IMPLICATIONS OF WEIGHTING METHODOLOGIES ON ENERGY SYSTEMS IN NET ZERO ENERGY BUILDINGS

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Abstract

With the current movement towards Net ZEB the weighting methodology and specifically the weights adopted will have implications on the technologies that will be included in future buildings. A parametric analysis was conducted on six buildings of different typologies and climates to assess how different weights will impact the technological solutions that could be installed in a range of buildings. The feasibility to obtain the zero balance with the PV installable on the roof depends on the building shape and building demands in addition to the applied technology and the weights. Biomass boiler often requires the least amount of PV to reach the balance, frequently installable on the roof, while Gas boiler is the worst. Asymmetric factors, rewarding export, facilitate the achievement of the zero balance, while quasi-static factor (CO_2-monthly 2050) are quite demanding and only a few combinations are able to reach the balance with the available roof space because of the low credit for summer export. The selected weights and the resulting favoured technologies will lead to different building-grid interaction. Some solutions (e.g., all-electric building) will tend to use the grid as seasonal storage, while other solutions will have a net export of electricity to the grid to compensate for the other energy carrier(s) that they need (biomass, gas, district heating). Therefore, the implications for the different electricity grid networks resulting from the weighting methodology should be also considered.

Keywords: Net Zero Energy Buildings, Net ZEB calculation methodology, energy weighting and conversion, technology and energy carriers influence, asymmetrical weighting, political weighting

1 Introduction

The need to reduce greenhouse gas emissions and depleting fossil energy resources highlights the importance to improve the performance of buildings, one of the major contributors of carbon dioxide emissions and energy consumer sector. Within this context, the EU Directive on Energy Performance of Buildings (EPBD) requires all new buildings to be Nearly Zero Energy Buildings by 2020 [1]. However, despite the current emphasis on Nearly or Net Zero Energy Buildings (Net ZEB), a clear definition of the Net ZEB concept is still lacking and it would impact many aspects, including the balance calculation and therefore the promotion of specific technological and efficiency strategies (and/or use of different energy carriers). The International Energy Agency (IEA) 'Towards Net Zero Energy Solar Buildings' [2] has been focusing on the multisided nature of the "Net Zero Energy Building" concept, listing its characterizing aspects and the several options available to policies makers when establishing a (national) Net ZEB definition [3] [4] [5]. In addition to assessing the balance, significant effort has been carried out with the objective to characterize the building related energy generation and energy consumption and therefore the interaction of the building with the grid, leading to the proposal of several indexes [5] [6] [7] [8] [9]. Both the building energy load and generation are time dependent and, therefore, a Net ZEB normally relies on the electricity (or district heating) grid to store the excess production for the disfavoured times.

Although each possible Net ZEB definition addresses the same overall scope (i.e., the reduction of environmental impact of the building in terms of greenhouse gas emissions or primary sources consumptions) this target can be achieved with largely different technological and design solutions. Generally, a Net ZEB is obtained by energy conservation and efficiency measures coupled with renewable energy generation. Each Net ZEB definition includes specific methodology to calculate the building energy balance needed for the verification of the achievement of prescribed performance targets. Several important aspects play a role in the definition and therefore influence the balance calculation. Among other factors, are worth mentioning the physical boundary (single building, group of buildings and location of renewable energy systems like on-site or off-site), the balance boundary (included specific energy loads like e.g. heating, cooling, ventilation, DHW, lighting, appliances, central services, electric vehicles, and embodied energy), the metric (e.g., final energy, primary energy including or excluding renewable parts, energy cost, carbon equivalent emission), and the balance period (see [5] for detailed discussion). Marszal et al. [6] and Voss et al. [10] present a comprehensive overview of the calculation methodology options available. The different methodology alternatives influence architectural solutions, energy systems, sources and products as well as the relative market development. Furthermore, a definition may lead towards a reduced number of feasible or favoured technology solutions, as some topologies turn out to be preferable compared with others. The influence of building regulations on the utilized technology systems has been documented [11]. Of specific importance is the definition of the metric utilized in the balance as well as the specific weighting factors applied to each energy carrier. Sartori et al. [12] assessed the implications that a specific definition (both for primary energy or carbon equivalent emission with defined weighting factors) has on the investigated heating systems for typical Norwegian houses. Kurnitski et al. [13] investigated the energy performance and cost optimality of different construction and technical systems. They reported the lowest total primary energy consumption for heat pumps based on Estonian current national factors. Stephens [14] investigated the influence of climate on passive and active measures for typical US home to size the required photovoltaic (PV) and assess the building dependence on the grid. The work mentioned above is relevant, however, to our knowledge, no study has investigated the influence that different weighting methodologies have on technological systems for a range of building types in different climates.

This paper investigates the influence that different weighting methodologies employed to assess the Net ZEB balance have on the selection of building technical systems and the balance. The weighting methodology is influence both by the value of the weight for the different carriers as well as by the nature of the weight (e.g., static, asymmetric, quasi-static). This paper presents a parametric analysis to investigate how the choice of energy carriers, the metrics and the weighting methodology used impact the energy balance for a variety of buildings and technical system options in several countries (expressed as the size of the required PV system). Herewith the practical feasibility of possible future scenarios as well as the interaction of the building with the grid for these investigated scenarios is assessed. The current analysis demonstrates how some technology could be favoured or disfavoured with specific definition choices. These implications should be taken in consideration by policy makers in the development of legislation, since they will impact the technologies that may be favoured in the buildings of the near future and therefore the grid networks.

2 Methods

A parametric analysis was performed on six European case studies of different typologies and climates to assess the impact of policy decisions on the technologies that may be favoured or discouraged. These cases are representative of typical Net ZEB buildings being designed built in Europe, whose information and data are available to the authors. As indicated previously, several aspects need to be specified when outlining a Net ZEB definition and the balance calculation procedure. Several parameters influence the balance, within this paper the impacts of balance weighting factors and the metric used were investigated. The paper refers to the different choices in the weighting methodologies as 'option', while the different energy systems are called 'technical solution'.

2.1 Tools for assessing the balance

The balance procedure defined in the "Net ZEB evaluation tool", an excel based tool developed within the subtask A of the above mentioned IEA Task40/Annex52 [2], was used. The study focused on the annual balance (between energy load and generation) of total energy considering only on-site renewable energy supply. Both primary energy and carbon equivalent emissions were considered and the balance methodology was carried out using simulated monthly data. These represent the most common calculation methodologies applied in building codes as indicated by [6]. The energy load and generation for each case study was simulated using appropriate tools fulfilling current national country regulations. In this way, we could evaluate the expected impact using simulation tools widely used in the countries. The energy demand of each building was not modified (same envelope qualities, window areas, buildings form and orientation, internal gains, occupancy profiles and boundary conditions) for the different combinations and included the demand for heating, cooling, domestic hot water (DHW), ventilation, auxiliaries, built-in lighting and plug loads as well as the specific inefficiencies of the systems and distribution.

The two German case studies “Die Sprösslinge” and “Kleehäuser” were calculated with the Excel based tool EnerCalC [15]. EnerCalC enables a building characterisation in terms of its energy use (usable energy, final energy and primary energy) and shows energy performance requirements for a building to be balanced in accordance with the German calculation regulation DIN V 18599. Furthermore, the program enables simplified static primary energy and carbon emission balancing in monthly resolution and provides information for designing the respective building as a "Net Zero Energy Building" according to the balance methodology of the above mentioned IEA program. A breakdown of different energy uses (heating, cooling, ventilation, domestic hot water, lighting) is possible as well as the input of monthly loads for additional consumers (e.g. appliances, IT, central services).

The calculations for ‘EnergyFlexHouse’ were performed with the Danish calculation tool Be10, which is the official tool for determination if a building complies with the energy requirements in the Danish Building Regulations. Be10 is a steady-state calculation tool based on mean monthly calculations. Be10 is mainly based on EU standards EN 13790, 15316 and 15193-1 and includes calculation of energy production from ST and PV but not CHP.

The Spanish case study ‘Circe’ was mainly calculated with the tool Calener GT, which is the official software tool provided by the Spanish government to perform the energy certification process. The tool Calener GT is used for big tertiary buildings and it is based on hourly simulations to determine the energy use (heating, cooling, ventilation, domestic hot water, lighting and auxiliary). Calener GT leaves equipment and appliances energy use outside the balance and some form of on-site renewable energy are considered in a simplified way. Details of Calener GT compared with other energy performance evaluation systems can be found in [16]. The monthly energy generation from renewables were computed with other tools based on hourly simulation: TRANSOL [17] and PVSyst [18].

The Swedish case studies were calculated using VIP Energy [www.strusoft.com] which is a dynamic calculation tool, validated with: IEA-BESTEST, ASHRAE-BESTEST and CEN-15265. Result data was summarised on monthly basis.

2.2 Parametric analysis

For each of the six case studies investigated, a parametric analysis was performed to assess how different weighting factors and technical solutions (needed to cover the buildings energy demand) would impact the Net ZEB balance. Different combinations of energy generating systems were tested in combination with different weighting factors. The area of PV panels needed to reach the Net ZEB balance was calculated as an indicator to compare the different technology combinations.

The following on-site energy generation technical solutions were considered:

1 Ground source heat pump (HP);
2 Gas condensing boiler (Gas);
3 Biomass boiler (Bio);
4 Gas powered combined heat and power plant (CHP);
5 District heating (DH)

Table 1 reports the efficiencies used for the different technologies in each case study. CHP technology solution was not considered for the Danish and Swedish case studies because of limitations in the used simulation software and because is not a common technology in these countries. Since the comparable indicator across the different combinations was the size of PV needed to reach the balance, all configurations included PV. Beside PV no other electricity generation option was considered (except electricity generated from CHP for some combinations). In addition, each technical solution was tested without and with solar thermal collectors (ST). ST was sized to provide 50% of DHW demand (load reduction), leading also to a reduction of the roof area available for PV installation according to their required space.

Table 1. Efficiencies for the energy generation systems considered by each case study.

Building	HP COP[1]	Gas boiler [%]	Biomass boiler [%]	CHP [%]	PV [%]	ST
Kleehäuser	4,3[3]	94[4]	67	99[5]	15	Flat plate
EnergyFlexHouse	3.5	98/107[2]	90	NA	15,5	Flat plate
Glasbruket	3.5	95	90	NA		
Die Sprösslinge	4,3[3]	94[4]	67	99[5]	15	Flat plate
Circe	3.5	98	88	70	15	Vacuum tube
Väla Gård	3.5	95	90	NA		

[1] Mean annual COP
[2] Full load and 30% load
[3] Water to water heat pump with outgoing flow temperature to underfloor heating of 35°C
[4] 1,03 if calorific value boiler is used
[5] With calorific technology performance

The weighting factors considered are summarized in Table 2. Some factors utilize as indicator primary energy (PE) while others carbon emission equivalents (CO_2). Table 3 to Table 5 indicate the values used for each factor. The weighting factors chosen for the analysis include static, symmetric, asymmetric and quasi-static (monthly changing) factors. We considered current national factors of the case study countries, a European common, although dated, standard (EN 15603). We also included other factors (asymmetric, quasi-static and Denmark (DK)-2020) close to finalization or that could be considered in the future, which are considered “strategic factors”. The strategic factors were simulated to evaluate the impact of different weighting strategies from the simple static and symmetric approach considered today that could be adopted in the future for a variety of reasons (e.g., favour export, favour systems and energy carriers, more appropriate account for the renewable fraction present in the grid). Table 3 summarizes the different national and European weighting factors used currently and in the near future. Weighting factors are a powerful tool for the policies makers to push the building stock transformation towards a specific direction. For the EN 15603 the non-renewable primary energy factors were used, for biomass we used the wood pieces conversion factors, while for district heating, since the factor would depend on the energy generation system producing the district heat (and the EN 15603 does not provide any factors), an average of the national values was selected (0,8 kWh_p/kWh_s for primary energy and 215 gCO_2/kWh_s for emissions of carbon dioxide equivalents). For the strategic factors in which only different electricity factors were considered, the current national factors were used for the other energy carriers. The Germany electricity asymmetric (PE-DE asymmetric) includes 2.8 for generation and 2.4 for demand for electricity, as summarized in Table 4. The quasi-static CO_2 monthly electricity factors for 2010 and 2050 were estimated based on [19] using a simulation with fixed weekly profile, and are reported in Table 5. The extremely values for the 2050 'Ultra Green' scenario are due to the a reduced demand, elevated contribution of renewables in the grid and increased transmission capacity. From Table 3 can be seen that electricity and gas have pretty uniform PE-factor, with EN15603 as the greatest values for both and low value of DK 2020 for electricity. The Swedish has a low CO_2-factor for electricity. For Biomass values have greater diversity ranging from 0 to 1 kWh_p/kWh_s for PE and 0 to 50 g CO_2/kWh_s for CO_2. Interesting situations are Spain that has 0 for both PE and CO_2 and Denmark with 1 for PE and 0 for CO_2. Some diversity can also be observed for DH, which may depend of the system used for generating DH in the different countries.

Table 2. Summary of the weighting factors used. The first three are static and symmetric; the next two are static asymmetric, while the last two are quasi-static symmetric. PE indicates primary energy and CO_2 carbon equivalent emissions.

Indicator	**Short Name**	**Explanation**
PE/CO_2	National Current	National static factors according to current national directives
PE/CO_2	EN15603	EU static factors according to EN15603, non-renewable part [20]
PE	DK 2020	Calculation result for Danish electricity and heating grid in 2020)
PE	DE asymmetric	Proposal from recast of German calculation regulation DIN V 18599 for asymmetric weighting of electricity (generation > load)
PE	DE asymmetric opposite	Opposite (compared to above option) asymmetric weighting of electricity (generation < load)
CO_2	EU Monthly-2010	Monthly (quasi-static) CO_2 factors for EU electricity grid in 2010
CO_2	EU Monthly-2050	Monthly (quasi-static) CO_2 factors for EU electricity grid in 2050

Table 3. Current national weighting factors for primary (PE) and carbon (CO_2) balance used in the different combinations investigated. The primary weighting factors are expressed as kWh_p/kWh_s, while the carbon weighting factors are in g CO_2/kWh_s.

Country		**Denmark**	**Spain**	**Germany**	**Sweden**	**EN15603, n. r.**	**DK 2020**
Energy carrier		PE-national, CO_2-national				PE-EN15603, CO_2-EN15603	PE-DK 2020
Electricity	PE	2.5	2.6	2.6	2.7	3.14	1.8
	CO_2	505	649	633	360	617	
Gas	PE	1	1.1	1.1	1.1	1.36	1
	CO_2	204	240	244	250	277	
Biomass	PE	1	0	0.2	0.2	0.09	1
	CO_2	0	0	6	50	14	
District heating	PE	1	0.11[2]	0.7	1.1	0.8[1]	0.6
	CO_2	192	26[2]	219	130	215[1]	
District cooling	PE		0.53[2]				
	CO_2		132[2]				

[1]Not part of the EN15603, average value across the countries of the case study buildings.
[2]Not part of the Spanish regulation. Values correspond to the district heating & cooling network in Barcelona.

Table 4. Asymmetric primary energy (PE) weighting factors for electricity. The asymmetry is given between electricity generation and load. For the other energy carriers current national factors were used. The primary weighting factors are expressed as kWh_p/kWh_s.

Energy carrier		PE-DE asymmetric	PE-DE asymmetric opposite
Electricity	Generation	2.8	2.4
	Load	2.4	2.8

Table 5. Quasi-static monthly CO_2 factors for EU electricity grid in 2010 and 2050 for electricity (CO_2-monthly 2010 and CO_2-monthly 2050). For the other energy carriers current national factors have been used. The carbon weighting factors are expressed in g CO_2/kWh_s.

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2010	378	377	367	349	342	346	350	345	354	357	370	377
2050	49	51	41	18	12	13	15	13	18	23	40	46

2.3 Description of Case studies

The parametric analysis described above was performed on six case studies. They were selected to attempt to encompass a variety of building types, climates, energy systems and energy carriers in an effort to generalize discussions and conclusions that would apply to several contexts.

Table **6** presents a general description of each building investigated whereas

Table **6** and

Table **8** present information regarding respectively the loads and the actual realized or planned technical solutions for each of the case study buildings. Only the two office buildings present cooling systems. Offices have greater consumption for lighting and plug loads, but reduced DHW load compared to residences. Interesting to notice the increased ventilation need for the nursery due to the requirement of this particular building type.

Table 6. Summary of case studies features. The study involved 3 residential buildings, 2 office buildings and one nursery.

Building	**Location**	**Building type**	**Gross floor area (m^2)***	**Energy infrastructure connections**
Kleehäuser	Freiburg, DE	Residential	2,965	Electricity and gas grid
Glasbruket	Malmö, SE	Residential	703	Electricity District heating
EnergyFlexHouse	Taastrup, DK	Residential	216	Electricity
Die Sprösslinge	Monheim, DE	Nursery	1,218	Electricity grid
Circe	Zaragoza, ES	Office and laboratories	1,700	Electricity and gas grid
Väla Gård	Helsingborg, SE	Office	1,671	Electricity

* Conditioned net floor area

Table 7. The load of each subsystem for each case study. They represents net loads (without system efficiencies), while the last column indicates the total end energy demand considering efficiency of generation, distribution and emission. The load for the auxiliaries has been either directly assigned to the associated categories or was incorporated directly in the 'total end energy demand' column.

Building	**Space heating**	**Cooling**	**Ventilation**	**DHW**	**Lighting**	**Plug loads & central services**[1]	**Total end energy Demand**[2]
	kWh/m^2 y						
Kleehäuser	28.6	-	5.2	17.3	13.9	5.4	70.2 (gas) 25.4 (el.)
Glasbruket	25.1	-	4.9 + 0.1	25.5	30.0		55.8

			Aux. energy				
EnergyFlexHouse	18.7	-	3.3	15.6	11.3		31.6
Die Sprösslinge	33.1	-	11.9	20.8	8.4	7.0	43.3 (el.)
Circe	23.1	3.8	4.8	6.0	19.0	23.1	17.6 (biomass) 46.1 (el)
Väla Gård	27.5	6.2	4.2 + 4.9 Aux. energy	1.6	14.8	14.7	45.8

[1] Includes appliances, elevators, moveable lights, IT and other electrical plug-in devices associated with building operation and use. It does not include e.g., plugged in electric cars.

[2] Includes system losses and loads not directly associated with any of the other loads indicated.

Table 8. Actual realized or planned energy system design for each base case. For the non-RES portion, the values in parenthesis indicate the system capacity (except CHP), while for the RES portion, the values in parentheses indicate the normalized end energy generation.

Building	**NON-RES**	**RES**		
		PV	**Wind turbine**	**Solar thermal**
Kleehäuser	Gas CHP (30 kW_{th}, 14 kW_{el}; 23.4 kWh_{el}/m^2y)	23 kW_p (7.7 kWh_{el}/m^2y)	26.5 kW (21.5 kWh_{el}/m^2y; off-site)	60 m² (7.8 kWh_{th}/m^2y)
Glasbruket	District heating	34 kW_p (41 kWh_{el}/m^2y)	-	108 m^2 (36.7 kWh_{el}/m^2y)
EnergyFlexHouse	GSHP + air to water/air heat pump	10.6 kW_p	-	4.8 m^2
Die Sprösslinge	GSHP (28 kW_{th})	49 kW_p (31.9 kWh_{el}/m^2y)	-	42 m² (12,5 kWh_{th}/m^2y)
Circe	GSHP (66 kW) + biomass boiler (160 kW)	5.3 kW_p (4.3 kWh_{el}/m^2y)	6 kW_p (7.9 kWh_{el}/m^2y)	6.4 m^2 (3.4 kWh_{th}/m^2y)
Väla Gård	GSHP	67.5 kW_p (38 kWh_{el}/m^2y)	-	

Note: PV= Photovoltaic, CHP = Combined heat and power plant, GSHP = Ground Source Heat Pump

2.3.1 Kleehäuser

The two apartment buildings "Kleehäuser" were built in Freiburg (Germany) in 2006. Freiburg is located in a sunny region of Germany that offers mild winters and risks of overheating during summer times. Nevertheless the climate challenge is based on heating and therefore an overall efficiency concept was necessary to meet the low demand goal. The ownership association followed the requirements of the 2000W-society (goal to consume an average of less than 500 watts of primary energy per person for residential use) and have the "zeroHaus" certification. This led to a highly insulated building envelope and a total primary energy demand less than 100 kWh/m²y (normative consumers without user specific consumptions) verified via a mandatory monitoring. Passive house design and energy conservation strategies (e.g. LED lighting, shared freezers and drying rooms or washing machines with hot water connections) enable to match the reduced primary energy consumption by energy generated with a combination of a small scale CHP plant, ST, two PV systems, and a share in external wind turbines [21].

2.3.2 Glasbruket

The proposed five dwelling terraced house was designed to be built in the city of Malmö (Sweden), a heating driven climate with reduced available of solar radiation for PV production. The building has a large roof (roof pitch 20°) and façade towards south-southwest, 200° (180°=south) with integrated PV modules. On the very top of the roof, which is horizontal, not integrated solar thermal collectors are mounted. The building is designed to be connected to the electricity grid and district heating network. The building relies on district heating for space heating and DHW. Additional information is available in [8].

2.3.3 EnergyFlexHouse

The EnergyFlexHouse® consists of a two-storied single-family house built in 2009. It is located in Denmark, a heating driven climate but with overheating risk during the summer if measures for prevention are not applied. EnergyFlexHouse is designed with focus on utilization of daylight. It has a ground sourced heat pump mainly for space heating via under floor heating, an air to water/air HP which recovers energy from the exhaust ventilation air (after a passive heat exchanger) and either preheat the fresh air or the domestic hot water. The domestic hot water is also preheated by ST collectors that together with a large PV area on the house roof make it a Net ZEB even including the household electricity. For simplification only a GSHP is considered in the calculations and the ST collector area is reduced to 4 m² is order to achieve a solar fraction on 50% on DHW.

2.3.4 Die Sprösslinge

This nursery was completed in 2009 in Monheim (Germany) as carbon-neutral building according to the EcoCommercial Building Program [22]. Since Monheim offers beside risks of overheating in summer a heating challenge, the building concept includes mostly efficiency components like good insulation and heat recovery. The energy consumption is reduced thanks to an optimised thermal insulation, maximum daylight utilisation, passive cooling measures and a solar thermal system. Heating consumption is covered by a geothermal heat pump. The electricity generation of the PV system equals the demands of building services and all user related equipment. The building is all-electric [21].

2.3.5 Circe

The Circe office building is located in Zaragoza, Spain, and is operational since June 2010. Climate in Zaragoza is characterized by extreme winters with local wind from the north and hotter summers when 35 °C is reached during several days. The building has a compact structure consisting of two floors with three main elements: a round core topped by a dome, the office rooms around the core and a rectangular body for laboratories. One of the main goals of the designers was to reduce the heating and cooling demands in a low-embodied energy building and using local and bioconstruction materials. Several passive solutions are used to reduce the building energy demands including the operation of the Greenhouse corridor around the core. Additionally, the thick walls are able to store energy and therefore reduce heating demand. For covering the space heating and cooling loads there is a ground coupled electric heat pump supported by a condensing boiler in the heating season. Radiant floor is used both for space heating and cooling. A ST system covers part of the DHW demand. Two other on-site renewable energy production systems are present: PV system and wind turbine.

2.3.6 Väla Gård

This two-story office building was built in the southern parts of Sweden in 2012. It has two main buildings with double pitched roofs, connected by a smaller building with a flat roof, a geothermal heat pump system, with four heat pumps located at the building site and variable speed compressors eliminating losses caused by stopping and starting of the system. Free cooling is extracted from the bore holes during summer. Roof sides facing southwest are equipped with PV panels. The geothermal heat pump system is sized to be able to cover also the load from the future buildings.

3 Results and Discussion

3.1 Influence of technologies and factors on reaching the balance

The following sections present and discuss the results from the simulations for the six cases considered, including the influence of technologies and weighting on reaching the overall net zero energy balance. Table 9 summarizes the fraction of the combinations reaching the balance with the PV installed on the available roof area. Approximately 43% of all combinations reach the balance with the available roof space, of which 47% with PE factors and 38% with CO_2 factors. A great influence on the fraction of successful combination can be attributed to the final energy demand of the different buildings (see Table 7). The PE-DE asymmetric is the weighting option with the greatest frequency of achieving the Net ZEB target using only the available roof area for PV (74%) because it rewards export by providing a greater factor for generation than for load; the opposite is true for the asymmetric opposite option (30%). The quasi–static CO_2-monthly 2050 has the lowest frequency (11%) of reaching Net ZEB because it has low factors for electricity during summer months when the highest PV production occurs and higher factors for electricity during winter times when import of electricity from the grid occurs. This is to reflect the predicted 2050 abundance of electricity available in the grid and high fraction of electricity from renewable sources during these months. As a consequence, this weighting option reward export during the summer months less than other factors. Therefore, with the current technologies and these factors Net ZEBs would not realistically be achievable with current technologies. For instance, even the flat nursery “Die Sprösslinge” that offers a good ratio between available roof area for PV and GFA no technological option has a roof area is large enough for the installation of the needed PV. Overall, the highest PV-areas occur for the gas powered solutions CHP and Gas, while HP and Bio, even with CO_2-monthly 2050 factors, could potentially be feasible for some buildings. With CO_2-monthly 2010, more combinations reach the balance with the available roof space, but none of those with CHP. For CHP indeed the ratio of lower summer credits for electricity generation and a high conversion factor for gas supply is not favourable. Bio (67%) and Gas (28%) are the technologies reaching the balance the most and least frequently (as Bio offers the best and Gas the worst conversion ratio, see Table 3), respectively, due to the greatly different factors (especially for CO_2) among these two carriers. However, the simulation for PE-DK 2020 indicate that HP (50%) and DH (33%) tend to reach the balance more frequently than the discouraged Bio (17%); this is because the PE-DK 2020 have relatively high factor for Bio to promote other technologies, especially DH and HP.

Table 9. Fraction of the tested combination without ST reaching the balance with the available roof space for all the case studies and technologies considered.

	PE-national	PE-EN15603	PE-DK 2020	PE-DE asymmetric	PE-DE asymmetric opposite	CO_2-national	CO_2-EN15603	CO_2-monthly 2010	CO_2-monthly 2050
HP	50%	50%	50%	83%	17%	50%	50%	33%	17%
Gas	33%	33%	17%	67%	17%	33%	33%	17%	0%
Bio	83%	83%	17%	83%	50%	83%	83%	83%	33%
CHP	33%	33%	33%	67%	0%	67%	33%	0%	0%
DH	50%	50%	33%	67%	50%	50%	33%	33%	0%

The figures below (from Figure 2 to Figure 7) present the amount of normalized PV area needed to reach the yearly Net ZEB balance for the combinations without ST, expressed as the ratio between the PV area needed and the GFA. The discussion often uses median values as metric of comparison with the goal of avoiding giving excess importance to single values different from the rest of the distribution. The combinations with ST have similar trends with lower PV required. The values range from 0,11 (for Danish house with Bio and CO_2-national) to 6,41 m^2/m^2 GFA (for the German nursery with CHP and CO_2-monthly 2050).

Figure 1, Figure 2 and Figure 3 present the normalized PV areas for the residential buildings (German apartment building Kleehäuser, the Swedish Glasbruket apartments and the Danish single family EnergyFlexFamily house). For apartment buildings is quite challenging to reach the balance with PV installation on the available roof space; none of the combination simulated for the German Kleehäuser and only 15% for the Swedish Glasbruket are actually able to reach the balance with the PV installation on the available roof space; this highlights the challenge for medium- and high-rise buildings to satisfy the energy needs with only PV installed on the roof, suggesting that often additional RES needs to be considered. This was already done in the built Kleehäuser apartments where a share of an external wind turbine was purchased. Different is the case for the two-story compact low-energy Danish EnergyFlexFamily house for which it is feasible to reach the balance (94% of the tested combinations), except for the CO_2-monthly 2050 factors. For this factor set only HP and Bio are able to reach the balance with the available roof space.

For the Kleehäuser apartments the area is greatly reduced by the installation of ST (median of 21%), due to the use of DHW by all the apartments, while the PV needed is only reduced by approximately 6%. For Glasbrucket the installation of ST to cover 50% of DHW demand leads to a reduction of available area for PV of 12%, while the PV needed is reduced by only 9%. Therefore, from a yearly balance standpoint may be better to occupy the roof with PV panels rather than ST collectors when using this technology and weighting options. The Glasbrucket apartments reach the balance 19% for the combinations without ST and 11% of those with ST. Three combinations (one for HP and two for Bio) reach the balance without ST but not with ST. However, a great reduction in PV area needed is observed for the CO_2-monthly 2050 when adding ST indicating that with factor minimally rewarding export, it makes sense to favour self-consumption. On the contrary, almost no impact on the PV area needed is observed between combinations with and without ST for PE-EN15603. For the EnergyFlexFamily house the reduction in the available area for PV installation with ST is approximately 6%, while the PV needed has a median reduction of 9% (19% with CO_2-monthly 2050).

For the Glasbrucket apartments only combinations with Bio (6 out of 9) and HP (1 out of 9) are able to reach the zero balance. For both the Glasbrucket and Kleehäuser apartments Bio is the most favoured technology for the factors considered (6 of 9 factor sets for Kleehäuser, 7 out of 9 for Kleehäuser), while Gas is often the worst technology due to its poor conversion factor and reduced efficiency. For DK 2020 the favoured solutions are DH and HP, while for CO_2-monthly 2050 is HP (although no combinations reach the balance for the apartments). For all the technologies the PE-DE asymmetric is the factor requiring the least amount of PV, except DH for the Glasbrucket apartments for PE-EN15603, due to the lower DH EN value compared to the Swedish DH value (0,6 versus

1,1 kWh_p/kWh_s. CHP (included in the Kleehäuser apartments) also requires reduced PV areas, except for CO_2-monthly 2010 and 2050 for which it needs the greatest amount of PV due to the not favourable ratio between gas supply and electricity generation in these weighting options.

For the EnergyFlexFamily house HP is the preferred technology with PE factors, except for PE-EN15603 for which Bio is favoured due to its quite low conversion factor that promotes biomass use, while other factors, including the PE-national Danish, are stricter and discourage Bio. Indeed, for all other PE factors (that use the Danish factor for Bio) Bio requires the greatest amount of PV. The PE-DK 2020 requires somewhat higher PV-area, but the ranking is unchanged with HP and DH favoured, while Bio and Gas are discouraged (which was the political intention). For the CO_2 factors Bio is the preferred technology, ranging between 0.11 and 0.15 m^2/m^2 GFA, for all weighting options due to the factor value of zero of the CO_2-national Danish factors. On the contrary, Gas requires the greatest PV-area to reach the balance (between 0.16 and 2.13 m^2/m^2 GFA). For each technology, the weighting factor that requires the least amount of PV is the PE-DE asymmetric for HP and Gas, the CO_2-national for Bio and the PE-EN15603 for DH.

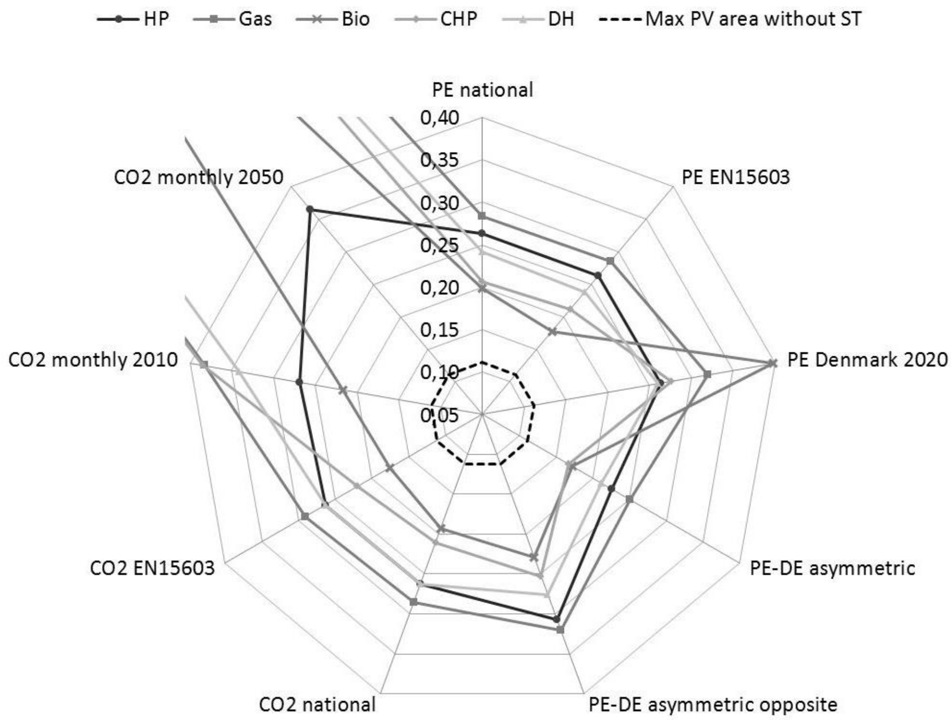

Figure 1. Normalized PV areas for the different combinations needed to reach the Net ZEB for the Kleehäuser apartments. The dashed black line indicates the maximum PV area installable on the roof. Gas boiler, Biomass boiler, CHP and DH for CO_2-monthly 2050 are out of the scale reaching 3.51, 0.95, 6.14 and 2.87 m^2 PV/ m^2 GFA, respectively.

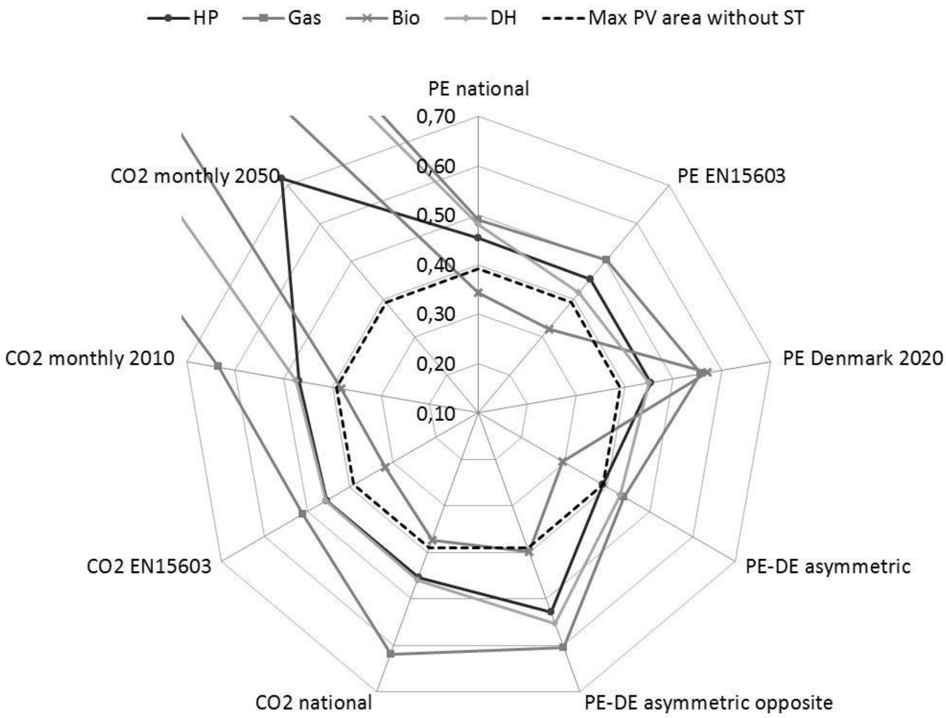

Figure 2. Normalized PV areas for the different combinations needed to reach the Net ZEB for the Glasbruket apartments. Gas boiler, Biomass boiler and DH for CO_2-monthly 2050 are out of the scale reaching 5.99, 1.63 and 3.19 m^2 PV/ m^2 GFA, respectively.

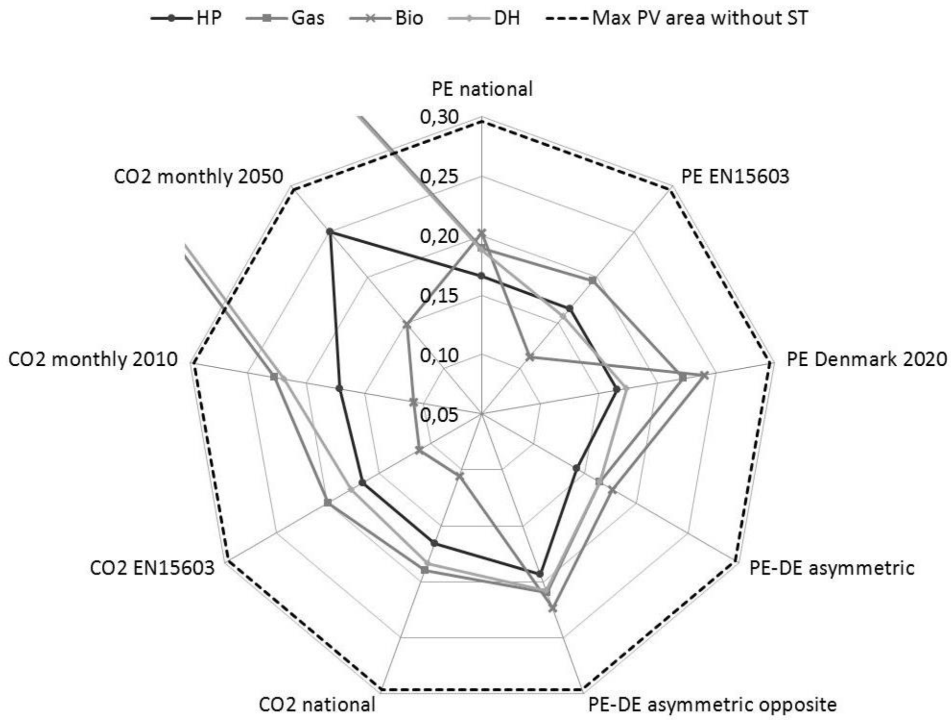

Figure 3. Normalized PV areas needed to reach the Net ZEB for the different combinations for the Danish EnergyFlexFamily house (m^2 PV/ m^2 GFA). Gas boiler and DH for CO_2-monthly 2050 are out of the scale reaching 2.13 and 2.03 m^2 PV/ m^2 GFA, respectively

The results for Die Sprösslinge nursery are summarized in Figure 4. Approximately 70% of the combinations simulated are able to reach the balance with the available roof area, partly due to the fact that the building is only one storey and, therefore, has a elevated ratio between roof area and GFA. Similarly to what observed for the other German case, CHP is the best technology for PE-DE asymmetric, DH for PE-DK 2020 and HP for CO_2-monthly 2050. Again, PE-DE asymmetric (all can reach the balance) and CO_2-monthly 2050 (none can reach the balance) are the best and worst factors respectively, for all technologies. Only HP and Bio are able to reach the balance with CO_2-mothly 2010. The installation of ST does not impact the feasibility to reach the balance since the amount of PV needed is reduced by the same amount, on a median basis, of the available area.

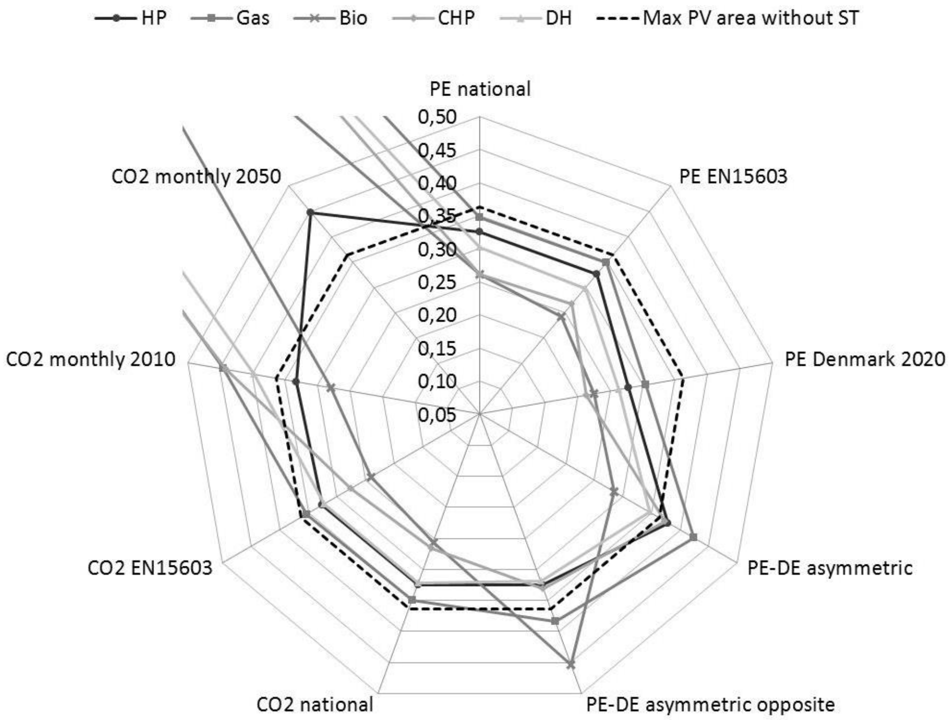

Figure 4. Normalized PV areas for the different combinations needed to reach the Net ZEB for the nursery Die Sprösslinge. Gas boiler, Biomass boiler, CHP and DH for CO_2-monthly 2050 are out of the scale reaching 3.67, 1.04, 6.41 and 2.91 m^2 PV/ m^2 GFA, respectively.

Figure 5 and Figure 6 show the normalized PV area for two office buildings, the Spanish Circe and the Swedish Väla Gård. Approximately half of the combinations are able to reach the balance with PV installed on the roof for Circe and 25% for Väla Gård. Therefore, office buildings in diverse climate regions could reach the balance if correct measures are implemented and technologies (with the associated energy vectors) are chosen. All the technologies reach the balance with PE-DE asymmetric for both buildings, while only Bio for Circe for the CO_2-monthly 2050. For both buildings the influence of ST is minimal due to the low DHW loads (see Table 3) compared with other case studies. The reduction of the available area for PV installation is 1.5% for Circe and 0.9% for Väla Gård, while the median reduction in the needed PV installation is 1.9% for Circe and 0.7% for Väla Gård. Bio is the favoured technology (followed by DH for Circe and HP for Väla Gård) for all weighting options except for the PE-DK 2020 for which is HP and CO_2-monthly 2050 for Väla Gård for which HP is favoured. In Spain Bio is extremely favoured because of the zero value used for both PE and CO_2, while DH is also quite low, whereas the PE-DK 2020, as indicated previously, has low electricity and DH factors, while relatively high Bio factor. CHP reaches the balance with CO_2-national, but not with PE-national; similarly, DH reaches the balance with PE-EN15603 but not with CO_2-EN15603. These two examples demonstrate that when the combinations are near the balance small difference can determine if the solution will reach or not the Net ZEB balance, with the available roof surface.

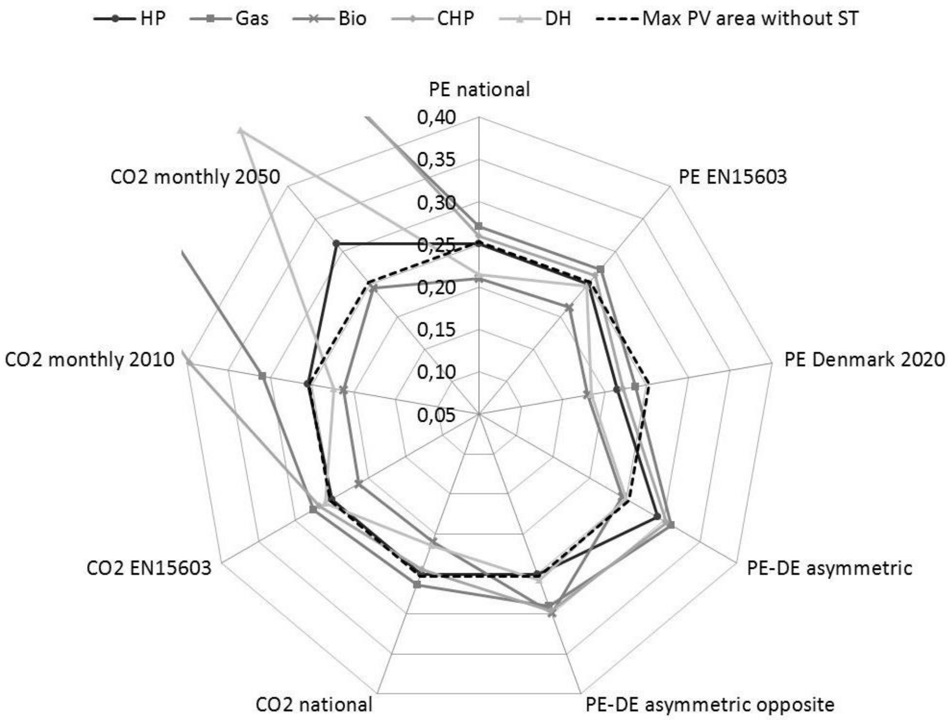

Figure 5. Normalized PV areas for the different combinations needed to reach the Net ZEB for the Spanish office building Circe. Gas boiler, CHP and DH for CO_2-monthly 2050 are out of the scale reaching 1.63, 2.85 and 0.49 m^2 PV/ m^2 GFA, respectively.

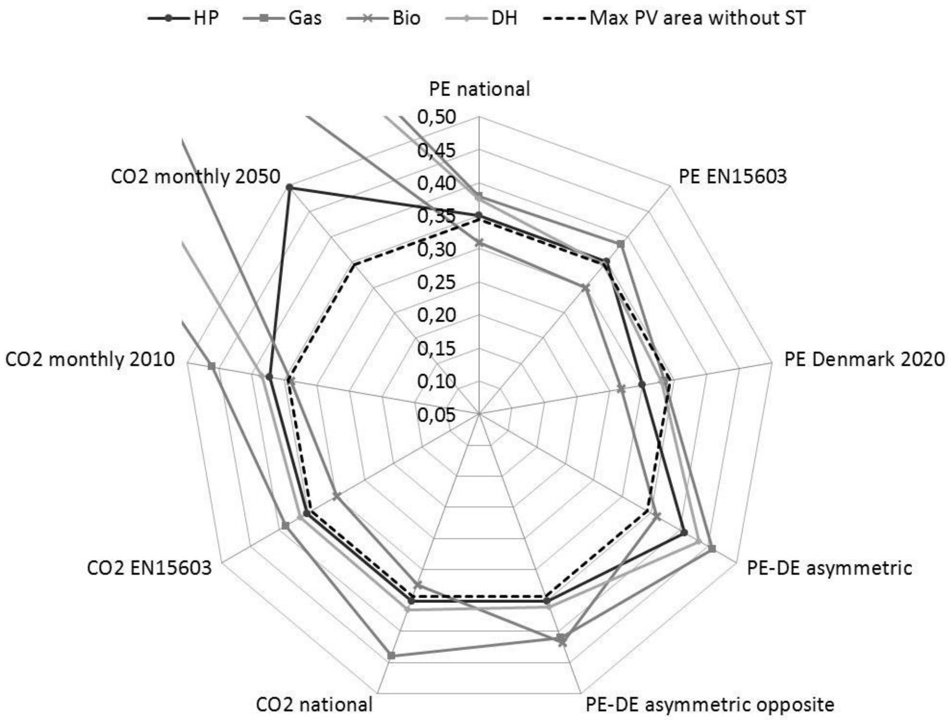

Figure 6. Normalized PV areas for the different combinations needed to reach the Net ZEB for the Väla Gård office building. Gas boiler, Biomass boiler and DH for CO_2-monthly 2050 are out of the scale reaching 2.99, 0.94 and 1.68 m^2 PV/ m^2 GFA, respectively.

Table 7 summarizes the preferred technology (from a yearly balance standpoint) for the different building-factor combinations for the solutions without ST. This table highlights the importance of the metric, its political emphasis and factors used on the technology that may be advantaged for reaching the zero balance. For 72% of the combination Bio is preferred, followed by the all-electric solution HP for 19%, DH (6%) and CHP (4%). The PE-EN15603, CO_2-EN15603, CO_2-national and CO_2-monthly 2010 always favour Bio as for these cases, except the Danish case, the non-renewable part is considered in the conversion factor lowering the values. The fact that for 72% of the combinations the Bio is preferred raises questions regarding whether, in the context of EPBD implementation, the low conversion factors chosen are in line with sustainability of forest and agriculture (without import from abroad) even considering very efficient or zero energy buildings [23]. Possibly, a higher value to limit deforestation and land depravation should be considered, as done in Switzerland where the primary energy conversion factor for wood was politically increased to 0.7 kWh_p/kWh_s.

The only current national factor that favour different technologies with PE and CO_2 factor are the Danish that favour HP with PE-national and Bio with CO_2-national (see the different values in Table 2). DH and HP are favoured by the PE-DK 2020, while CO_2-monthly 2050 tends to favour HP, although the needed PV area is quite elevated. For PE-

DE asymmetric (favouring electricity export) CHP is also favoured for two of three building tested. For the Spanish Circe the Bio PE factor of zero favoured even more the Bio technology. The fact that HP is often the favoured technology for CO_2-monthly 2050 is attributable to the fact that with low factors when export occurs is often better to self-consume the produced electricity instead of exporting to compensate for a different carrier. However, the zero CO_2 factor for the Bio favour greatly this technology, even for the CO_2-monthly 2050. Adding ST to cover 50% of DHW, reducing the roof area available for PV installation, can help reaching the yearly balance for some applications and combinations (almost half). For instance, it assists reaching the balance with several CO_2 factors, but it has a negative effect for apartment buildings with elevated DHW share; additionally, it has a minimal impact on the feasibility of reaching the balance for offices with lower DHW demand.

Table 7. Summary of favoured technology for all buildings and factors considered without ST.

	PE-national	PE-EN15603	PE-DK 2020	PE-DE asymmetric	PE-DE asymmetric opposite	CO_2-national	CO_2-EN15603	CO_2-monthly 2010
EnergyFlexHouse	HP	Bio	HP	HP	HP	Bio	Bio	Bio
Kleehäuser	Bio	Bio	DH	CHP	Bio	Bio	Bio	Bio
Glasbruket	Bio	Bio	DH	Bio	Bio	Bio	Bio	Bio
Die Sprösslinge	Bio	Bio	DH	CHP	Bio	Bio	Bio	Bio
Circe	Bio	Bio	HP	Bio	Bio	Bio	Bio	Bio
Väla Gård	Bio	Bio	HP	Bio	Bio	Bio	Bio	Bio

3.2 Assessment of building-grid interaction

In addition to determine the amount of PV needed to obtain the balance, the virtual (on a monthly basis) building self-consumption of the produced electricity and its interaction with the electric grid were investigated. **Error! Reference source not found.** presents a typical yearly electric load and generation profile of an all-electric Net ZEB in European and North American climates. The specific shape of the curves would be different for buildings using also other energy carriers. Section A in the figure is the electricity overproduction which is fed into the grid, B is electricity shortage which is not covered on a monthly basis by own generation and therefore supplied by the grid connection and C is the self-covered demand. Hence, A+C is the total electricity generation.

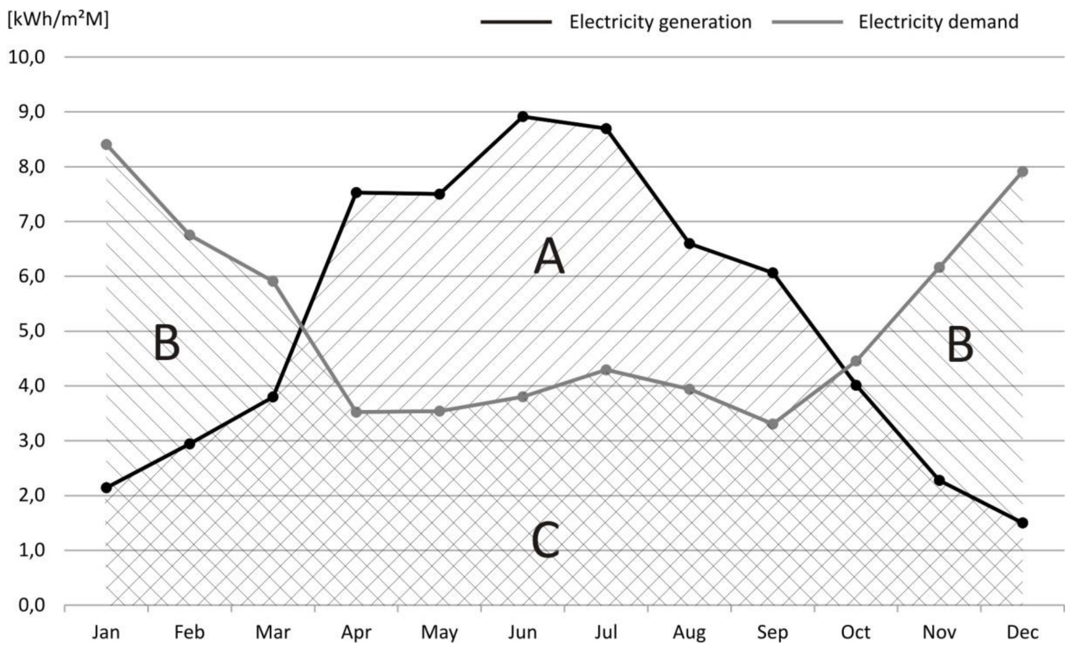

Figure 7. Typical annual generation and load profile for a Net ZEB in the northern hemisphere.

To characterize the interaction between the building and the electricity grid the supply cover factor (γ_s) indicating the self-consumption, as described by [24], and the Energy Carrier Compensation Factor (ECCF) were evaluated for one of the investigated cases, the German daycare Die Sprösslinge. These parameters are calculated as follow:

$$\gamma_s = \frac{C}{A+C}$$

$$ECCF = 1 - \frac{B}{A} = max\left[0;\ 1 - \left[\frac{\sum_{year} max\left[0, \left(l_{el}(m) - g_{el}(m)\right)\right]}{\sum_{year} max\left[0, \left(g_{el}(m) - l_{el}(m)\right)\right]}\right]\right]$$

Where $g_{el}(m)$ and $l_{el}(m)$ are the monthly electricity generation and load. The ECCF illustrates the fraction of the electricity overproduction that is exported to the grid to compensate (from an yearly balance standpoint) for the other energy carrier(s) being imported. These factors are useful to understand the virtual interaction between the building and grid to make consideration about what impact certain weighting and solutions could have on a specific grid network. These factors could also be applied to Nearly ZEB and Plus ZEB leading to different findings not discussed within this paper.

Error! Reference source not found. illustrates the two factors for PE-national for Germany and PE-DE asymmetric. With PE-DE asymmetric the γ_s (indicating which fraction of the production is self-consumed) is greater because a smaller PV installation is needed to reach the balance due to the lower amount of export required leading to a greater fraction being self-consumed. The technology reaching the highest share of self-consumption is HP (all electric building) followed by the Bio (due to the low Bio factor that require a small PV installation and reduced export). However, the virtual behaviour of these two technologies with respect to the grid is quite different since HP utilize the grid and re-import all the exported electricity (with symmetric and static factors), while the other technologies considered export more than they re-import to obtain the credits necessary to compensate for the other energy carrier they are using. CHP is the technology with the lowest share of self-consumption because of the additional electricity production of the CHP. When adding ST the γ_s increases for technologies using other energy carrier because the export is smaller and the heat needed to be generated by the technology is smaller. The ECCF is often inversely proportional to γ_s indicating that the not self-consumed production is exported to compensate for a different energy carrier. The ECCF for an all-electric building (HP) is 0, while it would be elevated for CHP since the winter electricity deficit is limited. With PE-DE asymmetric the ECCF often decreases compared to PE-national because the elevated credit for electricity export lead to smaller PV installation required and proportionally smaller compensation for the other energy vector. The ECCF for Bio is 0 for PE-DE asymmetric because of the low factor for Bio and the elevated credit for electricity export.

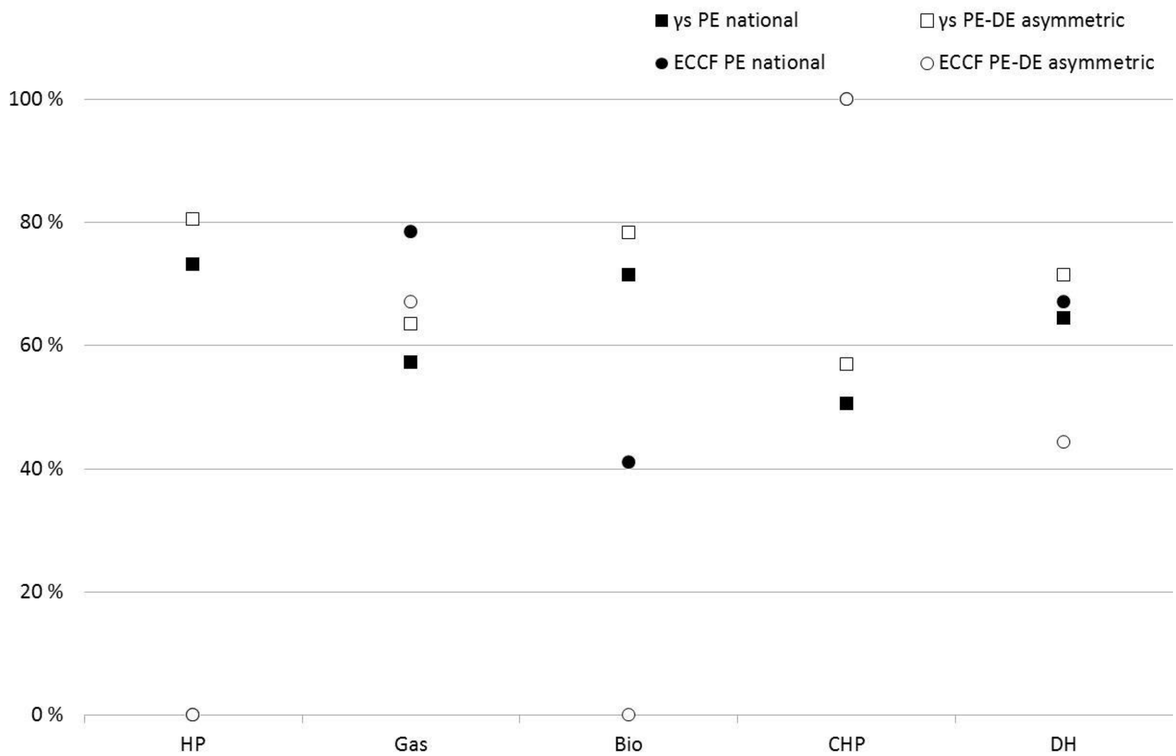

Figure 8. γ_s and ECCF for the PE-Germany and PE-DE asymmetric factors for the German daycare Die Sprösslinge.

Figure 9 illustrates the γ_s and ECCF for the CO_2-national for Germany and the CO_2-monthly 2050. The γ_s and the ECCF for the PE-national and CO_2-national for Germany are generally similar as the PV areas are also similar (see Figure 4). The γ_s for CO_2-mothly

2050 are small and lower (often even by 50%) than CO_2-national because of the oversized PV areas and constant demands; therefore, the grid should be able to absorb the excess production. The ECCF for CO_2-monthly 2050 are much greater than CO_2-national because due to the oversized PV needed only a small fraction of the electricity is re-imported. Even for the all-electric building (HP) due to the low summer values of the quasi-symmetric factor, only a fraction (65%) of the exported electricity is re-imported, therefore leading to a positive balance with the electricity grid.

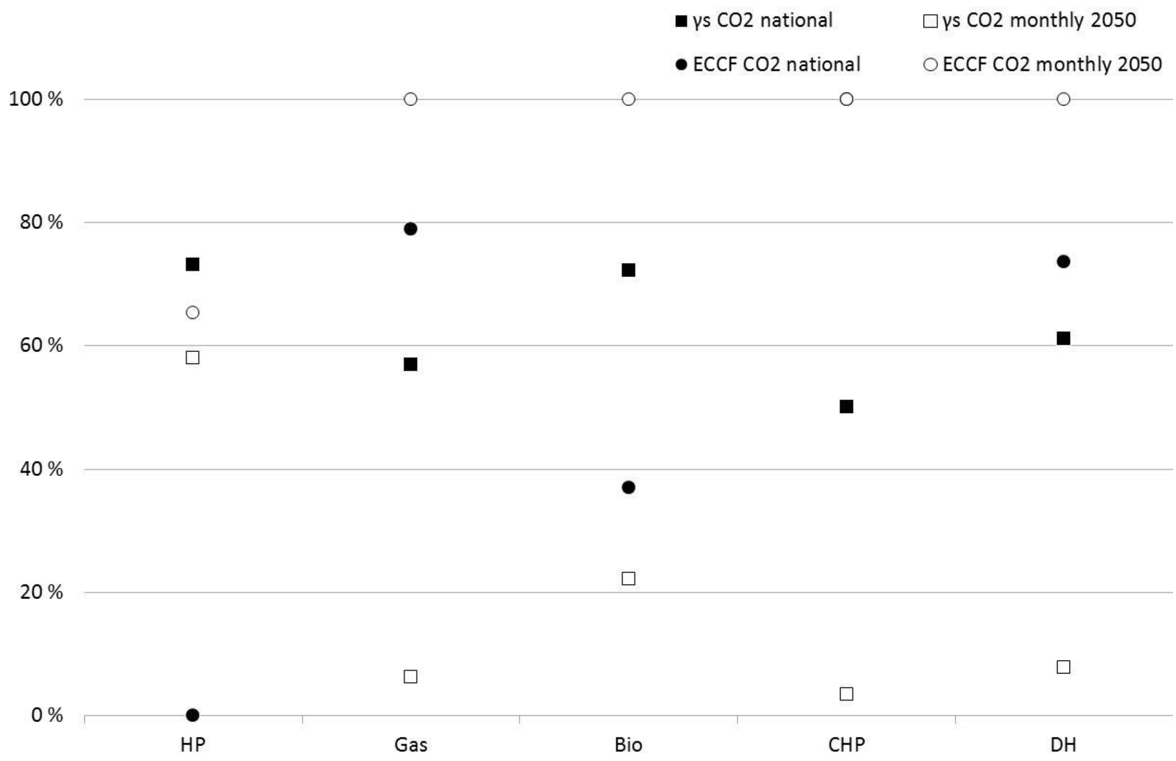

Figure 9. γ_s and ECCF for the CO_2-Germany and CO_2-monthly 2050 for the German daycare Die Sprösslinge.

The Renewable Energy Ratio (RER) proposed by REHVA (according to prEN 15603:2013 [25]) was also tested for the German daycare centre "Die Sprösslinge". The RER was calculated (see **Error! Reference source not found.**) for the equalized annual CO_2/primary energy balance of the five heating technologies and associated energy carriers (each with and without ST) and the same four weighting options used in Figure 8 and 9. For all the cases with symmetric weighting (PE and CO_2) the RER fits to the equalized balance results and is equal or above 100 %. In case of all-electric solutions no fictive electricity import or export occurs and therefore the RER is exactly 100 %, since the two numbers are identical. The amount of PV needed to reach the balance also influences the RER. For instance the good RER for Gas is due to an increased PV-area which is needed to reach an equalized energy balance. The fact that the RER takes into account both renewable and non-renewable portion for all imported and exported energy carriers influences the values depending on the carriers used. The elevated RER for gas-CHP, compared to Bio that has similar PV area, is due to the additional electricity produced which is a byproduct of the heat generation and used to cover on-site demands or to compensate the non-renewable gas import in the primary energy balance by its weighted export. If asymmetric primary energy factors are used the RER-result is always lower than 100 % as the annual overall electricity export is lower than would be really needed without the asymmetric fictive adjustment in the PE balance. This has an impact of the RER-calculation as the on-site generation is included without any weighting. In this case CHP solutions have the lowest RER as the gas supply is not covered with a higher electricity generation and weighted export. This is increased due to the use of CHP-electricity in the PE balance and the therefore smaller PV-capacity compared to other solutions. The use of non-static weighting factors (CO_2-monthly 2050) leads to RER much below 0 % except for HP. This is because, due to the much lowered summer credits, the annual electricity export greatly exceeds the energy demand. For HP solutions, electricity demand and generation are similar. The use of ST lowers the overall demand of the building and therefore the weighted import of any energy carrier. The highest influence of lowering the primary energy demand is visible for solutions with high PE factors of the energy carrier used for heating. For both symmetric and asymmetric weighting the RER-results tend to be closer to 100 % with ST compared to without because, due to the reduced building overall demand, there is reduced import and associated export needed for compensation.

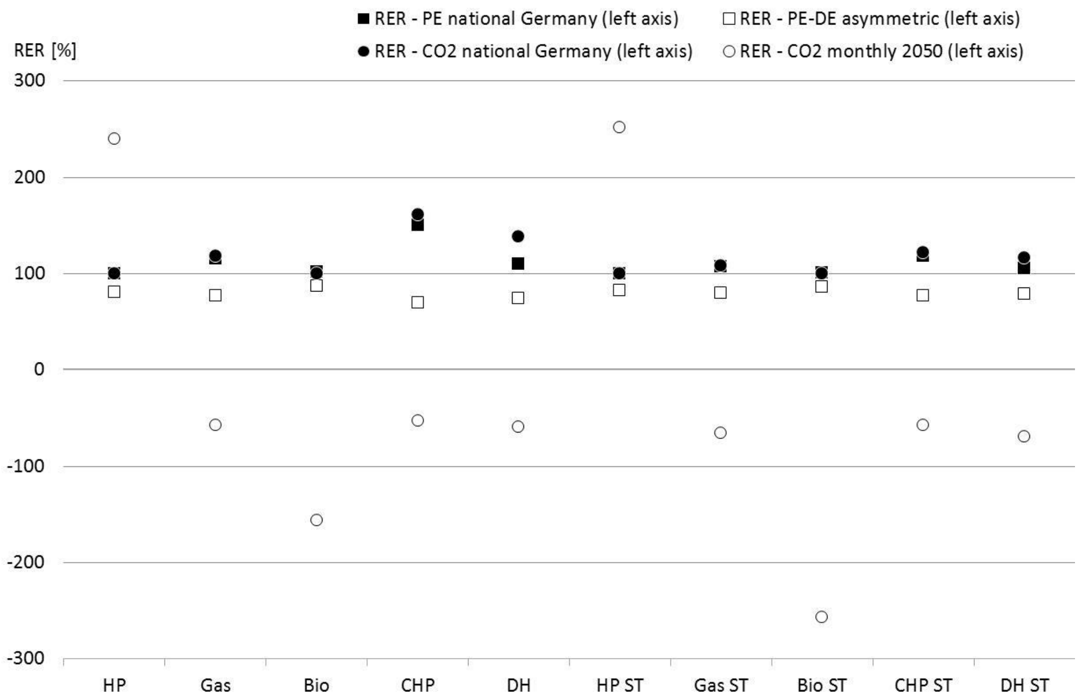

Figure 10. RER results according to four different weighting factor solutions. The primary energy respectively CO2 balance is zero in all cases. Source University of Wuppertal

4 Conclusions

The different weighting options and factors used to calculate the annual balance have a strong impact on the technologies that facilitate the achievement of the Net ZEB balance. Considering the requirement of the EPBD, these technologies will likely be favoured in the future since they will require less on-site RES to reach the balance with implications of the construction market, energy market and grid networks just to name a few. Generally speaking, the feasibility to reach the balance with the PV installable on the roof depends on the buildings loads, shape, technological solutions and energy carrier used. For tall building (e.g., apartment complexes) with reduced installable PV areas compared to GFA it is challenging to reach the balance and additional RES must be encountered. For these buildings, it is even more important to adopt good passive and energy efficient solutions; for shallow compact buildings with extended roof area compared to the GFA, it is feasible using current technologies and weighting to reach the balance with the roof space. For the diverse factors investigated (static symmetric from four different countries, asymmetric and quasi-static), it was observed that Bio is often the favoured technology, while Gas is the worst, requiring less amount of PV (often installable on the roof) compared to other technologies. It remains the question whether policies that greatly favoured the use of Bio is sustainable for European and Worldwide forests. A different picture is observed for PE-DK 2020 for which DH and HP are favoured, while Bio is discouraged. The PE-DE asymmetric factors reward export facilitating the achievement of the balance and require less PV to be installed. Indeed, even for the all-electric solutions less electricity is generated than consumed. On the contrary, it is extremely challenging with the current technologies to obtain the balance with the CO_2-monthly 2050 factor because of the reduced credit being provided for the electricity export during the summer months (when overproduction occurs). The building must produce greatly more electricity than consumed (often 50% more) to offset the lower credits received for the export. For these conversion factors HP is advantaged because it would only utilize the electricity factors and not having to compensate for a different energy carrier. It is debatable if these weighting scenarios fit to the original aims to reduce the overall energy demand and CO_2 emissions of the building sector, the primarily idea of a Net ZEB. The installation of ST tends to have a small impact on the feasibility of reaching the balance, especially for office building (where DHW demand is lower). Considering that the installation of ST would subtract roof area for the installation of PV (or other uses), several broader aspects must be considered.

Additionally, it is clear that the factor decision and the consequently technology adopted have a strong impact on the interaction between the building and the electricity grid. Generally speaking, solutions requiring low PV areas lead to greater self-consumption and lower energy carrier compensation (export electricity to obtain credit to compensate for a different energy carrier). All-electric building will utilize the electricity grid as a seasonal storage (export in summer and import in winter), while buildings utilizing different carriers will export summer overproduction to the grid and re-import only a fraction because the remaining will be used to compensate for the other carrier. As a consequence, the grid network should be flexible enough to adapt to the different interactions. Adding ST will increase self-consumption for all technologies expect HP since the energy produced is directly used compared to PV production.

5 Acknowledgments

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