
Reference	−576,449	−61,519					
1	−576,449	−7,690	186,618	351,110			
2	−576,449	−7,690	274,345	345,004			−360,222
3	−576,449	−7,690	183,643	225,704		283,039	−251,986
Near autonomous	−576,449	−7,690	5,647	323,039	−47,658	571,720	−195,416

Table 6: Electrical imports and exports

Concept	Grid import (kWh/y)	Grid export (kWh/y)	Peak import (kW)	Peak export (kW)
Reference	637,968		212	0
1	211,821	−67,511	173	−173
2	420,264	−95,342	231	−231
3	209,861	−66,123	167	−167
Near autonomous	2,182	−75,314	142	−164

Table 7: Yearly total thermal production and consumption (kWh/y)

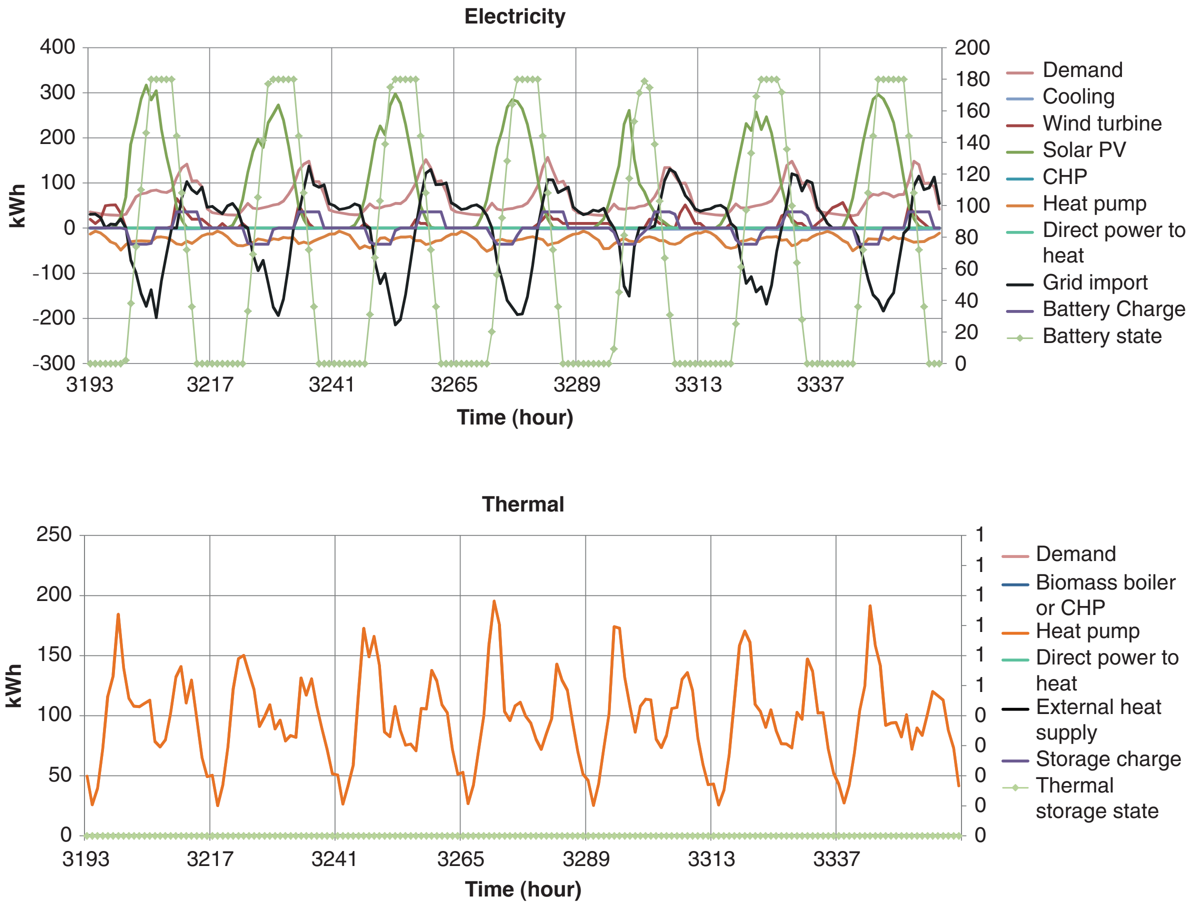
Concept	Heat grid demand	Biofuel boiler or CHP production	Heat pump production	Direct power to heat	External heat production
Reference	−1,867,817				1,867,817
1	−1,867,817	1,464,052			403,641
2	−1,867,817		1,368,845		498,973
3	−1,867,817	531,771	957,546		378,452
Near autonomous	−1,867,817	1,074,140	742,582	47,658	3,080

refrigerator with COP of 2.5 and the renewable concepts use a natural cooling source with COP of 20.

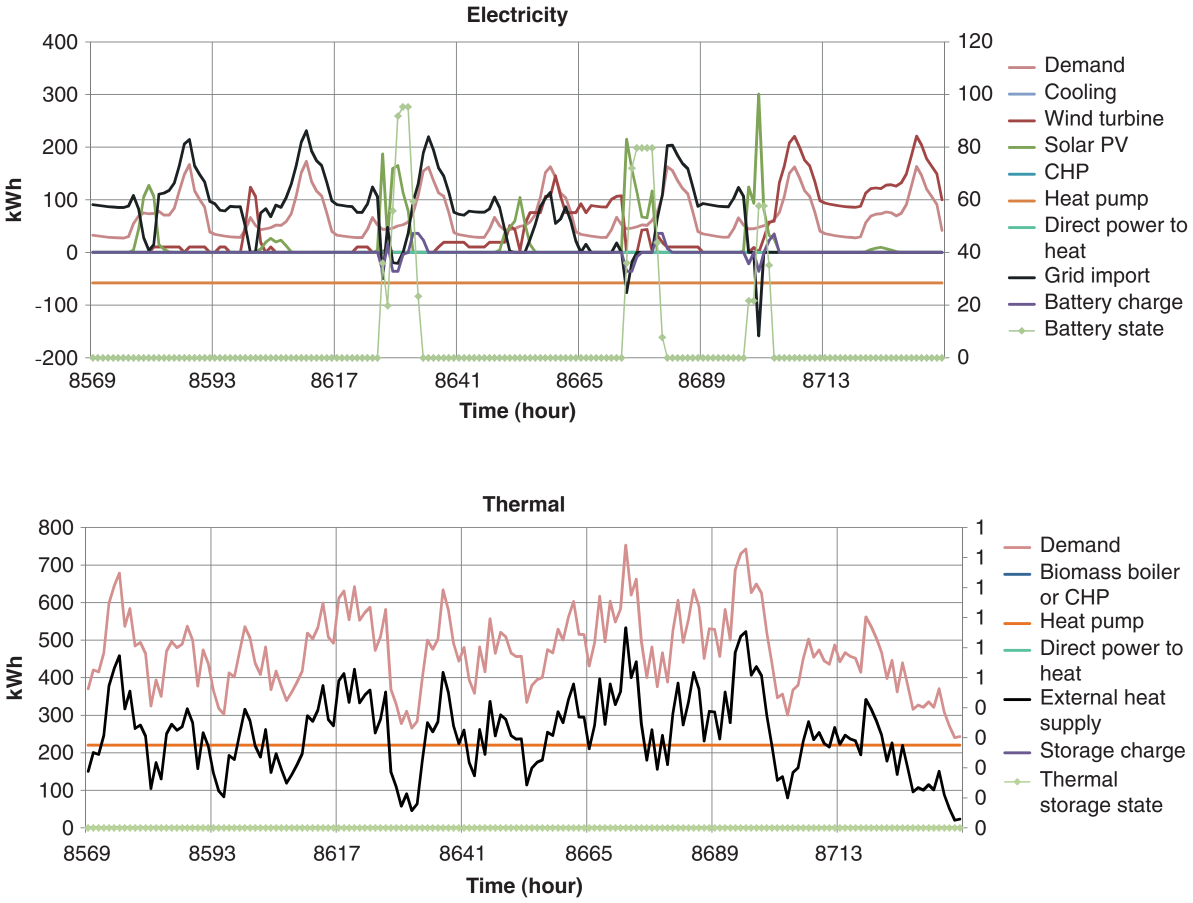
For Concept 1, 74% self-consumption of solar PV energy is achieved and 36% of the total electrical demand is imported from the grid. The heat demand is for 78% supplied by biofuel and the remaining part (22%) by the natural gas boiler (external heat). For Concept 2, 73% self-consumption of solar PV energy is achieved and 44% of the total electrical demand is imported from the grid. The heat demand is for 73% supplied by the heat pump and the remaining part (27%) by the natural gas boiler. For Concept 3, 88% self-consumption of solar PV and CHP electrical energy is achieved and 22% of the total electrical demand is imported from the grid. The heat demand is for 34% supplied by the CHP, for 50% by the heat pump and the remaining part (16%) by natural gas.

To evaluate hourly energy flows, two test weeks are shown in Figure 7. To avoid a lengthy discussion of the 3 concepts, we show only Concept 2 which is the most interesting when it concerns the interaction between electrical and thermal energy generation and demand. In this figure, the top diagram shows electrical, the bottom diagram thermal energy flows. The left axis is for the hourly energy flow values, the right axis is for the storage charge state. The test weeks consist of a summer week with abundant sunshine and the coldest week in the winter. For these 2 weeks we investigate: (1) how are the relatively high summer peaks of the solar PV generation utilized by the energy system, (2) which generators supply the high winter week thermal demand? Besides these questions, interactions between electrical and thermal demand and supply are particularly interesting to investigate.

During the summer week, a daily pattern of storage of excess solar PV energy is visible. The electrical demand (household and heat pump) is supplied by solar PV,



(a) power to heat, summer



(b) power to heat, winter

Figure 7: Energy flows Concept 2

electrical storage, wind energy and grid imports. The thermal demand is supplied entirely by the heat pump. Observe the minor contribution of wind energy during this period which demonstrates the complementary nature of solar and wind energy.

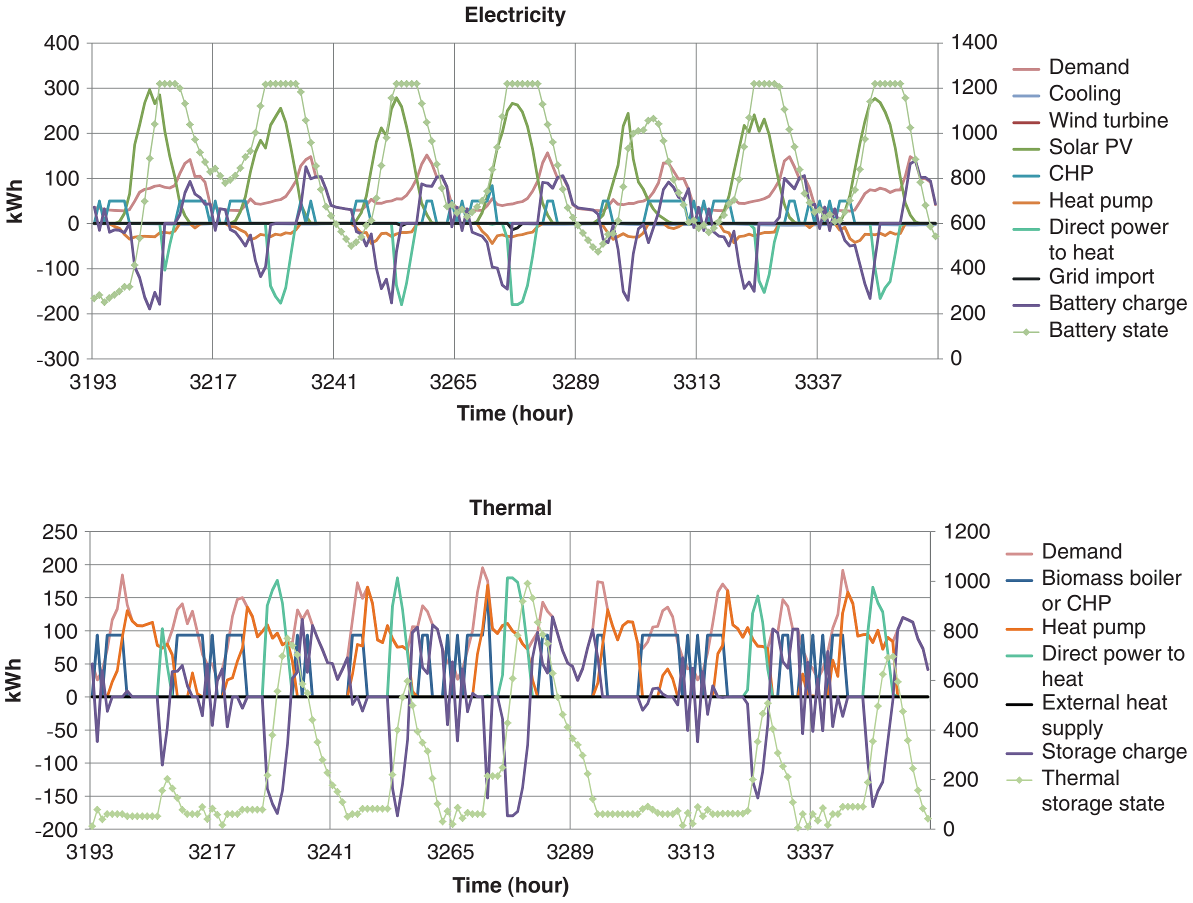
The winter electricity flows are entirely different: there is a lack of solar energy but a much larger contribution of wind energy. Hence there are only a few moments of electricity exports but large amounts of electricity imports from the grid. The heat pump is running continuously with additional support of the natural gas boiler (external heat). Observe that wind energy is able to supply the entire electrical demand on some days, but there are also days when it has only a minor contribution and on the same days there is also not much solar energy. This demonstrates that wind and solar energy are not always complementary.

4.4. Extending Concept 3 towards near energy autonomy

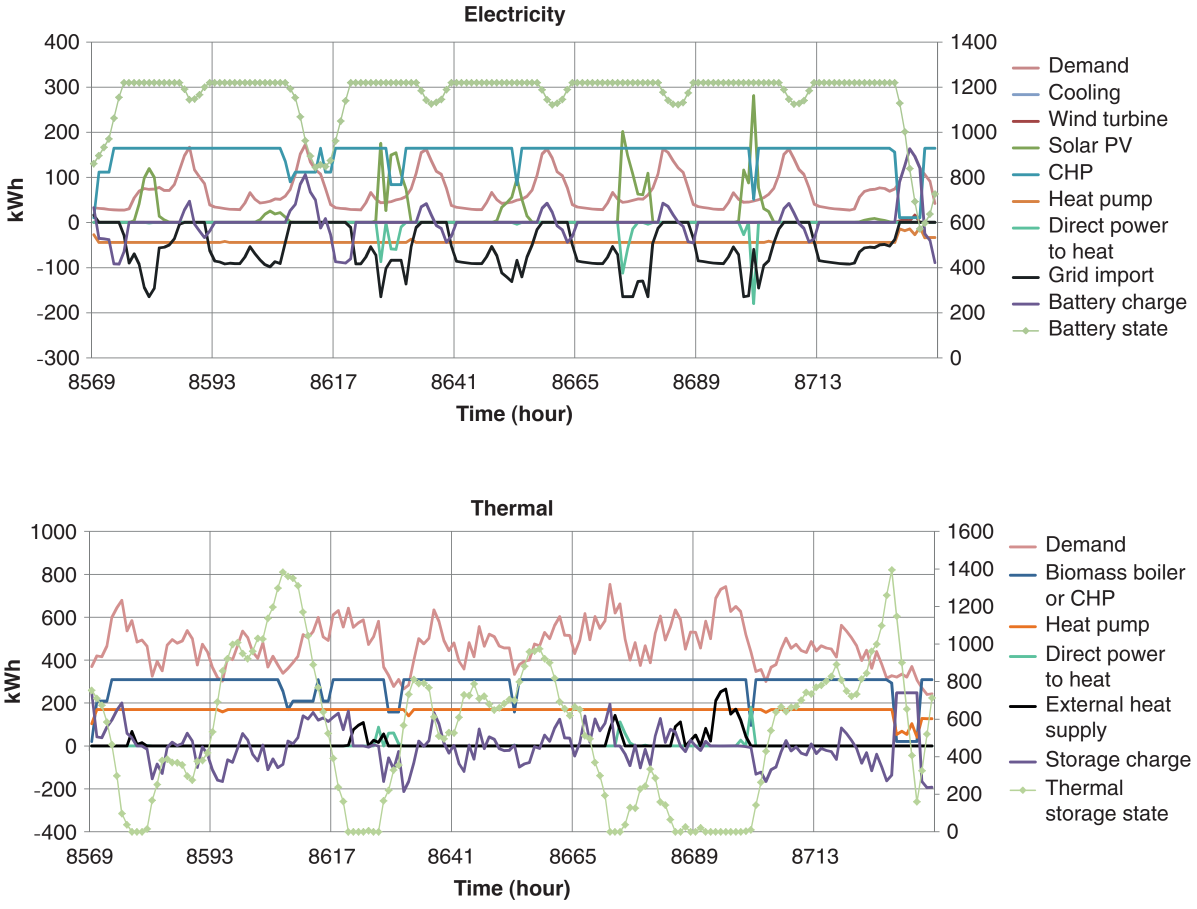
As Concept 3 enables complementary electrical generation by the CHP during periods of less solar PV and wind energy generation, the concept is extended towards near energy autonomy (no consumption of natural gas or imports of “grey” electricity from the grid), to further show the capabilities of the optimization model. To find capacities for such a system, we find that a different optimization objective is required which steers more rigorously towards zero CO_2 production and low grid energy exchanges. Simply increasing the penalty on CO_2 production appears to be insufficient and leads to high storage costs and large feed-in electricity peaks of renewable energy to the grid, which increases grid dependency. A penalty multiplication factor of 10 is introduced for the CAPEX and OPEX of the grid connection and a factor of 100 for the CO_2 costs. Besides that, we introduced a method to directly dissipate surplus electrical energy into heat for the district heating system, called “direct power to heat”. This method is implemented in the main algorithm after step 2.

In Tables 5, 6 and 7, the yearly electrical and thermal production sums show that this concept has nearly no natural gas consumption and grid imports. The generation capacities are shown in Table 4. The objective function in the last column is in this case not the objective used during the optimization, as this has little practical use due to the high penalties. Hence, we show here the same objective as the 3 renewable energy concepts to enable direct comparison.

In Figure 8 the summer week shows a much more dynamic energy flow interaction between electrical and thermal generation and storage. Due to high solar PV generation, interactions with electrical storage, heat pump, CHP and direct power to heat scheduling, zero electricity grid exchange is reached during this week. The winter week shows almost constant operation of the CHP and heat pump and only a few moments when the natural gas boiler (external heat) is required. The system is mostly exporting electrical energy to the grid. The direct power to heat application could be implemented in a smarter way, e.g. including a forecast of the thermal demand, such that a higher thermal storage state of charge is maintained which would avoid any natural gas consumption. The use of the electrical and thermal storage capacity is significant and we find large storage capacities during optimization, i.e. 1220 kWh electrical and 1410 kWh thermal capacity. This is equivalent to a battery of 6.1 kWh per house and 7.1 kWh or 95 liters (domestic water tank) thermal storage per house. Energy losses due to electrical and thermal storage are more significant for these larger storage sizes and therefore we will include these losses as part of future work.



(a) near autonomous, summer



(b) near autonomous, winter

Figure 8: Energy flows near autonomous concept

4.5. Economic and environmental analysis

The optimization objective, refer to Equation 1 is used to verify the economic most attractive concept in relation to the environmental performance. In Figure 9, costs included in the objective are shown for the case reference, the 3 renewable concepts and the near autonomous concept discussed in Section 4.4. Because the CO_2 costs were introduced with an artificial high price of 60 €/ton, we separate the economic comparison from a comparison on environmental aspects.

In general, fuel costs and electricity imports dominate the case reference, which has low CAPEX and OPEX, due to low cost equipment for heating. The renewable energy concepts show much higher CAPEX and OPEX, which is mostly visible for the near autonomous concept which requires a large investment in batteries. For Concept 1, 2 and 3, wind energy is an

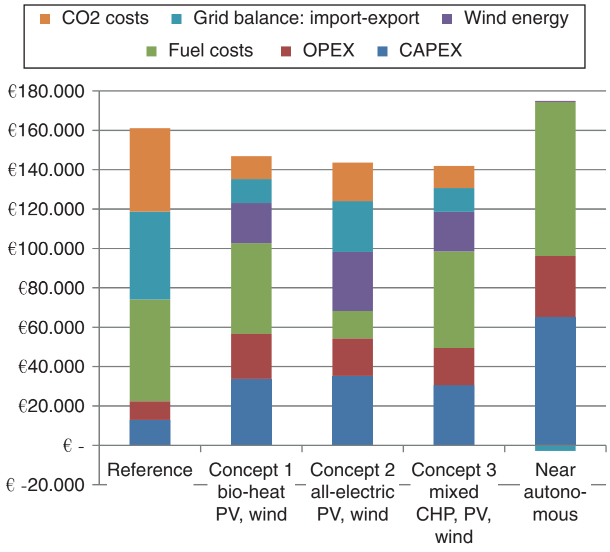


Figure 9: Comparison between concepts

important source to fulfill the electrical demand. However, the near autonomous concept requires almost no electricity imports and hence also no wind energy. Concept 2 has the largest electricity costs and Concept 3 has the largest fuel costs due to the high price of biogas. In fact, the biogas price is even estimated below the present day market price, otherwise a biogas CHP would not be feasible. The same price for biogas is used to evaluate the near autonomous concept so fuel costs also for this concept are underestimated. Hence, feasibility of Concept 3 and the near autonomous concept on the short term is questionable but this depends on possible subsidies. Concept 1 depends on the market price of wood chips. At present this price is more or less stable but when more urban energy projects decide to implement a biomass boiler, prices may increase.

Based on the total costs excluding CO_2, we conclude that Concept 2 at this stage is the most attractive renewable concept as the costs are only slightly higher than the case reference. However, the concept depends more than the other concepts on grid electricity imports and natural gas consumption to support the heat production. Hence, Concept 2 performs less on CO_2 emissions than the other concepts. Concept 2 reduces emissions by approximately 53% compared to the case reference, but Concept 1 and 3 reduce emissions by 73%. For the coming 5 to 10 years, the following infiuences are important for Concept 2:

- Natural gas prices in the Netherlands are expected to rise due to recent policies in favor of stimulating the energy transition away from natural gas consumption. It could be an option to connect the energy system of Concept 2 with a biogas network to eliminate the natural gas consumption entirely.
- Due to recent large scale offshore wind energy implementation plans, the percentage green energy of the electricity grid is expected to rise the coming years. This will lead to lower CO_2 production for Concept 2 in the future.

We should note that not all costs and benefits are part of the objective function, i.e.: a building for the central generation and storage equipment, the district heating network, household connections and energy consumption meters, organizational costs, insurances, heat sales revenues, electricity sales revenues. Hence, the cost comparison should not be used directly as a business case evaluation of the concepts.

4.6. Application within a collective or individual heating system

At present, the most common way of heating houses in the Netherlands is by individual natural gas boilers. This is why further development of individual directions receives much attention. Individual counterparts for the 3 concepts are:

- Concept 1: household wood pellet boiler, rooftop solar PV, household scale thermal and electrical storage.
- Concept 2: household heat pump with ground thermal source, rooftop solar PV, household scale thermal and electrical storage.
- Concept 3: biogas micro CHP/boiler combination, house hold air source heatpump, household scale thermal and electrical storage.

Considering flue gas emissions of a wood pellet boiler, the individual counterpart of Concept 1 is applicable only for less densely populated areas. Concept 2 and 3 are also applicable for densely populated areas.

Combined with electrification of personal transportation the coming years, an important issue for the individual all electric route is the large increase of electrical demand and high demand peaks which could lead to costly grid strengthening measures in low voltage power grids. For a large part this can be solved by local renewable energy generation, electrical storage and smart control, which is demonstrated in [29]. The grid in this case may be the national power grid, but also a regional or local grid which is able to operate more or less on its own.

The individual biogas route is attractive from the side of the existing infrastructure and household boilers. However, it requires large scale production of green-gas: either by upgrading biogas or in a further future the application of power to gas techniques, because the technology is presently still immature. At this moment, green-gas has a relatively high cost in comparison with the other options.

Interestingly, in the collective approach, district heating systems and interactions with the power system, heat generators and storage provide a platform for integration of renewable energy. In the individual approach, interactions between a “greener” power system and a future “greener” gas network provide a similar platform for integration [30]. It is well known that the choice for a certain infrastructure dominates further developments and possibilities for many decades. Hence, the interesting question arises which approach, collective or individual heating systems is the most attractive to integrate renewable energy for new and existing urban areas in the Netherlands? For this we should consider:

- Local possibilities and chances to integrate renewable energy. Some renewable options like waste heat simply require a collective heating system.
- Cost considerations: the costs of new district heating infrastructure versus the costs of individual supply systems. Today, individual natural gas boilers have a very low cost, but individual renewable heat options (e.g. heat pumps and a suitable source system) are much more costly. At this stage, a collective system may be more economic.
- Effects on local economy and jobs. Individual heat converters are connected to larger systems, e.g. the national gas and power grid. Collective heating systems usually operate on a local or regional scale. The development and operation of district heating systems therefore offers more opportunities for local/regional job creation which is an attractive outlook in today's society. The same can be said about house renovations with the purpose to improve energy efficiency. There are many houses to renovate and the process is labor intensive which creates jobs for a relatively long period of time. Combining house renovations, district heating and integration of renewable energy creates local jobs which is one of the successes of the Danish energy transition and a cornerstone of the fourth generation district heating concept [6].

These considerations presently dominate political discussions and conference themes in the Netherlands. Further investigation into these considerations is done within the scope of the WIEfm-project [31] and is part of our future work.

4.7. Influence of governance aspects on the business case

In the previous sections, some important governance aspects are already discussed, i.e. supportive tax and subsidy schemes to encourage local investments in renewable energy and job creation. Another important aspect for the discussed concepts is how permits are regulated for utilities to operate energy networks and to supply households with energy through these networks. For the electricity sector, the country is divided into several regions and for each region there is just one utility who has a permit to operate and maintain the low voltage electricity grid. In Meppel, the low voltage power grid utility is a different one than the utility who operates the district heating network. This is an obstacle for the integration of renewable energy as the district heating utility is not responsible for the supply of household electricity and therefore also has no interest in that. The renewable energy concepts presented in this paper produce significant amounts of renewable electricity with the assumption that the utility is able to sell this to the households. To achieve this, specific governance solutions are required, for which we discuss two possibilities:

- Both utilities (district heating operator and power grid operator) should cooperate and agree on the import (electricity from regional wind turbines, “grey” electricity) and export (locally produced by the district heating utility) tariffs.
- The Dutch government lately made it possible that a local private ESCO takes over the ownership and operation of a local low voltage power grid, provided that all households are part of the same postal code and all citizens within that district agree. This enables a truly local market for the supply of renewable electricity and heat, independent from the larger power grid.

With one of these measures, it is possible to implement a renewable energy concept of choice from the concepts discussed in this paper in such a way that the proposed business case may actually be positive. In the coming years we expect that more public and private partnerships are established which gain experience with these measures in the Netherlands.

5. Conclusions

In this paper a computer model for energy priority scheduling and capacity optimization of renewable urban energy systems is developed. Demand data is generated by simulations for a case study involving 200 houses which are part of a new urban district in Meppel, the Netherlands. The following renewable energy concepts to replace the case reference (central natural gas boilers for heating, an electric refrigerator for cooling and “grey” electricity for the electrical demand) are investigated:

1) Bio-heat: central biomass boiler, solar PV, regional wind energy, supported by thermal and

electrical storage, cooling by lake or ground source with high COP.

2) All-electric: central heat pump, ground source, solar PV, regional wind energy, supported by thermal and electrical storage, cooling by ground source with high COP.
3) Combined: central biogas CHP, central heat pump, solar PV, regional wind energy, supported by thermal and electrical storage, cooling by ground source with high COP.

Optimal generation and storage capacities are determined for each concept based on a general formulated objective. Results depend on the CO_2 price level for which €60/ton is assumed. Although the present market value of CO_2 emissions is only €7/ton, much higher price levels are needed for feasible renewable energy systems. However, if Dutch energy taxes for households are interpreted as CO_2 tax, the evaluated CO_2 price level is still moderate. As part of future work we will investigate in more detail the influence of CO_2 emission prices on the system capacities.

A cost comparison and environmental comparison on CO_2 emissions between the renewable concepts and the case reference reveals that the case reference is financially the most attractive but environmentally the least attractive. The renewable concepts show a change in the dominating cost factor, from fuel costs (case reference) towards CAPEX and OPEX (renewable concepts). Of the renewable concepts, the all-electric concept is financially the most attractive, but the bio-heat and combined concept perform better on CO_2 emissions. The combined concept can be extended to a concept which is able to operate near autonomous, i.e. a concept which uses almost no natural gas and almost no electric energy imports from the grid, resulting in almost zero CO_2 emissions. For this concept we find much larger electric and thermal storage sizes. Part of future work is to include energy losses due to the intense use of the electrical and thermal storage. The near autonomous concept is at this stage financially less attractive, mainly due to the high price of biogas and higher investment costs. The energy flows of the all-electric concept show relatively high grid peak imports and exports which cannot be avoided by energy storage alone. Hence, this concept could benefit from smart grid control of the heat pump, direct injection of power to heat into a thermal storage and smart charging of the electrical storage. Further flexibility for this is offered by the thermal capacity of the houses, thermal storage, electrical storage and possibly some household electrical devices. In [32] we develop such a smart control method in order to balance electricity production by a single CHP and demand of a large group of domestic heat pumps. Triana, a smart grid control method developed at the University of Twente may be applied for the control cases of this paper, for examples see [33], [34] and [35]. As part of future work, we intend to develop an urban energy analysis tool which includes energy priority algorithms and methods of smart control in order to investigate effects of smart control on system capacities and energy flows. As proposed in the related work section of this paper, our next step is to verify the results of this paper with Energyplan, using the least cost and least CO_2 scheduling methods of Energyplan.

Finally, the paper addresses a complex governance aspect of the Meppel case. There are two different utilities, one with a permit to operate the electricity grid and the other with a permit to operate the district heating network. This is an obstacle to reach a positive business case for one of the renewable energy concepts presented in this paper. One solution is to establish a joint venture between the two utilities, another is to establish a citizen involved local Energy Service Company who takes over the ownership of both local networks.

Acknowledgement

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Appendix A
Space heating demand model

The district space heating and cooling demand profile is determined by the following procedure:

1) Simulation with a realistic model of an average house. The process for this is illustrated in [21]. Based on specifications of the houses built in Meppel, we determined parameters for a 1R1C (1 Resistance, 1 Capacitance) thermal model of a house and schedules for occupancy (internal gains) and ventilation flows, refer to Equation 4 and Table 8.

$$C_z \cdot \frac{dT_z}{dt} = \frac{T_{sa} - T_z}{R_{za}} + \frac{T_a - T_z}{R_{win}} + q_{h,c} + A_w \cdot q_s + q_{int} + q_{vent}$$

$$T_{sa} = \frac{T_z + R''_{za}[\alpha q_s + U''_{wall} T_a]}{1 + U''_{wall} R''_{za}}$$

$$q_{vent} = \emptyset_v \cdot \rho_{air} \cdot c_{p,air} \cdot \left(T_a - T_z\right) \tag{4}$$

2) Determine heating and cooling demand of the house by simulation with climate data, for which we have taken the former Dutch reference climate year 1964 (weather station “de Bilt”). This data was used as standard for building heating and cooling simulations until 2008 and it has the advantage that this data is freely accessible by other researchers. The newer Dutch reference climate year [36] has slightly less degree days and contains tables with more extreme summer conditions which lead to higher cooling loads of buildings, which is more in line with expected longer term climate changes in the Netherlands. The issue of which reference year to use for simulations is much more important for individual building simulations, where the interest is on heating and cooling equipment capacity and inhabitant comfort than for larger district studies such as this paper where we study hourly variations and interactions between systems and conclude on the yearly environmental impact. As future work, more simulations with different reference years can be carried out in order to investigate the impact that this has on the results. We summarize the climate year 1964. For heating, the number of degree days in the Netherlands varies between extreme values of 2950 and 1950 degree days. The year 1964 had 2400 degree days [37]. Minimum temperatures in the Netherlands range between −2.5 °C and −17 °C and in 1964 the lowest temperature measured at station de Bilt was −9.8 °C in the

Table 8: Model parameters and variables

Parameter	Unit	Value	Signification
R_{za}	K/kW	47.0	thermal resistance of insulated walls
R''_{za}	m^2K/kW	5000	area specific thermal resistance
R_{win}	K/kW	47.5	thermal resistance of windows
α	—	0.7	brick wall solar absorptance
U''_{wall}	kW/m^2K	0.005	exterior wall surface heat transfer coefficient
C_z	kWh/K	10.51	capacitance of the zone
A_w	m^2	12.5	effective window area on South side of the building
ρair	kg/m^3	1.25	air specific density
$C_{p,air}$	kJ/kg.K	1.005	air specific heat

Variable	Unit	Type	Signification
T_z	°C	calculated	interior (zone) thermal mass temperature
T_a	°C	input	outdoor (ambient) temperature
T_{sa}	°C	calculated	sol-air temperature of the building exterior wall surface
q_s	kW/m^2	input	solar energy on building planes with windows
$qh,_c$	kW	calculated	space heating or cooling demand
q_{int}	kW	input	thermal gains by occupants and appliances
q_{vent}	kW	calculated	heat loss by ventilation air flow
$\emptyset_v$	m^3/s	input	ventilation air flow

beginning of the year and $-11.8\,^{\circ}$C at the end of the year. The year 1964 had an average summer period with maximum measured temperature of 30.5 °C. By comparison, the highest ever recorded temperature at station de Bilt was 38 °C. However, one or two extreme days may not have a significant influence on the total cooling energy during an entire summer of a year.

3) Create a number of different house patterns by randomizing part of the heating and cooling demand to compensate for differences in heating and cooling control and solar orientation of houses.
4) Sum the house patterns to create the district heating and cooling demand profile.

For the variables shown in Table 8, it is indicated whether these are calculated during the simulation or given as input.

The input variables q_{int} and $\varnothing_v$ are defined as time schedules. The sol-air temperature T_{sa} is the surface temperature of the exterior brick wall. This temperature increases to values above the ambient air temperature due to solar absorption, which causes an additional cooling load during the summer months. Solar gains into the house are calculated by mathematical relations and correlations given in [38] and [39], to translate horizontal solar irradiation into radiation on vertical building planes. In order to determine the space heating and cooling demand, a proportional control is programmed into the simulation. The purpose of this control is to keep the interior temperature within a narrow band around 18 °C as average temperature for the whole interior of the house in case of heating and between 20 and 24 °C in case of cooling.

Appendix B
Domestic hot water model

Based on [40] and [41] domestic hot water demand has a daily pattern which we approximate with the following Gaussian distribution:

$$\varnothing_i = \sum_j \frac{f_j}{\sigma_j\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{i-\mu_j}{\sigma_j}\right)^2} \qquad (5)$$

$$\dot{Q}_{dhw,h} = \varnothing_i \cdot \rho_w \cdot c_w \cdot \left(T_{hw} - T_{cw}\right)$$

In which $\varnothing_i$ a flow demand e.g. in liters/hour at hour time i ($i \in 1,\ldots 24$), ρ_w and c_w the specific density and specific heat of water, T_{hw} and T_{cw} the hot water and cold water supply temperature to the household. The equation for $\varnothing_i$ is the sum of j Gaussian distribution functions, each with different average μ_j, standard deviation σ_j and scaling factor f_j. In most cases, domestic hot water consumption of households and districts shows 3 moments per day of peak consumption, hence: $j = 3$. These parameters can be determined from simulated or measured data, which is a somewhat arbitrary process as this data is not existing for the Meppel project. The method is applied to the results shown in [41]. The obtained parameters result in a calculated profile which is shown in Figure 10 as an overlay (green line) to the results (aggregated district heating domestic hot water demand) shown in [41]. Defining a domestic hot water thermal demand profile for an average household is now a matter of scaling Equation 5. Based on [42] and [43] we estimate a yearly demand for domestic hot water per person of 3.2 GJ. Based on information from the project, the average number of persons per household is 3.5. From this, a daily average demand is calculated per household and a slightly varying profile for each day is obtained by multiplying the hourly values of the obtained profile with random numbers between 0.8 and 1.2. The domestic hot water profile is then multiplied by the number of households and added to space heating demand which results in an aggregated heating demand profile for the district D_h.

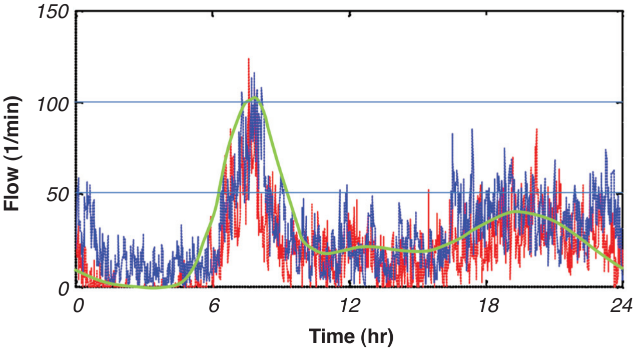

Figure 10: Resulting domestic hot water profile (green line) overlaid on results shown in [41] (blue and red line)

Appendix C
Wind turbine generation profile

The wind turbine hourly production profile is calculated in three steps:

1) Application of the wind profile power law to calculate average hourly wind speed at axle height from the wind speed data at 10 meters height given by the same weather data as used for the solar PV production and thermal demand of the houses.
2) Calculation of the possible power production by the kinetic energy relation 6.

$$P_w^* = C_p \cdot \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \tag{6}$$

In which C_p the power coefficient which is derived at 0.45 from supplier power curves. ρ the air specific density assumed constant at 1.25 *kg/m*^{3}. v the air velocity at axle height and A the through-flow area of the rotor.

3) Application of the following algorithm which limits the power production:
   - if $v < 3$ then $P_w = 0$
   - *if* $P_w^* > 1500$ *and* $v < 25$ then $Pw = 1500$
   - if $v > 25$ then $Pw = 0$.

Appendix D
Energy scheduling algorithms

The algorithms are shown on the following pages. For nomenclature of energy flow variables, refer to Table 1. In the algorithms, E is electrical energy balance, T is thermal energy balance, t is present time interval, τ is total evaluated time (8760 hours).

The following assumptions and principles for the generators and storage facilities are implemented in the algorithms:

- the electrical storage is charged and discharged in complete cycles as much as possible in order to improve lifetime of batteries,
- the thermal storage is only charged by the biofuel CHP or boiler, not by the heat pump (due to lower temperature of heat production from a heat pump) and not by the external heat supply,
- there is a maximum charge and discharge rate for all storage facilities which is determined by the maximum generation and storage capacities,
- to avoid unnecessary charging and thermal losses during periods with low heat demand, the maximum state of charge of the thermal storage is related to the longer term average heat demand around the present time interval. In practice this can be achieved with a storage which contains multiple heat exchangers and which is thermally stratified,
- the heat pump and external heat supply have an infinite number of operational states between 0 and maximum heat production and follow the demand without any time delay, and
- the biofuel generators are scheduled in a limited number of discrete production steps. An operational state is maintained for at least 2 hours, i.e. to increase efficiency and lifetime.

Algorithm D.1: Main algorithm: energy scheduling order

```
Input: $D_{hg}$, $D_c$, $D_e$ … the aggregated demand
Input: $P_w$, $P_{pv}$ … the aggregated non-scheduled renewable electricity production
Input: $Q_i$ , $E_i$ … the initial thermal and electrical storage state of charge
foreach $t \in \tau$ do
    begin Step 1
        $E_{1,t} = P_{pv,t} - D_{e,t} - S_{e,c,t}$
        $C_{e,1,t} =$ function(Echarge1)
    end
    begin Step 2
        $E_{2,t} = E_{1,t} + C_{e,1,t}$
        $P_{hp,2,t} =$ function(HeatPump2)
        $T_{2,t} = -D_{hg,t} + P_{hp,2,t}$
    end
    begin Step 3
        $E_{3,t} = E_{2,t} - \frac{P_{hp,2,t}}{COP_h}$
        $PTg,h,t =$ function(TSproduction3)
        $P_{hp,3,1,t} = \mathbf{MIN}\left(-T_{2,t}; PT_{g,h,t} \cdot \frac{eta_{e,chp}}{eta_{t,chp}} \cdot COP_h; P_{hp,max} - P_{hp,2,t}\right)$
        $T_{3,1,t} = T_{2,t} + P_{hp,3,1,t}$
        $[PHG_{g,h,t}; P_{hP,3,2,t}] =$ Procedure(BioFuel3)
        $P_{g,h,t} = PT_{g,h,t} + PHG_{g,h,t}$
        $P_{g,e,t} = P_{g,h,t} \cdot \frac{eta_{e,chp}}{eta_{t,chp}}$
        $P_{hp,3,t} = P_{hp,3,1,t} + P_{hp,3,2,t}$
        $T_{3,2,t} = T_{2,t} + P_{g,h,t} + P_{hp,3,t}$
        $Ch,t =$ function(TScharge3)
        $Q_t = Q_{t-1} + C_{h,t}$
    end
    begin Step 4
        $T_{4,t} = T_{2,t} + P_{g,h,t} + P_{hp,3,t} + C_{h,t}$
        $E_{4,t} = E_{3,t} + P_{g,e,t} + \frac{P_{hp,3,t}}{COP_h}$
        $C_{e,4,t} =$ function(Echarge4)
        $E_t = E_{t-1} + C_{e,1,t} + C_{e,4,t}$
    end
    begin Step 5
        $E_{5,t} = E_{4,t} + C_{e,4,t}$
        $P_{hp,5,t} =$ function(HeatPump5)
        $P_{hp,t} = P_{hp,2,t} + P_{hp,3,t} + P_{hp,5,t}$
        $S_{e,t} = -E_{5,t} - \frac{P_{hp,5,t}}{COP_h}$
    end
    begin Step 6
        $T_{6,t} = T_{3,t} + P_{hp,5,t}$
        $P_{ex,h,t} =$ function(ExHeat6)
    end
end
```

Algorithm D.2: Function Echarge1

```
Input: $E_{1,t}$ …electrical energy pool balance
Input: $D_{h,t}$ …heat demand
Input: $Ce_{max}$, $E_{max}$ …maximum charge rate and capacity
Input: $E_{t-1}$ …previous time step charge state
if $E_{1,t} > 0$ then
    if $E_{1,t} \cdot COP_{hp} \geq D_{h,t} \wedge (E_{t-1} \leq 0.1 \cdot E_{max} \vee E_{t-1} \leq E_{max})$ then $CE_{1,t} = 1$
    else $CE_{1,t} = 0$
else
    $CE_{1,t} = 0$
end
if $E_{1,t} > 0 \wedge CE_{1,t} = 1$ then
    $Ce_{1,t} = -\text{MIN}\,(Ce_{max};\, E_{1,t};\, E_{max} - E_{t-1})$
else if $E_{1,t} < 0 \wedge CE_{1,t} = 0$ then
    $Ce_{1,t} = \text{MIN}\,(E_{t-1};\, Ce_{max};\, -E_{1,t})$
else
    $Ce_{1,t} = 0$
end
```

Algorithm D.3: Function HeatPump2

```
Input: $E_{2,t}$ …electrical energy pool balance
Input: $Php_{max}$ …heat pump maximum capacity
Input: $D_{hg,t}$ … heat grid demand
if $E_{2,t} > 0$ then
    $Php_{2,t} = \text{MIN}\,(D_{hg};\, P_{hp,max};\, E_{2,t} \cdot COP_{h})$
else
    $P_{hp2,t} = 0$
end
```

Algorithm D.4: Function TSproduction3

```
Input: $C_{h,max}$ … maximum charging heat transfer to thermal storage
Input: $Q_{max}$ … thermal storage maximum charge state
Input: $Q_{min}$ … thermal storage minimum charge state
Input: $Q_{t-1}$ … previous time step thermal storage charge state
Input: $CT_{3,t-1}$ … previous time step thermal storage charge control variable
if $Q_{t-1} \leq Q_{min} \vee (CT_{3,t-1} = 1 \wedge Q_{t-1} < 0.9 \cdot Q_{max})$ then
    $CT_{3,t} = 1$
else
    $CT_{3,t} = 0$
end
$PT_{g,h,t} = CT_{3,t} \cdot \textbf{MIN}\,(C_{h,max};\, Q_{max} - Q_{t-1})$
```

Algorithm D.5: Procedure BioFuel3

```
Input: $E_{3,t}$; $T_{3,1}$ … electric and thermal energy pool balance
Input: $P_{hp,h,max}$; $Pg,h,max$ … maximum thermal capacity of heat pump and biofuel generator
Input: $P_{hp,2,t}$; $P_{hp,3,1,t}$ … heat pump production of previous steps
if $P_{hp,h,max} = 0$ then
    $P_{hg,g,t} = \text{MIN}\ (P_{g,h,max} - PT_{g,t};-T_{3,1})$
    $P_{hp,3,2,t} = 0$
else if $-T_{3,1} \geq P_{g,h,max} - PT_{g,t} + P_{hp,h,max} - P_{hp,2,t} - P_{hp,3,1,t}$ then
    $P_{hg,g,t} = P_{g,h,max} - PT_{g,t}$
    $P_{hp,3,2,t} = P_{hg,g,t} \cdot \frac{eta_{e,chp}}{eta_{t,chp}} \cdot COP_h$
else if $\frac{-T_{3,1}}{1 + \frac{eta_{e,chp}}{eta_{t,chp}} \cdot COP_h} \geq P_{hp,h,max} - P_{hp,2,t} - P_{hp,3,1,t}$ then
    $P_{hg,g,t} = \text{MIN}\ (-T_{3,1} - (P_{hp,h,max} - P_{hp,2,t} - P_{hp,3,1,t}); P_{g,h,max} - PT_{g,t})$
    $P_{hp,3,2,t} = P_{hp,h,max} - P_{hp,2,t} - P_{hp,3,1,t}$
else if $E_{3,t} \geq 0$ then
    $P_{hg,g,t} = \text{MIN}\left(P_{g,h,\max} - PT_{g,t}; \frac{-T_{3,1}}{1 + \frac{eta_{e,chp}}{eta_{t,chp}} \cdot COP_h}\right)$
    $P_{hp,3,2,t} = P_{hg.g.t} \cdot \frac{eta_{e,chp}}{eta_{t,chp}} \cdot COP_h$
else
    $P_{hg,g,t} = \text{MIN}\left(-\text{T}_{3,1}; P_{g,h,\max} - PT_{g,t}; -E_{3,t} \cdot \frac{eta_{t,chp}}{eta_{e,chp}} - \frac{T_{3,1}}{(1 + \frac{eta_{e,chp}}{eta_{t,chp}}} \cdot COP_h)\right)$
    $P_{hp,3,2,t} = P_{hp,h,max} - P_{hp,2,t} - P_{hp,3,1,t}$
end
```

Algorithm D.6: Function TScharge3

```
Input: $T_{3,2,t}$ … thermal pool balance
Input: $Q_{max}$; $C_{h,max}$ … thermal storage maximum capacity and charge rate
Input: $Q_{t-1}$ … thermal storage state of previous time step
if $T_{3,2,t} \geq 0$ then
    $C_{h,t} = -\text{MIN}\ (T_{3,2,t};\ Q_{max} - Q_{t-1};\ C_{h,max})$
else
    $C_{h,t} = \text{MIN}\ (-T_{3,2,t};\ Q_{t\text{-}1};\ C_{h,max})$
end
```

Algorithm D.7: Function Echarge4

```
Input: $E_{4,t}$ … electrical energy pool balance
Input: $E_{max}$; $C_{e,max}$ … electrical storage maximum capacity and charge rate
Input: $C_{e,1,t}$; $E_{t-1}$ … previous step charge rate and previous time step storage state
if $E_{4,t} \leq 0$ then
    $C_{e,4,t} = 0$
else if $C_{e,1,t} \geq 0$ then
    $Ce,4,t = -\text{MIN}\ (E_{4,t};\ C_{e,max};\ E_{max} - E_{t,1})$
else
    $C_{e,4,t} = -\text{MIN}\ (E_{4,t};\ C_{e,max} + C_{e,1,t};\ E_{max} - E_{t,1})$
end
```

Algorithm D.8: Function HeatPump5

```
Input: T4,t … thermal energy pool balance
Input: $P_{hpmax}$ … heat pump maximum capacity
Input: $P_{hp}$,2,t; $P_{hp}$,3,t … previous step heat pump production
if $T_{4,t} < 0$ then
    $P_{hp,5,t} = \text{MIN}\ (-T_{4,t};\ P_{hp,max} - P_{hp,2,t} - P_{hp,3,t})$
else
    $P_{hp,5,t} = 0$
end
```

Algorithm D.9: Function ExHeat6

```
Input: $T_{6,t}$ … thermal energy pool balance
if $T_{6,t} < 0$ then
    $P_{ex,h,t} = -T_{6,t}$
else
    $P_{ex,h,t} = 0$
end
```