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DOI
10.1016/j.egypro.2016.09.094

Publication date
2016

Document Version
Final published version

Published in
Energy Procedia

Citation (APA)
Alsema, EA., Anink, D., Meijer, A., Straub, A., & Donze, G. (2016). Integration of Energy and Material Performance of Buildings: I=E+M. *Energy Procedia*, *96*, 517-528.
https://doi.org/10.1016/j.egypro.2016.09.094

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 96 (2016) 517 – 528

Energy Procedia

SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki

Integration of Energy and Material Performance of Buildings: I=E+M

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Abstract

A new methodology is proposed to assess integral performance of building with respect to energy and materials requirement over the building life cycle. Because the method builds on existing methods for Energy Performance and Materials Performance of Buildings, as defined by Dutch National Building Code, it provides an easily applicable method that allows optimized building design with respect to environmental impacts. Two case studies, one for building renovation and one for new Near Zero Energy Building show the advantages of integral assessment. Extending this approach for building assessment to other countries seems a logical step as it gives designers a better insight in total building performance.

Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.

Keywords: environmental impacts, life cycle assessment, building performance, near zero energy buildings, building renovation, energy performance.

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1. Introduction

The introduction of an energy performance requirement in the building regulations in Europe has resulted in major improvements in the energy efficiency of new buildings. Governed by the framework of the Energy Performance of Buildings Directive (EPBD Recast [1]) each EU member state has formulated a methodology for energy performance evaluation for different building types. These calculation methods, as well as performance standards, have been implemented in the national building regulations in each country. This legislation has been very

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Peer-review under responsibility of the organizing committee of the SBE16 Tallinn and Helsinki Conference.
doi:10.1016/j.egypro.2016.09.094

successful in reducing the energy demand of buildings and in stimulating technological development for energy-efficient energy systems, building insulation and renewable energy generation. As a result, the energy demand of new buildings has been reduced by a factor 10-100 since the 1970’s. Moreover, from the year 2020 onwards all new buildings in the EU will have to conform to a “near-zero energy” standard [1].

Now that (near) zero energy buildings become the new standard, the role of building materials and embodied energy or related CO_2-emission is becoming more and more important. It is recognized that a focus on energy efficiency only, entails a clear risk of having buildings not necessarily performing very well with respect to other environmental criteria [2, 3]. Also the European Commission has identified the importance of building materials when it states that: “*The construction and use of buildings in the EU account for about half of all our extracted materials and energy consumption and about a third of our water consumption. The sector also generates about one third of all waste and is associated with environmental pressures that arise at different stages of a building's life-cycle including the manufacturing of construction products, building construction, use, renovation and the management of building waste”* [4].

However, a broader assessment of the environmental impact of buildings, including the building materials, is not done regularly yet. Already for a long time there exists within the building community a great demand for methods to support the selection of environmentally benign materials for buildings. Formerly, lists of “preferred materials” or “materials to be avoided” were used [5]. Although such lists are easy to use, the draw-back is that they do not allow for performance-based building design and optimization of the design with respect to materials choice.

In the research community Life Cycle Assessment (LCA) is a broadly accepted methodology to assess the environmental impacts of products [6] . This LCA method has been applied to buildings as well (see, for example, ref [7]). Also in the EU-FP6 project Super buildings different aspects of “sustainability and performance assessment” for buildings were investigated [8]. However, among architects, technical consultants and construction companies the use of Life Cycle Assessment for building design and building maintenance is no common practice yet, mainly due to the relative complexity of LCA tools. It has, for example, has been estimated that currently less than 0.5% of the buildings has received an environmental assessment certificate [3].

In order to fill this gap a process was started 20 years ago in the Netherlands to develop an LCA-based calculation method which was specifically focused on buildings and relatively easy to use [7]. Moreover, this calculation method was meant to become part of the National Building Code, just like the energy performance method. Next to a calculation method, also a national LCA database for building materials was set up, which should provide the necessary data for the assessments. And, in the third place, the software tools for such materials assessments were “harmonized” so that all tools would give the same final results for specific buildings. As a result of this development process the so-called “material performance assessment of buildings” has become obligatory for new building projects (dwellings and offices) as from the year 2014 [9]. Important to state is that the new method is restricted to *only the materials* used in the construction and maintenance of the building. This restriction to materials impacts only was applied because the operational energy consumption of buildings is already governed by the existing Energy Performance standard.

So effectively there are now in the Netherlands two different performance indicators for buildings, one for the energy consumption during building use and one for the environmental impacts from the materials used for the building. Although no required limit value for the materials performance has been formulated yet, the idea is that designers will try to adapt their building design in order to reduce the materials impact. Moreover, legally binding limit values for materials performance may be implemented in the near future.

The existence of two different performance indicators raises the problem, however, that for designers it is difficult to determine the most optimal solutions with respect to energy systems and the selection of materials with an impact on energy efficiency. For example, the installation of solar panels or the addition of extra insulation to a building will result in a negative effect on the material performance because additional materials are needed, while on the other hand they improve the energy performance of the building. As the two indicators have an entirely different way of “impact assessment” and of normalization the indicators cannot be compared or balanced against each other.

As mentioned, the need for an integral evaluation of materials impacts *and* energy performance is becoming more and more important now that the energy requirements for buildings are being reduced towards zero. In essence, the energy performance standard also has the objective to address an environmental problem, namely climate change and fossil fuel depletion. So, from a scientific point of view it would be quite logical to consider all environmental impacts from the building life cycle in one assessment system, and not divide it in two separate, incomparable assessments. On the other hand, the building sector is very much accustomed to the use of energy performance methods and standards and a change towards an entirely new methodology would be quite problematic.

In order to tackle this problem, we have developed a new framework to integrate the existing assessment methods for energy and materials performance of buildings, in such a way that their respective results are aggregated into a single indicator. In this method the LCA impacts of operational energy consumption in the building are calculated and combined with the LCA results of the building materials, into a single impact score: I = E +M.

Below we will first outline the setup of the two existing assessment methods and describe how they were combined into a single, aggregated indicator. After that we will discuss a number of practical examples assessed with the new methodology and draw some conclusions.

2. Existing methods for assessment of building performance

2.1. Energy performance of buildings (EPG)

The method for calculation of the energy performance of buildings has been set up differently in each European country. In the Netherlands the method called "Energie Prestatie van Gebouwen" (EPG) is based on a quite detailed energy balance for the building, together with a typical meteorological year and a standardized building use (e.g. with respect to room temperatures and hot water consumption). Local energy conversion systems (e.g gas boilers or PV systems) are modelled with either standardized or customized conversion efficiencies.

As result from these model calculations the energy consumption is determined in terms of the quantities of final energy carriers entering the building (i.e. electricity, natural gas, heat from district heating, biomass) in a typical year. The final energy consumption values are subsequently converted into equivalent primary energy requirements by means of standard conversion factors. The total primary energy requirement is then normalized with the primary energy demand of a standardized building of the same type, so that a dimensionless Energy Performance Coefficient (EPC) is obtained. Note that the actual energy demand of the building, as registered by energy meters, has no role in this calculation.

According to the present building standards [9] a new residential building must have an EPC of 0.4, which corresponds to a primary energy demand of 60 kWh/m2 for a typical row house.

2.2. Material performance of buildings (MPG)

As explained above the evaluation method called "MilieuPrestatie van Gebouwen" (MPG) is a relatively new, standardized method to assess the environmental impacts of the materials used during the life cycle of a building [10]. This life cycle includes resource winning and production of building materials as well as the construction, maintenance and decommissioning of the building. Also energy requirements during construction and decommissioning are included. The assessment is based on LCA methodology and all data on about the building materials are derived from a national database of environmental impact data (Nationale Milieu Database, NMD [11]) which is filled with producer-specific and more generic data for building materials and related products. This database is managed by an independent organization which also safeguards the quality of LCA data submitted by producers.

Note that energy requirements for production of materials ("embodied energy"), as well as GHG emissions from material production ("embodied CO_2") are all included in the MPG evaluation. So all effects caused by building construction, maintenance and demolishment, except for operational energy consumption, are in principle covered by this method.

Within the MPG method, certain standard values are predefined, for example with respect to the expected service life of buildings: 75 years for residential buildings and 50 years for non-residential buildings. More importantly the MPG definition document [10] prescribes the impact assessment method that needs to be used. Important is that it was decided to perform the impact assessment in the first step on the basis of the CML method for Life Cycle Impact Assessment [12] which discerns 10 impact categories (Table 1). Because the assessment method has to be useful for building designers a second step is applied in which all impacts are aggregated into *one single impact score,* with weighting factors based on the so-called "shadow price" for each impact category.

The result per environmental category is derived by multiplying the characterized impact scores with the weighing factors per unit, as given by Table 1. No normalization is performed. The so-called "one-point score" is finally calculated by adding up all scores per impact category[†].

The shadow price was set equal to the virtual cost to avoid or prevent the damage of an environmental impact. For example, for global warming the shadow price is determined by the cost of CO_2 mitigation by means of wind turbines. According to the MPG definition the following weighting factors are to be used:

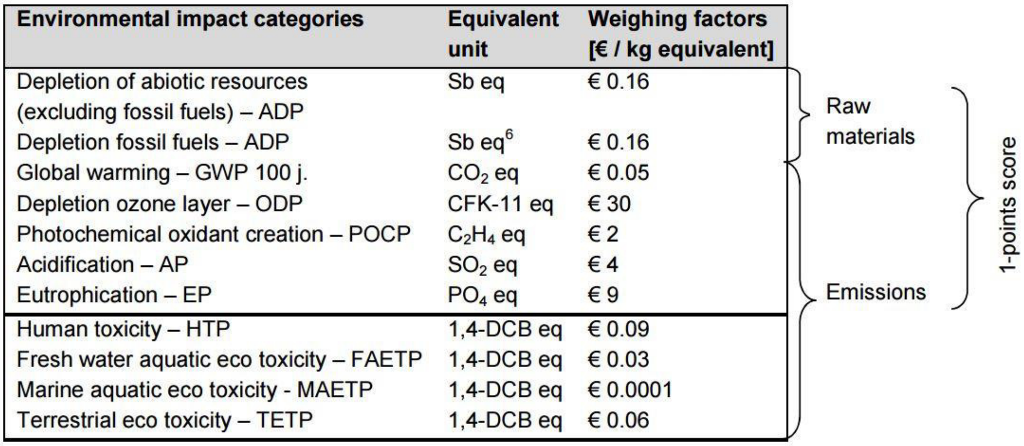
With the method outlined above the impact of materials used in the building life cycle are expressed into one final score which is called the "MPG indicator score". Because the functional unit for a building, prescribed by the MPG method is "square meters per year", the MPG score is finally expressed as "€ per m^2 per year"[‡].

3. New Method: Integral Performance of Buildings

As outlined above it is not always convenient to have two different assessment systems and performance indicators when actually it is the environmental life cycle performance of the building that one would like to consider. For an integral performance indicator we therefore take the life cycle methodology as starting point. The material performance indicator (MPG) is already evaluated according LCA methodology, so we need to assess the impacts of operational energy consumption (i.e. energy consumption during the *utilization* of the building) with the same impact assessment method. The amounts of energy consumed may then be derived from the energy performance calculation (EPG).

This sounds fairly simple, but it should be done very carefully in order to avoid double counting or not accounting some material or energy flows. For that we have to take a close look at the *system boundaries* defined in the two respective assessment methods (Figure 1).

Table 1: Weighting factors for the environmental impact categories as used by the Materials Performance of Buildings (MPG) method [10]



Environmental impact categories	Equivalent unit	Weighing factors [€ / kg equivalent]
Depletion of abiotic resources (excluding fossil fuels) – ADP	Sb eq	€ 0.16
Depletion fossil fuels – ADP	Sb eq[6]	€ 0.16
Global warming – GWP 100 j.	CO_2 eq	€ 0.05
Depletion ozone layer – ODP	CFK-11 eq	€ 30
Photochemical oxidant creation – POCP	C_2H_4 eq	€ 2
Acidification – AP	SO_2 eq	€ 4
Eutrophication – EP	PO_4 eq	€ 9
Human toxicity – HTP	1,4-DCB eq	€ 0.09
Fresh water aquatic eco toxicity – FAETP	1,4-DCB eq	€ 0.03
Marine aquatic eco toxicity - MAETP	1,4-DCB eq	€ 0.0001
Terrestrial eco toxicity – TETP	1,4-DCB eq	€ 0.06

[†] Please observe that this MPG one-point indicator it is different from the "single aggregated score" mentioned at the end of section 1. The MPG score considers only materials, while our newly defined, aggregated score combines *energy and materials.*

[‡] Note that these euros are used to express a virtual "shadow price" and cannot be directly compared to conventional costs in euros.

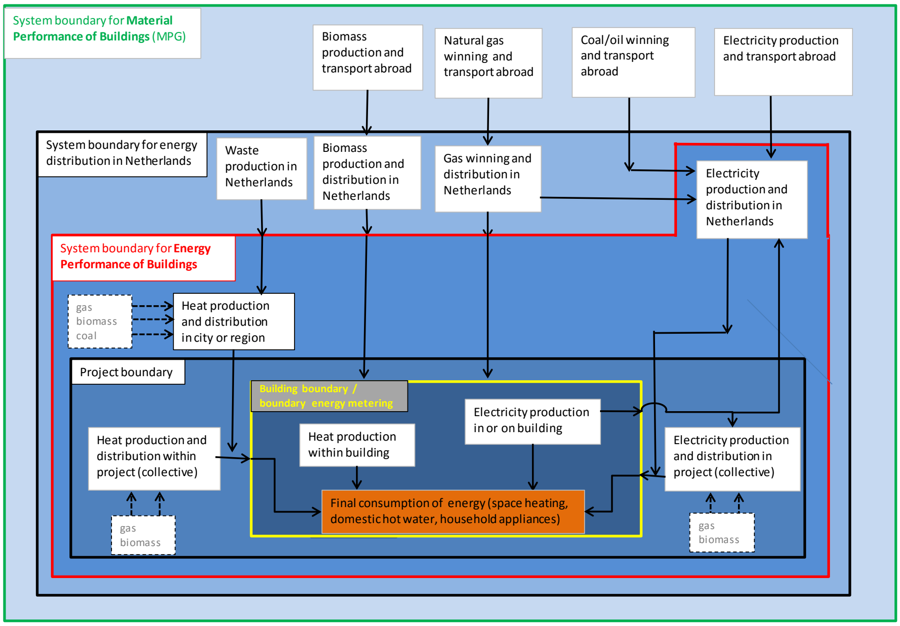


Figure 1: System boundaries for existing Dutch evaluation methods of energy and material performance of buildings (EPG and MPG)

In Figure 1 we can discern 5 different boundaries which are relevant for our considerations, namely:

- the building boundary, where also energy flows entering the building are being measured (energy metering);
- the project boundary (i.e. a group of buildings with collective energy services);
- the system boundary for Energy Performance of Buildings calculation (EPG);
- the system boundary for energy distribution within the Netherlands;
- the system boundary for assessment of Material Performance of Buildings (MPG).

Whereas the Material Performance evaluation considers in principle a global system boundary, in line with general LCA methodology, the method for Energy performance considers a national or even subnational system boundary. Winning and distribution of natural gas, biomass and waste is not accounted explicitly in the EPG method, and production of electricity is only accounted with a standard conversion factor for primary energy and for CO_2 emission. Also notice that environmental impacts from the energy distribution system are outside the scope of both the EPG and the MPG methods.

For all energy conversion processes it should be considered carefully whether or not their material and energy flows are accounted in one of the methods. For example, if we look at the conversion of natural gas in a gas boiler within the building we can notice that the inflow of gas into the building is well accounted for by the EPG method because it carefully models the efficiency of the heating system. But the emissions from the combustion process to the atmosphere (i.e. CO_2, NO_x) and to the water (acids) are *not* accounted for anywhere.

So, in order to obtain a complete assessment of environmental impacts, on the basis of the results of EPG and MPG evaluation results, we need to consider *for each energy flow entering the building*:

- Are all upstream impacts from the energy winning, conversion and distribution activities taken into account?
- Are all emissions and material inflows for the energy conversion processes within the building taken into account?

Table 2. Environmental impact factors (shadow price) for some energy carriers, in the Dutch energy supply system.

	Unit	$IF_{external}$	$IF_{internal}$
Electricity	€/MJ	$6.09 * 10^{-2}$	0
Natural gas, combusted in high efficiency gas boiler	€/MJ	$3.45 * 10^{-3}$	$1.60 * 10^{-3}$
External heat supply, from district heating	€/MJ	situation dependent	0
Biomass	€/MJ	Dependent on biomass source	Dependent on combustion technique

In practical terms this means that for each final energy carrier that may be consumed during utilization of the building we have to establish an impact factor (or a set of impact factors) which allows us to assess all environmental impacts of the energy consumption using this carrier. For energy carrier inflow into the building (E_i) we have defined the corresponding environmental impact EPG_i^* as:

$$EPG_i^* = IF_i \times E_i \tag{1}$$

where

E_i = final energy consumption for energy carrier "i" (in MJ), as derived from the EPG calculation

IF_i = environmental impact factor for energy carrier "i" (impact unit per MJ)

E_i^* = environmental impact for energy carrier "i" (in impact units)

And

$$IF_i = IF_{i;internal} + IF_{i,external} \tag{2}$$

for, respectively, activities occurring *internal* to the building (i.e. gas combustion in boiler) and activities *external* to the building, i.e. gas winning and distribution. Note that the latter factor should also include the impacts from the materials of the energy distribution network (gas pipes, electric cabling) right up to the perimeter of the building. If no energy conversion occurs within the building, for example in case of electricity, only the external activities have to be considered.

The unit of the impact factor varies, according to the impact category (e.g. kg $CO_{2,eq}$ for climate change category) or it can be the "euro shadow price" if we consider the one-point score of the MPG method (see 2.2). In Table 2 the impact factors are shown, expressed in the euro shadow price per unit energy, as we have determined them for a number of major energy carriers, all for the context of the Dutch energy supply system. Impact factors for some energy carriers, like external heat supply, are so much situation-dependent that no single value can be given. For biomass too, the impact factor depends on so many factors that we cannot give one value.

If we add up the EPG*-results over all relevant energy carriers flowing into the building (e.g. gas and electricity) a total environmental impact score for the operational energy consumption of the building EPG* can be obtained:

$$EPG^* = \sum_i EPG_i^*, \tag{3}$$

Finally, the integral environmental impact of the building is defined as:

$$IPG = MPG + EPG^*, \tag{4}$$

The IPG score gives us the desired score assessing the environmental impacts for operational energy consumption *and* the impacts related to materials use. As mentioned before, impacts of embodied energy for materials are included in the MPG score too.

Now for LCA practitioners and scientists in general the described method might sound as a cumbersome way to obtain results that can also be found by way of a standard LCA approach. The important difference, however, is that in our approach we make use of the results that are obtained from standardized calculation methods that are implemented in the Dutch Building Code and which are therefore familiar to the building community. In other words, without setting existing methods aside, we are able to derive integral impact scores for the building performance by applying just a few simple additional calculations. Moreover, the extra calculation step can easily be included in existing software tools for energy and material performance evaluation, like GPR Building [13] and in that case requires almost no extra efforts from building designers.

In the next section we will explain what new insights can be gained from this new assessment tool for two case studies, one on renovation of existing dwellings and one on the construction of new houses.

4. Case study 1: Energy-efficient renovation of an existing apartment building

For this case we examine renovation options for an apartment building as it was typically constructed in ‘60íes and ‘70ies in many cities and towns in The Netherlands. Each 7-storey block, as built in 1969, comprises 42 apartments. The floor area per apartment varies from 64 (2-rooms) to 82 m^2 (5 rooms). Presently the building has an energy label F and an energy consumption for space heating and domestic hot water (DHW) of 225 kWh/m^2.This is consumed in the form of natural gas. Including the building-related electricity consumption (i.e. pumps, lighting, ventilation, but *excluding* household appliances) the primary energy consumption according to the Energy Performance calculation method is 308 kWh/m^2.

The building has poor insulation of walls, roof and floor (U-values 1.0-1.7). Most windows have single glazing, some double glass. Heat supply for space heating is produced by a collective gas boiler, while domestic hot water is prepared with an individual gas-fired flow water heater. Ventilation is based on natural ventilation only, so no mechanical exhaust.

Average energy costs for building-related energy (i.e. excluding household energy demand) will be around € 120 per month (and the additional energy cost for household appliances may be in the order of € 30-50 per month). The building is owned by a social housing company and the rent would be typically around € 350-400 per month. This means that energy costs are unacceptably high in this kind of situations.

Table 3. Energy- related measures for renovation of apartment building.

Building element	Unit	Present situation	Basic Renovation	High insulation	Basic + PV
Roof	W/m²K	U=1.0	U=0.3	U=0.14	U=0.3
Façade	W/m²K	U=1.7	U=0.4	U=0.14	U=0.4
Bottom floor	W/m²K	U=3.0	U=0.4	U=0.14	U=0.4
Windows**	W/m²K	Single glass, U=5.2	Low-E, double glass, U=1.8	triple glass, U=1.4	Low-E, double glass, U=1.8
Heating installation		Collective, gas-fired	Individual gas boiler, high efficiency	Individual gas boiler, high efficiency	Individual gas boiler, high efficiency
Domestic hot water		Flow heater, gas	Combi with gas boiler	Combi with gas boiler	Combi with gas boiler
Ventilation		Natural	Mechanical exhaust	Mechanical, heat recovery, CO_2-control	Mechanical exhaust
Renewable energy generation	kWh/unit	-	-	-	430 (570 Wp/unit)
Primary energy consumption	kWh/m^2	308	140	108	120
Energy label		F	B	A	A
EPG* gas	€/m2/yr	6,16	2,20	1,50	2,20
EPG* electricity	€/m2/yr	0,39	0,79	0,88	0,37
Material Performance (MPG)	€/m^2/yr	0.38	0.43	0,51	0,46
Integrated Performance (IPG)	€/m^2/yr	6.93	3.43	2.89	3.03

* For reasons of space the scenario “high insulation + PV” is not shown separately in the table, input data for this can be easily derived from the other scenarios and results from figure 2.

** U-values for windows are for glass plus frame

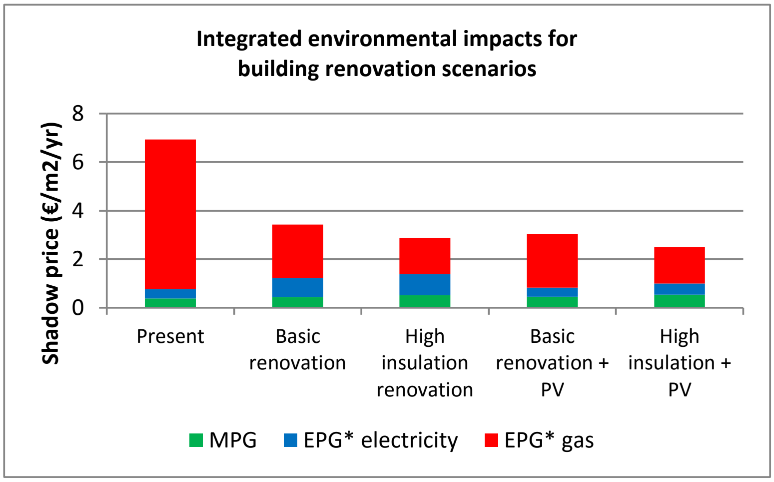


Figure 2: Integrated environmental impacts of building for a number of renovation scenarios. Contributions are shown from materials (MPG), energy consumption gas (EPG* gas) and energy consumption electricity (EPG* electricty). Environmental impacts are expressed in shadow price per functional unit according to the Dutch national method for environmental impact assessment of buildings.

Apart from other deficiencies the building might have, it is quite clear that the energy consumption is much too high, both for the tenants and in view of climate policy targets. According to the national “Covenant on Energy” the social housing companies in the Netherlands have promised to improve the energy performance of their housing stock up to an average level of energy label B until the year 2020. Moreover, for the year 2050 there is the national ambition to get all buildings at the net-zero energy level.

For the building described above we consider four renovation options:

1. Basic renovation to energy label B (primary energy demand about 140 kWh/ m^2)
2. Extra high insulation levels
3. Basic renovation plus PV panels on the roof
4. Extra high insulation + PV panels, so a combination of measures from scenario 2 and 3

For all renovation scenarios we assume that the building can be exploited for an additional 30 years after the renovation. Table 3 below shows the kind of measures which are applied in each scenario and the results in terms of energy consumption, EPG*, MPG and IPG. Figure 2 shows the latter results in graphical form.
There are some observations we can make on the basis of the table and figure:

- For a building like this, the energy-related impacts dominate the materials-related impacts, even after high-level renovation;
- The materials impact is somewhat increased by the renovation, because some materials are removed before their end-of-life, and some new materials are added to the building. On the other hand, we have also increased the remaining building life time, thus reducing the yearly materials impact from the existing structure.
- For the high-insulation + PV scenario the materials impact is increased by 40%, from 0.38 to 0.54;
- The high-insulation scenario has only a slightly lower IPG (=2.89) than the PV option (IPG=3.03). In view of the costs of a renovation, which are probably much lower for the PV variant, the latter may be an attractive alternative. Addition of some 200 W_p of PV panels per dwelling, i.e. about 55 m^2 of panel area per building, would be sufficient to bring the PV variant to the same IPG level as the high insulation variant.
- A high-level renovation with high insulation values and PV panels will obviously result in the lowest impact at IPG=2.50, which is almost 75% lower than the present situation.

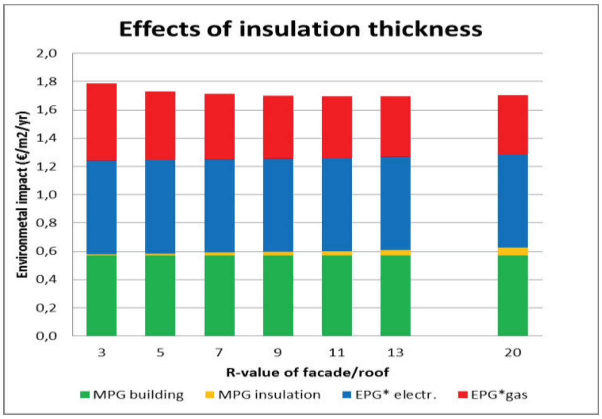


Figure 3: Integrated environmental performance of NZEB residential building in relation to insulation thickness. MPG is materials impact, EPG* is the environmental impact from energy consumption.

An overall conclusion is that worries with regard to extra materials use for building renovation are not necessary yet, because in every scenario the *reductions* in energy-related impacts far outweigh the *increase* in materials-related impacts.

5. Case study 2: New Net Zero Energy Buildings (NZEB)

The methodology of Integrated Performance assessment of Buildings should also be very useful for optimized design of new buildings especially as these have to meet the Net Zero Energy Building (NZEB) standard.

As a reference we start with a row house, between neighboring houses, which is built to comply with the draft NZEB standard for the Netherlands [14]. This house has a usable floor area of 124 m^2, R-values for the building envelope of 6-7 (m^2K/W), triple glass windows (U=1.1 $W/m^2.K$) and a high-efficiency gas boiler for heating and DHW supply. In order to make it NZEB it is also equipped with about 20 m^2 of PV panels (3 kW_p) and a Solar Hot Water system (2.5 m^2).

First the effects of increased insulation thicknesses in the façade and roof of the dwelling are investigated. A feeling among designers may be that increasing insulation is not good for the environment because of the higher environmental load of the required materials. As insulation material for walls and roof we have selected EPS because it is a rather common choice. The effects of other constructive adaptations, necessary for the increased insulation thickness, have been neglected here.

Figure 3 shows how the environmental effects from reduced energy consumption (EPG* gas and EPG* electricity) and the increasing environmental impact from the materials "MPG-insulation" add up. The MPG value for the rest of the building, excluding insulation, is shown in the lowest band. We can observe that the MPG contribution from the insulation material is very small, even if we would go to an unrealistically high R-value of 20 m^2.K/W. But what is also clear is that the energetic effects of insulation beyond R=5, are very small too. Partly this is due to type of house we have chosen (row house) which has only 98 m^2 of exterior surface area in the façades and roof. For a free-standing house the energy saving effects would have been larger. For other insulation materials, such as PU, the materials impact will be slightly higher but overall we expect that here too the material-related effects will be quite small too. In other words, there is no immediate reason to save on insulation thickness, because of concerns about the materials impact. The optimal thickness can be determined for each building type and climate, by using an analysis as shown above.

More significant effects from design choices can be seen in the next set of calculations where we look at the effects of solar energy installations. In figure 4a we depict our NZEB house in 3 variants: 1) without solar energy installations, 2) with only photovoltaic panels[§] (20 m^2, $3kW_p$) and 3) a solar hot water installation of 2,5 m^2 and a slightly smaller PV panel area (17,5 m^2). Note that we kept the total area for solar installation constant at 20 m^2, so part of the PV panel area is replaced by solar hot water collectors. Figure 4a is a bit complicated because the PV panels generate more electricity than is used by the building (excluding domestic appliances!), which results in a negative impact from the PV generation. For this reason, we show in a separate bar in Figure 4a the IPG-value, which is the sum of all impacts: IPG = MPG-building + MPG-solar + EPG*-gas + EPG*-electricity.

Although the MPG-value from the PV installation is quite significant, about 50% increase in total MPG, the overall effect of the PV panels is very positive, the IPG-value is reduced from 1,61 to 0,19 €/m^2/yr. It is interesting to observe that the replacement of 2,5 m^2 of PV panels by a solar hot water collector results in a slightly worse overall impact (0.24 €/m^2/yr). In other words, for this case the choice for a solar hot water system gives no improvement in environmental terms. (A positive effect, not covered by our analysis, is that it reduces the load on the electricity distribution network). Figure 4b shows the effects of choosing a different type of heating installation, either a gas boiler or an electrical heat pump (with ground water as source), both in the context of our NZEB dwelling. Because the heat pump uses a substantial amount of electricity (from the grid) this has a significant negative effect. However if we add a PV installation (20 m^2) to the house the total impact reduces to a level which is about 30% better than the case with only a gas boiler (and no PV). Nonetheless, the situation with gas boiler and PV (Figure 4a) if found to be most environmentally friendly choice for this building. To make the all-electric variant of this building the most environmentally friendly we need to install an additional area of PV panels.

One conclusion from this is that the choice of installation for heating or for renewable energy generation has more effect on the total environmental impact than the level of insulation, beyond a certain adequate insulation level.

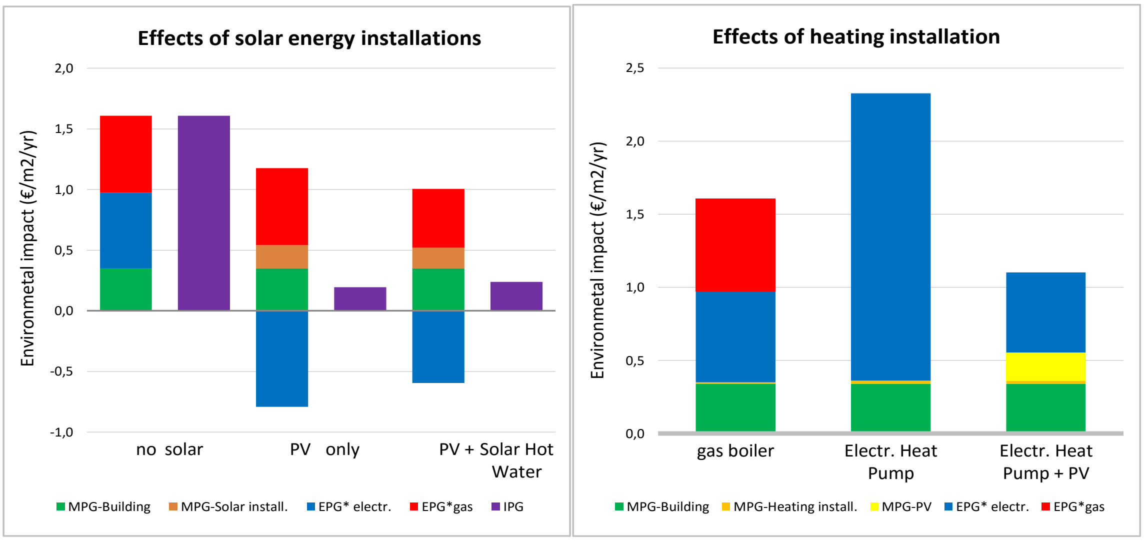


Figure 4: Effects on total environmental impact of building in relation to choice of solar energy installations and choice of the heating installation.

[§] Assessment of the PV installation is based on crystalline silicon panels with a 15% module efficiency and a yield of 850 kWh/kWp/yr. LCA inventory is adapted from data in Ecoinvent 2.2 and ref. [15]. Excess PV electricity exported to grid is accounted in same way as electricity imported from grid (symmetric factor for import/export). Changes in the electricity supply system over the building life time are not considered.

6. Discussion

The results presented above with regard to renovation options and choices in NZEB design are dependent on a large number of assumptions and specific conditions. The most important factors (with our choices) are:

1. The climatic conditions in which the building operates (Netherlands);
2. The energy supply systems which provide the final energy carriers (electricity and natural gas) to the building, including the technical system to produce electricity (in our study the Dutch energy supply system, status 2014);
3. The Life Cycle Inventory data that are used to determine environmental impacts for building materials and energy carriers (data from the NMD, the Dutch national database with LCA data of building materials);
4. Life times of buildings and building components: for residential buildings we used a standard of life time of 75 years as prescribed by the national MPG method. (N.B.: in case of renovation the building life time may be increased, thus reducing impacts). Building installations have standard technical service lives of 15 years, except solar energy installations which last 25 years;
5. The assumed efficiencies of energy installations in the building and the effectiveness of insulation materials: some of our assumptions were described above, for the rest we used estimates for state-of-the-art technology as used as default in the national method for energy performance calculation (EPG);
6. The physical characteristics of the buildings and way the energy balance of the building is modelled: here to we used the standard EPG calculation method for the Netherlands and applied this to the typical buildings as defined for the Dutch building stock;

It is clear that many assumptions affect the precise outcome of our calculations. Therefore, the reader should be quite careful to extend the results beyond the scope and background data of our study. On the other hand, the more general conclusions with regard to energy-related versus material-related impacts of façade and roof insulation should be fairly robust. Also our conclusion about the large effects of the choice of energy conversion equipment for heating and the effectiveness of PV systems should be reasonably robust as long as the background energy supply system is not entirely different from the Dutch system (for instance 100% hydro-electricity).

Further work is needed to broaden the data for the impact factor of energy carriers like external heat supply (i.e. district heating) and biomass. Both types of energy carriers are being used fairly often in The Netherlands or its use is growing (biomass). Because the impact assessment for these energy carriers is very specific for the source of the heat respectively the biomass and also, in case of heat supply, highly dependent on the distribution infrastructure we could not determine one generic impact factor. Another extension could be to make selection of green electricity as an energy carrier possible, thus giving building owners the option to assess the effects of green power contracts. Because this is a decision for the building user, and not for building designer, we have until now not included green power contracts and similar options which relate to the building management.

7. Conclusions

A methodology has been developed that makes it possible for building designers in The Netherlands to make an integral assessment of the environmental impacts of a new building or for building renovation projects. The new aspect is that our method is built on two existing building assessment methods that are already in use in the building community and which are part of the Dutch National Building Code. Because it builds on existing methods it is very easy for the building designer to determine the integrated environmental impact indicator for his plans, without necessity to learn complicated LCA tools.

In a number of typical examples we have shown the added value of the integrated assessment when designing an energy-efficient or near-zero energy building renovation or when designing a new construction at NZEB level. Although the numeric results are highly dependent on building typology, climate and numerous background assumptions and data sets, there are some general trends that we consider to be fairly robust. All-in-all the impact from materials choice and material amounts is not always very significant but its importance increases if we go towards near zero energy levels. For photovoltaic panels the material-related impact is fairly high (in comparison with other building components) but overall PV systems are shown to have a very large beneficial effect on the life cycle performance of the building. The choice of heating technology, especially when this involves a switch from gas to electricity as energy carrier (for example when switching from gas boilers to a heat pumps) can have very big effect on the environmental impact of the building. This negative effect is less obvious when only primary energy is considered as is done in standard energy performance assessments.

Our general conclusion is that the proposed methodology to determine integrated environmental impacts provides valuable new insights for building designers. The new methodology and the related tools, will assist designers in making the right choices for specific buildings in specific circumstances. In our opinion it would be fruitful to develop and apply comparable methodologies in other countries. Our approach has the advantage that it provides a relatively easy assessment system for building designers without the need to learn new LCA tools which are not specific for buildings. A precondition, however, is that a country already applies a method for materials assessment of buildings, next to methods and tools for energy performance assessment. Unfortunately, many countries follow an approach in which only building *products* receive an environmental product declaration, and it is not so often that a system for environmental impact assessment at the building level is implemented.

In view of the EU policy objectives to reduce the broader environmental impacts of buildings [4] it would be advisable to develop further convenient methods and tools for life cycle impact assessment *at the building level*, such as described in this paper. Moreover, such tools should be easily applicable, so that they will be used in practice by building designers that wish to optimize their design with respect to integral environmental quality.

Acknowledgements

The authors wish to acknowledge the support and critical input from partners in the project TKI KIEM and furthermore the financial support from the research programme TKI ENERGO is gratefully acknowledged.

References

[1] European Commission, EPBD Recast, Directive 2010/31/EU of the European Parliament and the Council of 19 May on the energy performance of buildings (EPBD), Brussels, 2010

[2] Antink, R. et al. Greening The Building Supply Chain, Sustainable Buildings and Climate Initiative, United Nations Environment Programme, UNEP-2014

[3] Herczeg et al; Resource efficiency in the building sector - Final report; Ecorys; Rotterdam, 23 May 2014

[4] European Commission, On Resource Efficiency Opportunities in the Building Sector, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee Of The Regions, COM(2014) 445 final, Brussels 2014.

[5] Anink, D., Boonstra, C. and Mak, J. 1996. Handbook of Sustainable Building. London: James & James Science Publishers.

[6] Heijungs R., et al., Environmental Life Cycle Assessment of products: Guide. Leiden: Centre of Environmental Science (CML), Leiden university, 1992

[7] Kortman J., van Ewijk H., Mak J., Anink D., Knapen M., Eco-quantum the LCA-based computer tool for the quantitative determination of the environmental impact of buildings, Proceedings of Buildings and Environment in Asia Conference, Singapore, 1998,

[8] Häkkinen, T. (Ed.), Sustainability and performance assessment and benchmarking of building – Final report, VTT, Espoo 2012.

[9] Bouwbesluit 2012 (National Building Code 2012), Netherlands Ministry of Internal Affairs, The Hague, 2012

[10] Anink, D. et al., Assessment of the Environmental Performance of Constructions and Civil Engineering Works, Stichting Bouwkwaliteit, 2015, https://www.milieudatabase.nl/imgcms/Brochure_Assessment_Method_Environmental_Performance__TIC_versie.pdf

[11] Nationale Milieu Database, http: https://www.milieudatabase.nl/

[12] LCA Impact Assessment methodology developed by the Center of Environmental Science (CML), Leiden University, The Netherlands, version 4.1 (April 2013), http://www.cml.leiden.edu/software/data-cmlia.html

[13] GPR Building, software for sustainability assessment of buildings, http://gprsoftware.nl/english/sustainability-assessment/gpr-building/

[14] P. Staal-Gruit, Resultaten verkennende studie voor eisen aan Bijna Energie Neutrale Gebouwen, DGMR, Arnhem, 2015

[15] Wild - Scholten, M.J. de; Alsema, E.A.; Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic System Production, ECN-E--06-019 2006, https://www.ecn.nl/publications/ECN-E--06-019