PROPOSAL OF A NORWEGIAN ZEB DEFINITION: ASSESSING THE IMPLICATIONS FOR DESIGN

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ABSTRACT

Conceptually a Zero Emission Building (ZEB) is a building with greatly reduced energy demand and able to generate electricity (or other carriers) from renewable sources in order to achieve a carbon neutral balance. However, a clear and agreed definition of Zero Emission Building (ZEB) is yet to be achieved, both internationally and in Norway. However, it is understood that both the definition and the surrounding energy supply system will affect significantly the way buildings are designed to achieve the ZEB goal. A formal definition of ZEB is characterized by a set of criteria that are: the system boundary, feeding-in possibilities, balance object, balancing period, credits, crediting method, energy performance and mismatch factors. For each criterion different options are available, and the choice of which options are more appropriate to define ZEBs may depend on the political targets laying behind the promotion of ZEBs, hence may vary from country to country. This paper focuses on two of these criteria: energy performance and credits used to measure the ZEB balance. For each criterion different options are considered and the implications they have on the building design are assessed. The case study is on a typical Norwegian single family house. It is shown that for certain choices on the two criteria options, a paradoxical situation could arise. When using off-site generation based on biomass/biofuels, achieving the ZEB balance may be easier for high energy consuming buildings than for efficient ones. This is the exact opposite of what ZEBs are meant to promote: design of energy efficient buildings with on-site generation options. Recommendations on how to avoid such a paradox are suggested.

KEYWORDS

ZEB definition, design, low energy, passive house

1 INTRODUCTION

The primary objective for the Norwegian Zero Emission Building (ZEB) centre is to develop solutions for existing and new buildings, both residential, commercial and public owned, in order to bring about a breakthrough for buildings with zero greenhouse-gas (GHG) emissions associated with their construction, operation, and demolition.

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However, a clear and agreed definition of Zero Emission Building (ZEB) is yet to be achieved, both internationally and in Norway. Relevant works on the subject as Torcellini *et al.* (2006), Marszal *et al.* (2011) and ECEEE (2009) can be a useful introduction to the issue. ZEBs are of great interest both in the US (US DOE, 2010) and in Europe. In the ongoing process to recast the EU directive on energy performance of buildings there is a certain focus on ZEBs, even though with some reserves because the directive refers to nearly zero energy buildings (EU, 2010):

> *In Article 2:*
> (1a) "nearly zero energy building" means a building that has a very high energy performance […]. The nearly zero or very low amount of energy required should to a very significant extent be covered by energy from renewable sources, including renewable energy produced on-site or nearby;
>
> *In Article 9:*
> a) by 31 December 2020, all new buildings are nearly zero energy buildings […]
> b) after 31 December 2018, public authorities that occupy and own a new building shall ensure that the building is a nearly zero energy building […]
> […] Member States shall […] stimulate the transformation of buildings that are refurbished into nearly zero energy buildings […]

A parallel work is ongoing in a project of the International Energy Agency (IEA) under the joint Solar Heating and Cooling programme (SHC) Task 40 and the Energy Conservation in Buildings and Community Services programme (ECBCS) Annex 52: "Towards Net Zero Energy Solar Buildings"(Task 40/Annex 52, 2008). In this project the various definitions found in literature are reviewed, state of the art examples of zero or close to zero energy buildings are collected into a database, and a thorough analysis of a possible set of definitions is in progress.

Conceptually, a Zero *Energy* Building is a building with greatly reduced energy demand, such that the energy demand can be balanced by an equivalent generation of electricity (or other energy carriers) from renewable sources. In a Zero *Emissions* Building such balance is achieved not directly on the energy demand and generation but on the associated carbon equivalent emissions. The energy imported from the grids into the building is accountable for certain emissions. The export of renewable energy from the building to the grids is accountable for avoiding similar emissions by other (non-renewable) energy producers connected to the same energy grids. Therefore, the definition of ZEB is intrinsically connected to the energy infrastructure, which the buildings are part of. It is understood that the ZEB definition will affect significantly the way buildings are designed to achieve the goal.

In the first part of this paper a series of criteria is described to characterise a formal and comprehensive ZEB definition, based on Sartori *et al.* (2010a) and further elaborated in Sartori *et al.* (2010b). The second part the paper focuses on two of these criteria: *credits* used to measure the balance and the building's *energy performance*. For each criterion, different energy supply and demand options are considered and the implications they have on the building design are assessed, based on Sartori *et al.* (2010c).

2 CRITERIA FOR ZEB DEFINITION

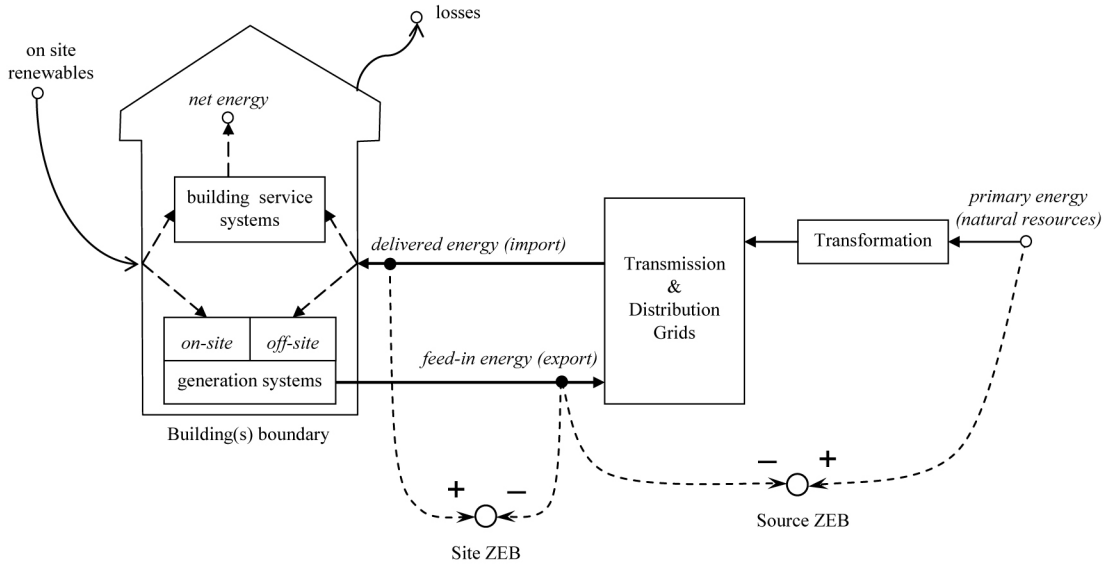
2.1 The ZEB Balance Inequality

The concept of balance is central in the definition of zero energy/emissions buildings. A ZEB is connected to one or more energy infrastructures, such as electricity grid, district heating and cooling system, gas pipe network, biomass and biofuels distribution networks. These infrastructures are here addressed with the general term energy grids. Figure 1 shows a sketch of the connection between buildings and energy grids, reporting the most important terminology.

The term *net energy* indicates the total demand for energy services in a building, i.e. heating, cooling, hot water, lighting and so on. Net energy demand can partly be satisfied by direct exploitation of renewable energy sources available on site, e.g. solar energy. The term *delivered energy* indicates the total amount of energy supplied by the grids to the building in order to satisfy the remainder of the net energy demand. The losses arrow in the figure represents both envelope thermal losses and systems' inefficiencies. Passive houses and, to some extent low energy buildings make thorough use of both passive and active measures to achieve high energy efficiency, and so they require significantly less delivered energy than conventional buildings found in the stock.

ZEBs can also *feed-in energy* into the grids, and that happens primarily by means of generating electricity. In general, also other energy carriers can be considered; i.e. a district heating system able to supply and receive hot water at predefined conditions. Distinction shall be made between *on-site* and *off-site* generation. Systems such as PV and mini wind turbines generate electricity exploiting renewable energy sources available at the building site, and so they are called on-site options.[1] On the other hand, generation of electricity from cogeneration, such as a Combined Heat and Power system (CHP) or fuel cells, rely on fuels that are not available on site and need to be imported; e.g. wood from a distribution network. Thereof these options are called off-site.

FIGURE 1. Connections between buildings and grids.



[1]In Torcellini *et al.* (2006) a further distinction is made between *footprint* and *on-site* options, here both summarized with the term on-site.

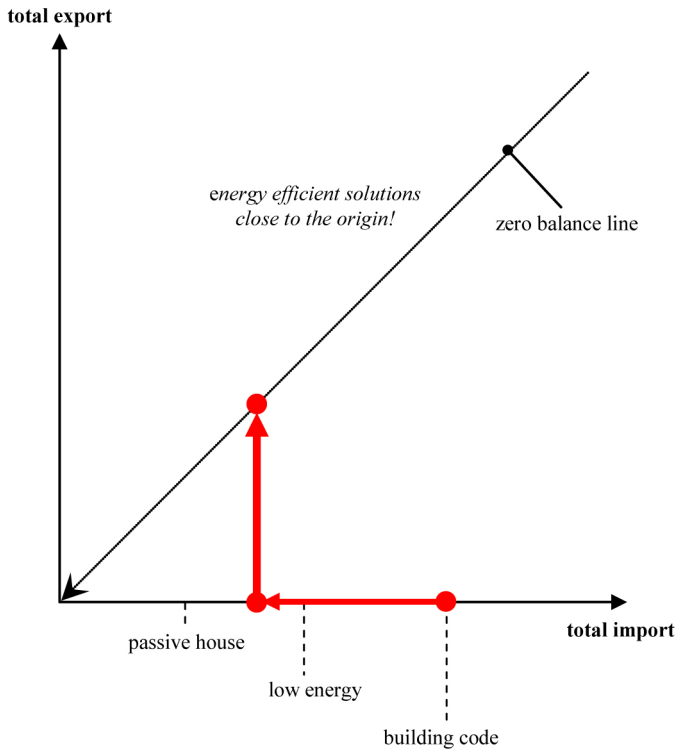
For a ZEB the balance between energy *export* (feed-in energy) and *import* (delivered energy) over a period of time must be zero, or even positive, i.e. when embodied energy/emission in materials also have to be balanced off. The following balance inequality defines a ZEB:

$$ZEB: |export| - |import| \geq 0 \quad (1)$$

Figure 2 gives a graphical representation of a general pathway to the design of ZEB. First step: reduce energy demand, or related carbon emissions. Second step: generate renewable energy to get enough credits to achieve the balance.

The balance is normally calculated by means of some sort of "credits" rather than directly on physical units of energy. A definition based on direct measurement of physical units of energy is called *Site-ZEB* (Torcellini *et al.*, 2006). This definition has the advantage of being easy to understand and measure, but it has the disadvantage of not valuing the differences between energy carriers. Indeed, in terms of natural resources use, emissions, environmental costs etc. one kWh of electricity has a different value than a kWh of thermal energy contained in refined gas or hot water in a district heating system. To be able to grasp such differences it is necessary to use some conversion factors, or credits, that value the quantity of interest, as total primary energy or CO2 equivalent emissions, etc. In this case the definition is called *Source-ZEB* (Torcellini *et al.*, 2006).

FIGURE 2. Graphical representation of the pathway to ZEB. First step: Reduce energy demand, or related carbon emissions. Second step: Generate renewable energy to get enough credits to achieve the balance.



The terms of the above ZEB balance inequality are then expressed as follows:

$$import = \sum_i delivered - energy(i) \times credits(i) \quad (2)$$

$$export = \sum_i feed\text{-}in - energy(i) \times credits(i) \quad (3)$$

where i = energy carriers

In design phase it is convenient to assume all the energy demand—estimated according to the relevant national norms—as being delivered energy from the grids, and all the energy generation—estimated with the due losses, e.g. DC/AC power conversion for photovoltaic—as being feed-in energy to the grids. In reality a certain amount will be self consumed, but this data is normally not estimated at design stage.

Due to the complexity of the energy infrastructure, it is normally feasible to estimate such credits only as average values for a period of time and for a specific energy infrastructure. The credits will then vary over time and from location to location. Electricity may be considered with average European values, in the assumption that the European electricity grid and market will eventually become fully integrated; while other energy carriers, i.e. district heating or biomass, should be credited according to the national or regional context, according to the actual availability of resources in the area.

The next step consists in identifying a series of criteria that characterise a ZEB definition. Evaluation of such criteria and selection of related options becomes a methodology for elaborating sound ZEB definitions in a formal, systematic and comprehensive way.

2.2 Description of the Criteria

A series of criteria need to be evaluated in order to achieve a sound ZEB definition. Some of these might be covered by national building energy codes already. The criteria are interconnected and choices on one could influence or eventually force the choices on another one.

1. System boundary: Is the boundary on a single building or on a cluster of buildings? Photovoltaic installation, e.g. on the roof, belongs to the building or to the grid?

The Norwegian ZEB centre is primarily oriented to research on buildings. However, building settlements may be considered as well. Where to put the boundary would affect, for example, the evaluation of a local district heating system. Suppose there is a small scale district heating system in place that serves a neighbourhood. If the entire neighbourhood is to be defined as ZEB, then the carbon emissions to offset are calculated considering the fuel mix and the efficiency of the actual plant in use, because it is inside the system boundary. Alternatively, if each single building is to be defined as ZEB, the carbon emissions to offset could be calculated differently. The energy imported into the system (one building) is in the form of hot water. Then it would make sense, for the sake of generality and/or for lack of specific data, to refer to regional or national aggregated data on fuel mix and efficiency of district heating systems.

It follows that a ZEB definition for a settlement would be easier to achieve when the local energy grid performs better than the national average. Consider for example the small district heating system above as running exclusively on biomass and/or biofuels. Internalising such a plant into the system boundary does reduce the amount carbon emissions to offset, when compared to the average district heating system that uses a mix of waste, renewable source, fossil fuels and electricity.

2. Feed-in possibilities: How can the building feed-in energy into the grids? Is electricity the only option or are there other carriers available, e.g. hot water in district heating system?

The simplest situation is when only electricity is available as a form of energy export from the building to the grid. Alternatively, it is possible to export energy in the form of other energy carriers, in case the grids are predisposed for it. This is the case of hot and chilled water in a district heating and cooling system that works two-ways, or hydrogen produced on site from electrolysis with surplus electricity from a photovoltaic roof, in a hypothetical hydrogen infrastructure.

3. Balance object: What goes into the balance of a ZEB definition? Divided in two parts:

3.1 Balance object I, Life time: What is the scope of the definition? Is it solely the energy used for operation of the building? Or the energy calculated from a complete LCA analysis? Or a middle way, e.g. energy for operation and embodied energy in materials and technical installations?

The definition could focus solely on the balance of emissions during the normal operation of the building. Alternatively the definition could consider the complete Life Cycle Analysis (LCA) of the building, which includes the emissions embodied in materials and technical installations and emissions caused in construction, renovation and demolition phases, eventually considering also material recycling and waste management options. Another option is to balance emissions caused by operation of the building and emissions embodied in materials and technical installation, while neglecting the construction and demolition phases, knowing a priori that they are far less significant.

When the balance is not solely on the operation of the building the implication is that the building must achieve an excess of emission credits, i.e. it must produce more energy than it consumes, in order to payback also for the embodied emissions.

3.2 Balance object II, Operation: What comfort standards have been followed to calculate the building loads, i.e. for heating, cooling and ventilation? Are user loads, i.e. domestic hot water, lighting, plug loads, included in the balance? Are electric vehicles included in the balance?

In Norway the physical parameters of comfort and standardized user loads to be used as the basis for design and evaluation of energy performance are defined in the norm NS-3031 (2007).

Charging of electric vehicles in the garage is not considered in the Norwegian normative. However, this is a form of user load and even though it does not contribute to the building's internal gains, it may represent a form of storage of excess electricity produced on-site. Load from charging of electric vehicles could be considered. Other loads may also be worth considering, such as server rooms and water treatment.

4. Balancing period: What is the basis for calculating the balance? Yearly, seasonal or monthly balance? or a balance upon many years, e.g. a reference period of 30-50 years?

The first intuitive choice is to calculate the balance of emissions over a year. Alternatively, a monthly or seasonal period could be chosen. These options would capture variable availability of renewable energy and discourage great disparity between winter demand and summer generation. In both cases the embodied emissions, if considered, should be normalized on a yearly basis. Furthermore, changes in the climate are likely to happen in the forthcoming decades and average temperatures and precipitations are already different today than how they are in reference weather data files (e.g. in the TMY and TRY weather file formats that are

given as averages over the last 30 years). If this aspect is to be considered, then yearly and sub-yearly evaluations should be performed with a set of different reference climatic years, known and forecasted.

Alternatively, the balance can be performed over a period of many years, i.e. 30 or 50 years. This option reckons the fact that after such a period a building is likely to undergo major renovation work and alter significantly its properties. In this case the calculations could be performed with stochastic weather input.

5. Credits: What is the metric to calculate the balance? Is it energy measured at site or source level? Or is the balance calculated on carbon emissions or other environmental indicators associated with energy? Is there any crediting of activities related to external investments such as wind farm shares etc. or green electricity?

The target of the Norwegian ZEB centre is to do research on zero emission buildings. However, carbon emissions are not always the most obvious choice and it is worth analysing also other possible credits.

The most intuitive way to give credits for the energy demand and generation of a building would be based on energy units itself. Such credits would then look different depending on where the energy is measured in the energy chain, i.e. delivered or primary energy as shown in Figure 1. Such cases are regarded in literature as site ZEB and source ZEB (Torcellini *et al.*, 2006), respectively. A summary of pros and cons of each choice is given in Table 1. In case of source ZEB the credits could be given on total primary energy or on the non-renewable part of primary energy.

The choice of crediting carbon equivalent emissions implies the adoption of a source ZEB definition, because it is at source level that a direct correspondence between energy and emissions can be calculated. It shall be noticed that not all renewable energy sources are equally abundant or available on the planet, i.e. biomass vs. solar. Renewable energy resources with low GHG emissions are not necessarily equally environmental friendly and beneficial from a local perspective. An option for the ZEB definition could then be to account for some sort of environmental credits that are defined with a broader scope than just GHG emissions, i.e. environmental cost analysis.

Other options could be to give credits on the basis of energy or emission costs, or on exergy. The former option is likely to be very unstable and imprecise due to energy price volatility and economic externalities. The latter may be difficult to understand for anybody not acquainted with such a physical property as exergy. It is even debatable whether exergy would actually be a good proxy of environmental performance of buildings.

TABLE 1. Comparison of site and source ZEB definitions.

Type of definition	Pluses	Minuses	Notes
Site ZEB	• Emphasis on energy efficiency. • Easy to measure. • Robust, repeatable and consistent.	• Blind on primary energy (hence emissions). • May favour all electric buildings.	
Source ZEB	• Easier to achieve than Site ZEB. • Values primary energy. • Better model for national energy policy.	• May favour generation options vs. energy efficiency.	Site-to-Source conversion factors needed (*credits*).

6. Crediting method: How are the credits accounted for? Statically with average values? Or dynamically on a hourly basis? Or a semi-dynamic accounting with average values but with daily bands for base/peak load? Furthermore, is electricity from gas fueled cogeneration and fuel cells to be considered in the balance?

A static crediting method is based on average values of the electricity generation mix. Such evaluation should be regularly updated, i.e. every 5 or 10 years. As mentioned it is meaningful to use the generation mix at European level, because of the expected integration of the EU electric grid. In reality though, the generation mix does vary both with the time of the year and the hours of the day, according to load levels (base or peak generation technology), availability of intermittent Renewable Energy Sources (RES) at local and regional level, storage capacity and trans-national power transmission. To account for such variations a dynamic crediting method should be used, based on hour-by-hour evaluation of the credits, e.g. from the hourly clearing of the electricity market. This option is more meaningful because it would reflect nearly real time, on the spot, what is the actual impact of the electricity consumption by the building. However, it is more difficult to implement. It is already standard procedure for the electricity market to operate on hourly prices, but it is debatable to what extent electricity prices can be a good proxy of the associated environmental impact. An intermediate solution could be a semi-dynamic crediting method where average values are considered together with an hour-of-the-day classification into different levels, i.e. corresponding to average load levels.

It shall be noticed that some of the energy carriers, i.e. electricity, should be evaluated at European level, while others like gas, biomass, biofuels and district heating/cooling should be evaluated considering the regional and local infrastructure.

A controversial issue is how to consider the off-site generation, see Figure 1, based on natural gas rather than biomass or biofuels. The electricity so generated cannot be said to come from renewable sources. However, the overall efficiency of electricity and heat generation is high (often > 80%) because the waste heat can be directly used for meaningful purposes in the building, without heat transmission losses. So, this use of gas is more efficient than in a gas power plant where the waste heat is dispersed in a cooling tower. As long as the electricity grid has a poor environmental performance, i.e. it is largely based on fossil fuels, it may be justifiable to credit also gas fueled off-site generation.

7. Energy performance: Is it necessary to specify explicit minimum requirements? If yes what standards would define, for example, low energy and passive house buildings?

A major advantage of the ZEB approach is claimed to be the absence of energy performance indicators, hence avoiding the need to set internationally agreed limits. So, the first option is to give no requirements. With reference to Figure 2 this means letting the balance between import and export credits to be found anywhere in the graph area. This means that energy consumed and produced is valued equally, and cost optimisation will determine where the balance is to be found case by case.

Alternatively it is possible to set minimum requirements, which in Figure 2 it means to work as close as possible to the origin. This corresponds to value energy conservation more than energy production, according to the principle that the best form of clean and renewable energy is the energy which is not used.

In Norway a standardised definition of *low energy* and *passive house* buildings for residential buildings is found in the norm NS-3700 (2009) and for non-residential buildings in SINTEF Byggforsk project report 42, *Dokka et al.* (2009). One option is to require that a ZEB must be at least a low energy building in terms of its energy efficiency. Alternatively,

it could be stated that a ZEB must be a low energy building when it uses thermal carriers for heating while it must be a passive house if it is an all-electric building. This would give a rough yet helpful *a priori* consideration that electricity is an energy carrier more valuable than thermal carriers and should be devoted to other purposes than heating, especially outside of the building sector.

8. Mismatch factors: is it necessary to define requirements on the mismatch between energy generation and the building load? And the needs of a grid? And the substitution of fuels?

The mismatch factors give a better appreciation of the qualities of ZEBs than the simple overall balance of credits. Mismatch requirements assure higher design standard and lower stress on the grids. Mainly three different forms of mismatch are under analysis in the activities of IEA Task40/Annex52 (Voss *et al.*, 2010):

- the temporal mismatch of the energy generation with the building load: building performance mismatch
- the temporal mismatch of the energy transferred to a grid with the needs of a grid: grid interaction mismatch
- the mismatch between the type of energy imported and exported: fuel switching mismatch

The first two forms of mismatch are correlated. The temporal mismatch may occur at daily level, e.g. excess PV generation at daytime and consumption of electricity during night, and it can occur at seasonal level, e.g. the highest load in winter while generation mainly in summer. Strategies for reducing building performance and grid interaction mismatches are under evaluation. However, solutions that tend to improve the matching between load and generation in the building will automatically contribute also to reduce the mismatch with the grid, because more energy is used on site and less is fed back into the grid.

Finally, the balance of primary energy or emission budget might result from energy source switching, such as taking natural gas from a grid during the heating season and feeding solar electricity back into another grid during summer. This may be a good strategy for the building as it avoids seasonal storage. On the other hand it might not match with the needs of the grids. Ways to quantify this aspect are also under evaluation in the activities of IEA Task40/Annex52, see for example (Voss *et al.*, 2010).

3 IMPLICATIONS FOR DESIGN

3.1 The case study

A theoretical case is presented based on a typical Norwegian housing unit in the Oslo climate. The house has a heated floor area of 160 m^2, divided in two storeys, for a total air volume of 440 m^3. Windows cover an area equal to 20% of the floor area.

Concerning the criteria described above, the following options apply to this case study. The boundary is on a single building and the sole feed-in possibility considered is electricity. The balancing object is solely the energy used during the operational life time of the building, hence no embodied energy is considered, and it includes the building load and the user loads. The balancing period is one year and the crediting method is static, hence based on average values, and no mismatch factor is considered. Two types of *credits* are considered: primary energy credits and carbon emission credits. The *energy performance* is given in three cases: a house representative of the stock, a house built according to the new Norwegian building

code TEK-2010 following the prescriptive requirements of §14.3 in the norm, and a house built according to the Norwegian passive house standard defined in NS 3700 (2010).

More in detail, the passive house has a heating demand < 20 kWh/m^{2}a and is equipped with a solar thermal system that covers 50% of the domestic hot water demand, DHW, which corresponds to 30% of the total heating demand (space, ventilation and DHW). The "House TEK-2010" and the "Passive House" have a balanced ventilation system supplying a constant airflow of 1,2 m^3/h·m^2 day and night. The "Stock house" has natural ventilation assumed at a constant air change of 0,5 ach. Internal loads are taken from NS 3031 (2007) for the Stock house and the House TEK-2010, while for the Passive House they are taken from NS 3700. Other relevant parameters are reported in Table 2.

The Norwegian labelling system for the energy performance of buildings is based on delivered energy, NVE (2010). The energy classes are labelled with letters from A to G, where A is the most energy efficient class and G the least efficient. Assuming as an explanatory case that the three versions of the single family house are all heated with direct use of electricity (efficiency ~ 1), they would be labelled as follows: the Stock house would receive a label of energy class E (on the border to class D); the House TEK-2010 would receive a class C and the Passive House a class A.

Two different credits are considered for measuring the balance between imported and exported energy: primary energy factors, as found in IEA 28-books (2007) and EN 15603 (2008), and CO_2 equivalent emission factors, as found in Dokka *et al.* (2009). A summary of the credit values is shown in Table 3. The credits are converted into electricity equivalent figures in order to allow a direct comparison between electricity and the thermal carriers. When thermal carriers are used for heating purposes, the equivalent amount of electricity is used to calculate the imported credits, see Eq. (2). When excess electricity is generated (no matter if

TABLE 2. Main parameters for the three cases.

Parameter	Stock house	House TEK-2010	Passive House
U-value outer walls [W/m^{2}K]	0.40	0.18	0.11
U-value roof [W/m^{2}K]	0.28	0.13	0.10
U-value ground floor [W/m^{2}K]	0.33	0.15	0.13
U-value windows [W/m^{2}K]	2.9	1.2	0.8
Thermal bridge normalized [W/m^{2}K]	0.10	0.03	0.01
Infiltration (at 50 Pa) [ach]	3.0	2.5	0.6
Heat recovery ventilation, yearly [%]	0	70	90
Specific Fan Power (SFP) [kW/m^3/s]	0	2.5	1.5

TABLE 3. Credits for the different energy carriers considered.

	Primary energy credits		Emission credits	
Energy carrier	$kWh_{primary}/kWh_{delivered}$	electricity equiv.	gCO_{2eq}/kWh	electricity equiv.
Electricity	3.31	1.00	395	1.00
District heating	1.12	0.34	231	0.58
Gas	1.36	0.41	211	0.53
Biomas/Biofuel	1.10	0.33	14	0.04

TABLE 4. Heating system characteristics.

Heating system	Heating load covered (incl. DHW) %			Heating system efficiency (electric back-up) η	Electricity generation efficiency ε
	Stock	TEK2010	PH (solar)		
Heat pump	75	75	60 (30)	2.20 (0.98)	-
District heating	100	100	70 (30)	0.88	-
Biomass	100	100	70 (30)	0.77	-
CHP biomass	85	85	60 (30)	0.50 (0.98)	0.30

on-site or off-site generation) and exported to the grid the exported credits are calculated, see Eq. (3). To achieve the ZEB balance the imported credits have to be equal or higher than the sum of all imported credits, as given by Eq. (1).

A number of different heating systems is considered as shown in Table 4, including cogeneration, CHP, that can generate electricity while supplying heat to the building. Data on the efficiency of heating systems are taken from Pettersen *et al.* (2005) and from Onovwiona and Ugursal (2006), Alanne and Saari (2004) and Pilavachi (2002), as reported by Frydenlund *et al.* (2010). The heating system based on CHP biomass is meant as a mini CHP unit, serving a group of houses, because micro CHP units (of low enough power to serve just one housing unit) based on biomass are not yet a fully mature technology, Frydenlund *et al.* (2010).

Calculations of the building energy demand are performed according to the Norwegian calculation procedure NS 3031 (2007), using the software SIMIEN (v5.004). For each heating system it is calculated the amount of on-site electricity generation needed—i.e. how big the PV system should be—to achieve the ZEB balance.

3.2 Results and Discussion

Results for the three different levels of energy performance are reported in Table 5, Table 6 and Table 7 for the Passive House, the House TEK-2010 and the Stock house, respectively; a graphical visualisation is given in Figure 3, Figure 4 and Figure 5, respectively. Results show how the differences between the various cases can be significant, and how certain choices on the two criteria may favour one design solution or another. The tables show the amount of net energy required by the building together with the delivered energy and corresponding energy class label obtained with the different heating systems. Depending on the energy carrier used for heating the total amount of credits necessary to achieve the zero balance varies. The amount of credits also varies according to the credit metric adopted, whether primary energy or carbon emission, according to the values given in Table 3.

When a building is all electric, i.e. the heating system is based on heat pump, the credits balance is achieved generating as much on-site electricity as it is consumed by the building. When thermal carriers are used for heating, the required electricity generation is always less than in an all electric building, see Table 3. This implies, for example, that a smaller PV system is sufficient to achieve the ZEB balance. When the heating system is run by a cogeneration machine, a certain amount of electricity is generated; this is the off-site generation. The remainder of the credits (total minus off-site) has to be generated on-site in order to achieve the ZEB balance.

TABLE 5. Results the Passive House.

Heating system based on	Passive House		Electricity generation credits [kWh/m^{2}a]					
	Delivered energy		Primary energy credits			Carbon emission credits		
	[kWh/m^{2}a]	Class	On-site	Off-site	Total	On-site	Off-site	Total
(Net demand)	(84)							
Heat pump	54	A	54	0	54	54	0	54
District heating	75	A	49	0	49	58	0	58
Biomass	81	B	50	0	50	37	0	37
CHP biomass	100	B	42	18	60	24	18	42

TABLE 6. Results for the House TEK-2010.

Heating system based on	House TEK-2010		Electricity generation credits [kWh/m^{2}a]					
	Delivered energy		Primary energy credits			Carbon emission credits		
	[kWh/m^{2}a]	Class	On-site	Off-site	Total	On-site	Off-site	Total
(Net demand)	(137)							
Heat pump	101	B	101	0	101	101	0	101
District heating	150	C	82	0	82	107	0	107
Biomass	164	D	86	0	86	52	0	52
CHP biomass	214	D	66	46	112	21	46	67

TABLE 7. Results for the Stock house.

Heating system based on	Stock house		Electricity generation credits [kWh/m^{2}a]					
	Delivered energy		Primary energy credits			Carbon emission credits		
	[kWh/m^{2}a]	Class	On-site	Off-site	Total	On-site	Off-site	Total
(Net demand)	(247)							
Heat pump	164	D	164	0	164	164	0	164
District heating	276	E	120	0	120	178	0	178
Biomass	309	E	130	0	130	50	0	50
CHP biomass	424	F	83	106	189	0	106	84

It follows that when a building with high heating demand is equipped with CHP, the off-site electricity generation is also high. This is because the cogeneration in buildings is driven by the heating demand and electricity is seen as the by-product; the opposite of what happens in power plants with cogeneration. The off-site generation of electricity may eventually be enough to provide all the necessary credits, or even give a surplus. This would lead to the absurd consequence that using off-site generation options, such as CHP, it is easier to achieve the ZEB balance with a high energy consuming building than with an efficient one, see tables below.

Comparing Table 6 and 7 one sees that the biomass heating asks for less CO_2 compensation credits in the Stock house (i.e. 50 kWh/m^{2}a) than in the TEK-2010 (i.e. 52 kWh/m^{2}a). The explanation is that in the Stock house the demand for electric specific services (lighting, appliances) is less than in the house TEK2010 (that also include fans for mechanical ventilation).

The results can be plotted as in the following figures in order to give an immediate visual understanding. For each of the three energy performance levels two graphs are shown; one for the primary energy credits and one for the carbon emission credits. Delivered energy, light blue bars, off-site electricity generation from CHP, red bars, and on-site electricity generation needed to achieve ZEB balance, yellow bars, are shown (*y*-axis) for the different heating systems considered (primary *x*-axis). The energy class label, A-G, is also shown (secondary *x*-axis). The white bar on the left hand side of the graphs shows the net energy demand.

The horizontal black line shows the amount of electricity that can be generated on-site by a PV system mounted on the roof. The average production is assumed being 120 kWh/a per square meter of PV area, and the available roof area is assumed equal to the building's footprint area, i.e. the area of one storey. The PV generation capacity is normalized per square meter of heated floor area in order to be directly comparable with the other variables. It follows that the generation capacity is 60 kWh/m^{2}a.

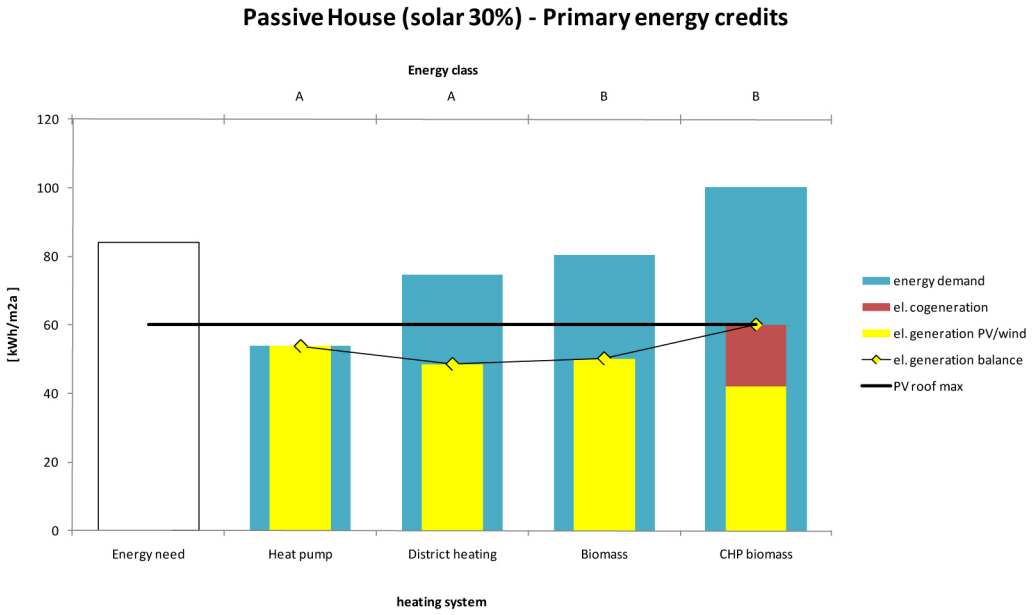
It shall be reminded that all cases shown in the figures satisfy the ZEB balance inequality given in Eq. (1).

Figure 3 shows the case of the Passive House. The net energy demand is 84 kWh/m^2 (15 covered by the solar thermal system); note that the end of scale value for the *y*-axis is 120 kWh/m^2. For all other heating systems, proceeding from left to right the delivered energy increases due to the diminishing efficiencies, as given in Table 4, and the corresponding energy class varies from A to B. According to conversion factors given in Table 3, adopting primary energy credits, Figure 3*a)*, the necessary on-site generation shows roughly a decreasing trend from left to right, while adopting carbon emission credits, Figure 3*b)*, gives especially low generation requirements for the systems running on biomass. In either case the PV roof is always sufficient to satisfy the ZEB balance – the required on-site generation, yellow bars, is always lower than the PV roof maximum capacity, black line.

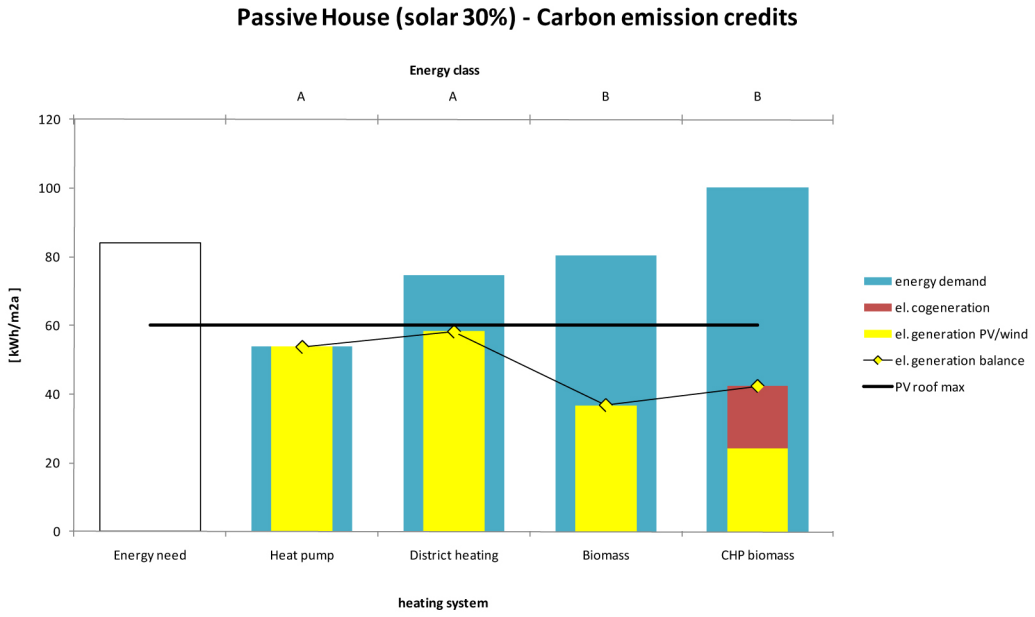
Figure 4 shows the case of the House TEK-2010. The net energy demand is 137 kWh/m^2; note that the end of scale value for the *y*-axis is 250 kWh/m^2. As before, proceeding from left to right the delivered energy increases and the corresponding energy class varies in this case from B to D. Adopting primary energy credits, Figure 4*a)*, the PV roof alone is never sufficient to achieve the ZEB balance—the required on-site generation, yellow bars, is always higher than the PV roof maximum capacity, black line. Adopting carbon emission credits, Figure 4*b)*, the PV roof is sufficient only when using biomass based systems. In all other cases the generation from the PV roof is not enough and additional on-site generation capacity is needed. This could be provided, for example, by extra PV capacity or mini wind turbines mounted on the building site, nearby the building.

Figure 5 shows the case of the Stock house. The net energy demand is 247 kWh/m^2; note that the end of scale value for the *y*-axis is 450 kWh/m^2. As before, proceeding from left to right the delivered energy increases, with the corresponding energy class varying in this case from D to F. As for the House TEK-2010, adopting primary energy credits, Figure 5*a)*, the PV roof is never sufficient to achieve the ZEB balance. Adopting carbon emission credits, Figure 5*b)*, the PV roof is sufficient only when using biomass based systems. It is worth focusing the attention on the fact that with carbon emission credits and using CHP run on biomass the credits obtained with off-site generation are already higher than the total credits necessary to achieve the balance. Therefore, in this case a PV roof becomes superfluous for achieving the ZEB balance.

FIGURE 3. Summary graph for the Passive House when using a) Primary energy credits and b) Carbon emission credits.

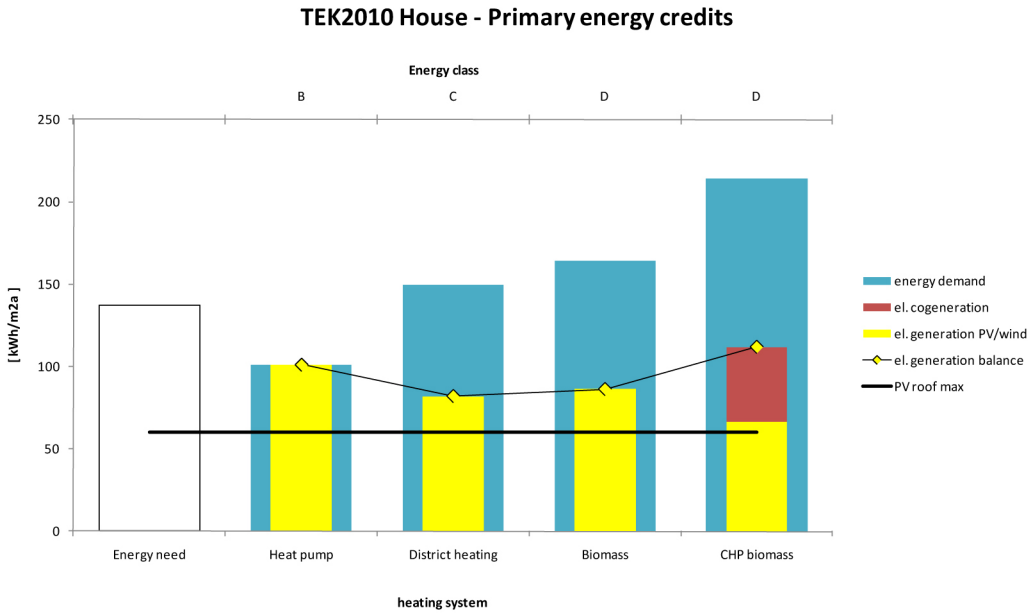


(a)

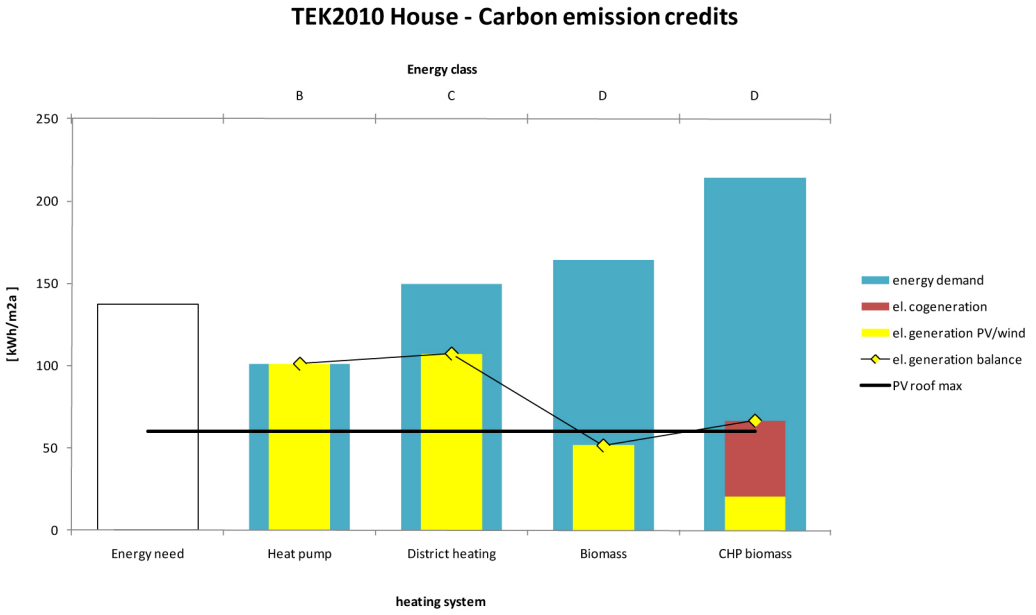


(b)

FIGURE 4. Summary graph for the House TEK-2010 when using a) Primary energy credits and b) Carbon emission credits.

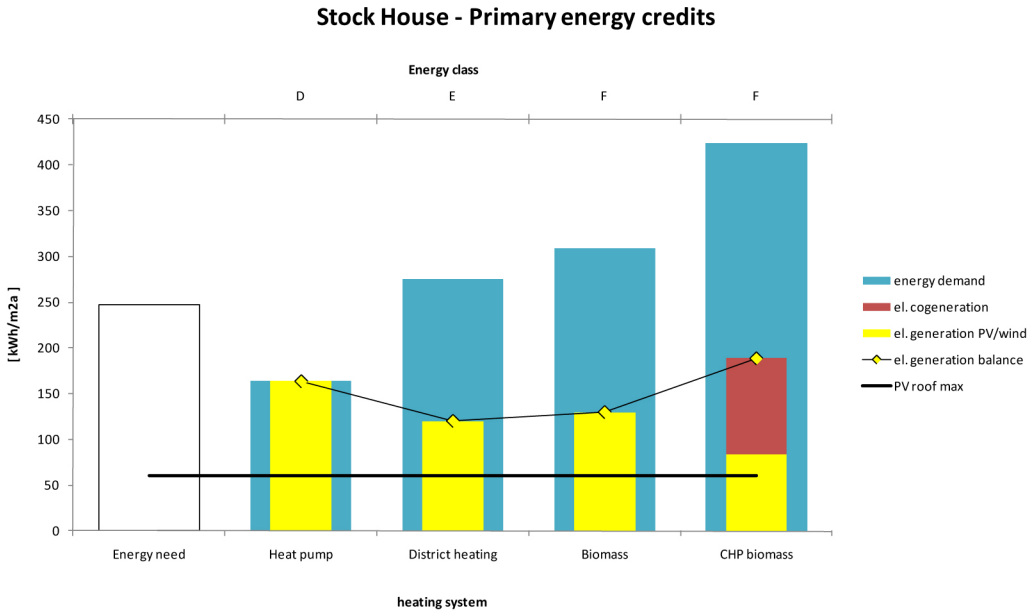


(a)

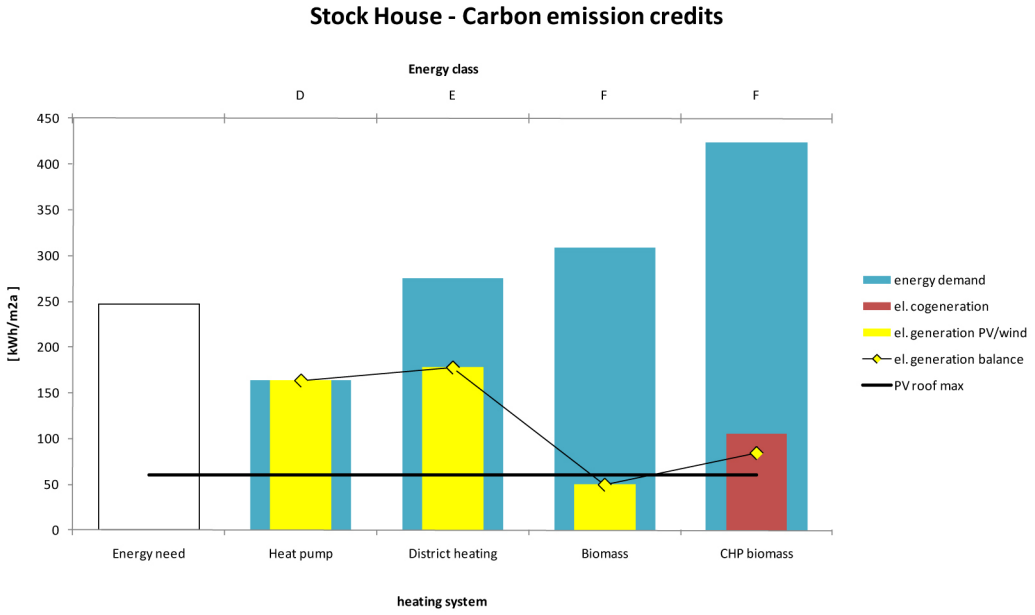


(b)

FIGURE 5. Summary graph for the Stock house when using a) Primary energy credits and b) Carbon emission credits.



(a)



(b)

4 CONCLUSIONS

A series of criteria that characterise the most relevant aspects of a ZEB definition have been presented. For each criterion a number of options are available and evaluation of such criteria and selection of related options becomes a methodology for elaborating sound ZEB definitions in a formal, systematic and comprehensive way.

This methodology has been applied to a case study in order to show the effects of different options in two of the criteria: *credits* and *energy performance*. The case study showed that when using off-site generation based on biomass, achieving the ZEB balance could be easier for high energy consuming buildings than for efficient ones (with the given conversion factors). This is the exact opposite of what ZEBs are meant to promote: design of energy efficient buildings with on-site generation options.

In order to avoid this paradoxical situation the following recommendations should be considered. The first recommendation is on the ZEB definition criterion *energy performance*: establish clear minimum requirements, so that only energy efficient buildings are eligible as ZEB. In Norway this can be achieved adopting the definition of low energy and passive house buildings given in NS 3700 (2010). This is also in line with the recast of the EU directive on energy performance of buildings, EU (2010) that calls for the establishment of "cost optimal energy efficiency" requirements at national level. However, such requirements are yet to be defined as well as the common methodology for their evaluation; this should be defined at EU level within 2011.

The second recommendation is on the ZEB definition criterion *credits:* adopt credits that do not overemphasize the benefit of biomass and biofuels. Such a choice would reflect the fact that biomass is a limited resource and its availability varies significantly with the geographical area. On the contrary, solar energy is virtually unlimited and is available everywhere, even though with the due differences between low and high latitudes. To this respect primary energy credits seem to be more suitable than carbon emission credits. Alternatively, other credits could be defined. In Norway an example of alternative credits is given by the weighting factors described in Pettersen *et al.* (2005), which are based on the environmental cost analysis of various energy carriers. Given that electricity has a weighting factor of 1, the weighting factor they suggest for biomass is 0,35. This value is very different from the electricity equivalent factor of 0,04 given in Table 3 for carbon emission credits. Not surprisingly, it is similar to the value of 0,33 given here in the same table for primary energy credits.

Finally, another recommendation could be to assign a sort of priority to the generation options to be adopted for achieving the ZEB balance. This is what is done in Torcellini *et al.* (2006), where the generation options are categorised in four levels, and on-site generation options are given priority over the off-site generation options.

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