Studying the Dynamic Relationship between Energy Supply Carbon Content and Building Energy Demand

DIDIER VUARNOZ[1], THOMAS JUSSELME[1], STEFANO COZZA[1],
EMMANUEL REY[2], MARILYNE ANDERSEN[3]

[1] *Building 2050 Research Group, Ecole Polytechnique Fédérale de Lausanne (EPFL), Fribourg, Switzerland*
[2] *Laboratory of Architecture and Sustainable Technologies (LAST), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[3]*Interdisciplinary Laboratory of Performance-Integrated Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*

ABSTRACT:
Due to different temporal combinations of energy generation processes, the global warming potential (GWP) of energy supply evolves constantly. Despite this, the greenhouse gas (GHG) emissions related to the energy consumption in buildings are commonly assessed with yearly averaged carbon content of the energy supply. The knowledge of the hourly carbon content of the energy supply, would allow a more realistic assessment of the GHG emissions. Moreover, a temporal relationship between the GWP energy supply and building energy demand for reducing carbon footprint could be addressed. In this study, different methods to evaluate the hourly carbon contents of the on-site available energies are presented. The potential of load shifting for GHG emission mitigation is also investigated. To test the methodology, an application to a case study where the energy is supplied from the electrical grid and on-site renewables is proposed. The chosen case study is the smart living building, currently being designed and expected to be built by 2020 in Fribourg, Switzerland. This study points out significant differences between a yearly average and an hourly dynamic carbon emission assessment. Carbon footprint benefits by load shifting at day scale are found to be very limited in the context of the smart living building.

Keywords: Decarbonisation; GHG emission mitigation; Building energy supply; Load shifting

INTRODUCTION

Switzerland has introduced the 2050 energy strategy by fixing new policies to face climate change in particular, by decreasing and limiting the greenhouse gas (*GHG)* emissions. The built environment is responsible for a large amount of these emissions and it is therefore compulsory to have an accurate method for the assessment of *GHG* emissions related to the energy supply of buildings. Up until now, the most common way to asses these emissions is based on yearly averaged values of global warming potential *(GWP)* emissions per unit of energy. In the case of electricity, its production is achieved by different processes (e.g. nuclear plants, fossil fuels sources, renewables, etc.) with different environmental impacts and capacities of production. To provide the necessary amount of electric energy, various sources are combined together and therefore the carbon content of the electricity mix varies with time over the day and over the year (e.g. Weisser, 2007). Instead of yearly averaged values, the use of time-dependent *GWP* data of the energy supply would allow an improvement in the assessment of *GHG* emissions due to building energy consumption. The availability of such data would also allow a possible reduction of carbon footprint by temporal relationship between the *GWP* energy supply and the building energy demand.

The paper first intends to outline the difference in *GHG* emissions generated by a building's energy demand when assessed with an hourly carbon content of the energy supply instead of its yearly average value. The second objective is to quantify the potential *GHG* emission mitigations by possible temporal relationship between the *GWP* energy supply and the building's energy demand. These possible relationships take into account onsite renewable electricity generation and load shifting (*LS*). A methodology of the assessment of the hourly *GWP* energy supply is proposed. A carbon-based load shift method is then presented. To test the methodology and quantify the possible gain in accuracy and mitigation of the *GHG* emissions, a high-efficiency building planned to be built in central Switzerland is taken as a case study. For both, the Swiss grid and onsite renewable electricity generation, the hourly carbon content is assessed. The share between renewable electricity produced onsite together with the one coming from the grid is analyzed. The *GHG* emissions caused by the building energy use are compared for four days of the year 2014, depending on whether they are assessed with an annual average GWP^a or with an hourly GWP^h (the study is restricted to only 4 days because of data availability). Respond demand by *LS* is also explored and its significance on *GHG* emission mitigation is assessed.

METHODOLOGY

Firstly, the hourly carbon contents of the on-site available energies are evaluated. Secondly, the hourly energy demand of a building is assessed with dynamic simulation and expected dweller usage. Thirdly, the *GHG* emissions of a building's energy consumption assessed with an hourly carbon content of the energy supply instead of its yearly average carbon content are compared. Lastly, temporal relationships between *GWP* energy supply and building energy demand for reducing carbon footprint are assessed. These temporal relationships include a priority use of the available energy supply with the lowest *GWP* and a carbon-based *LS*.

An application of this method to a case study allows a quantitative analysis of the improvement in the assessment accuracy related to *GHG* emissions due to the energy supply and its possible mitigation by temporal relationships between *GWP* energy supply and building energy demand. Moreover, the methodology explained in this paper helps in the sizing an appropriate *BIPV* infrastructure and in the choice of the energy supply at a given time. An appropriate case study should include a documented hourly energy demand of the building, supplied with different kinds of energy sources. Energy generation processes involved for the energy supply must be known within an hourly time step. The smart living building, currently being designed and expected to be built by 2020 in Fribourg, Switzerland, fulfills all these requirements and is therefore chosen to be the case study. The building's energy needs were considered to be electricity provided by building integrated photovoltaic (*BIPV*) panels or by the Swiss grid.

For the sake of coherence, the only environmental impact database that will be used in this study is the *KBOB* database (Friedli et al., 2014). Based on the ecoinvent methodology, this database takes into account industry data and is used for the analysis of construction projects according to the Swiss norms. The *KBOB* database provides for a large panel of elements and construction materials the cumulative energy demand and its non-renewable part, as well as the *GWP*. In this study, only the *GWP* is taken into consideration. On the other hand, for components where technologies evolve constantly (e.g. *BIPV*), the database is not representative of cutting-edge products.

Electricity mix assessment

Electricity provided by a domestic grid is considered to be a mix of domestic production and imports from surrounding countries. For each national production, different means of electricity generation are involved. Each of these generation processes is linked with the *KBOB* database (Friedli et al., 2014) regarding their specific *GWP*. The GWP^h_G of a domestic grid is assessed on an energy volume pro rata basis of all the different *GHG* contributions. Values of GWP^h_G evaluated in this study are spatially averaged for each considered country.

BIPV assessment

The amount of renewable energy harvested by *BIPV* is evaluated with the help of Meteonorm software (Meteonorm, 2016) with *TMY* data. The lifetime of a photovoltaic system is set to be 25 years. The yearly averaged *GWP*s of *BIPV* (GWP^a_{BIPV}) are evaluated on the base of their embodied energies (Friedli et al., 2014) together with their predictable energy generation over its entire lifetime. The time-dependent *GWP* of the electricity provided by *BIPV* (GWP^h_{BIPV}) is evaluated with the hourly production ratio related to given orientation.

Carbon-based load shift method

LS is one possible means of demand response and is a possible way to enhance the building autonomy and penetration of renewable electricity - see e.g. (Molderink et al., 2009), (Pina et al., 2012). Usually based on power load consideration, this study proposes to look at *LS* for a possible way for *GHG* emission mitigation and its assessment. The principle to shift an amount of the electric energy provided by the grid at a day scale uses a threshold value σ for the GWP^h_G. σ corresponds to a value beyond which a given amount δ of electricity is reduced from the demand. This amount of energy is compensated on the demand during the period of time when the GWP^h_G of the electricity is below σ. An example of the *LS* method is presented in Fig. 1.

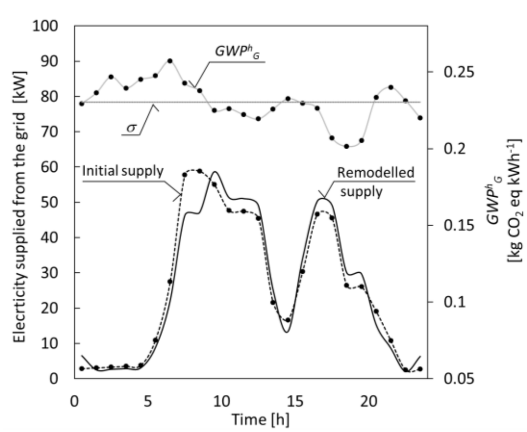

Fig. 1: LS method of the electricity consumption supplied by the grid based on the specific carbon content of the electricity. The case depicts the situation related to the specific case study developed in the next section (17/12/2014 with δ=20%).

The means by which the energy consumption is shifted (e.g. storage, demand side management, etc.) is not detailed in the present study but could be found elsewhere (see e.g. Molderink et al., 2010). The threshold value σ which defines the moment when the energy shift must be done, should be set at a different value throughout the year. In our study, σ is chosen to be the daily average of GWP^h_G.

APPLICATION TO A CASE STUDY

Assessment of the Swiss electrical grid

The location of the chosen case study is Fribourg-Switzerland. As it is seen in Figure 2, the Swiss electrical grid is powered by domestic production as well as by imports and exports from surrounding countries.

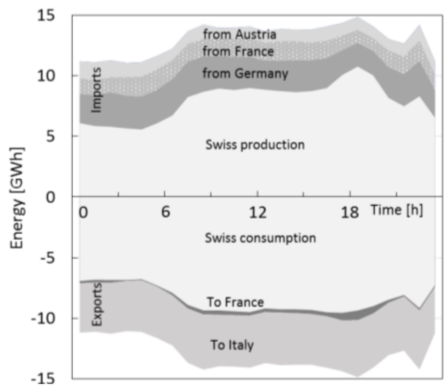

Fig. 2: Electricity in Switzerland is composed by the domestic production and imports from surrounding countries (positive values) as well as consumption and exports (negative values). Representation for 17/12/2014. Data from (Swissgrid, 2016).

Even though domestic electricity production and related involved generation processes at an hourly time step are available for a full year for France (Réseau de transport de l'électricité, 2015) and for Germany (Frauhofer institute, 2015), these data are difficult to be found for other countries. For instance, similar data are found only four days per year for Switzerland (Office fédéral de l'énergie, 2015) and no corresponding data for Italy and Austria have been found. In this study, we propose to evaluate the feasibility of the GWP^h_G assessment with our proposed method and restrict the analysis to the four days with accessible data (19/03; 18/06; 17/09 and 17/12 of the year 2014).

Because of the small amount of electricity imports in in France and Germany (respectively of 1.9% and 6.6% for the year 2011 (Itten et al., 2014)), origins of electricity in these countries have been evaluated with the sole domestic production. According to the four given days, the Swiss electricity production together with French and German imports represents 86-97% of the electricity available in Switzerland. Consequently, in this study the GWP of the Swiss electricity mix is hourly evaluated based on the Swiss domestic production, and imports from France and Germany. The influence of the three contribution regarding the electricity origin (CH, F and DE) on the resulting GWP^h_G of the Swiss mix is detailed in Fig. 3. The hourly assessment of the Swiss mix carbon content GWP^h_G is shown for the four given days in Fig. 4.

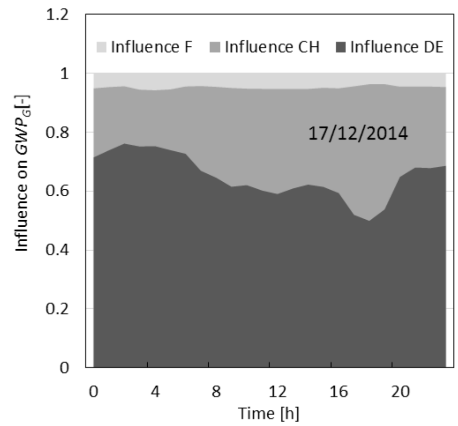

Fig. 3: Influence of the electricity origin on the resulting GWP^h_G of the Swiss mix.

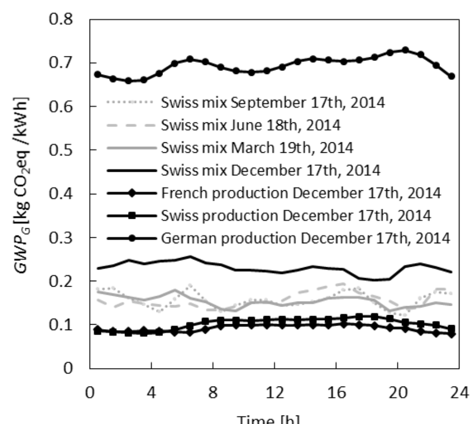

Fig. 4: GWP^h_G from different countries evaluated based on Fig. 2 and the KBOB database (Friedli et al., 2014).

Obtained results of GWP^h_G presented in Fig. 4 allows the following observations: the GWP^h_G of the electricity in Switzerland evaluated for the 17/12/2014 is higher than the ones representing the three other dates. The reason resides in the electricity generation processes involved for covering the high amount of energy needed in winter. The biggest discrepancies between GWP^h_G and GWP^a_G - value of 0.1386 kg CO_2 eq/kWh provided by $KBOB$ database (Friedli et al., 2014) - are obtained on 17/12/2014. GWP^h_G curves of the Swiss mix are relatively flat whatever the given date is. One of the reasons is the Swiss consumption of self-produced electricity during peak hours. Almost all values of GWP^h_G are above GWP^a_G during the selected days. When looking specifically at the results obtained for 17/12/2014, the GWP^h_G of the electricity produced in France and Switzerland are quite similar. The GWP^h_G of the electricity produced in Germany shows a value of circa seven times higher than those of France and Switzerland.

Assessment of the onsite renewable energy production
The envelope of the building taken as a case study is partially covered by *BIPV* and solar thermal collector (59 m²) for domestic hot water (*DHW*) production. The solar thermal collectors allow a solar fraction of 0.6. The *BIPV* installation has been sized in order to fit the criteria of net-zero energy building (*NZEB*) type A (Pless and Torcellini, 2010). The *BIPV* surfaces and specific *GHG* emissions for *BIPV* for given orientations are reported in Table 1. Obtained values for GWP^a_{BIPV} are always smaller than those of GWP^h_G.

Table 1: Surface area, peak power, GWP per unit of delivered energy and energy harvested annually given for each BIPV orientation. BIPV on roof are south oriented with a tilt of 35°. East and west BIPVs are located on the façades of the building.

Location	Surface (m^2)	Power (kWp)	GWP^a_{BIPV} ($kgCO_{2eq}kWh^{-1}$)	E (MWh/yr)
Roof	209	37	0.06696	46.0
East	376	67	0.10548	50.7
West	376	67	0.12708	42.1

The smart living building and its electric consumption
The chosen case study is the smart living building that explicitly aims to achieve the intermediate 2050 goals of the 2000-watt society vision. The building consists on a mix program made up of apartments, offices and laboratories. The surface allocated to each destination of use is reported in Table 2.

Table 2: Surface area considered for each zone of the smart living building.

Destination of use	Surface (m^2)
Housing	957.6
Offices	1529.1
Meeting	145.1
Experimental	775.4
Others	553.1
Technical non-heated zone	193.5
Total	4153.8

The hourly evaluation of the building electricity consumption based on the Swiss norms (SIA 2031) is assessed with the LESOSAI 2015 software (Lesosai, 2015). Annual electricity consumption by usage is presented in Table 3. The use of a heat pump is considered for the space heating and partial covering of the *DHW*.

Table 3: Annual electricity use.

Designation	E (MWh)
Space heating	22.0
DHW	4.1
Ventilation	17.9
Lighting	44.0
Appliances	47.6

The simulated building electricity consumption of the smart living building for the four days considered in this study is presented in Fig. 5. The dweller usage intensity is a priori the same since it is always a Wednesday. It can be observed (also with Table 3) that appliances and lighting seek to represent the main energy consumption of the building.

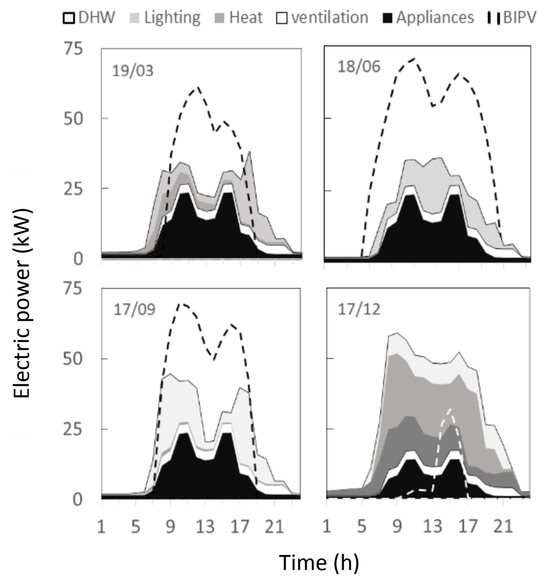

Fig. 5: Smart living building electricity power consumption on four given days of the year with a repartition of the different sectors of use. Dashed lines represent the BIPV production.

RESULTS

The amount of carbon emissions related to the building's electricity usage differs depending on the kind of *GWP* taken into account during the assessment (yearly average our hourly values). Table 4 presents how differently *GHG* emissions are evaluated for eight cases considering different *GHG* emission assessments.

The two first cases (*A* and *B*) are about a building without onsite production of electricity by *BIPV*. The difference between these two cases depends on the choice of the grid *GWP* (annually averaged or hourly) used for the assessment of *GHG* emission. As for *C* and *D*, the share of electricity generated by *BIPV* is always provided by oriented panels associated with the lowest *GWP (*see

Table 1). This optimization is technically rather difficult to implement in real buildings. Difference between Case *C* and *D* resides in the choice of the grid *GWP* (annually averaged or hourly) used for the assessment of *GHG* emissions. Cases *E* and *F* assume that the part of electricity provided by *BIPV* is a mix between harvested electricity coming from different oriented panels on a pro rata basis of their respective production. The difference between cases *E* and *F* resides in the choice of the grid *GWP* (annually averaged or hourly) used for the assessment in *GHG* emissions. Cases *G* and *H* explore the impact of the *LS* strategy applied to the grid supply on *GHG* emissions. σ is chosen to be the daily average of the grid electricity $GWP^h{}_G$. The assessment method uses the hourly *GWP* for both grid and *BIPV* supply.

Table 4: Set of cases where the GHG emissions were assessed with different GWP values and with different electricity consumption coverage.

Case	*BIPV*	Grid	*LS*
A	-	$GWP^a{}_G$	-
B	-	$GWP^h{}_G$	-
C	$GWP^a{}_{BIPV}$	$GWP^a{}_G$	-
D	$GWP^a{}_{BIPV}$	$GWP^h{}_G$	-
E	$GWP^h{}_{BIPV}$	$GWP^a{}_G$	-
F	$GWP^h{}_{BIPV}$	$GWP^h{}_G$	-
G	$GWP^h{}_{BIPV}$	$GWP^h{}_G$	$\delta = 10\%$
H	$GWP^h{}_{BIPV}$	$GWP^h{}_G$	$\delta = 20\%$

Figure 6 presents *GHG* emissions obtained with different mixes of electricity supply and different methods of assessment. It can be observed that the daily amount of carbon emissions related to the grid use is always under evaluated when assessed with $GWP^a{}_G$ instead of $GWP^h{}_G$.

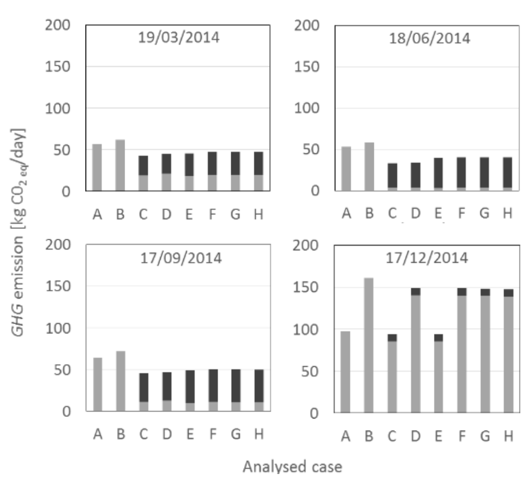

Fig. 6: GHG emissions due to electricity consumption of the smart living building depending on different cases described in the study. Dark grey represents used electricity from BIPV and light grey electricity from the grid.

As seen in Fig. 6, the use of renewable energy produced onsite with *BIPV* has a large potential for carbon emission mitigation when compared to the sole use of the electrical grid. This tendency is obtained no matter the annual or hourly *GWP*s used in the assessment (respectively cases *A* and *C* or *B* and *F* in Fig. 6). As expected, this potential is at its minimum on 17/12/2014 when solar radiation is at its lowest.

As it is often the case within the *NZEB* framework, the building is not able to use the *BIPV* production integrally due to the temporal mismatch between renewable energy generation and energy consumption (see Table 5). Renewable electricity injected into the grid has an unmeasurable increased *GWP* due of the line infrastructure and transport losses. Therefore, the onsite produced electricity redirected to the grid has not been taken into account in the carbon balance. Implementation of energy storage would increase the electricity environmental impact but would also increase the building self-consumption of renewable energy. A priority delivery of electricity produced by oriented *BIPV* with lowest $GWP^a{}_{BIPV}$ would allow the minimum amount of *GHG* emissions.

Table 5: Daily energies of the BIPV electricity used onsite, electricity coming from the grid, share of the building electricity consumption provided BIPV and share of the BIPV generation exported to the grid.

	19/03	18/06	17/09	17/12
E_{BIPV} (kWh)	277.5	361.7	391.2	91.7
E_G (kWh)	131.9	25.4	72.2	616.0
S_{BIPV} (%)	67.8	93.4	84.4	13.0
S_{BIPV} to grid (%)	40.2	55.5	38.1	0.0

LS shows a very limited potential of *GHG* emission mitigation for the four chosen days. This potential is directly related to the amplitude of $GWP^h{}_G$ taken into account. On 17/12/2014 the Swiss electricity mix shows an amplitude of its hourly carbon content of +-22%. This amplitude is the largest among the four considered days, but not enough to provide substantial CO_2 emissions savings by *LS*. As it is seen in Fig. 5 the *LS* method's highest potential is in winter when the on-site electricity production is the lowest and the grid contribution is high. Vice-versa, when *BIPV* production is substantial during sunny days, the method could only be applied during night time. The amount of *GHG* emissions related to the grid use is a linear function of δ. But the amount of the *GHG* mitigation is very limited even when the amount of energy temporally shifted is considerable (on 17/12/2014, $\delta = 20\%$ leads to 0.7% of reduction of the emission related to the usage of the grid). Reducing σ at a lower value than the $GWP^h{}_G$ daily average has a positive effect but limited impact on the *GHG* emission mitigation (with δ=20% and $\sigma = 0.95 * \overline{GWP^h{}_G}$, 2% of reduction of the emission due to the usage of the grid is expected). Lower values of σ seem difficult since the corresponding shifting time would tend to zero (see Fig.1).

CONCLUSION

The aim of the study was to propose an assessment method of the *GHG* emissions related to energy consumption in buildings which is more accurate than the common method using the yearly averaged *GWP* of the energy supply. Instead, when considering time-dependent *GWP* data of the energy supply, better quality results are believed to be secure. Moreover assessment of possible carbon footprint reduction by temporal relationship between *GWP* energy supply and the building energy demand is also enabled. The proposed method helps also in the adequate sizing of a *BIPV* infrastructure during the building design process and in the choice of a proper energy supply during its operation. The feasibility of the proposed method has been tested on a case study consisting of a high-efficiency building planned to be built in central Switzerland. The building electricity demand, considered to be supplied either by *BIPV* and the grid, has been assessed with LESOSAI software. The onsite renewable system has been sized to enable the project a *NZEB* label.

The feasibility of assessing the hourly *GWP* of the Swiss electrical grid suffers from the lack of available data regarding the contribution of processes in domestic electricity generation. As a consequence, only four days have been assessed. It has been found that, during these days of evaluation, the hourly *GWP* of the Swiss grid has a higher value than the annual average given by the *KBOB* database. Hence, hourly *GWP*s generates always higher rates of carbon emissions. The significance of this study lies in the compelling differences obtained in the *GHG* emissions assessment when using yearly averaged *GWP* or hourly *GWP* of the electricity supply.

This paper points out also the potential of different measures to reduce the carbon emissions associated to the electricity demand of a building. In the case study, the use of *BIPV* as renewable source of electricity offers the largest potential of *GHG* emission mitigation. A priority delivery of electricity produced by oriented *BIPV* with lowest *GWP* would allow substantial savings in *GHG* emissions and therefore must be recommended. It has also been shown that within a *NZEB* framework, even though the share of a building electricity consumption provided *BIPV* is high, the share of the *BIPV* generation exported to the grid is also important. This statement gives importance to the problematic question regarding the assessment of the *GHG* emissions related to electricity export from the building.

The potential of *GHG* emissions mitigation by load shifting based on carbon content of the electricity is found to be directly related to the amplitude of variation of carbon content of the considered electricity mix. Despite the fact that load shifting allows smoothing peak loads, the relatively low amplitude of the hourly carbon content of the Swiss grid does not allow significant savings in the present case study. Future evolution of domestic electricity generation (environmental impacts and shares in production) should be monitored and further development should include a clear identification of the grid typologies where load shifting could be used efficiently for *GHG* emission mitigation.

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NOMENCLATURE

δ	Amount of shifted electricity demand, (%)
σ	Threshold value, (kg CO_2 eq/kWh)
S	Share
E	Energy (kWh)

Indices

G	Grid
BIPV	Building Integrated Photovoltaic

Exponent

a	annually averaged
h	hourly

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