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ENERGETSKA EFIKASNOST U STAMBENIM ZGRADAMA, RAZLIKA IZMEĐU PREDVIĐENE I STVARNE POTROŠNJE ENERGIJE

Hugo Hens, *hugo.hens@kuleuven.be*, Catholic University Lueven

Apstrakt:

Od devedestih, uzastopne EU direktive i odgovarajuća nacionalna i regionalna regulativa zahtjevaju da nova gradnja i obnova postojećih bude što energetski efikasnija. Nekoliko mjera koje bi trebalo korak po korak da smanjuju primarnu energiju korištenu za grijanje i hlađenje su postale obavezne kao uslov. Međutim, u stvarnosti, predviđene uštede ovim mjerama nisu vidljive u praksi. Dva efekta su odgovorna za ovo. Prvi je navika stanara, koji su više energetski štedljivi nego što proračun pretpostavlja. Zapravo, dok u energetski neefikasnim objektima, navike u prosjeku dovode do 50% niže potrošnje energije za grijanje nego što se predviđa, ovaj procenat pada na nulu ili je čak i negativan u ekstremno energetski efikasnim domaćinstvima. Drugi problem je sa niskovoltažnim distribucionim mrežama koje nisu dizajnirane da transportuju maksimume u električnoj energiji koji se javljaju tokom ljetnih sunčanih dana, što ujedno znači i manje generisane obnovljive energije. To ilustruju i primjeri koji bi u teoriji trebali biti energetski neto-nula objekti zbog primijenjenih mjera i prisustva dovoljno fotonaponskih ćelija na svakom krovu. Može se zaključiti da je upitna politika zahtijevanja ekstremne energetske efikasnosti koja je daleko iznad trenutne ukupne optimalne vrijednosti za stambene objekte. Ali, uprkos ovim činjenicama, vlade i administracije nalažu još ekstremnije zahtjeve u pogledu energetske efikasnosti.

Ključne riječi: energetska efikasnost, navike stanara, fotonaponske ćelije

ENERGY EFFICIENCY IN RESIDENTIAL BUILDINGS, LESS STRAIGHT FORWARD THEN PRESUMED

Abstract

Since the 1990s, the successive EU directives and related national or regional legislations require new construction and retrofits to be as much as possible energy-efficient. Several measures that should stepwise minimize the primary energy use for heating and cooling have become mandated as requirement. However, in reality, related predicted savings are not seen in practice. Two effects are responsible for that. The first one refers to dweller habits, which are more energy-conserving than the calculation tools presume. In fact, while in non-energy-efficient ones, habits on average result in up to a 50% lower end energy use for heating than predicted. That percentage drops to zero or it even turns negative in extremely energy-efficient residences. The second effect refers to problems with low-voltage distribution grids not designed to transport the peaks in electricity when sunny in summer. Through that, a part of converters has to be uncoupled now and then, which means less renewable electricity. This is illustrated by examples that in theory should be net-zero buildings due to the measures applied and the presence of enough photovoltaic cells (PV) on each roof. We can conclude that mandating extreme energy efficiency far beyond the present total optimum value for residential buildings looks questionable as a policy. However, despite that, governments and administrations still seem to require even more extreme measurements regarding energy efficiency.

Keywords: energy efficiency, dweller habits, photovoltaic cells

1. AN EP-LEGISLATION AS EXEMPLARY CASE

Till the early 1970s, energy was not an issue. Coal, oil and gas were so cheap nobody cared about the quantities burned. But in 1973 the Jom Kippoer war and the oil ban by OPEC lead to a sudden rise in prices. As a reaction energy efficiency became a hot topic with the first research programmes launched and for the building sector a better thermal insulation as a main subject of interest. The Iran crisis in 1979 still lifted the energy prices and turned less energy consumed definitely into an economic must. How far to go with energy efficient construction from an economic point of view and how to insulate correctly without degrading moisture tolerance and durability became the focus of research in building physics. When the energy prices relaxed in the 1980s, global warming, with CO_2 as main culprit, took over as driver for more energy efficiency.
Energy performance legislation replaced motivating, with for buildings legal tools to predict primary energy use for heating, cooling and domestic hot water with inclusion of building coupled renewable production.

2. AN EP-LEGISLATION AS EXEMPLARY CASE

In Flanders, Belgium, the insulation decree came into force in 1992, followed by an energy performance decree by January 1, 2006, containing four requirements for new residential construction with control and fines if not realized [1]:

- U-values for the building parts equal or lower than given upper limit values
- An overall insulation level (K) for the whole building lower or equal to a given limit value, K being defined as (see figure 1):

$$C \leq 1 \quad K=100U_m \qquad 1 \leq C \leq 4 \quad K=100\frac{U_m}{\frac{C}{3}+\frac{2}{3}} \qquad C>4 \quad K=50U_m \tag{1}$$

With U_m the mean thermal transmittance, included thermal bridging, of the envelope having a surface A_T (m^2) enclosing the protected volume V (m^3) and C compactness of the building, defined as:

$$C=V/A_T \tag{2}$$

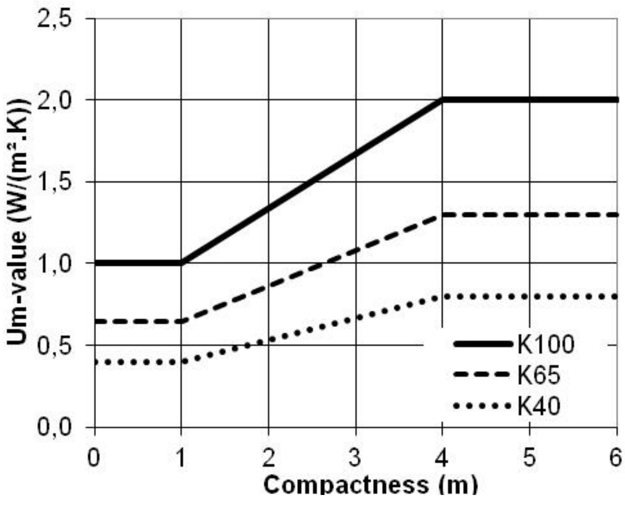


Figure 1. Level of thermal insulation

- A level of primary energy consumption (E) for the whole building lower or equal to a given limit value, E being defined as:

$$E=100\frac{E_{char,ann,prim,en,cnos}}{115A_T+70V+167.5V\left[0.2=0.5\exp\left(-\frac{V}{500}\right)\right]} \quad (3)$$

With $E_{char,ann,prim,en,cons}$ the calculated annual primary energy consumed for heating, cooling, electric auxiliary power and domestic hot water, using a legally mandated energy calculation tool, mainly based on the EN-ISO 13780 standard.

- A control on overheating

In the building energy simulation tool (BES) used, a few parameters are preset. Imposed is a month-based reference year with temperature and solar radiation as variables. 18°C is the indoor temperature to use all over the heated volume. The infiltration flow is $0.04n_{50}V$ $[m^3/hour]$ with n_{50} the infiltration rate at 50 Pa overpressure indoors in 1/h, equal to 12/C if not measured, otherwise as measured. Only the windows give solar gains, while the internal gains equal (0.67+220/V)t_{mo}V with t_{mo} the length per month in Ms. Does the overheating indicator pass 8000 Kh, then active cooling becomes likely, though unavoidable when touching a value 17500 Kh. To stay below, extra passive measures that temper overheating are needed. Active cooling is penalized as it lifts the E-level quite importantly, while a solar boiler and PV lower it.

Since 2006 the requirements became tighter stepwise, see table 1, 2 and 3. Since January 1, 2018 an S-level combining insulation, solar gains and air-tightness of the envelope in one number, replacing the K-level. One could discuss this as calculating solar gains is loaded with uncertainties, while they do not only lower energy use but also increase overheating risk. Common dweller habits as hanging curtains, or a broadleaf tree in front of a window also have a hardly predictable impact. Insulation instead is a dweller habits independent measure with performance guarantee, at least if correctly executed.

Table 1. U_{max}-values and R_{min}-values, per year mentioned from January 1 on

Building part year →	$U_{max}[W/(m^2K)]$ / $R_{min}[(m^2K)/W]$ 1992	 2006	 2010	 2012	 2014	 2015	 2016-..
Envelope							
Windows	3.5	2.5	2.5	2.2	1.8	1.8	1.5
The glazing		1.6	1.6	1.3	1.1	1.1	1.1
Roof	0.6	0.4	0.3	0.27	0.24	0.24	0.24
Opaque facade parts	0.6/1.0	0.6	0.4	0.32	0.24	0.24	0.24
Curtain walls	3.5	2.9	2.9	2.2	2.0	2.0	2.0
The glazing		1.6	1.6	1.3	1.1	1.1	1.1
Walls below grade	/ 1	/ 1	/ 1	/1.3	0.4/1.5	0.4/1.5	0.24
Floors: facing outdoors	0.6	0.6	0.6	0.35	0.3	0.3	0.24
Facing non-frost free spaces	0.6	0.4/1	0.4/1	0.35/1.3	0.3/1.75	0.3/1.75	0.24
Facing frost free spaces	0.9	0.4/1	0.4/1	0.35/1.3	0.3/1.75	0.3/1.75	0.24

On grade	1.2	0.4/1	0.4/1	0.35/1.3	0.3/1.75	0.3/1.75	0.24
Outer doors	3.5	2.9	2.9	2.2	2.0	2.0	2.0
Other							
Party walls	1.0	1.0	1.0	1.0	1.0	0.6	0.6
Partition walls between flats	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Walls contacting non frost-free spaces outside the protected volume	/ 1	/ 1	/ 1	/1.2	/1.4	/1.4	0.24

Table 2. Level of thermal insulation (K)

1992	1993	2006	2010	2012	2014	2015	2016	2018
65	55	45	45	40	40	40	40	S-level replaces K

Table 3. Level of primary energy consumption (E)

2006	2010	2012	2014	2016	2018	2020	2021
100	80	70	60	50	40	35	30

2.1. Other countries

In the Netherlands, energy efficiency is evaluated using the EPC-number, the ratio between the primary energy consumption as calculated ($Q_{\text{tot,a,calc}}$ in MJ/a) and a reference value:

$$\text{EPC}=\frac{1}{1.12}\left(\frac{Q_{\text{tot,a,calc}}}{300A_{\text{fl}}+65A_{\text{T}}}\right) \quad (4)$$

with A_{fl} floor area and A_T the envelope surface, both in m². The primary energy use as calculated includes heating, domestic hot water, electric auxiliary power, lighting, cooling plus (de)humidification, subtracting the primary energy PV delivers, but added an agreed primary energy quantity for failing summer comfort if no active cooling is installed. In Germany, an EPR-value judges energy efficiency:

$$\text{EPR}=e_{\text{primar,heiz,a}}q_{\text{heizen,a}}+e_{\text{primar,w,a}}q_{\text{w,a}} \quad (5)$$

with $q_{heizen,a}$ and $q_{w,a}$ end use respectively for heating and domestic hot water, both in kWh per year and m² floor area. $e_{\text{primar,heiz,a}}$ and $e_{\text{primar,w,a}}$ are the related primary conversion factors.

3. LESS STRAIGHTFORWARD?

Two effects share responsibility for a less straightforward relation between energy consumption as predicted by the mandated energy calculation tools and reality: dweller habits and distribution grid troubles with too much PV generated electricity

3.1. Dweller habits

As explained for Flanders, the legal tools use fixed dweller habits, permanently 18°C indoors, ventilation depending on protected volume and system installed, internal gains linked to the volume, no dweller impact on solar gains, etc. The question is: does this fit with reality? The answer is no. Rebound behavior is changing things [2]. Figure 2 confronts energy use for heating as calculated with data measured in 1050 dwellings [3] [4].

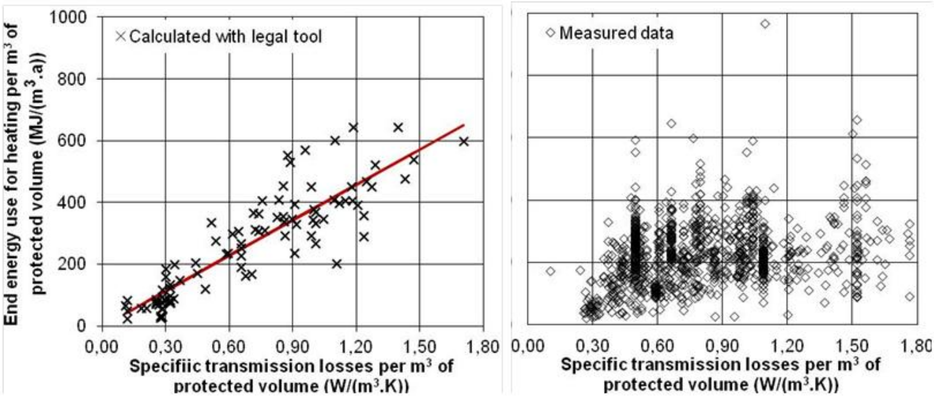


Figure 2. Calculated versus measured energy use for heating

The differences are striking. While calculated a more or less linear relation surfaces between use and transmission losses, both per m^3 of protected volume, the measured data reflect a more or less exponential relation with on average less use in less well insulated residences and a move to what's calculated in well insulated ones. The least square curves equal (see figure 3):

$$\text{Calculated: } \frac{Q_{heat,a,ref}}{V} = 382\left(\frac{U_m A_T}{V}\right) \qquad r^2=0.94$$
$$\text{Measured: } \frac{Q_{heat,a,meas,norm}}{V} = 253\left(\frac{U_m A_T}{V}\right)^{0.52} \qquad r^2=0.85 \tag{6}$$

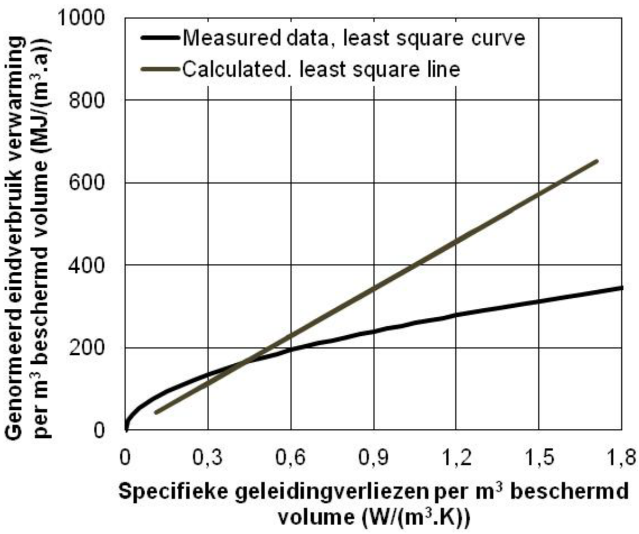


Figure 3. Calculated and measured data, least square line and curve

Both allow calculating what is called the rebound factor ($a_{rebound}$), which represents the impact the inhabitants statistically have on the annual end energy use for heating when considering large numbers of residences. As a formula that factor looks:

$$a_{rebound}=1-0.663\left(\frac{U_m A_T}{V}\right)^{-0.48} \quad (7)$$

Figure 4 gives the actual result and that published in a previous study, proving the rebound curve is very sensitive to how it's calculated.

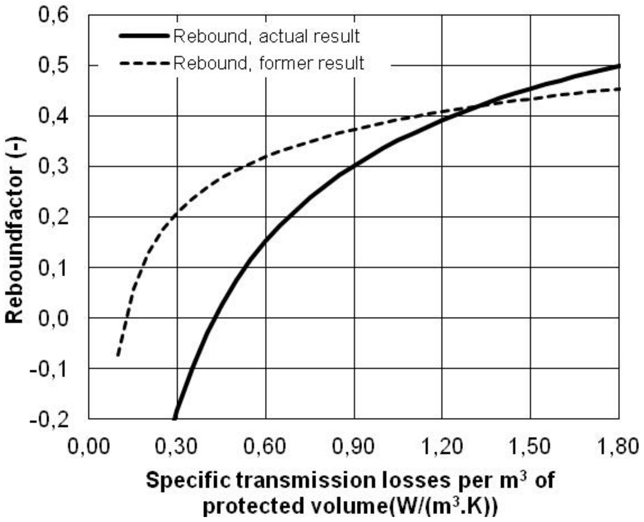


Figure 4. Rebound factor

For large numbers of residences, the overall end energy for heating ($E_{\text{end,heat,tot}}$ in MJ/a) so totals most likely:

$$E_{end,heat,tot}=\sum_{1}^{n}\left(1-a_{rebound,n}\right)Q_{heat,a,ref,n} \quad (8)$$

with $Q_{heat,a,ref,n}$ the annual end energy for heating as calculated with the legal tool. Future changes to that tool will change the rebound curve as calculated. The effect as such of course remains. An important remark is that rebound factor as calculated does not apply at the level of one dwelling or apartment.

What are the reasons for such explicit rebound effect? A first and apparently most influential one is that inhabitants hardly heat bedrooms as table 5, giving weekly mean temperatures measured as function of the weekly mean outdoor temperature, underlines.

Table 4. Measured temperatures in dwellings

Where	Number of rooms	Least square line $\theta_i = a + b\theta_e$ a, °C	b	Correlation coefficient, r²
Daytime rooms	283	19.5	0.11	0.06
Bedrooms	338	13.8	0.32	0.26
Bathrooms	37	16.5	0.34	0.43

While in daytime rooms the values look comfortable and hardly depend on the temperature outdoors, those measured in sleeping rooms are far below what is comfortable and largely change with the value outdoors, proving no heating is quite standard.

That non heated sleeping rooms turn warmer when a dwelling is better insulated see related energy benefit decrease, explaining why the rebound factor drops with lower transmission losses per m3 of protected volume, table 5 illustrates for a simple dwelling with the daytime rooms at the first and the bedrooms at the second floor.

Table 5. Simple dwelling, sleeping rooms not heated

Dwelling	U_m $W/(m^2K)$	n_{50} $1/h$	End use for heating, MJ/a All rooms heated	Bedrooms not	$a_{rebound}$ %
Footprint 10 x 10 m², 2 floors, V=600 m^3, A_T=540 m², windows south	1.48	12	204590	143060	30
	0.27	12	58870	5093	13
	0.27	3	38580	36310	6

A second reason is a wide spread use of on/off control with the heating on during the hours at home and off when absent and at night.

Besides rebound behavior, also tool limitations induce an overestimation of energy use for heating, among them neglecting the solar gains across opaque building parts. In fact, a steady state evaluation shows a sunlit wall in North-western Europe sees its monthly losses per m² drop with:

$$Q_{sungain,mo}=U\left(\frac{\alpha_s E_{sun,T}-10.4 d_{mo} e_L F_{s,sk} F_{Ts,sk} J}{25}\right) \quad \left[\frac{MJ}{mo}\right] \tag{9}$$

where $E_{sun,T}$ is the total solar irradiation in MJ on the part's outside face for the month considered, α_s the short wave absorptivity and e_L long wave emissivity of that face, d_{mo} the number of days in the month considered, $F_{s,sk}$ the view and $F_{Ts,sk}$ the temperature factor for radiation with the sky and J the monthly cloudiness factor. For a south facing non insulated cavity wall, U=1.4 W/(m².K), that gain touches 13 MJ/m² in January of the reference year, 3.2°C cold, reducing the loss from 56 to 43 MJ/m² if on average it's 18°C indoors. After insulating the wall realizing a U-value 0.24 W/(m².K), that gain drops to 2.2 MJ/m².

In the Netherlands and Germany analogous trends surface, see figure 5, showing the rebound factors based on data from both countries [5]. The same holds for the UK [6].

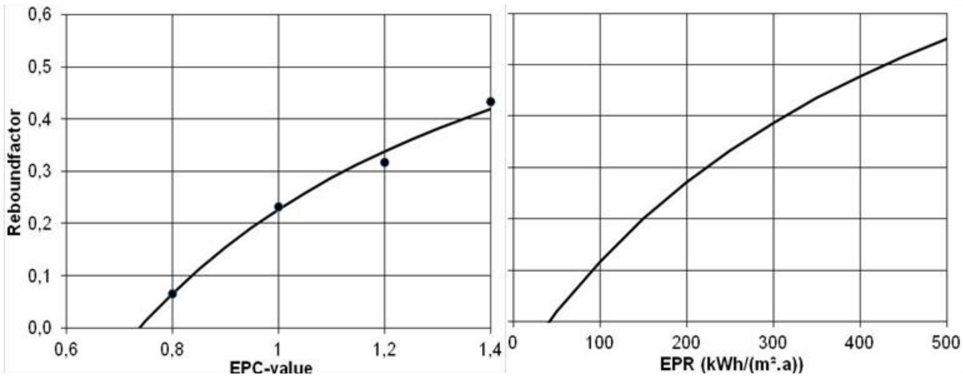


Figure 5. Left the rebound factor based on Dutch, right the rebound factor based on German data

4. PV TROUBLING THE LOW-VOLTAGE DISTRIBUTION GRIDS

4.1. In general

In Northwest Europe electricity production by PV peaks during the warmer half-year with a maximum at noon, but hardly matters during winter, see figure 6 [4].

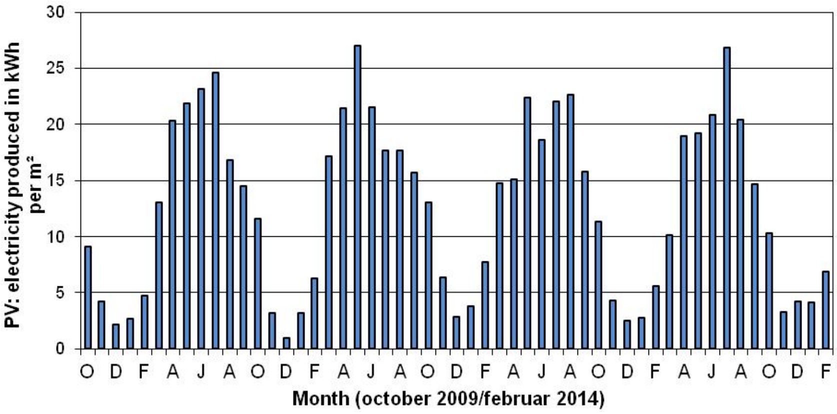
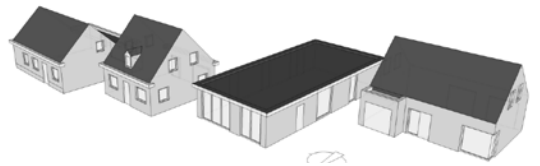


Figure 6. PV on a SW looking pitched roof with slope 40°, measured electricity produced per m²

In summer much power so is directly injected in the low-voltage grid because electricity use is mainly a morning and evening coupled reality then. When many close-by PV-installation inject simultaneously, transformers and linked low voltage grids may endure voltages and losses beyond the limits allowed.

A simulation showed what happens in an estate of 33 detached net zero energy dwellings, each dwelling designed to produce annually as much renewable electricity as primary energy is consumed for heating, ventilation, domestic hot water, lighting and appliances [7]. When the case, the dwellings are nZEB degree 1. A value below 1 characterizes dwellings that aren't net zero, a value above 1 dwellings that are net plus energy, Table 6 lists the main characteristics per dwelling type in the estate.

Table 6. Four dwelling types: main characteristics

Characteristics	Type 1	Type 2	Type 3	Type 4
				
Heated floor area (m²)	127	98	149	123
Window to heated floor ratio (-)	0.12	0.19	0.16	0.13
Compactness (m)	1.23	1.10	0.81	1.18
Mean U-value ($W/(m^2K)$	0.15	0.17	0.16	0.16
Heating power (W)	2600	2740	3220	3190

The insulation thicknesses in floors, facades and roofs equal the economic optimum for residences [8]. Air-tightness touches 0,6 1/h at 50 Pa overpressure indoors. An air to water heat pump with storage tank cares for heating and domestic hot water, while a purpose designed balanced ventilation system with 84% efficient air to air heat recovery guarantees a healthy indoors. Enough mass, outside shading and window operation prevents overheating. The 34 degree sloped PV panels all look south and are coupled to a radial low voltage distribution grid.

Without PV all dwellings would only consume electricity, causing the grid voltage to drop the closer to the line's end, reason why the transformer to the mid-voltage grid guarantees 230+2 % =234,6 V. PV injection lowers that power flow, even reverses it at higher injection rates with too high voltages as possible consequence. If passing 244 V, an increasing number of PV converters have to be switched off to avoid such overload, turning related PV injection to zero.

Starting from a stochastic distribution of habits and appliance use, each dwelling got an own energy profile. Related PV-generation is modelled on a minute-basis, this to acceptably approximate reality.

4.2. Energy use and PV generation

Left, figure 7 shows the electricity used annually for lighting and appliances, Next stands the one for heating and domestic hot water use per m² of heated floor area. Then comes the heat pump's seasonal performance factor (SPF), with at the right the PV peak power installed, ranging from 2,2 to 7,1 kWp, needed to compensate for the annual primary energy use. Related PV area goes from 12 to 42 m² for cells with peak power 177 W/m². Of course enough south looking roof surface is needed for that.

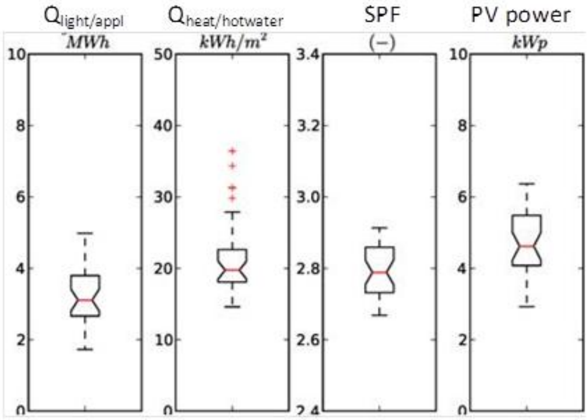


Figure 7. Left annual electricity use for lighting and appliances, next the same for heating and domestic hot water per m² of floor area, then the SPF of the heat pump, right installed PV peak power

4.3. The two not balanced

Are used to describe the balance, the supply (γ_S) and coverage degree (γ_D). The first indicates how much of the electricity generated is used in the dwelling itself, while the second learns which fraction of the electricity a dwelling consumes could be covered by the PV installation. In general, dwellings with few PV, say an nZEB degree 0.04, have a high supply degree, 0.92 ± 0.5, as nearly all electricity produced then is consumed in the dwelling, limiting the extra load on the grid to nearly zero. An nZEB degree 1 instead sees that supply degree drop to some 0,26 ± 0,03, indicating that on average 74 % of the electricity generated must be injected in the grid. Figure 8 shows how things look year round in an nZEB degree 1 dwelling.

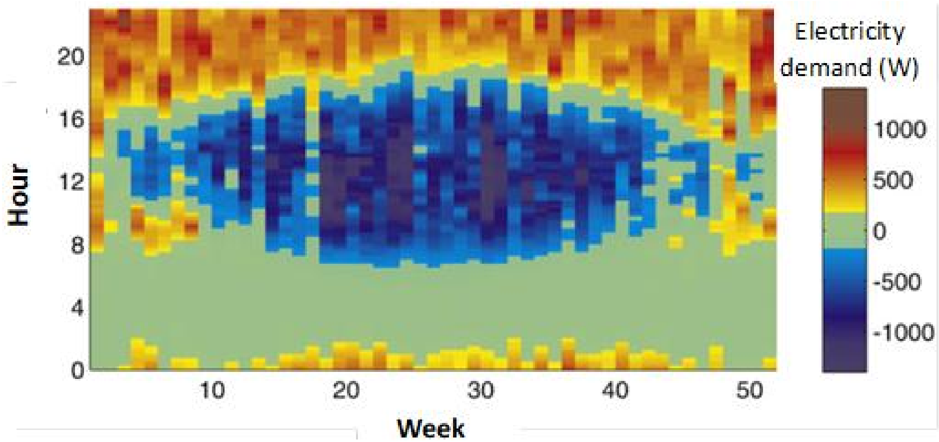


Figure 8. nZEB 1 dwelling, electricity coming from (red) or injected (blue) in the grid

Blue stands for the PV injecting power in the grid and red for the dwelling using electricity from the grid. Reality disappoints, mainly due to the heating demand in winter and the many inhabitants that are working, so are at home only in the evening, at night and next morning, with most electricity used when in winter the rare sunny days sees the sun gone and when in summer the noon solar peak still has to come and is passed.

4.4. Impact of the low voltage grid

Local grids allow a dwelling where electricity consumption is shifted in time compared to others to benefit from PV electricity generated by the other. Anyhow, grid capacity induces two restrictions: voltages may not pass 244 V and avoid 1 à 2 % extra cable losses. Besides, injection of the PV-surplus in the mid voltage grid should not overload the transformer to low voltage.

As an example, figure 9 shows the supply (γ_S) and coverage degree (γ_D) at dwelling and estate level for different grid configurations for each of the 33 dwellings having an nZEB degree going from 0 to 2.

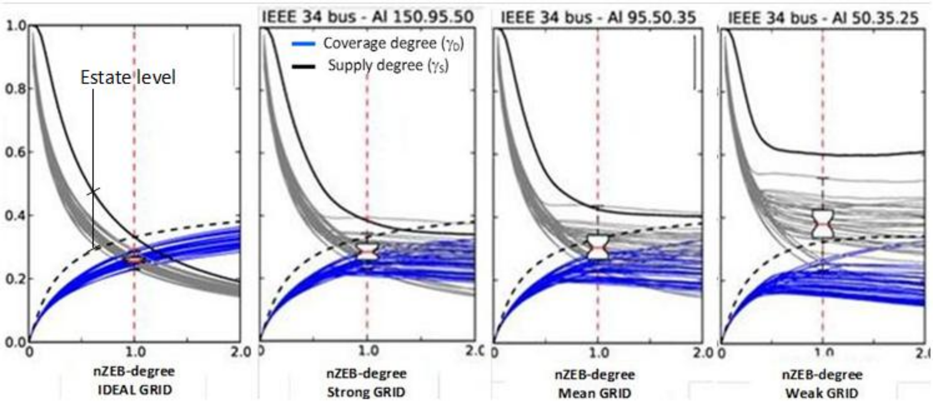


Figure 9. Supply (γ_S, gray) and coverage degrees (γ_D, blue) at estate and dwelling level for different grids depending in the dwelling nZEB degree. The symbol shows the mean γ_D and spread for all dwellings being nZEB1

Independent of grid quality, the supply degree at estate and dwelling level rises thanks to the electricity exchange between dwellings. For a very low nZEB degree, 0.04, that degree's value touches up to 0.99, while for nZEB 1, 0,33 is the result. Despite the upgrade compared to no exchange, still 67 % of all PV electricity is stored in the grid that, if weak, sees the voltage easily touch 244 V, requiring a shut-off of PV converters, so limiting the total renewable electricity generated. Of course, what's left gets more easily redistributed over all dwellings, what helps the supply degree.

What happens with the nZEB degree at estate level, figure 10 shows.

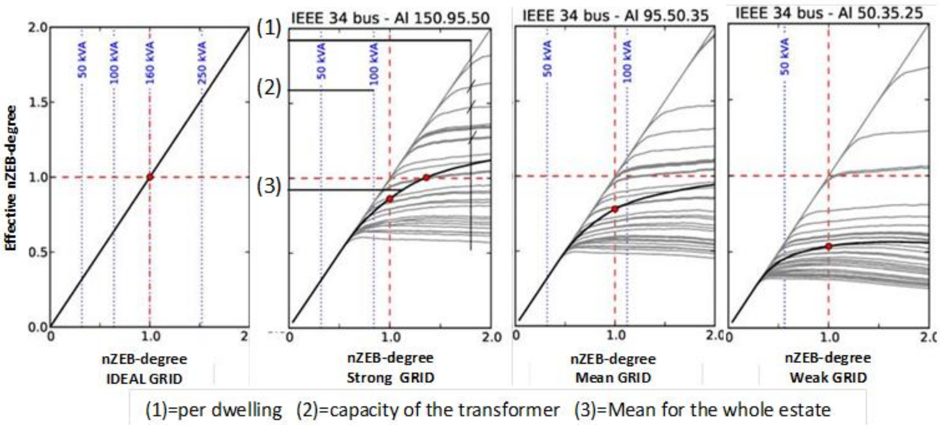


Figure 10. Net zero at estate level depending on the nZEB degree of the dwellings as designed. The vertical blue dotted line show the transformer capacity needed

With a strong low voltage distribution grid, the need to shut off PV converters lowers the nZEB degree for the estate with all dwellings designed nZEB 1, to 0.86 but for the dwelling farthest away from the transformer that value is only 0.59. A weak grid lowers both to respectively 0.53 and 0.33. Otherwise said, where in the estate a dwelling is located has its consequences. Those farther away from the transformer loose an ever increasing part of what the installed PV could generate, included the related economic return.

4.5. How to solve?

Minimizing converter shut off presumes several interventions. The distribution company may upgrade the local low voltage distribution grid and related transformers. Going for smart dishwashers, washing machines, drying machines, deep freezers and perhaps refrigerators may move part of the electricity use to the hours when solar energy is most likely available. This of course presumes changes in inhabitant habits [9]. The electricity PV generates can also help heating the storage vessels in the 33 dwellings or being stored in a battery for shifted use.

5. CONCLUSIONS

Moving to ever more severe insulation and EP-requirements as most countries do is less effective than predictions based on mandated BES tools advance. Advised therefore is to stop mandating additional measures once at the total present value optimum. Also all net zero energy talks require moderation, firstly because balancing non renewable energy use peaking in winter with building-linked PV electricity peaking in summer is not by definition the right way to go, secondly because the low voltage distribution grid quality largely impacts to what extend the production potentiality offered will be available in reality when promoting widespread installation, if not accompanied by measures such as upgrading grid quality, promoting smart appliances, instructing how to adapt habits and using hot water vessel or battery storage!

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