Chapter 19
On the Use of Agent-Based Simulation for Efficiency Analysis of Domestic Heating Using Photovoltaic Solar Energy Production Combined with a Heatpump

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Abstract In this paper agent-based simulation is used to analyse the efficiency of domestic heating based on a heatpump together with photovoltaic (PV) solar energy production. A simulation model for the cost (in terms of required kWh per day) of a heating agent based on a heatpump over a year is used, in addition to a simulation model for the yields of a PV production agent estimating the produced solar energy (in kWh per day). In particular, for the heating agent it is analysed how its performance depends on the outdoor temperature, and for the PV-installation agent how the yields depend on irradiation. Based on empirical temperature and irradiation data over a year it is found out which fraction of the energy required per year for heating can be covered by the yields of the PV installation.

19.1 Introduction

In many countries a substantial amount of domestic energy usage per year is used for heating. Due to the negative impacts on the environment of traditional heating systems based on not renewable resources such as gas and oil, often a heatpump is considered as an interesting alternative (e.g., [1, 4, 6, 9, 15]). Most often a heatpump is considered which takes thermal energy from the air (air to water heatpump), as this is most easy to install. The heatpump is driven by electrical energy, which preferably should be produced in a renewable manner as much as possible. Two possibilities for that are by wind energy or by solar energy. In this paper the possibility to use photovoltaic solar energy to produce electricity to drive the pump is analysed. At first sight it may seem that the fact that most solar energy is

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produced in the warmer season when no or not much heating is needed, will lead to a mismatch between demand and production. This may be true to some extent, but the study reported here was undertaken to find out in more detail which fraction of the required energy still can be covered by solar energy produced by the PV-installation.

The agent-based simulation model consists of a model for the performance of a heating agent depending on the daily outdoor temperature (described in Sect. 19.2) and a model for the performance of a solar energy production agent depending on the amount of irradiation per day (described in Sect. 19.3). In Sect. 19.4 a setup of the simulation experiments combining the two agent models is described and some of the results are discussed. Finally, Sect. 19.5 is a discussion in which further possibilities of the approach are pointed out.

19.2 Modeling Performance of the Heating Agent

In [14] a detailed model for an of an air to water heatpump-based heating agent was introduced. For the current paper, this agent model will be adopted. A central element of the model is the seasonal performance factor (*SPF*) which indicates how much electric energy (in kWh) is needed (to run the heatpump) as input to get a certain amount of heating energy as output for the heatpump over a certain time period:

$$SPF = \frac{energy\ output}{energy\ input}$$

This factor usually varies between 2 and 4; for a given water temperature of the heating system, it strongly depends on the outdoor temperature, and in particular the difference between these two temperatures. Manufacturers often only give indications of these performance factors for just a few water and outdoor temperatures. However, to determine the electricity usage of a heatpump over a year, with all its variations in outdoor temperature, it is needed to have a more systematic estimation of *SPF* for a given water temperature and each possible outdoor temperature, in a realistic context. To obtain a reasonable estimation of how for a given water temperature the performance factor depends on the outdoor temperature, theoretical analyses or lab experiments can be performed. However, such theoretical analyses are often not guaranteed to provide values that occur in realistic situations. A different route is to take empirical data from realistic contexts as a point of departure and make an interpolation and approximation of them by a mathematical function. For example, in [16, p. 2372] this was done based on the manufacturer's catalog data. However, a useful source of more realistic real world data can be found at the website www.liveheatpump.com. This approach was used in [14] and is adopted here as well. In Fig. 19.1 a graph is shown with values from this Website for the average day temperature on the horizontal axis

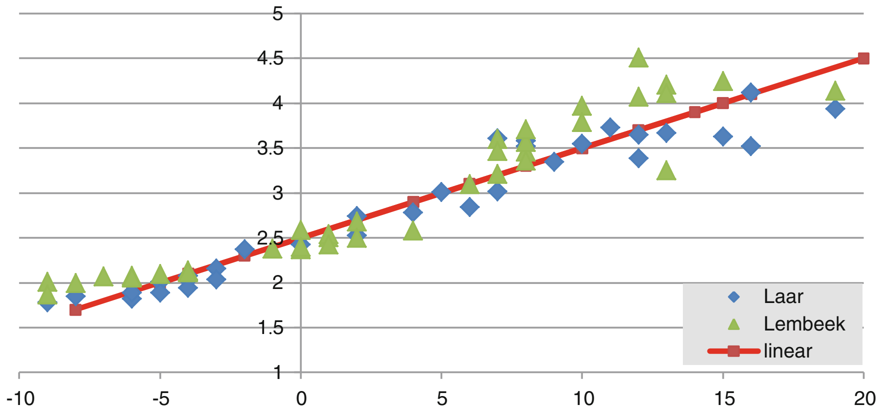

Fig. 19.1 Linear approximation of seasonal performance factors in relation to outdoor temperature compared to empirical data over 2012 for sites in Lembeek and Laar (water temperature 50 °C)

and the performance factor on the vertical axis (for water temperature in the heating system approximately 50 °C).

More specifically, this has been done for the sites at Lembeek and Laar, where the General Waterstage HT heatpump combination WH16/WOH16 is used. Moreover, in Fig. 19.1 a linear approximation of *SPF* for the interval from −10 °C to +20 °C is drawn; this is assumed of the form

$$SPF(T_{od}) = 7.5 - 0.1 * (T_{water} - T_{od}) \quad \text{with} \quad T_{water} = 50$$

Note that in [14] also a quadratic approximation was shown, as was done in [16]. Using the linear approximation (for the sake of simplicity) shown in Fig. 19.1, the seasonal performance factor *SPF* can be estimated on a daily basis throughout a year, when the day temperatures are given. This is one basic ingredient of the model for the heating agent used. A second ingredient of the model concerns how much energy for heating is needed, also depending on the outdoor temperature. A general format to determine how much energy is to be provided for the heating makes use of the concept of *degree day*, denoted by *dd*. This concept is based on the assumption that the amount of energy needed to maintain a difference in temperature (between indoor and outdoor) is proportional to this difference (e.g., see [10]). The number of degree days for a given day linearly relates to the difference between the daily outdoor and the indoor temperature T_{id} (when the latter is higher than the former, else 0):

$$dd(t) = \begin{array}{ll} \sigma(t)^{*}(T_{id}(t) - T_{od}(t)) & \text{when} \quad T_{id}(t) > T_{od}(t) \\ 0 & \text{Otherwise} \end{array}$$

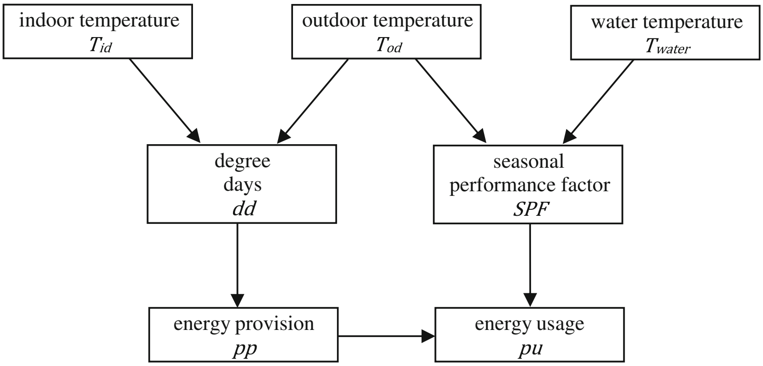

Fig. 19.2 Dependencies of the variables for the model of the heating agent

Here *σ(t)* is as seasonal correction weight factor which is 1.1 for the months November, December, January and February, 1 for the months March and October, and 0.8 for the months April, May, June, July, August and September.

Figure 19.2 shows the variables used in the heating agent model and the dependencies between them, and Table 19.1 summarizes them. The right hand side in Fig. 19.2 describes how the performance factors are determined, and the left hand side describes how the energy demand is determined.

The model results in the electrical energy usage *pu(t)* needed as input for the heating agent. This is determined from the heating energy *pp(t)* provided (as output) to the heating system (*kWh* provided for heating at day *t*) as follows. For each degree day an amount ε of energy (in *kWh*; the value 4.0 kWh/dd is used here) has to be provided as output. Therefore *pp(t)* is determined as (see also Fig. 19.2):

$$pp(t) = \varepsilon \, dd(t)$$

This is the amount provided as output to the heating system, but not the amount *pu(t)* used as input by the heatpump itself, since part of the provided energy *pp(t)* comes from the air in the environment. This is expressed using the seasonal performance factor *SPF*; recall that by definition this is the heatpump's output divided by its input. Therefore the following is obtained:

$$pu(t) = pp(t)/SPF(T_{od}(t)) = \varepsilon \, dd(t)/SPF(T_{od}(t))$$

In addition to the model to determine the energy usage per day a model to describe the cost has been included. Assuming that one *kWh* electricity costs π_{el} euro, the costs *pc(t)* of heating for day *t* by the heatpump is given by

$$pc(t) = pu(t) * \pi_{el} = (\pi_{el}\varepsilon/SPF(T_{od}(t)))\, dd(t)$$

Table 19.1 Main concepts for the heating agent

Notation	Description	Unit
SPF	Seasonal performance factor	
$T_{od}(t)$	Average outdoor temperature at day t	°C
$T_{id}(t)$	Average indoor temperature at day t	°C
$T_{water}(t)$	Average water temperature of the heating system at day t	°C
$\sigma(t)$	Seasonal weight factor	
$dd(t)$	Degree days at day t	dd
$pp(t)$	Heat pump heating energy provision for day t	kWh
$pu(t)$	Heat pump electrical energy use for day t	kWh
$pc(t)$	Heat pump electrical energy cost for day t	euro
ε	Energy needed per degree day	kWh/dd
π_{el}	Price of electrical energy	euro/kWh

Note that this cost parameter π_{el} depends on the source of the electrical energy. If it is taken from an external production company it may be higher than when it is taken from the own PV-installation. This is discussed further in Sect. 19.4.

19.3 Modeling the Photovoltaic Solar Energy Production Agent

In [13] a detailed agent-based model of a photovoltaic solar energy production system has been described. The agent model used here will be an abstracted form of the agent-based model from [13] in two ways. A main difference is that in [13] the PV installation is modelled as a system composed of multiple agents, where each agent consists of one solar panel and one connected micro-inverter. In contrast, here the PV installation as a whole is modelled as one solar energy production agent. This is a form of abstraction in the agent cluster dimension (cf. [3]). A second type of abstraction with respect to the model in [13] takes place in the temporal dimension (cf. [3]). While [13] describes a dynamical model for the pattern over time in detail at a grain size of the hours or minutes of a day (e.g., with updated states per half an hour), in the current approach these processes are aggregated into a dynamical model based on states per day as follows. For a summary of the symbols used, see (Table 19.2). In general, the power $P_{out}(u)$ generated as output at time u can be described as a function of:

- used irradiation at u, which itself depends on
  - the available irradiation $irr(u)$ at time u
  - the efficiency ρ_a due to angle and orientation of the panel
  - the efficiency ρ_s due to shadow

- the maximal power $P_{panelpeak}$ of the panels (Watt peak)
- the efficiency ρ_{panel} of the panels
- the maximal power $P_{inverterpeak}$ of the inverters
- the efficiency ρ_{inv} of the inverters

Note that as another form of temporal abstraction all efficiency factors ρ_i are assumed to be aggregated over a year, so that they are taken constant within the year. The following relations are assumed for each point in time t:

- Provided power $P_{panel}(u)$ by panel: $\min(P_{panelpeak,}\ \rho_a\ \rho_s\ irr(u))\ \rho_{panel}$
- Provided power $P_{out}(u)$ by inverter: $\min(P_{inverterpeak}, P_{panel}(u))\ \rho_{inv}$

Given that $\rho_{panel} < 1$, when it is assumed that $P_{inverterpeak} > P_{panelpeak}$ and $P_{panelpeak} > \rho_a\ \rho_s irr(u))\ \rho_{panel}$, this can be simplified into:

$$P_{out}(u) = \rho_a \rho_s \rho_{panel} \rho_{inv}\ irr(u)$$

Such a relation can also be aggregated to the energy (in kWh) obtained for a day t, where the integration is taken over times u within day t:

$$\begin{aligned} E_{day}(t) &= \int P_{out}(u)du \\ &= \int \rho_a \rho_s \rho_{panel} \rho_{inv} irr(u)du \\ &= \rho_a \rho_s \rho_{panel} \rho_{inv} \int irr(u)du \\ &= \rho_a \rho_s \rho_{panel} \rho_{inv} irr_{day}(t) \end{aligned}$$

For the case of no shadow $\rho_s = 1$. For cases that a most optimal angle is used, also the value for ρ_a can be set to 1; for example, for mid-Europe often 30 or 35 is assumed for this optimal angle. In such a case it simplifies into:

$$E_{day}(t) = \rho_{panel} \rho_{inv} irr_{day}(t)$$

In the general case as the model addresses in particular how the energy production is distributed over the days in a year, the energy fraction $EF_{day}(t)$ of a day relative with respect to the year production is a relevant notion:

$$EF_{day}(t) = E_{day}(t)/E_{year}$$

with

$$E_{year} = \Sigma E_{day}(t) = \rho_a \rho_s \rho_{panel} \rho_{inv}\ irr_{year}$$

Table 19.2 Main concepts for the energy production agent

Notation	Description	Unit
$P_{panelpeak}$	Watt peak of panel (W)	W
ρ_{panel}	Efficiency of the panel	
$P_{invpeak}$	Max power of inverter (W)	W
ρ_{inv}	Efficiency of the inverter	
$P_{out}(u)$	Outgoing power at time u	W
$irr(u)$	Irradiation at time u	W/m^2
ρ_a	Efficiency due to angle and orientation	
ρ_s	Efficiency due to shadow	
$E_{day}(t)$	Produced energy on day t	kWh
$EF_{day}(t)$	Fraction of the year production of produced energy on day t	kWh

where

$$irr_{year} = \Sigma irr_{day}(t)$$

When this division $E_{day}(t)\ /E_{year}$ is done, the constant efficiency factors $\rho_{a},\ \rho_s$, ρ_{panel}, ρ_{inv} are divided out, and a dependence of $EF_{day}(t)$ on the day irradiation remains:

$$EF_{day}(t) = irr_{day}(t)/irr_{year}$$

This provides the form of temporal abstraction (cf. [3]) for the solar energy production agent model used in the simulation experiments described in Sect. 19.4.

19.4 Simulation Experiments

In the previous two sections it was described how models can be made for the two agents. These agent models can be used in particular to describe consumption of energy by a heatpump for the heating agent over days in a year, and production of energy by a PV-installation agent over days in a year. In general the distribution of the consumption over days in a year (high during winter, low during summer) has a far from perfect match with the distribution of the production over days in a year (low during winter, high during summer). In the simulation experiments discussed here empirical data have been used for the year 2012 in the Netherlands, covering both the irradiation per day and the average day temperature per day. As a first example, in Fig. 19.3 the day distributions of the day fractions (of a year) of production and consumption are shown for a case in which the year production is assumed exactly equal to the year consumption. It can be seen that in November, December, January and February (from about day 305 to day 60) the consumption strongly exceeds the production, whereas from May until August (from about day

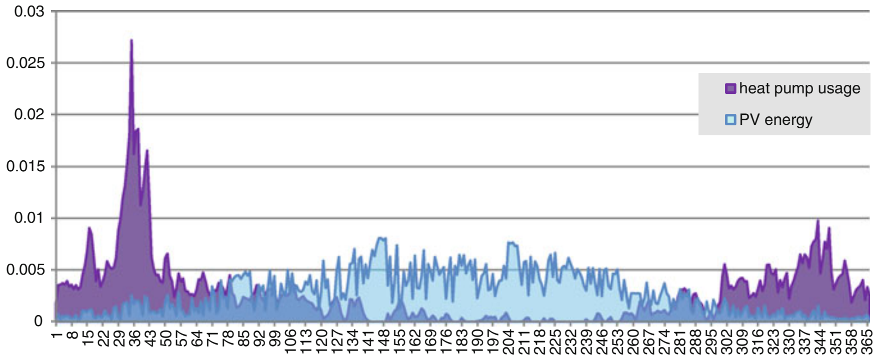

Fig. 19.3 Distributions and overlap for equal overall year production and consumption over 2012 (0.33 of consumption covered)

120 to day 250) it is the other way around. Nevertheless, an overlap can be found that in total covers a non-neglectable fraction 0.33 of the year consumption amount, mostly concentrated in the periods March to May and September to October.

In a general case the overall year production and consumption will not be exactly the same. It might also be wise to go for a higher production level per year in order to increase the 33 % coverage of the consumption. It has been analysed in how far this would increase the coverage. In Fig. 19.4 two of such (a bit extreme) cases are depicted, respectively for production 5 times the consumption (upper graph, resulting in 72 % coverage of consumption) and for 10 times the consumption (lower graph, resulting in 91 % coverage of consumption); note that the vertical scales are shown more condense here. This shows that increasing the production level indeed can increase the coverage.

Similar simulations have been done for a number of different proportions between production and consumption, for a factor 0 to 20 of production with respect to consumption. The results are as shown in Fig. 19.5. For very high production levels per year with respect to consumption, an asymptote of 1 is reached.

As a further step assumptions have been made for costs. It is assumed that per kWh the own produced energy is much cheaper than the energy that has to be bought externally. For values 0.05 resp. 0.25 euro per kWh for own resp. externally produced energy, the graph shown in Fig. 19.6 (with derivative in Fig. 19.7) is found. Here an asymptote is found with value 0.20 (consumption fully based on own produced energy). The derivative can be used to assess how much investment in additional capacity of the PV installation is reasonable.

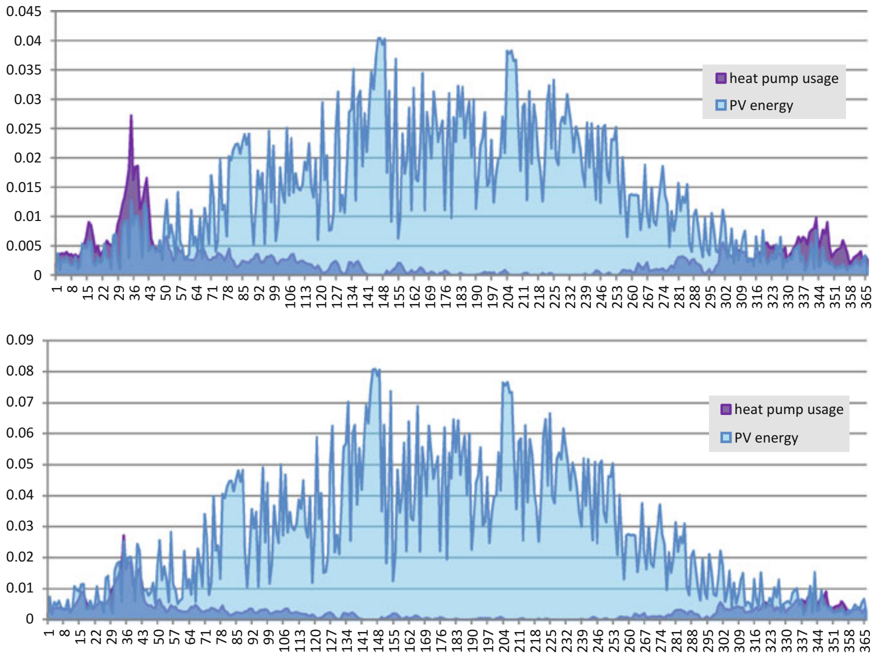

Fig. 19.4 Unequal distributions of overall year production and consumption over 2012: **a** *upper* graph: year production 5 times year consumption (0.72 of consumption covered), **b** *lower* graph: year production 10 times year consumption (0.91 of consumption covered)

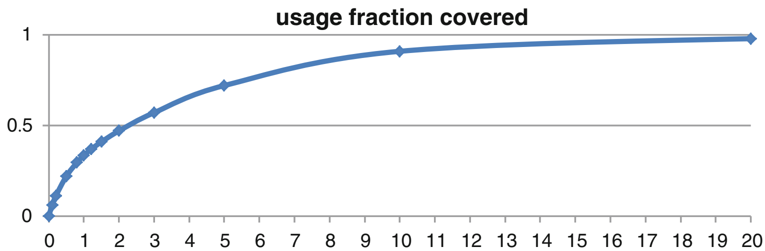

Fig. 19.5 Consumption coverage fraction for different factors for overall year production w.r.t. overall consumption over 2012

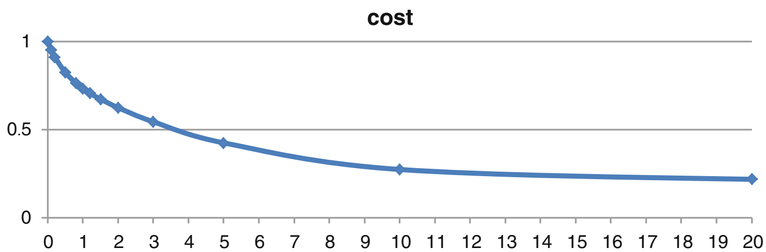

Fig. 19.6 Cost for different factors of overall year production w.r.t. overall consumption over 2012

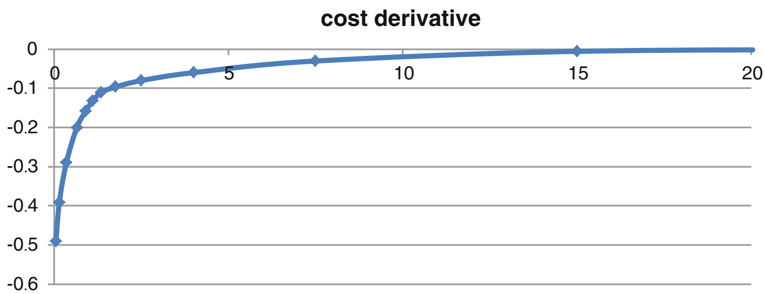

Fig. 19.7 Derivative of cost for different factors of overall year production w.r.t. overall consumption over 2012

19.5 Discussion

In this paper it was shown how the efficiency of domestic heating based on a heatpump together with photovoltaic (PV) solar energy production can be analysed by agent-based simulation. The simulation model covers of two agents: a solar energy production agent and an energy consuming agent for heating based on an air to water heatpump. For both agents their efficiency strongly depends on dynamically varying environmental circumstances, in particular on the amount of irradiation (production agent) and on the outdoor temperature (heating agent). For the heating agent it was analysed how exactly its daily performance depends on the outdoor temperature, and for the PV-installation how the daily yields depend on irradiation. Based on empirical temperature and irradiation data over a year it was found out for different settings which fraction of the energy required per year for heating can be covered by the yields of the PV installation.

Within a day the heatpump usage was assumed to fit to the time the PV energy production takes place. During this period of sunshine the temperatures may be higher than the average day temperature, so the performance factor may be a bit better in reality than estimated in the model used here. However, there may well be as well a need to heat when there is just little or no sunshine, for example early in the morning. This will count in the opposite direction. To inverstiage this variation, the simulations also have been performed for the minimun and maximum day temperatures instead of the average day temperature. For example, for the case of equal overall production and usage, this provides a variation around the 33 % coverage (for average day temperatures) from 30 % coverage (for minimum day temperatures) to 36 % coverage (for maximum day temperatures). To obtain a more detailed approach for such types of intraday effects, a refined model is needed in which hours or even minutes per day are considered and the lifestyle and choices of the customer concerning when exactly heating is needed.

The combination of solar energy and heatpumps have been studied as well in other literature such as (e.g., [2, 5, 7, 8, 11, 12, 15, 16]. In all of these cases the source of the heatpump was not air but ground or water. Moreover, the solar energy installation used was in the form of solar thermal collectors and added to the heatpump loop to heat the water. In these respects they address situations quite different from what was addressed in the current paper, in which the source was air, and the solar energy production was based on photovoltaic panels to obtain electrical energy, not thermal energy.

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