THE IMPACT OF LOAD PROFILE ON THE GRID-INTERACTION OF BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) SYSTEMS IN LOW-ENERGY DWELLINGS

R. Baetens,[1] R. De Coninck,[2,3] L. Helsen,[2] and D. Saelens[1]

ABSTRACT

A building integrated photovoltaic system (BIPV) system may produce the same amount of electricity as consumed in the building on a yearly base. The simultaneity of production and consumption however needs to be evaluated: the distribution grid is regarded as virtual storage and is loaded unconventionally or even overloaded. A detailed bottom-up modelling approach of the domestic load, thermal installations and the local generation of BIPV system may give more insight. The present paper aims at quantifying the impact of domestic load profiles on the grid-interaction of BIPV-equipped dwelling in a moderate Belgian climate wherefore the cover factor is defined. For a yearly electricity production that equals the yearly domestic demand, a cover factor of 0.42 is found if a classic heating system is installed, denoting that more than half of the produced electricity will be passed on to the grid and withdrawn on another moment. If a heat pump is used for space heating and domestic hot water, the cover factor decreases to 0.29.

KEYWORDS

domestic load profile, photovoltaic, BIPV, cover factor, smart grid

1. INTRODUCTION

Due to a favorably subsidized system in the Flemish region since the year 2006, the market of photovoltaic (PV) installations grew exponentially. By the end of year 2009, the total installed capacity grew to a cumulated capacity of 312 MWp in Belgium making it the fifth largest market for PV systems in Europe (Neyens 2009, VREG 2009). From the currently total installed capacity, nearly eighteen thousand installations with a size between 2 and 4 kWp are positioned on the sloped roofs of private houses in Flanders, practically all privately financed by the owners of the dwellings and the government subsidies (Neyens 2009) and—so far—all grid-connected (EurObserv'ER 2009). Although the total installed capacity is high, the total electricity production of all PV installations together remains relatively low due to low solar radiation levels in the moderate Belgian climate.

For a business-as-usual model where no further attempt is made towards optimizing the energetic advantage of the BIPV installation—as in most of the current dwellings where the PV installation is installed on existing buildings—the reduction of the grid electricity demand of the dwelling is expected to remain rather low as the PV power output peaks around 12h whereas an average domestic load profile is expected to peak around 8h and after 18h (see Fig. 1). On the other hand, the challenges for the distribution grid become high in neighbourhoods with a high penetration of BIPV. The grid is seen as a virtual storage unit for electricity and, as a high share of the produced PV power will be directed to the grid, instability of the grid may form a major drawback.

For quantifying the reduction of the grid electricity demand by a BIPV installation in a business-as-usual model and illustrating the auto-consumption and grid injection of such a PV installation, a

[1]Division of building physics, Department of civil engineering, K.U.Leuven, BE-3000 Leuven, Belgium, ruben.baetens@bwk.kuleuven.be.
[2]Division of applied mechanics and energy conversion, Department of mechanical engineering, K.U.Leuven, BE-3000 Leuven, Belgium.
[3]3E, BE-1000 Brussels, Belgium.

multi-zone TRNSYS model for a dwelling with an electricity-driven, air-to-water compression heat pump for both space heating and domestic hot water (DHW), domestic consumers and on-site photovoltaic generation is set-up. In order to simulate correctly the dynamics of the system, a small time-step of 1 minute is chosen. The model is used to visualize grid-interactions, the influence of the user behaviour and the influence of the heating system on the auto-consumption and grid-injection of BIPV, and to visualize bottle-necks for possible large-scale implementation of BIPV generation.

2. BOTTOM-UP DOMESTIC POWER DEMAND

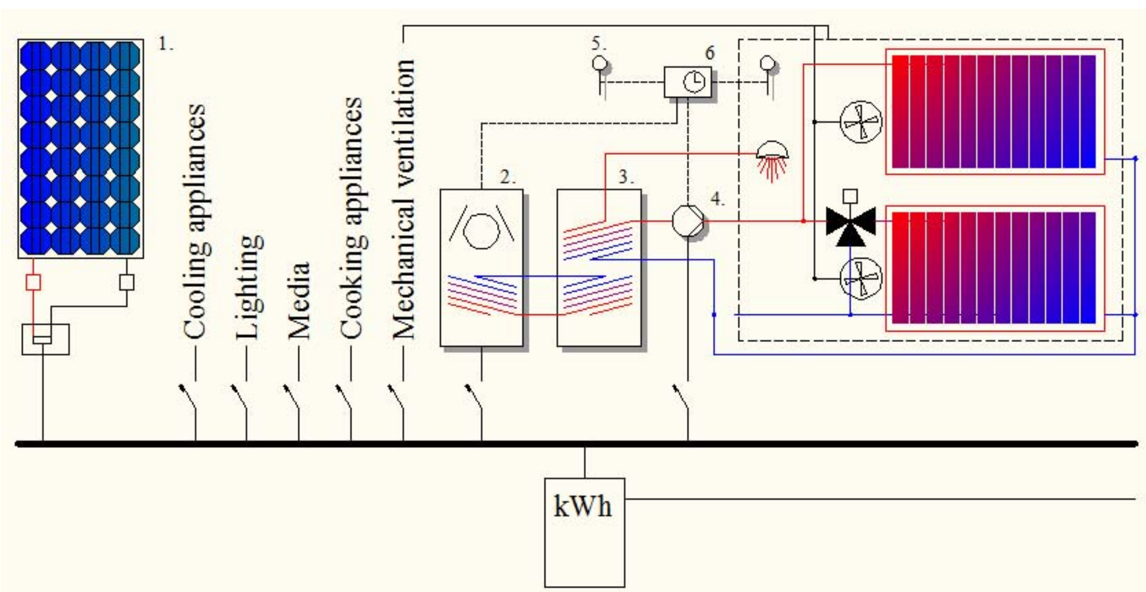
An extremely low-energy detached house is modeled in detail for simulating the profile of electricity demand (see also figure 1). The dwelling is modeled as a multi-parameter multi-zone building in TRNSYS (Solar Energy Laboratory 2009) where each single room is a zone. It has a usable area of 210 m^2, a roof area of 270 m^2 and U-values of 0.17, 0.20 and 1.17 $W/(m^2K)$ respectively for the fa_ade, roof and window panes. The total extract air flow is 175 m^3/h and the air tightness n_{50} is 4 h^{-1}. Furthermore, internal gains of 8 W/m^2 are taken into account for both the day zone and night zone. Within the model, 4 major groups of domestic electricity consumption are taken into account:

1. standby power and domestic cooling appliances,
2. non-shiftable occupancy and behaviour based power demand (i.e. lighting, ventilation, cooking and the use of media),
3. shiftable power demand (i.e. washing machines, tumble dryers and dishwashers) and
4. heat production for space heating and domestic hot water by means of an electricity-driven, air-to-water compression heat pump.

The use of the washing machine and tumble dryer are not modeled in detail as its current use is determined by the day and night regime of electricity and due to a lack of statistical data. Also small electric appliances which show a higher power demand but are used for a very short period are not modeled.

Some groups such as the cooling appliances (1), lighting and ventilation (2), as well as for space heating and domestic hot water (4) have a high potential for optimisation towards a higher system efficiency with BIPV systems because they can be shifted in

FIGURE 1. Schematic representation of the modelled dwelling and installation with (1) a BIPV system, (2) an air-to-water heat pump, (3) a storage tank, (4) pump, (5) outdoor temperature sensor and (6) central room thermostat.



time or influenced by design. The power demand for most appliances is hard to shift as it strongly depends on human behaviour and the appliance characteristics. Washing machines, tumble dryers and dishwashers (3) form an exception on these domestic appliances as they are not strongly connected to human behaviour. Here, some improvements may be achieved by means of a domestic energy control system.

In the current Belgian building stock, it is not common to use electricity for space heating and domestic hot water (DHW). However, heat pumps are currently gaining high interest in low-energy or passive dwellings for both space heating and DHW. As such, two different situations are considered: A dwelling (i) without electricity demand for space heating and DHW, and (ii) with a heat pump for both space heating and DHW.

Modelling of each of the electricity demands in a business-as-usual setting is described in the following sections.

2.1 Standby and cooling appliances

In order to define the base line for power demand, distinction is made between the standby power of appliances and the electricity consumption of the cooling appliances. Based on the work of Almeida et al. (2008) a standby power of 40 W is considered as an average based on standby power and ownership rates. The distinction between two categories within the continuous power demand is necessary due to the small simulation time step of 1 minute: whereas the standby power demand of electric appliances is constant through time while domestic cold appliances will permanently switch between an on and off state within a certain time interval (Firth et al. 2008, Liu et al. 2004). The effective power profile depends on the used model of cold appliance, whereas a 120 W appliance with a 40′ interval is taken into account. The impact of the room temperature or opening of doors on the power demand of cold appliances (Meier 1995, Saidur et al. 2002) is not taken into account.

2.2 Occupancy-based electricity demand

Within this work, both occupancy and lighting demand profiles are generated with the available model tool *Domestic Lighting Model 1.0c* (Richardson & Thomson 2008) provided by Richardson and Thomson (Richardson et al. 2008, 2009). The occupancy model for energy demand simulations generates ten-minute domestic building occupancy profiles with the Markov-Chain Monte Carlo technique. Here, the transition probability matrices are derived from a large time-use survey conducted in the United Kingdom in the year 2000 (Office For National Statistics 2003). The governing parameters in the model are (i) the number of residents of the dwelling and (ii) the day of the week. From the resulting occupancy profile, the lighting demand is derived based on the model by Stokes et al. (Stokes et al. 2004). For the purpose of detailed energy prediction and simulation, the original tool (Richardson & Thomson 2008) has been coupled to minute global irradiance data derived from Meteonorm 6.1 (Meteotest 2008) for Uccle, Belgium. This results in a daily variation of the climate and—as only a single building is simulated—the installed lighting power is defined instead of statistically chosen for each day. Here, 1 461 W is taken into account as the average installed lighting power in Stokes et al. (2004).

A balanced mechanical ventilation is supposed to be installed in the dwelling. The nominal electric power for operating of the fans of the mechanical ventilation needs to be defined based on the exact design of the ventilation network in the dwelling. For generalisation, the required electric power for mechanical balance ventilation may be defined as $\phi = 0.235\ V_{sec}$ (W) (Flemish Region 2006) where V_{sec} (m^3) is the volume that is ventilated. As such, the required power is 95 W for the modelled dwelling. The required electric power for ventilation has been correlated to the occupancy pattern of the habitants, i.e. ventilation will be switched on when persons are present in the building.

Domestic cooking results in short but high peaks in the domestic electricity demand. The probability matrices for cooking are derived based on a time-use survey conducted in Belgium in the year 1999 (Glorieux & Vandeweyer 2002). The parameters are (i) the domestic occupancy pattern and (ii) the day of the week. During the week, cooking is concentrated sharply around 12h20 and 18h20, whereas the peaks in the weekend may be found more distributed and later on the day. The installed total power for cooking in dwellings may peak up to 10 kW (Wood & Newborough 2003) whereas 7 kW is taken into account in the model.

The use of television and the use of computer is modelled through probability matrices derived based on the same time-use survey (Glorieux & Vandeweyer 2002). Also here, the parameters are (i) the domestic occupancy pattern and (ii) whether it is a weekday or weekend. On average, habitants watch 2.5 h/day television and work 1h on the computer at home. The required power for a television ranges from 50 W to 340 W, with 150 W as an average. For personal computers, a power demand of 200 W is depicted (TPDCB 2010).

2.3 Heat generation by means of a heat pump

Because of the limited heat demand and the resulting possibilities for low-temperature heat emission systems in low energy dwellings, a heat pump is often used for space heating. The same heat pump is also used for the production of DHW.

The modeled extremely-low energy dwelling is equipped with classic hydronic low-temperature (i.e. with a supply temperature of 45°C) radiators and an electricity-driven, air-to-water compression heat pump. The required electricity demand is closely related to the occupancy pattern of the habitants: comfort has to be met whenever persons are present in the building. In the model, 21°C is used as set-point temperature for the central room-thermostat during occupation periods at which the space heating system is allowed to be switched off, while the room temperature may never drop below 16°C.

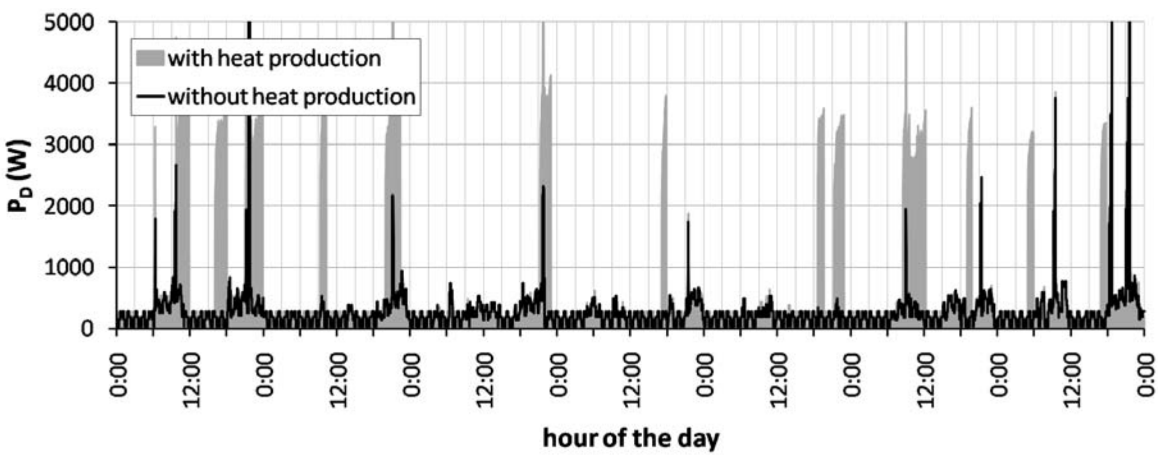
DHW profiles are generated based on (i) the occupancy profiles and (ii) the daily probability distributions in Jordan & Vijen (Spur et al. 2006, Jordan & Vajen 2001) for both small and medium loads, bathing and showering. For the use of 'alternative' sources of energy, a DHW temperature of 45°C is accepted in general (Spur et al. 2006) whereas a seasonal cold water temperature of 10 ± 3°C is assumed.

The installation consists of a storage tank for heating with an integrated domestic hot water heat exchanger coupled to the pump with a nominal power of 10.0 kW and a COP of 4.26 at nominal conditions (i.e. 2/35°C). A seasonal energy efficiency ratio (SEER) of 3.0 is found by simulation. The total electricity demand by the heat pump in the model is 6 MWh/a of which 2.8 MWh/a for DHW. This results in an electricity demand for space heating of 15 kWh/(m^2a).

2.4 Results and limitations of the model

The resulting electricity demand profiles of the dwelling can be found in Figure 2. For the situation with a classic heating system, the profile shows an increased electricity demand typically between 6h and 10h in the morning and between 18h and 23h in the evening. During the weekend, a higher demand may be found during the complete day.

FIGURE 2. Example week profile for a typical mid-season week of the modelled electricity demand P_D (W) for a dwelling without (black) and with (grey) electricity-based heat generation for space heating and DHW.



Due to the combination of appliances, the demand fluctuates between 0.1 kW and 0.9 kW within these periods. Short but high peaks up to 5 kW may be found on average around 12h and 18h30 due to the use of cooking appliances. For the situation including space heating and DHW, more peak consumption between 3 kW and 4 kW can be denoted due to the electricity demand of the heat pump. During heating season, this high demand coincides in general with the occupancy pattern due to the impact of space heating. In summer, only DHW results in short but lower (i.e. due to the higher outdoor temperature) peaks in electricity demand.

The average yearly electricity consumption for the modeled situation is 8.4 MWh/a including space heating and DHW, and 2.4 MWh/a without heat production. For Belgium, the average domestic electricity consumption for a similar dwelling is 3.5 MWh/a. The difference may be explained as follows:

- Shiftable load profiles such as the washing machine and tumble dryer are not modeled. Their current times of use are highly determined by the current day and night regime of the electricity supply, but are not bound to a moment of the day based on human behavior. Based on the number of cycles, the average electricity consumption per cycle and the ownership rates (Danish Energy Agency 1995), these appliances count for an average annual electricity consumption of 0.7 MWh/a.
- The remaining difference might be explained by small electric appliances which might show a higher power demand but are used for a very short period.

3. PV POWER SUPPLY

The photovoltaic power output P_{PV} (W) is modelled with the available TRNSYS Type 194 implementing the basic 5-parameter model developed by the research group of Beckman (Duffie & Beckman 1991)

$$P_{PV} = I_{PV}V$$

where

$$I_{PV} = I_L - I_0\left[\exp\left(\frac{V + I_{PV}R_S}{a_{ref}}\right) - 1\right] - \frac{V + I_{PV}R_S}{R_{sh}} \quad (1)$$

where I_L (A) is the light generated current, I_0 is the reverse saturation current of the diode, R_s (Ω) is the series resistance of the cells, R_{sh} (Ω) is the shunt resistance of the cells and a_{ref} is the modified ideality factor for compensation of second-order effects depending on the cell, the number of cells in series within a module and the cell temperature.

The method for determining the necessary parameters in Eq.1 is based on the model described by De Soto et al. (2006). Here, the five parameters a_{ref}, I_0, I_L, R_s and R_{sh} are defined for reference conditions based on manufacturer data, whereafter these values are used to calculate the parameters at any other operating conditions. The necessary manufacturer data are the short circuit current I_{sc} (A), the open circuit voltage V_{oc}, the current at maximum power point I_{pm} (A) and the temperature coefficient β_{Voc} of the open circuit voltage. The five parameters depend on the operating conditions by means of the operating cell temperature, the incidence angle and the mass of air the beam radiation has to traverse.

The positioning of the PV panels has been chosen to maximize the total power output over an entire year for the climate data of Uccle (Belgium), i.e. they have an inclination of 34° and are oriented directly to the South (Huld & Suri 2010). No effects of elevated horizons or possible shadow of the environment on the tilted surface of the PV module are taken into account. For retrieving a high-resolution power output of the photovoltaic system, minute values for the sky diffuse and beam radiation on the tilted surface of the PV cells and the solar zenith angle are generated from Meteonorm 6.1 (Meteotest 2008) for Uccle (Belgium). An example resulting PV output is shown in Fig. 3. The PV installation is dimensioned for each situation in such way that a zero energy building is achieved, i.e. the total yearly delivered energy equals the total electricity consumption, resulting in a 4 kWp to 12 kWp installation in a Belgian climate. As such, an attempt is made to exclude the effect of the PV installation size on the results. As a single climate file is used instead of a stochastic weather generator, the power output of a modeled installation is predictable and the yearly balance can be achieved by running each simulation twice.

FIGURE 3. Example day-profile of modeled minute-values for the photovoltaic power supply P_{PV} (W) for a random winter (grey) and summer (black) day.

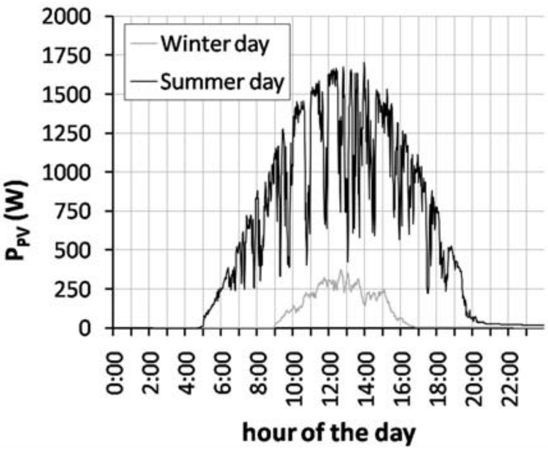
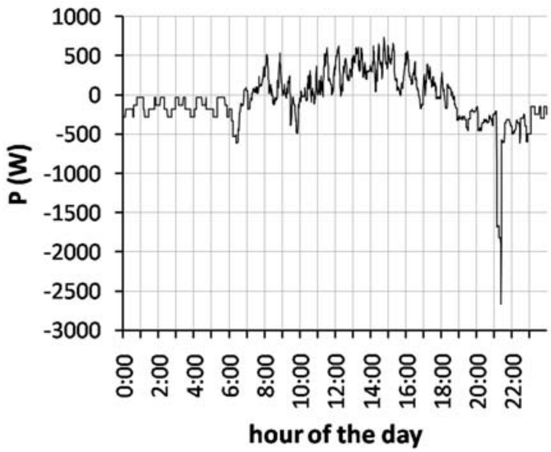


FIGURE 4. Example day-profile of modeled minute-values for the power balance of the dwelling. Positive values indicate supply to the grid.



4. RESULTS

4.1 Cover factors γ_D and γ_{PV}

In this paper, the effectiveness of the building integrated photovoltaic system for reducing the electricity demand from the main distribution grid is expressed by quantifying the cover factor. In general, a cover factor γ (-) is a number that indicates to what extent a set of threads is covered by another set of threads. Within this context, the cover factors γ_D and γ_{PV} provide efficiency-like information and are defined as "the ratio to which the power demand is covered by the BIPV supply" and "the ratio to which the BIPV supply is covered by the power demand" respectively

$$\gamma_D^{[t_1,t_2]} = \frac{\int_{t_1}^{t_2} \min\{P_{PV},P_D\}}{\int_{t_1}^{t_2} P_D}$$

and

$$\gamma_{PV}^{[t_1,t_2]} = \frac{\int_{t_1}^{t_2} \min\{P_{PV},P_D\}}{\int_{t_1}^{t_2} P_{PV}} \qquad (2)$$

where P_{PV} (W) is the BIPV supply power i.e. here from the photovoltaic system and P_D (W) the power demand. The term $\min\{P_{PV},P_D\}$ represents the part of the power demand covered by the supply power or the part of the supply power covered by the power demand equalling the minimum of P_{PV} and P_D.

In a business-as-usual model where no attempt is made towards power load matching and thus increasing γ_D and γ_{PV}, a maximum value $\gamma_{D,max}$ for the cover factor γ_D on daily basis can be defined based on the length of daytime and the resulting maximum daily period during which power output of the PV array is possible as function of the locations latitude. This $\gamma_{D,max}$ expresses the ratio of the electricity demand during sunshine to the total electricity demand, independently of the PV installation. Within this context, the cover efficiency $\varepsilon_{\gamma D}$ is as "the ratio of the effective cover factor to the maximum cover factor for a certain time interval"

$$\varepsilon_{\gamma_D}^{[t_1,t_2]} = \frac{\gamma_D^{[t_1,t_2]}}{\gamma_{D,max}^{[t_1,t_2]}} \quad \text{where} \quad \gamma_{\mathrm{D,max}}^{[t_1,t_2]} = \frac{\int_{sunset}^{sunrise} P_D}{\int_{t_1}^{t_2} P_D} \qquad (3)$$

4.2 Results

For the modelled dwelling without heat pump, a γ^{year} of 0.42 for a of $\gamma_{max}{}^{year}$ of 0.48 is found. These values change to a γ^{year} of 0.29 for a $\gamma_{max}{}^{year}$ of 0.63 if heat is generated by the heat pump. Even if a zero energy building is aimed at determining the PV system, this results in low cover factors in a Belgian climate and the need for the main distribution grid to act as a virtual storage (see Fig. 4).

Both γ_D and γ_{PV} (see Fig. 5–6) show a seasonal pattern for both situations. The seasonal pattern of γ_D and $\gamma_{D,max}$ may be explained by the length of the day. As the electricity demand peaks in the morning and evening, the higher demands fall out of the day during winter. The seasonal pattern of γ_S can be explained by a higher solar radiation on the BIPV system due to a higher solar zenith and longer days.

From the point of view that grid demand reductions of the building is aimed at, several findings can be made based on the derived cover factors γ, γ_{max} (see Fig. 5–6) and cover efficiencies ε (see Fig. 7):

- The cover factor γ_{PV}^{day} does not reach unity in the winter while on the same time also $\varepsilon_{\gamma D}$ does not reach unity for both situations. Even when only limited power supply of the BIPV system is available, a substantial part of the PV power is put on the grid.

  The finding is more pronounced for the situation including the heat pump: whereas the average γ_{PV}^{day} is 0.74 and $\varepsilon_{\gamma D}^{day}$ is 0.67 during winter for the situation without heat pump, the average γ_{PV}^{day} is only 0.65 however $\varepsilon_{\gamma D}^{day}$ is 0.43 if heat production is included. The reason may be found in the high power demand during relatively short periods of time (see Fig. 2), e.g. for cooking but mainly for the heat production—although here dimensioning of the storage tank, the heat pump nominal power and its control plays an important role.
- For both modelled situations, the cover efficiency $\varepsilon_{\gamma D}^{day}$ does not reach unity in summer while on the same time also γ_{PV}^{day} does not reach unity. Even when a high power supply of the BIPV system is available, a substantial part of the domestic load during the day is not covered by the PV system.

Also here, the finding is more pronounced for the situation including the heat pump: whereas the average $\varepsilon_{\gamma D}^{day}$ is 0.95 and γ_{PV}^{day} is 0.37 during winter for the situation without heat pump, the average $\varepsilon_{\gamma D}^{day}$ is only 0.88 however γ_{PV}^{day} is 0.22 if heat production is included. The reason is probably the same as mentioned earlier.

Both in winter and summer, the BIPV systems use the main distribution grid for "storage" of electricity to cover electricity demand on another moment of the day when BIPV power supply is expected. Possible consequence of using the grid as virtual storage plant is the local instability of this grid which might be avoided by limiting the required storage capacity of the grid and using or storing more energy in the building itself.

FIGURE 5. γ_D^{day} (bold), $\gamma_{D,max}^{day}$ (black) and γ_{PV}^{day} (dashed) through the year for a modelled dwelling without space heating and domestic hot water by means of a heat pump. A resulting γ^{year} of 0.42 and a value $\varepsilon_{\gamma D}^{year}$ of 0.87 is found.

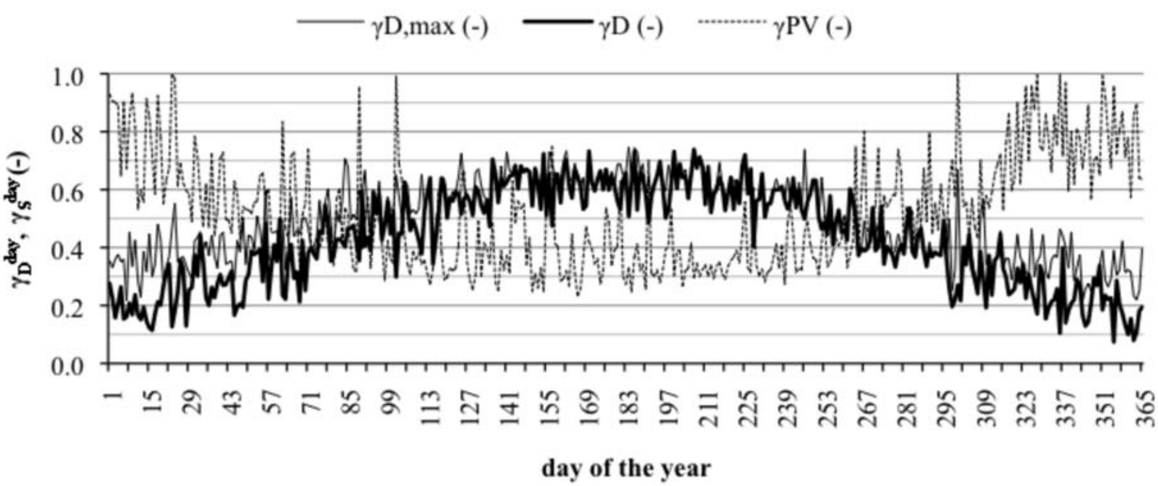


FIGURE 6. γ_D^{day} (bold), $\gamma_{D,max}^{day}$ (black) and γ_{PV}^{day} (dashed) through the year for a modelled dwelling with space heating but without domestic hot water by means of a heat pump. A resulting γ^{year} of 0.29 and a value $\varepsilon_{\gamma D}^{year}$ of 0.46 is found.

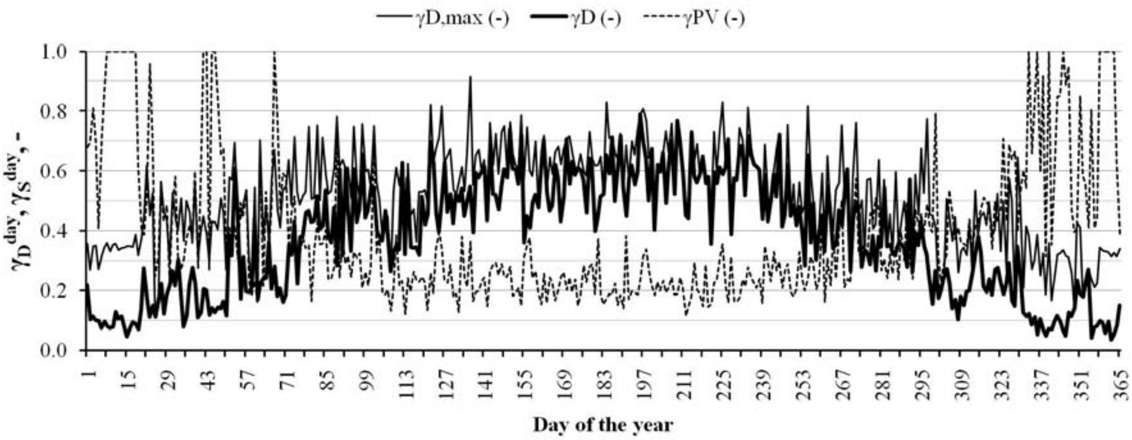
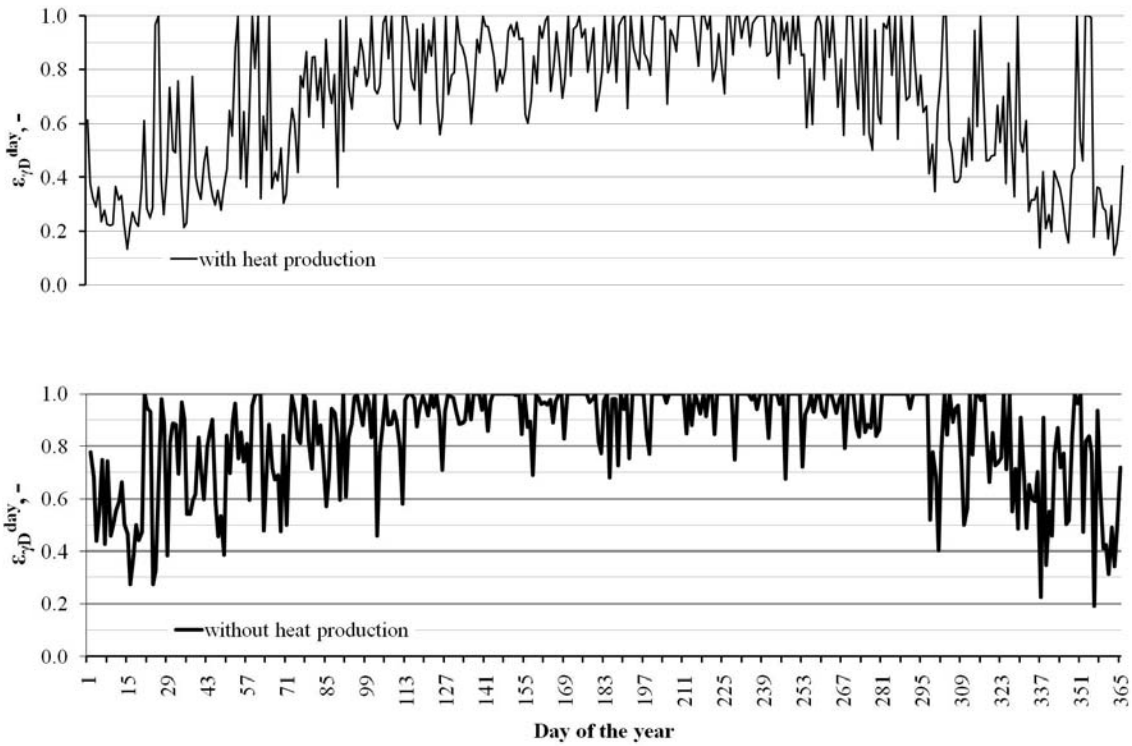


FIGURE 7. $\varepsilon_{\gamma D}^{day}$ through the year for a modelled dwelling with (upper graph) and without (lower graph) space heating and domestic hot water (DHW) by means of a heat pump.



5. DISCUSSION

The simulations show that only a fraction of the electricity demand of the dwelling is covered by the BIPV system, implying that somehow the excess of produced energy should be stored or used by other consumers. In this section, some options at different scales to overcome the injection of electricity in the main distribution grid are discussed.

5.1 Single dwelling

When studied at the building level only, the BIPV installation is generally seen from the objective to maximize the total output on a yearly basis in order to compensate the total consumption of the dwelling or from an economic perspective: when on yearly basis a total energy production is achieved that equals the total consumption, this dwelling or building might be depicted as a zero energy building. However—as shown above—the dwelling remains strongly dependent on the electricity grid as virtual storage as only a limited ratio of the energy consumption is covered by its own production, and a zero emission building is far from achieved intrinsically due to the domestic load profile. Electricity with zero marginal greenhouse gas emission is injected into the grid and again extracted from the grid when necessary (e.g. during the night). If no distribution problems occur, the input of BIPV generated electricity may result in a reduction of greenhouse gas emission at district level.

If only studied at the scale of a single building, the cover factor γ_S could be influenced based on several possibilities such as:

- Raising $\gamma_{D,max}$ by controlling time-shiftable loads such as washing machines, dryers and dishwashers. Based on the electricity consumption per cycle (Danish Energy Agency 1995) for the mentioned wet appliances, an increased $\gamma_{D,max}^{year}$ is retrieved from 0.49 to 0.61 if the complete electricity demand of these appliances is considered to ly completely in the day regime. However, increasing $\gamma_{D,max}$ by shifting these appliances does not automatically result in a raised γ_D due to possible high peak loads and attention should be paid to the demand profile of these appliances cycles.
- Influencing the domestic electricity demand profile of space heating and domestic hot water. Due to the differences in results (see Ch.4.2) between the modeled situation with and without heat generation by means of a heat pump and storage tank, it becomes clear that the choice and sizing of the installation have a high potential to increase the cover factor. As an example—instead of basing the control on the heat demand—controlling heat supply based on the BIPV power supply and limiting peak power demands might raise de cover factors, the maximum cover factor and cover efficiency significantly.
- Influencing the PV energy supply profile by orienting the PV arrays so that a high power supply is achieved at the same time as a high power demand of the dwelling.

5.2 Buildings at district scale

Due to the unbalanced profiles of electricity consumption and production of a single dwelling with BIPV, the dwelling will act as a net electricity provider on many moments (see Fig. 4). When studied at the level of the building stock at district scale, different aspects are to be taken into account such as the variety of load profiles and the grid connecting individual buildings.

Due to the varied mixture of different load profiles at district scale, a higher cover factor γ of the PV installation could be achieved if the factor is not determined for a single dwelling but for a group of dwellings or buildings in general. As such, (i) peak demands are flattened out in the calculations and (ii) the possibility of a BIPV system on one dwelling delivering electric power to another dwelling can be considered. The exchange of PV power between different buildings in the same district could be one of the major advantages of distributed electricity generations by BIPV systems: due to the large variety of load profiles, the reduction of green house gas emission at district level might be easier to achieve, e.g. by implementing a smart grid, as a major part of the electric power extracted from the grid by the individual dwellings might be PV generated. However, if the electricity exchange between different buildings is simulated by the model additional phenomena such as transportation losses, the possibility for two-way transport on the grid and additional power and inefficiencies due to control devices should be accounted for.

5.3 Integrated point of view

Improvements achieved at the building scale might not scope with the potential of possible adaptations made on the district level and vice versa. To evaluate the potential of BIPV systems and the impact of the domestic load profile on this potential, an integrated approach from different levels is necessary. If not, each optimum found at a single level will remain a sub-optimum if not all different levels are considered.

6. CONCLUSIONS

A one-minute multi-zone TRNSYS model for a dwelling with classic heating on the one hand and with heat pump for both space heating and domestic hot water on the other hand, electricity consumption by domestic consumers and BIPV generation has been set-up for a typical Belgian climate. The model is used to illustrate the influence of the user behaviour, the influence of the domestic heat installation and grid-interactions on the possibilities of BIPV systems. By coupling the electricity demand and production within the same model, it is shown by means of a cover factor that the domestic load profiles due to human behaviour do not coincide with the output of photovoltaic systems. The BIPV system is sized to cover the electricity demand of the dwelling on a yearly basis but no attempt is made to balance the electricity demand and supply. For the traditional heating installation and boiler, a cover factor of 0.42 is found indicating that more than half of the produced electricity will be passed on to the grid and withdrawn on another moment. If a heat pump is used for space heating and DHW, the cover factor decreases to 0.29 due to the increased consumption in the morning and evening periods and high peak power demands caused by the heat pump.

Large-scale implementation of BIPV systems require energy storage within the same or another energy vector at building level or the implementation of smart rids in which not the energy supply of a single dwelling is considered but a cluster of buildings with different load profiles.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the K.U.Leuven Energy Institute (EI) for granting a research project, entitled Optimized energy networks for Buildings, for funding this research.

REFERENCES

Almeida, A., Fonseca, P., Bandeirinha, R., Fernandes, T., Araœjo, R., Nunes, U., Dupret, M., Zimmermann, J.P., Schlomann, B., Gruber, E. (2008). "REMODECE—Residential monitoring to decrease energy use and carbon emissions in Europe—Final report.".

Danish Energy Agency (1995). "Washing machines, Driers and Dishwashers—Final Report." 76.

De Soto, W., Klein, S.A. and Beckman, W.A. (2006). "Improvement and validation of a model for photovoltaic array performance." *Solar Energy,* 80, 78–88.

Duffie, J.A. & Beckman, W.A. (1991). *Solar Engineering of Thermal Processes, 2nd ed.,* Wiley.

EurObserv'ER (2009). "Baromètre photovoltaïque / Photovoltaic barometer : 9 533,3 MWc dansl'UE / in the EU." *Systèmes solaires—Le journal du photovoltaïque,* 1, 72–103.

Firth, S., Lomas, K., Wright, A. and Wall, R. (2008). "Identifying trends in the use of domestic appliances from household electricity consumption measurements." *Energy and Buildings,* 40(5), 926–936.

Flemish Region (2006). "Bijlage I—Bepalingsmethode van het peil van primair energieverbruik van woongebouwen."

Glorieux, I. and Vandeweyer, J. (2002). "Statistische studie nr110—24 uur . . . Belgische tijd, een onderzoek naar de tijdsbesteding van de Belgen."

Huld, T. and Suri, M. (2010). "PVGIS, PV Estimation Utility." Available at: http://re.jrc.ec.europa.eu/pvgis/.

Jordan, U. and Vajen, K. (2001). "Realistic domestic hot-water profiles in different time scales—Final raport." 18.

Liu, D., Chang, W.R. and Lin, J.Y. (2004). "Performance comparison with effect of door opening on variable and fixed frequency refrigerators/freezers." *Applied Thermal Engineering,* 24, 2281–2292.

Meier, A. (1995). "Refrigerator energy use in the laboratory and in the field." *Energy and Buildings,* 22(3), 233-243.

Meteotest (2008). METEONORM Version 6.1—Edition 2009.

Neyens, J. (2009). "The PV market in the Flemish region—Status May 2009." 4.

Office For National Statistics (2003). "The United Kingdom 2000 Time Use Survey." Available at: www.statistics.go.uv.

Richardson, I. and Thomson, M. (2008). "Domestic lighting demand model 1.0." *Loughboury University.* Available at: http://hdl.handle.net/2134/4065 .

Richardson, I., Thomson, M., Infield, D. and Delahunty, A. (2009). "Domestic lighting: A high-resolution energy demand model." *Energy and Buildings,* 41(7), 781–789.

Richardson, I., Thomson, M. and Infield, D. (2008). "A high-resolution domestic building occupancy model for energy demand simulations." *Energy and Buildings,* 40(8), 1560–1566.

Saidur, R., Masjuk, H.H. and Choudhury, I.A. (2002). Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigerator-freezer energy consumption. *Energy Conversion and Management,* 43(6), 845–854.

Solar Energy Laboratory (2009). TRNSYS 16—A transient system simulation program.

Spur, R., Fiala, D., Nevrala, D. and Probert, D. (2006). "Influence of the domestic hot-water daily draw-off profile on the performance of a hot-water store." *Applied Energy,* 83(7), 749–773.

Stokes, M., Rylatt, M. and Lomas, K. (2004). "A simple model of domestic lighting demand." *Energy and Buildings,* 36(2), 103–116.

TPDCB (2010). "The power consumption database." Available at: www.tpcdb.com.

VREG (2009). "Marktmonitor 2009." 82. Available at: http://www.vreg.be/vreg/documenten/rapporten/RAPP-2009-10.pdf.

Wood, G. and Newborough, M. (2003). "Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design." *Energy and Buildings,* 35(8), 821–841.