Trade-offs for a cost-efficient transformation of the residential buildings sector

Sam Hamels

February 2020

NEPBC

Table of contents

Trade-offs for a cost-efficient transformation of the residential buildings sector

Sam Hamels

1. Introduction

A conceptual framework for the transformation of the buildings sector

Climate scientists have made clear that CO_2-equivalent emissions[1] should be reduced by 80-95% by the year 2050. Within the buildings sector, this could mean that *net-zero* emissions should even be achieved, because there are several other sectors that are more difficult to decarbonize[2]. It has been estimated that more than 90% of the European building stock needs to be adapted to make this possible [1]. That can be partially realized by replacing existing buildings with newly built ones, but large-scale renovation will also be inevitable. The future building stock will largely consist of buildings that have already been built today. However, both the newly built- and renovation rates are currently much too low to realize the 2050 goal. Assuming that newly built- and renovation activities will gather the necessary pace, billions of euros will be spent on the decarbonisation of the building sector across the next decades. Allocating these resources *efficiently* is a critical success factor and thus one of the main challenges policy makers are facing today.

In Belgium and other European countries, resources going towards the transformation of the buildings sector are mainly focused on reducing its primary energy use (PE). Energy performance requirements have been introduced for both renovation and newly-built activities, primarily aimed at the reduction of a building's heat demand[3,4]. This can be framed as a strategy to reduce carbon emissions (CE), but the perspective taken in this report is that these two should in fact be distinguished as separate goals. The final end-goal of any measure that is taken as part of the transformation of the buildings sector – and in fact, the goal of that transformation itself – is ultimately to either reduce PE or CE. While the measures taken to reach each goal can to some degree overlap, a *cost-optimal* transformation requires a dedicated focus on what it is that policy makers really want to achieve.

Many different measures can be taken, spread across various parts of the energy system as depicted in figure 1a. On a basic level, PE and CE 'occur' at one of two 'locations' in the (building related) energy system. Either the heating system of a building locally consumes fuel (typically heating oil or natural gas), causing a certain primary energy use and (local) emissions. Or, the building is heated by a technology that relies on electricity or district heat. In this case the PE and CE take place at the other ends of the respective grids (i.e. where electricity or district heat is generated). The simplified representation in figure 1a can be used as a tool by providing a framework of reference. It should however be noted that more complex situations can occur when, for example, the electricity consumed by a buildings' heat pump is partially produced by a local solar PV installation. In this case, the PE and CE of the building occur at both 'locations' in the schematic (A and B)[5].

---

[1] Henceforth referred to as CO_2-emissions, carbon emissions (CE), or simply 'emissions'.

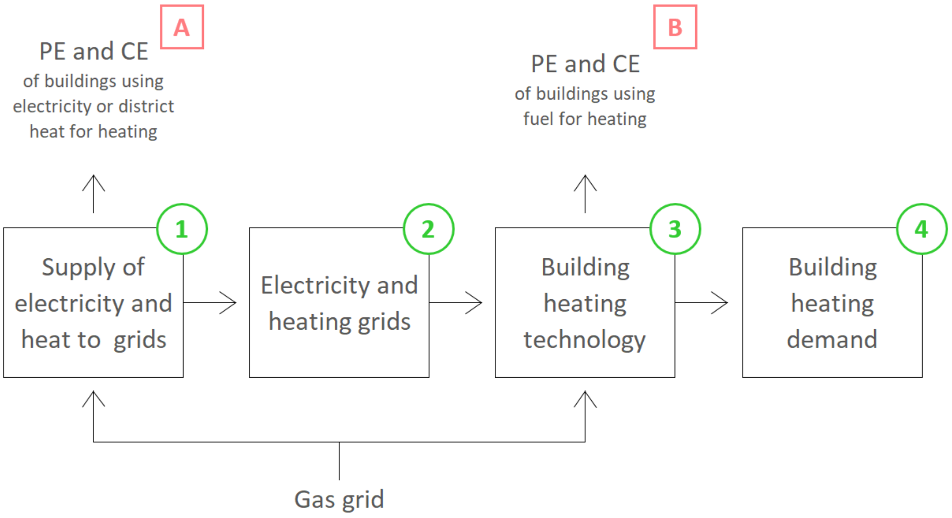
[2] These typically include the steel, cement, aviation, shipping and agricultural sectors. They are considered to be both *technically* more difficult as well as *more expensive* to decarbonize.

[3] Depending on the country and climate, reducing cooling demands may also be considered.

[4] The term 'heat demand', as used in this report, is in line with what is called '*netto-energiebehoefte*' within the Flemish context.

[5] Although electricity generated by a PV installation is associated with zero operational carbon emissions (i.e. the only emissions related to the operation of the heat pump in this case, occur at location 'A'), it *may* be attributed

Figure 1a: Origins of PE and CE associated with building heating demand



Source: Self-generated

Numbers 1 to 4 in Figure 1a represent the various parts of the energy system where measures can be taken to reduce PE and CE. For example, the electricity generation system can be further decarbonized ('1'), an old non-condensing gas boiler can be replaced with a new and highly efficient condensing boiler ('3'), or the insulation of a building could be improved to reduce heating demand ('4'). Measures taken at the level of electricity and district heating grids (number 2) do not directly reduce PE or CE, but they can be required to *enable* those reductions. Some reductions in PE and CE require a *shift* from 'B' to 'A'. For example, a building's emissions can be reduced by switching from a gas boiler to a heat pump, in which case the CE related to that building shift from 'local emissions' coming out of the building's chimney ('B'), to 'non-local' emissions that originate in the electricity generation system ('A'). If such measures are taken at a large scale, additional investments in the electricity distribution and transmission grids may become necessary ('2'). Hence, these 'grid investment measures' are taken within the context of reducing PE and CE, even though they do not directly result in those reductions themselves.

Once a goal is chosen (i.e. reducing PE or CE by a certain amount), the question arises which combination of measures – spread across 'locations' 1 to 4 – achieves that goal at the lowest cost. In other words, what is the *cost-optimal package of measures* to achieve a stated goal? Answering this question is very challenging, due to the complex nature of both the building energy use itself, as well as the interplay with electricity and district heating systems.

Figure 1b illustrates that three trade-off's can be distinguished when determining the cost-optimal package. First of all, the optimal package will consist of a certain *balance* between demand and supply-side measures. This distinction, as proposed in this report, helps us to separate all measures that are directly aimed at reducing a building's heating demand (e.g. roof insulation, high performance windows, wall insulation, etc.) on one side, and *all other* measures aimed at reducing PE or CE on the other side. This distinction is useful because the policy debate around the transformation of the buildings sector tends to focus rather heavily on what we here call 'demand side' measures. Hence, one point that needs to be stressed in the debate – by highlighting this particular trade-off – is the

---

a positive PE (e.g. 1 kWh_{PE}/kWh_e, depending on the PE accounting methodology, see section 2.2). Hence, part of the PE associated with a building with this setup would occur at both locations ('A' and 'B').

need to avoid an exaggerated focus on either side and instead to seek an optimal balance between the two.

The second trade-off depicted in figure 1b is the trade-off between 'energy efficiency' (EE) and 'renewable energy' (RE) measures. This alternative distinction coincides with the fact that EE and RE are often framed as the two main pillars that policy makers need to focus on within the context of the building sector transformation. On one side, all measures that somehow reduce our energy use, can be labeled as 'energy efficiency measures'. This does not only include measures that reduce heating demands, but also all 'supply side' measures that reduce PE. For example, choosing for a local heating system with a higher efficiency, of switching to district heating altogether (which can also reduce the overall PE, depending on the point of reference). On the other side, all measures that increase the share of renewable energy in the building sector's overall energy use, can be labeled as 'renewable energy measures'. Typical measures of this kind include investments in solar PV or heat pumps, but increasing the share of renewable energy in the electricity generation system or in the heat supply of a district heating network can also be labeled as such[6]. These measures typically focus on *decarbonization* (CE reduction), although an increase in renewables also has an impact on PE[7].

Finally, a trade-off can be identified between measures that are taken at the 'individual building level' and measures taken at the 'societal level'. By the former, we mean each measure that can in principle be taken by an individual homeowner. These measures can of course be taken at a large scale as well, thereby realizing PE and CE reductions 'at the societal level', but we reserve the term 'societal level measures' for those measures that can *only* be taken at the societal level. For example, a decision to invest in electricity or district heating grids cannot be made by an individual homeowner. Such decisions can only be made at the broader societal level, which can vary from the neighborhood or city level, to the national or even European level. For certain societal level measures, the most appropriate decision level may lie at the city-scale (e.g. the construction of a district heating grid, which is typically highly customized to local circumstances), while it may lie at the European level for others (e.g. the optimal build-out of a European renewable electricity system, which will to a large degree rely on the interchange of available renewable electricity across country borders). Similar to the previous two trade-off's, an optimal *balance* will need to be struck between 'individual' and 'societal level' measures. In addition to a trade-off, these terms also reflect two separate *levels of analysis* at which the identification of a cost-optimal package of measures can occur. When the cost-optimal package is determined for a single individual building (e.g. the perspective of a single homeowner), measures that can only be taken at the societal level are 'out of scope' (cf. chapter 2). In the framework of figure 1a, measures on this level of analysis can only be taken at 'locations' 3 and 4. Meanwhile, if we take the perspective of the policy maker that wants to reduce the PE or CE of the entire building stock, *all* potential measures ('1 to 4' in figure 1a) are included in the analysis (cf. chapter 3).

---

[6] Other noteworthy RE technologies include solar thermal and various forms of biofuels like solid biomass and biogas. In addition, green hydrogen could be categorized under RE, although hydrogen is more typically categorized as an *energy carrier* rather than a *source* of (renewable) energy.

[7] In the electricity sector, there are also non-renewable technologies available to achieve decarbonization, like nuclear energy and carbon capture and storage (CCS). However, these technologies are not focused on in this report.

Figure 1b: Taxonomy of measures and trade-off's to reduce primary energy use and carbon emissions associated with buildings

MEASURES

to achieve reduction **GOALS** (i.e. reducing PE or CE)

TRADE-OFF'S

in the cost-optimal package of measures

	Demand vs Supply side	**Energy Efficiency vs Renewable Energy**	**Individual vs Societal level[5]**	**Reduce or shift**	Measure location in Fig. 1a **1 to 4**	Reduction location in Fig. 1a **A vs B**
Reduce annual heating demand[1]	D	EE	I	Reduce	4	A or B[10]
Temporally shift electricity/heating demand[2]	D	EE / RE[4]	I	Reduce	3	A or B[10]
Same individual building heating technology but upgrade efficiency	S[3]	EE	I	Reduce	3	A or B[10]
Change individual building heating technology	S[3]	EE / RE[8]	I	Reduce	3	A or B[10]
Add solar thermal to individual building	S[3]	RE	I	Reduce	3	A or B[10]
Add solar PV to individual building	S[3]	RE	I	Reduce	3	A
Same district heating technology but upgrade efficiency	S	EE	S	Reduce	1	A
Change district heating technology	S	EE / RE[8]	S	Reduce	1	A
Change electricity generation technology mix	S	EE / RE[8]	S	Reduce	1	A
Build district heating grid	S	n/a[9]	S	Enable shift from B to A	2	n/a
Upgrade electricity (transmission and/or distribution) grid[6]	S	n/a[9]	S	Enable shift from B to A	2	n/a
Increase controllable electricity generation capacity[6,7]	S	n/a[9]	S	Enable shift from B to A	1	n/a

1: Includes all measures that improve building insulation and ventilation. In the Flemish context, this measure refers to the 'netto energiebehoefte'. Although not the focus of this report, cooling demand could also be included in this 'measure'.

2: The goal of this measure is to shift demand away from sub-annual periods with a relatively high PEF or CI and towards periods with a relatively low PEF or CI. The temporal scale of the sub-annual periods can range from seasons to hours. For example, an electrochemical battery or a heat pump that is operated in a 'smart' way, can shift the timing of a building's electricity consumption on a timescale of a few hours. Meanwhile, long-term heat storage technologies can shift heat from the summer to the winter period (i.e. in large-scale water tanks).

3: It should be noted that our framing of these measures as 'supply side' is somewhat arbitrary. While we only consider the heating demand itself as the 'demand side', the alternative definition 'everything on the building side' could also be used (i.e. such that changes to the building heating technologies or the inclusion of PV would also be considered 'demand side'). In that case, only the supply of heat, fuels and electricity from 'outside the building' would be considered the 'supply side'.

4: Shifting electricity demand to periods with a low PEF can be seen as an EE measure, while shifting towards periods with a low CI can be seen as a measure that makes more or better use of RES in the electricity system.

5: Each 'individual building level' measure can be extrapolated to various societal levels (city, country, etc.). Hence, measures are only categorized as 'societal level' if they *cannot* be taken at the individual building level.

6: Required to some degree when building sector heating is increasingly electrified.

7: The degree to which controllable capacity is needed in the (future) electricity generation system is a subject of ongoing academic research and debate.

8: Depending on the technology, a relative improvement can be realized in either the PE, CE or both.

9: Although these measures can be seen as 'enablers' for the energy efficiency improvements and the increase in renewable energy, they cannot be classified directly as EE or RE.

10: Depends on whether the pre-existing (or new) heating technology uses local fuel combustion, electricity, or district heat.

It is important to note that there are not only trade-off's between different potential measures, but also *synergies*. For example, reducing a buildings' heat demand ('demand side' measures) allows for a smaller dimensioning of the heating system and, if the case of a heat pump, a cheaper electricity grid and a smaller electricity generation capacity ('supply side' measures). In some cases, certain measures on one side of a trade-off are *technically necessary* to enable the use of measures on the other side of the trade-off. For example, a sharp reduction in heating demand may be necessary to enable a connection to a low-temperature renewable district heating system. Several trade-off's are at play in this example. A "demand-side", "energy efficiency", "individual building level" measure is required to unlock a "supply-side", "renewable energy", "societal level" measure.

Relying too heavily on any single category of measures (e.g. 'demand side measures') is disincentivized by the fact that their abatement costs (irrespective of whether PE or CE is being abated) increase in a non-linear fashion. In other words, all measures aimed at the reduction of the PE and CE associated with the buildings sector are subject to diminishing returns. A prime example of this is the improvement of a buildings' insulation thickness. While a rudimentary improvement of insulation can be highly cost-effective (especially if the starting point is an old and poorly insulated building), each *additional* centimeter of insulation material will result in a lower reduction of PE and CE. Meanwhile, the associated costs continue to increase linearly. Diminishing returns can be further exacerbated when a more ambitious improvement of a buildings' insulation becomes increasingly *complex* to realize (e.g. due to the building's geometrical characteristics). Ultimately, the consequence of diminishing returns is the fact that alternative measures become more attractive at a certain point. For example, a 'tipping point' can be identified beyond which any further investments in demand-side measures become more expensive than alternative supply-side measures with the same effect in terms of PE or CE reductions. Similar tipping points can be identified for the other trade-off's. RE at some point becomes cheaper than EE, and societal-level measures at some point become cheaper than individual-building level measures.

In some cases, it may not only be sub-optimal to rely too heavily on measures that lie at one side of a trade-off, but it may also simply be *infeasible*. For example there are certain limitations on the use of biomass for heating, because the supply of sustainable biomass is limited. The degree to which may vary on a country-by-country basis, but the fact that there are supply limitations that need to be taken into account is out of question, especially if the supply is restricted to waste-streams (i.e. avoiding the use of virgin biomass)[8]. Similarly, there are certain limitation on the maximum amount of hydro, wind and solar power that can be generated in the electricity system, especially within the scope of individual countries. In the case of Germany, it has been shown that these maximum potentials could easily be exceeded if the *current* heating demands of the German building stock would have to be met exclusively with electricity from renewables [2]. It is therefore abundantly clear that the cost-optimal package will always consist of a *mix* of measures that lie at each side of the various trade-off's.

Where the optimum lies is largely driven by 'local circumstances' other than the supply-limitations of renewable energy. At the individual building level, the geometric characteristics of a building can heavily influence the costs and benefits associated with certain measures. Herein lies a major difference between newly-built and renovation projects, as the former have the freedom the take those measures into account in the design process (e.g. room for thick insulation layers, etc.), while the latter do not. Developing and implementing custom-made solutions to help reach very low PE or CE levels – for buildings with an almost unlimited variety of unique characteristics – can be an

---

[8] In addition to the supply-side limitations for biomass, regulators may also limit or even forbid the use of biomass in certain jurisdictions. For example, traditional firewood stoves may be forbidden in dense urban areas to safeguard local air quality levels.

extremely costly endeavor. Especially because most existing buildings have not been designed with the possibility of a ‘deep retrofit’ in mind. From the same individual building perspective, the availability of a district heating network to connect to can similarly be seen as a ‘local circumstance’ that needs to be taken into account.

At both the individual and societal levels of analysis, the local *climate* also drives the relative merits of different measures. For example, local levels of solar irradiation co-determine the relative attractiveness of solar energy technologies. And similarly, local temperatures co-determine the relative attractiveness of EE and demand-side measures. A cost-optimal package likely consists of much more ambitious insulation measures in very cold climates, as opposed to locations with a milder climate.

The cost-optimal balance between different kinds of measures is not necessarily the same at the individual building level and the societal level. In fact, they may even be *contradictory*. A solution that is optimal at the individual building level may not be so at the societal level and vice versa. Some case studies have shown that renewable heating technologies are never part of the cost-optimal package for individual buildings (they are estimated to be ± 20% more expensive)[3]. However, it is still feasible in these cases that the cost-optimal approach at the *societal level* does include a large share of RE. Changing the incentives at the individual building level may then be necessary to steer individual decisions towards the societal optimum. This also means that individual homeowners at some locations may need to be strongly *disincentivized* to choose for certain measures. For example, it may be desirable from a societal cost-efficiency point of view to disincentivize homeowners in a certain neighborhood from installing solar PV and heat pumps, if the local electricity distribution grid is exceptionally expensive to upgrade. Likewise, deep retrofits may need to be disincentivized in areas where a low-cost, renewable and high-temperature district heating grid is (potentially) available, if the goal is to realize the societal cost-optimum [4].

The scope of this report is limited to cost-optimality from a techno-economic perspective. Identifying what is cost-optimal from this perspective is already immensely challenging, especially if the analysis is performed at the societal level. However, it should be noted that this leaves many important aspects out of scope. First of all, there are many non-energy benefits related to the various measures discussed in this report. For example, homeowners that improve the insulation and ventilation of their buildings may also benefit from a decrease in moisture, mold and draught related issues, and an improvement in indoor air quality. In a similar fashion, the aesthetics and market value of a building may be improved. Another element that is out of scope in this report is the macro-economic impact of a roll-out of certain measures. For example, large-scale renovation activities or a sharp increase in the share of RE in the electricity sector, can potentially affect GDP growth and employment figures. Depending on the degree to which these measures are supported by subsidies and other fiscal measures, they may also have a large impact on the government budget. Finally, another aspect that is not taken into account in this report is mobility and urban planning. To efficiently reduce the PE and CE related to the buildings sector, a large role may need to be played by densification and reducing the transport needs associated with buildings that are located in isolated rural areas. Inefficient urban planning and the transport demands it gives rise to (in addition to the higher costs for providing public utilities) can be associated with a high amount of PE and CE, but it is extremely challenging to integrate into the models discussed in the following chapters.

Reflections on the current policy approach

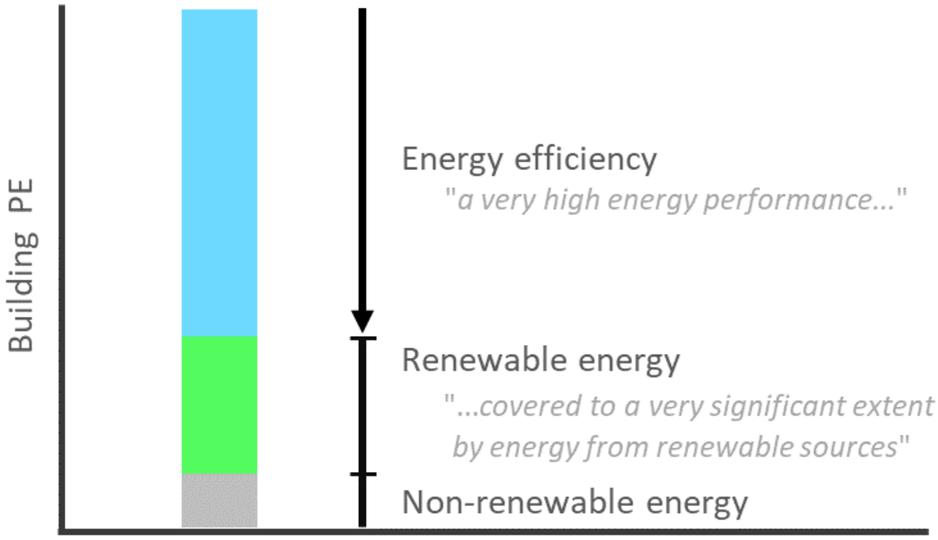
The transformation of the buildings sector has been actively driven by policy for more than a decade. At the European level, the most relevant policy initiatives are the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED), which have both received a significant update in 2018 [5,6]. These updates have officially entered into force in July and December of 2018 respectively, and now have to be implemented into the national legislation of EU Member States by mid-2020. The updates include more stringent targets towards the year 2030 and several novelties like the introduction of a 'smart readiness indicator' for buildings, but the overall reasoning of the framework has remained unchanged.

The central concept in the EPBD is Nearly-Zero Energy Buildings (NZEB's), which is defined as follows in the 2010 version of the Directive:

> *"[…] a building that has a very high energy performance […]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources […]"*

The reasoning behind the NZEB concept is illustrated graphically in figure 2. From a methodological point of view, we can label NZEB's as a simple *heuristics* approach to the transformation of the buildings sector. The first heuristic is to reduce as much as possible the primary energy use, while the second is to cover the remainder as much as possible with renewable energy. While this has the benefit of being easy to understand for policy makers and citizens across the EU, it should be noted that – in terms of concrete implementation – there is no consensus about what the expressions "nearly zero" or "very low" mean in practical terms. Moreover, the NZEB concept (in and of itself) does not put forward a need to find an *optimal balance* between different kinds of measures.

Figure 2: Graphical representation of the NZEB framework



Source: Self-generated

In the EPBD more broadly, the idea of identifying a cost-optimal package of measures *is* put forward to some degree. The 2010 version of the Directive introduced an ‘official calculation methodology’, aimed at the identification of cost-optimal levels of *primary energy use*. In this ‘EPBD method’, the main emphasis lies on the balance between the cost of energy efficiency improvements on one hand, and the resulting decrease in energy costs on the other. The method was introduced as part of a larger process put forward by the EPBD, which goes as follows. First, Member States are asked to use the EPBD method to perform a range of studies that identify the ‘cost-optimal’ level of PE for existing (i.e. to be renovated) and newly-built dwellings. Second, the Member states are then advised by the EPBD to put their energy performance requirements for renovations and newly-built projects at this identified ‘cost optimal’ level. Finally, the Directive urges Member States to take the necessary measures that can help reduce the cost optimal level further in the future, with the aim of eventually lowering it to the level of NZEB’s. An overview of the studies performed in this context – across many different European countries – is provided in [7]. Several of these studies concluded that the long-term goals for the buildings sector will *not* be reached, if measures are limited to the identified cost-optimal levels [8–10]. A more detailed description of the EPBD method is provided in chapter 2, alongside a discussion of the official studies that were performed within the Belgian context.

The prioritized end-goal of the EPBD, its central NZEB concept and its proposed calculation method, is the reduction of primary energy use instead of carbon emissions. In fact, estimating the reduction of carbon emissions is not even included (explicitly) in the EPBD method. The name of the Directive also stresses this prioritization; it is called the *Energy* Performance of Buildings Directive instead of the *Emissions* Performance of Buildings Directive. Renewable energy technologies are ‘included’ in the framework and its proposed method, but are only looked at from the perspective of how they perform in terms of primary energy use. For example, solar PV is seen as a way to reduce a buildings heating related primary energy use, even if the building does not use an electrically-driven heating technology. If a reduction in CE would be prioritized instead, investments in PV and heat pumps would be evaluated primarily on the basis of how much emissions they help avoid.

In terms of the three trade-off’s identified in figure 1b, the EPBD framework is heavily skewed towards one side of each of them. First of all, it is skewed towards demand-side measures and away from supply-side measures. To achieve the goal of a low PE, NZEB’s primarily aim to reduce a buildings heating (and cooling) demands, while supply-side measures that can (perhaps more efficiently) help reach this goal, are paid less attention to in the approach. Examples of such supply-side measures are district heating grids and the reduction of PE in the electricity sector. If the energy system is considered more broadly than it is within the EPBD, the heavy reliance on demand-side measures can be put into question.

In terms of the second trade-off, the EPBD focusses more heavily on energy efficiency measures than on renewable energy measures. Renewable energy is mentioned in the NZEB definition, but only as a suggested means of providing the remaining “nearly-zero” energy demand. Not as an *alternative* for the relatively extreme energy efficiency levels that are proposed in the NZEB concept. A few Member States (including Belgium) have put an explicit emphasis on renewables in their implementation of the EPBD [11]. However, in these rare cases, a secondary ‘renewable energy production requirement’ is simply added on top of the existing energy efficiency requirements. Energy efficiency requirements remain of *primary* importance.

Thirdly, the EPBD approach is skewed towards individual-building level measures, and away from societal-level measures. This is again implied in the name; the Energy Performance *of Buildings* Directive. Buildings are considered more or less in isolation from the rest of the energy system, even though they are heavily intertwined in practice with the electricity generation and transport system, and (in some cases) with district heating grids. The supply of (decarbonized) electricity and heat by generators outside of the building premises is considered a mere boundary condition. In the latest revision of the EPBD in 2018, the ‘skewedness’ with regards to each of the three trade-off’s, and the near-compete focus on the PE-reduction goal, have each remained fully intact.

In the following chapters, we further explore the challenges related to identifying the cost-optimal package of measures to reach a certain reduction goal for PE or CE. In chapter 2, we first consider how to tackle this challenge at the individual building level. In the first section, we discuss a calculation method that can be applied to both newly built as well as renovation projects, and for both the goals of reducing PE or CE (section 2.1). This section is supplemented with a deeper look into three separate subjects that are of particular interest within this context, namely the calculation of the primary energy factor (section 2.2), the calculation of CO_2-emissions related to a buildings’ electricity consumption (section 2.3) and the importance of considering a life-cycle perspective (section 2.4). In chapter 3 we consider trade-off’s at the societal level, which introduces a whole range of additional challenges (discussed in sections 3.1 and 3.2). We also review the current state of the art; studies that consider the societal level (section 3.3). This is supplemented with a thought-experiment on the fully integrated modelling efforts that *would be* required to perform the truly comprehensive analysis of the different trade-off’s (section 3.4).

2. Identifying the cost-optimal approach at the individual building level

2.1. Existing calculation methodologies

Studies that have attempted to identify cost-optimal packages at the individual building level, use a variety of methodologies. In this section, we focus on the methodology developed as part of the 'Annex 56 project', but first we discuss the aforementioned EPBD method in more detail. It should be noted that a variety of methodologies is used in the scientific literature. Sometimes the EPBD or Annex 56 methods are explicitly mentioned, but many studies use an ad-hoc method instead. Some researchers choose to further simplify the approach, while others use more advanced methods that rely on state-of-the-art simulation and optimization tools. An example of the latter can be found in [12], where a cost-optimal approach for the renovation of apartment buildings is identified. The study uses a dynamic multi-zonal building energy simulation tool, in combination with a multi-objective optimization based on genetic algorithms. Ad-hoc methods are usually customized to the content of the studies themselves, to avoid both under- and overcomplicating the search for an answer to the stated research question. For two reviews of recent studies on the subject of cost-optimal building energy performance measures at the individual building level, we refer to [7,13].

EPBD methodology

As discussed in the introduction, the 2010 EPBD requested Member States to use its official methodology to identify cost-optimal levels of energy performance (expressed in terms of PE). In this section, we focus on four Belgian studies that were written in response to this request, to explain the EPBD method in more detail. The first two studies – one focusing on renovation and one on newly-built activities – were published in 2013 [14,15], with two follow-up studies being published in 2015 [16,17]. All four of the studies focus on residential buildings[9].

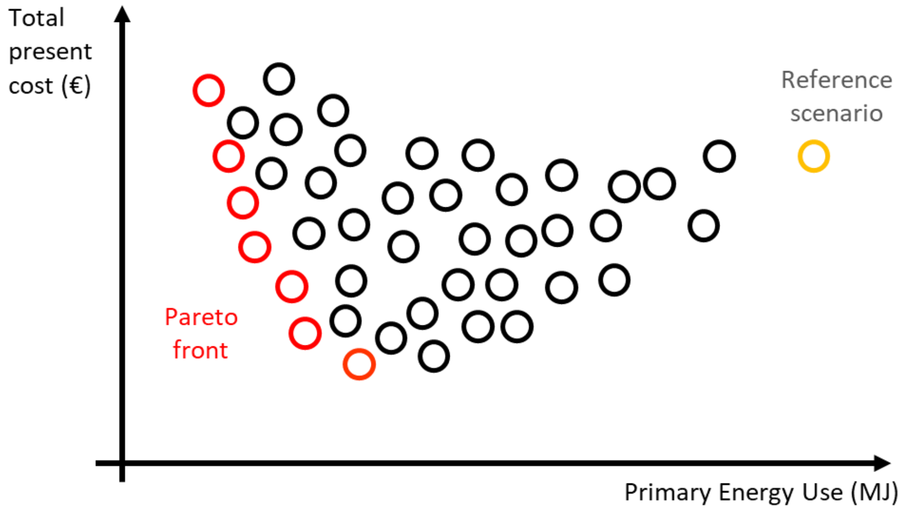
Both the renovation and newly-built studies begin their analysis with a selection of 'representative buildings'. To these buildings, different measures (and combinations thereof) are applied. The goal is to identify which packages of measures lie on the so-called 'pareto front', where an improvement of either the total cost or the estimated PE is no longer possible without worsening the other. This principle is illustrated in figure 3. Scenarios for a single 'representative building' are shown. Each circle represents a different (simulated) combination of measures that is performed on the building. A single 'reference case' is also simulated, to compare each potential combination of measures with the 'typical' situation for a particular representative building (at the time of writing). The total present cost[10] is a sum of all investment and operational costs over the lifetime of the building. Subsidies and CO_2 costs may also be included in this metric, depending on the applied perspective (cf. infra), as well as a 'residual value' for building elements that are not yet end-of-life at the end of the analysed period. The analysed period is 30 years, as prescribed by the official calculation methodology.

---

[9] In 2017, a further follow-up study was published that focusses on non-residential buildings [86].

[10] 'Totale Actuele Kost' in Dutch, the language of the reports.

Figure 3: Identification of pareto-optimal combinations of measures



Source: Self-generated, based on [14–17].

The EPBD methodology prescribes that the calculations should be performed once from a 'micro perspective' and once from a 'macro perspective'. Depending on which perspective is applied, different assumptions are used with regards to the interest rate and the inclusion of subsidies, taxes and CO_2 costs. Although this perspective aims to take into account a 'societal point of view', the calculations performed in these reports should not be confused with a true 'societal level analysis' as discussed in chapter 3. It should also be noted that CO_2-emissions are not included as an optimization objective. Renewable energy measures are only viewed from the perspective of their impact on PE. The only reason why CO_2 emission intensities are used in the reports (e.g. for electricity or locally combusted fossil fuels), is to calculate CO_2 *costs* that are included in the total present costs when the 'macro perspective' is applied. In summary, the EPBD method provides a solid foundation for the identification of cost-optimal packages of measures, but its limited focus on the goal of reducing PE falls short for the analysis proposed in this report.

Annex 56 methodology

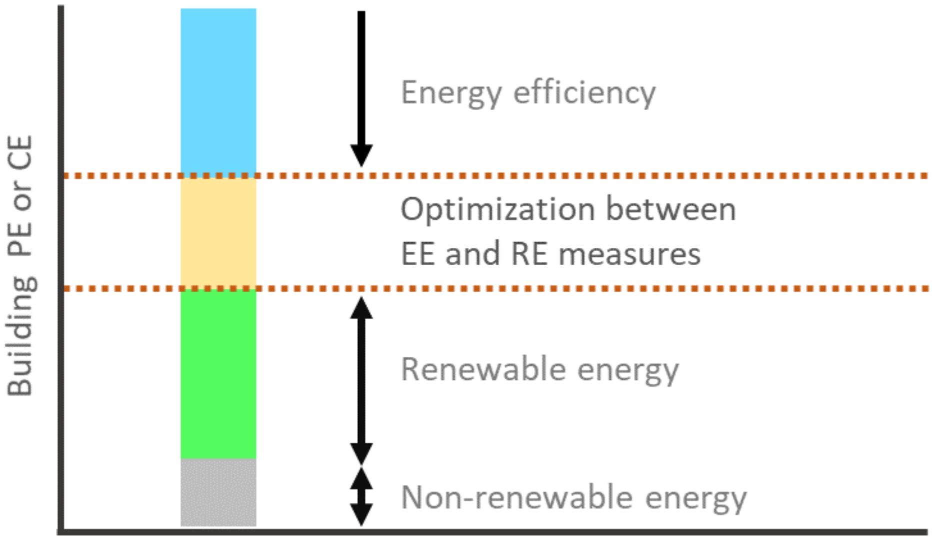
The IEA 'Annex 56 project' was completed in 2017 and provides a more comprehensive analysis framework to calculate cost-optimal packages than the traditional EPBD method. Although the two methods largely overlap, the main difference is the fact that the Annex 56 method leaves it up to the user whether PE or CE reduction goals are chosen to identify the cost-optimal package. Although not explicitly mentioned in the Annex 56 documentation, it is clear that the method is largely based on the EPBD method. However, unlike the EPBD method, its intended geographical applicability extends beyond the European Union[11].

---

[11] The Annex framework of the IEA includes participants from several non-European countries. For more info, visit https://www.iea-ebc.org/.

The Annex 56 project outcome consists of a range of extensive reports, each focusing on different sub-aspects as well as several academic publications [18–33]. In this section, we first discuss the methodology proposed by Annex 56 and afterwards provide some critical reflections on it. In the final part of this section, we take a closer look at the debate on the necessity of 'deep retrofits', which is closely related to the topic of this chapter.

Figure 4: Simplified representation of the trade-off between energy efficiency and renewable energy



Source: Self-generated, based on [28]

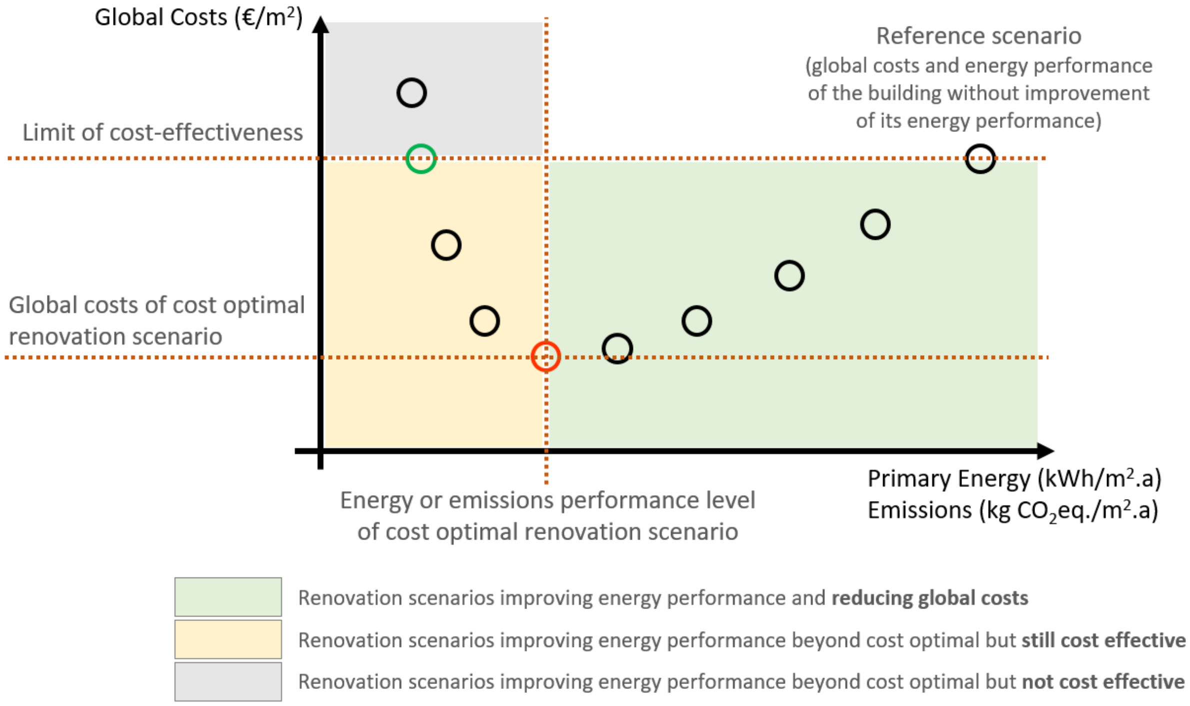
The core idea behind the Annex 56 methodology is to consider a variety of possible combinations of measures for an individual building and to calculate the long-term results for each of them in terms of global costs, energy use and/or emissions. Global costs consist of the total sum of investment and operational costs from the perspective of the individual building owner. It can either be represented as a discounted total sum or be translated into an expected *annual* amount of costs.

A long term perspective of several decades is applied when calculating costs, energy use and emissions. This is done to take into account the (relatively higher) benefits and (relatively lower) costs that take place beyond the typical pay-back period of the considered measures. For example, energy cost savings continue to benefit the homeowner even after an initial investment in improved insulation has been recovered. Similar to the EPBD method, the Annex 56 method also applies a 'residual value' to assets that are not yet end-of-life at the end of the analyses period. A simple linear depreciation heuristic is used to calculate this residual value.

Unlike the EPBD method, the Annex 56 methodology and the related publications focus entirely on renovation, taking the most basic level of 'anyway renovation' – in which only the necessary long-term maintenance of the building is taken into account – as a reference scenario. Every combination of potential renovation measures that goes further than simply maintaining the building in its original state is then plotted onto a graph as shown in figures 5 and 6, by calculating its global costs, energy use and emissions. Renovation scenarios can be generated freely by the user by varying the included measures in each scenario. Any kind of measure that can be taken at the individual building level, can be included in a scenario. In terms of demand-side measures, many varying degrees of insulation (in one or several parts of the building) can be included. On the supply-side, scenarios may include a variety of renewable and non-renewable heating technologies. One point on the graph could represent a scenario with a traditional natural gas boiler in combination with extreme insulation levels, while another may represent a combination of a biomass heating system and a much milder level of insulation. Given the right simulation tools, hundreds or even thousands of potential combinations of renovation measures can be simulated, to identify the lowest cost package at each PE or CE level.

We can argue that this general methodology could also be used in the case of newly built homes, although this is not done within the Annex 56 project. In this case, there would be no ‘anyway renovation’ starting point to consider. Still, many different ‘newly built scenarios’ with varying degrees of insulation and different heating systems could still be plotted onto a similar graph. Similar to the EPBD method, the ‘reference scenario’ could be replaced with a ‘typical approach’ for the building in question if newly-built scenarios are being calculated.

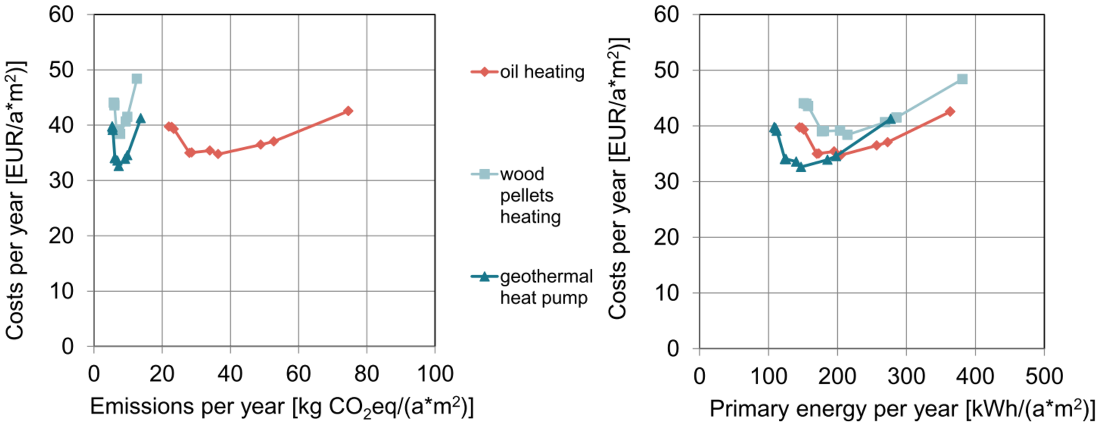
Figure 5: Generic Annex 56 representation of a range of different renovation scenarios



Source: Self-generated, based on [22]

Note: Although the Annex 56 project is focused on renovation, this graph can also be generated for different design options for a newly built project (i.e. different combinations of insulation levels and heating systems)

Figure 6: Real-world application of the Annex 56 methodology considering several renovation scenarios



Source: [24]

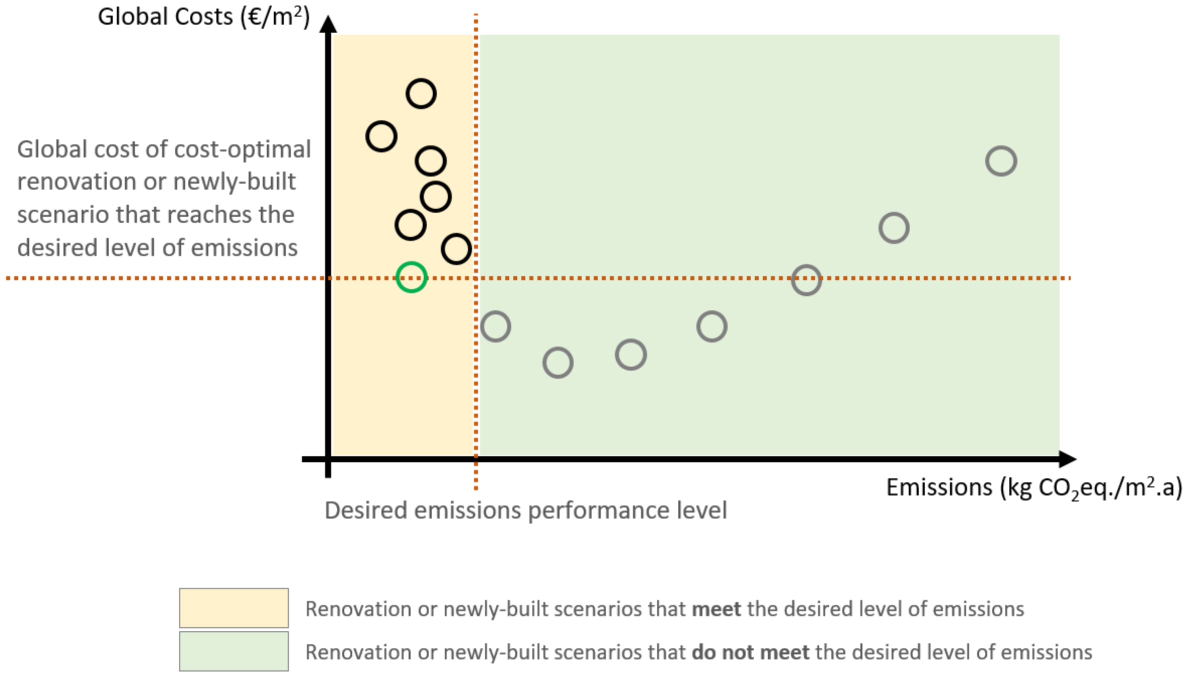
Note 1: The results shown in these graphs are based on calculations for a generic building in Switzerland (see [24]*)*

Note 2: Each point on the graphs represents a different combination of heating system technologies (grouped by color) and varying levels of energy efficiency measures (e.g. different levels of insulation etc.)

As illustrated by figures 5 and 6, a single cost-optimal package can be identified (red circle) but choosing which package should be picked is ultimately left to the person using the methodology. The authors of the Annex 56 project suggest to go further than the cost-optimal package of measures and strive for the furthest possible ‘cost effective’ package that still has a global cost that is lower than or equal to the ‘anyway renovation’ scenario. This means that the global cost of the assumed reference scenario heavily drives the boundary of cost-effectiveness. In figure 5, the best-yet-still-cost-effective scenario is represented by the green circle.

By plotting out different renovation scenarios or different design options for a newly built project as shown in the figures above, the cost-optimal balance between energy efficiency and renewable energy measures at the level of an individual building can be identified. One would simply use carbon emissions as the X-axis and project a vertical line at the desired emissions reduction level. Then, the different renovation or newly built scenarios that succeed in reaching the given level of carbon emissions can be compared in terms of global costs. This way of using the methodological framework provided by the Annex 56 project is illustrated in figure 7. It should be noted that this is not proposed in the Annex 56 project itself, but is an entirely separate suggestion made within the context of the present report. There is also no official emissions target for residential buildings in the current European policy framework (to impose on the X-axis). However, BPIE has proposed a target of <3 kg CO_2eq./m^2.a for newly built dwellings in order to reach the long-term carbon reduction goals [18]. Switzerland already has similar targets in place today, namely a maximum of 2.5 kg CO_2eq./m^2.a for newly built dwellings and 5 kg CO_2eq./m^2.a for renovated dwellings [18].

Figure 7: Proposal for using the Annex 56 methodology as a tool to select the cost-optimal renovation or newly built scenario that reaches a desired level of emissions



Source: Self-generated, based on [22]

The Annex 56 methodological framework strives to take into account country-specific variables that influence the global cost calculation at the individual building level. One such variable is the local climate. When comparing a physically identical renovation or newly built project in either Portugal or Finland, the calculated global costs and emissions of each package of measures could be plotted at entirely different locations on the graph. Demand-side measures like heavy insulation will lead to a much larger reduction in both energy costs and emissions in a very cold Finnish climate than in the much warmer Portuguese climate. Conversely, supply-side measures like installing solar PV or solar thermal would lead to entirely different levels of emissions savings in sunny Portugal as opposed to Finland. Another country-specific variable that is taken into account in this framework is the primary energy factor and carbon intensity of the electricity consumed by the building[12]. This can result in large differences in the calculated emissions and primary energy use, especially in scenarios where an electrically-driven heating technology like a heat pump is chosen.

The Annex 56 framework also intends to take into account specific characteristics of the considered dwelling, in terms of the building structure as well as other exogenous factors like the presence of a district heating network which the building can be connected to. The calculation outcomes for any combination of measures can be completely different for terraced, semi-terraced or detached dwellings. The introduction of certain levels of insulation or certain renewable heating technologies may or may not be technically feasible and affordable in a certain type of dwelling. For example, a geothermal heat pump or a solar thermal installation may be particularly difficult and expensive to realize in the case of a terraced dwelling with a small roof and garden. In comparison, a detached

---

[12] Note that these are completely exogenous variables at the individual building level, while it is in principle endogenous in a societal-level assessment as discussed in chapter 3.

dwelling *could* potentially install these technologies and their case-specific costs can be fully taken into account. It is also possible to consider a district heating network and its heating source (renewable or not) in the Annex 56 framework. However, both the availability of the network and the heat source that it uses are purely exogenous factors that an individual home owner cannot change. Within this framework, the only choice that can be made is thus whether or not to connect to such a network. Building district heating networks or changing their heating source is only a possible (supply-side) measure at the societal level (cf. chapter 3).

Both the synergies and trade-offs between different kinds of measures can be fully analyzed using the proposed framework. Global costs, primary energy use and emissions can each be calculated for *any* scenario imaginable by the architect or building owner. This can include scenarios that rely very heavily on either energy efficiency measures or renewable generation, if a comparison between such scenarios seems desirable for the given building. Unfortunately, the Annex 56 project does not include any case-studies where the extremes of any trade-off are actively explored. For example, no comparison is made between scenarios with a very high level of energy efficiency but no renewables on one side, and scenarios with a mild level of energy efficiency but a larger investment in renewables on the other. The cost- and emissions-outcomes of such scenarios would be of a particular interest within the context of this report, but are nowhere to be found at the time of writing. Some of these scenarios can however be found in the aforementioned Belgian studies that made use of the EPBD method. There, some scenarios are identified on the pareto-front with an extreme level of energy efficiency and demand-side measures, and only limited investments in terms of the supply-side or renewables. Some scenarios with only a mild reduction in the heating demand, in combination with heavier investments in a heat pump and solar PV, were also part of the pareto-front for at least one of the 'representative buildings' [15,17].

In the case-studies performed within the Annex 56 project, two important synergies were found that influence the global costs. The first one is the fact that a renewable heating installation can be dimensioned to a smaller size if combined with a certain amount of energy demand reduction measures, leading to additional cost savings. Secondly, in the case of using a heat pump, its operational efficiency[13] increases when energy efficiency measures enable a decrease in the air or water temperature that needs to be reached in the heating system. To identify all relevant synergies and trade-offs between energy efficiency and renewables within this methodological framework, the main requirement would be to explore a sufficiently large variety of renovation or newly built scenarios.

Critical reflections on the Annex 56 methodology

The methodological framework provided by the Annex 56 project is the best starting point currently available to evaluate the optimal balance between different kinds of measures at the individual building level. As figure 7 shows, it can be used to find and select the "cost-optimal" renovation or newly built scenario (i.e. with the lowest global cost), as long as a sufficiently large variety of scenarios are calculated. However, the Annex 56 methodology can also be criticized on several fronts.

First of all, the time-horizons used to perform the calculations in the Annex 56 project are extremely long. The so-called lifecycle cost (LCC) perspective used in this project means that discounted costs and benefits of any investment scenario are considered over a period of several decades. The project authors support this choice for a very long time-horizon by arguing that (high) benefits and (low) costs

---

[13] Typically expressed as a Coefficient of Performance (COP) or – more accurately – as a Seasonal Performance Factor (SPF).

beyond the pay-back period of the investments should not be ignored if the desired level of PE and CE reductions are to be achieved. This however strongly deviates from the views of most consumers investing in newly built or renovation projects, who typically apply much shorter time-horizons[14]. Even though the use of twenty- to thirty-year mortgages is well established in the housing sector, such time-horizons are seldomly used when thinking about renovations. Therefore, it is highly unlikely that consumers will choose the furthest possible renovation scenario (in terms of the achieved PE or CE reduction) that is still slightly 'cost-effective' on the very long term (green circle in figure 5).

Secondly, many parameters used in calculations within this framework are highly uncertain. For example, several studies have found that projected fuel prices and discount-rates both have a large influence on the outcome of the calculations [8,20]. Other uncertain parameters include the investment costs of certain technologies as well as their installation and maintenance costs [9]. This applies both to the energy efficiency and demand side measures on one side (e.g. different types of insulation or windows) and to the variety of renewable energy and supply-side measures on the other side (e.g. what is the total cost – including installation, maintenance, etc. – of different types of heat pumps). While these uncertainties are unavoidable to some degree, they are made worse by the extremely long time-horizons applied in the Annex 56 methodology. Applying more conventional time-horizons and putting a higher emphasis on pay-back times should therefore be considered.

The Annex 56 project also forgets to take into account the future tariffication schemes for electricity consumption. This parameter is also uncertain in the long term, but is nevertheless an essential part of any future-proof assessment. Electricity prices paid by residential consumers – especially in the future – are heavily influenced by the regulatory regime and the types of contracts offered by electric utilities. It is possible that residential electricity prices will fluctuate throughout time on an hourly basis and that a larger share of the electricity bill would be determined by the power capacity of the connection (peak demand) rather than the amount of kilowatt-hours that are consumed. A whole field of academic research is currently working on optimal tariffication schemes for the future. It is highly unlikely that a simple fixed 'price per kilowatt-hour' is a satisfactory methodology to calculate future electricity consumption costs within a newly built or renovation scenario (especially when a period of 20 years or more is being considered). The expected structure of the future tariffication scheme for electricity can be especially important to consider in scenarios that include an electrically-driven renewable heating technology or a solar-PV installation. The fact that it is very challenging to take this parameter into account does not justify ignoring it in the proposed calculations, because its potential impact is significant. The ongoing debate on dynamic electricity pricing, digital metering, power capacity pricing and the inclusion of additional levies and taxes on the residential electricity bill is too important to ignore when we estimate the optimal balance between different kinds of measures at the individual building level.

In theory, taking the evolution of tariffication-schemes into account would ideally be complemented with a sophisticated modelling methodology to determine the 'smart flexibility' of electricity consumption in future dwellings. This can include both demand side management (DSM) and energy storage. Under certain future tariffication schemes, electricity costs paid by residential customers can be largely driven by the degree to which they can flexibly move their electricity demand to certain hours of the day or reduce their peak power demand. Calculating the amount of flexibility that is available to minimize the electricity bill requires state-of-the-art modelling techniques that would need to be applied for each 'scenario' being considered. Under some circumstances, the degree of energy efficiency measures in a particular scenario can influence the flexibility potential. A smaller heating

---

[14] In PRIMES models, it is conventional to use a discount rate of 12% for renovation investments made by home owners, indicating a limited time-horizon and a high degree of risk-aversion [87].

demand results in a smaller amount of energy (kWh) that can be stored or remunerated on the market, as well as a lower peak demand (kW) that can be manipulated to capture a system-level benefit. It will not necessarily be the evolution of the average electricity price that drives the calculated global cost of a scenario with an electrically-driven heating system (like a heat pump), but rather the hourly fluctuating electricity prices and the degree to which the building can (automatically) shift its consumption of electricity away from hours with high prices and towards hours with low prices. Moreover, shifting electricity use away from hours with a high PEF or CI of electricity on the grid (which can potentially correlate with high prices), can also help reduce a building's PE or CE. These additional layers of complexity are fully ignored in the Annex 56 methodology, but they are equally important to take into account when seriously considering investments with a time-horizon looking far into the future.

A third point of criticism on the Annex 56 methodology can be made regarding its perspective on renovation costs. To our best understanding, Annex 56 seems to apply a rather narrow perspective on 'costs'. Only the CAPEX and OPEX of the various measures (e.g. a new wall, a new roof, etc.) are included, without considering the potentially large costs related to the planning, execution and evaluation of the related structural works. Most importantly, the many 'man hours' of labor that are required to execute the stated measures are not explicitly included in the analysis of the various scenarios. The argument used for this in the Annex 56 publications, is that many costs can to some degree be 'ignored' because the building is assumed to be in dire need of an 'anyway renovation' (which is necessary to simply maintain the structural integrity and functionality of the building). In such a situation, the large structural works are being executed *anyway*, so only the 'additional costs' of measures need to be considered. For example, only the 'cost of 10 additional centimeters of insulation' is considered, instead of the full out-of-pocket costs that the building owner would have to pay in order to realize the insulation in practice.

It should be noted that it is not impossible that some renovations *do occur* in a context of 'anyway renovation', in which case the method proposed by Annex 56 *can* be appropriate. However, it remains important to stress that the perspective of an 'anyway renovation' is not *always* accurate. If we consider the renovation rate that is required to reach the 2050 climate and energy goals, it is obvious that we cannot wait for every building to reach a state where 'anyway renovation' is direly needed. Therefore, the Annex 56 case-studies paint a picture that is likely too optimistic. When home owners that do not face a dire need for an 'anyway renovation' decide on whether or not to renovate, they will most likely consider the full costs of the proposed measures. In that case it seems highly likely that the calculated global costs and pay-back periods will be significantly less attractive. The scenario with the lowest global cost may even change from a net-positive to a net-negative financial proposition. However, this does not mean that such a cost-optimal scenario cannot still be identified. Moreover, the scenario with the lowest global costs *that reaches a certain PE or CE target* can also still be identified (regardless of its financial attractiveness). In any case, it is important not to (wrongly) claim that certain renovation measures are financially attractive in any situation, simply by assuming (without exception) that an 'anyway renovation' is always taking place.

It is unclear what the impact of 'full costs' would be on the balance between different kinds of measures in terms of the identified trade-off's. We can however speculate that energy efficiency and demand-side measures generally cause higher costs related to structural building works than renewable energy and supply-side measures. For example, the costs of installing a biomass heating system or connecting to an available district heating system are very low, compared to the costs associated with a sharp reduction in a building's heat demand. A more realistic perspective on the costs related to renovation *may* thus shift the optimal balance away from demand-side and energy efficiency measures and towards supply-side and renewable energy measures. However, this is not guaranteed because the 'full costs' associated with renewable energy and supply-side measures may also be significant is certain cases. For example, connecting to a low-temperature district heating system may require large structural works to install a low-temperature heating system (like floor-heating).

A final point of criticism that can be made regarding the Annex 56 methodology, is the fact that it can lead to suboptimal approaches *if representative buildings are used* in the analysis. While the methodology can in principle be used to identify cost-optimal packages for a specific case-study, it may also be applied to a range of representative buildings, similar to the approach taken in the Belgian studies in the context of the EPBD. In this case, caution is advised when the analysis puts forward a set of generic principles for cost-optimal approaches in each 'typical segment' of the building stock. While the cost-optimal approaches are calculated for *average* buildings and occupancy profiles in each segment, there may still be a lot of variety in practice. Details in the characteristics of the actual buildings and the occupancy profiles can therefore turn the identified cost-optimal approaches into highly *sub*optimal ones, when simply extrapolated (and enforced) on a large scale.

Debate on the necessity of comprehensive and deep retrofits

Policy makers and academics often promote 'comprehensive retrofits', where most if not all of the building elements (floors, walls, windows, roof, heating system,…) are upgraded to some degree. They may do so for several reasons. First of all, the *number of measures* taken in a renovation project has a bigger influence on the energy- and emissions-savings than the *performance level* of individual measures. When comparing several renovation scenarios as shown in figures 5 and 6, the Annex 56 project found that scenarios with a higher number of measures achieved better results than those with a lower number of very ambitious measures [23–25,30]. Mildly improving the energy efficiency of *many* building elements results in a larger decrease in primary energy use than heavily improving the energy efficiency of *one* building element (e.g. only replacing single-glazed windows by very high energy performance windows).

A second reason for promoting comprehensive retrofits –especially those where a very high energy performance is achieved, also called 'deep retrofits' – is to avoid the risk of creating a 'lock-in' of mediocre building upgrades. If incremental upgrades are made and new building elements achieve only a mediocre level of energy performance, the remaining economic case to renovate the building again at a later point in time (in order to reach a very high level of energy performance) is significantly diminished [30]. The pay-back time of investments that bring an already mildly renovated building to a very high level of energy performance are less attractive because the additional energy cost savings that can be realized are relatively small. This relates to a third and final reason for promoting comprehensive retrofits, namely the fact that renovating everything in one 'single step' is more cost-efficient than increasing the energy performance of a building in several steps with many years in between. Each time large structural works have to be carried out to upgrade insulation levels, large costs have to be incurred that go beyond the cost of the additional insulation layer itself (as discussed in the previous paragraph). Incurring the costs related to large structural works several times instead of once is obviously more expensive.

While the arguments in favor of comprehensive retrofits are persuasive, they come in to conflict with several practical realities. The most important barrier is the fact that renovations of this kind require very large investments and homeowners need to be able to finance them. Not all home owners have access to a sufficient level of financing, making comprehensive retrofits difficult to realize.

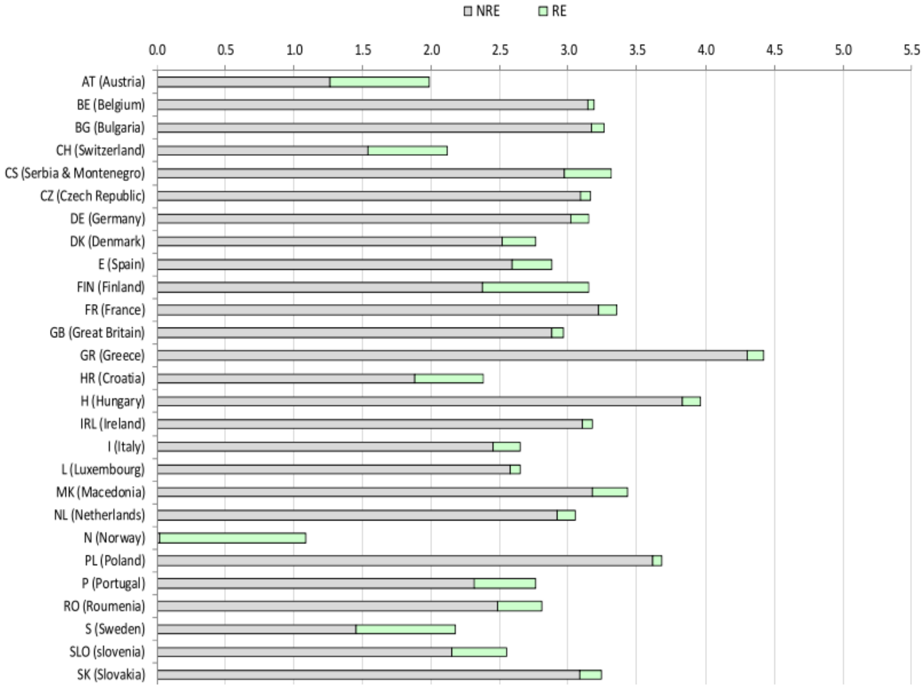
Comprehensive retrofits also require very thorough planning and conventionally create a need to temporarily live at another location. These and other barriers prevent comprehensive retrofits to take place on a large scale. Smaller step-wise renovations that cause less disturbance to daily life and are easier to finance are therefore much more popular in comparison. To achieve high levels of energy performance in the very long term, the idea of introducing 'building renovation roadmaps' has been suggested [34,35]. In such a roadmap, the long-term planning of different step-wise building upgrades is optimized to minimize costs. By carefully planning a long-term stepwise renovation process (potentially spanning across the ownership period of several owners), it may be possible to achieve a high energy performance level without creating costs that are much higher than a one-step deep retrofit project. From the perspective of the present report, a crucial step in developing such a long-term roadmap would be to strike a cost-efficient balance between different kinds of measures to achieve the long-term emissions reduction goal. If the same carbon emissions savings can be realized more affordably through a deep retrofit that relies more on supply-side measures and less on demand-side measures, that could potentially limit the financing constraints that currently form a significant barrier.

2.2. Primary energy factor methodology

The methodology proposed in the previous section requires an accurate calculation of the expected primary energy use in all considered newly built or renovation scenarios. An entire area of research is dedicated to improving the methodologies used to calculate this primary energy demand. This research is addressing many challenges, including modelling improvements for user behavior, grid-interaction, multi-zone heating and many other technical aspects. Within this context, one issue that is of particular importance when trying to find the optimal balance between different kinds of measures is the *primary energy factor* (PEF). The PEF is a technical parameter used to calculate the amount of primary energy that corresponds to the final energy consumption in a residential building. A PEF can be calculated for each energy carrier consumed at the residential level, including heating oil, natural gas, biomass and electricity. For each of the carriers, it indicates how much primary energy was used to either generate the electricity or a unit of useable thermal energy. The consumed amount (e.g. 100 kWh of natural gas or 100 kWh of electricity) is multiplied with the respective PEF to calculate the overall primary energy use.

The PEF for each energy carrier is itself a calculated value, for which a particular methodology is used. In the case of fuels like oil, gas and biomass, the calculated value of the PEF (the 'PEF of gas', the 'PEF of biomass', and so forth) can be higher than 1 if the primary energy consumption related to its extraction and transportation are also taken into account. This approach represents a 'life-cycle perspective'. To simplify matters, it is however more conventional to use a value of 1 for the fuels themselves. The calculated value of the PEF is much more important in the case of electricity. To calculate the 'PEF of electricity' (henceforth PEF_E), the primary energy use in the electricity system needs to be considered. The electricity consumed by a residential end-customer is generated by a mix of electricity generation technologies, which differs from country to country. All technologies that consume fuel to generate electricity (biomass, nuclear, coal, gas,…) have a particular conversion efficiency. Due to thermal losses, generating one kWh of electricity requires more than one kWh of primary energy (contained in the fuel). The average thermal efficiency of each electricity generation technology is different. For example, a combined-cycle gas power plant is up to 60% efficient, while a coal- or biomass power plant has a typical efficiency around 45%. The conversion efficiency of renewable technologies that do not consume a fuel to generate electricity (wind, solar, hydro, geothermal) is generally considered to be equal to 1 because no primary energy is considered to be ‘lost’ in their production process. To calculate the overall PEF_E, the weighted average is taken of all generator efficiencies, depending on their respective share in the electricity production mix of the given country. Grid-losses that occur when transporting electricity can also be taken into account. Due to the differences in the electricity production mix of different countries, the calculated PEF_E varies between 1.15 and 4.45 in Europe (see figure 8).

Figure 8: Average PEF of electricity in European Member States (kWh$_{PE}$/kWh$_e$)



Source: [18]

Note: (N)RE stands for (non-)renewable energy, indicating the respective shares in the total electricity produced in each Member State in 2015

The PEF plays a crucial role in the European energy and climate framework, especially in the EED. The European energy efficiency goals are expressed as a reduction in primary energy consumption (-20% by the year 2020 and -32.5% by the year 2030)[15]. Reaching a sub-target for the residential buildings sector can heavily depend on the PEF-values used to calculate the sectoral primary energy demand. For the PEF_E, the approach currently taken within the European framework is to use a single average value in all European Member states [5,36]. This is not only the average across the differences between Member States (cf. figure 8), but also the average across the year (i.e. looking at the share of each electricity generation technology in the total electricity production in each country across the whole year). The value of the PEF_E can have a large impact on the relative merits of different technologies used in the residential buildings sector. One technology may appear more attractive in terms of primary energy use than another, depending on the value. Heating technologies that consume a combustible fuel as opposed to electricity may appear relatively *more* attractive if a high PEF_E-value is used. In that case, electric heating technologies are ‘penalized’ by multiplying their electricity

---

[15] Technically, these goals are expressed as a reduction compared to the *projected* primary energy consumption for the respective years (2020 and 2030). See annex 1 for more information.

consumption by a high number (e.g. ≥ 2.5) to calculate their primary energy use. PEF-values can also influence the relative attractiveness of different renewable heating technologies. For example, if the 'fuel-PEF' (henceforth PEF_F) of biomass is set to a low value (e.g. 0 ≤ 1 or even 0), biomass could be more attractive from an energy efficiency standpoint than a heat-pump consuming electricity that needs to be multiplied with a high PEF_E.

The importance and consequences of PEF-values has led to an ongoing debate on the optimal PEF calculation methodology [37]. From a scientific perspective, this debate is about objective choices that need to be made between different methodological considerations. One such consideration is the value that should be attributed to biomass as a fuel. Some argue that this should be set to 0 (or close to 0) to reflect the renewable nature of the fuel, while others argue that the value should be 1 because the primary energy stored in the chemical bonds should simply be considered (as is the case with the PEF_F of fuels like gas and oil). Another methodological consideration is the PEF_E-value that should be used when producing both electricity and heat with a combined heat and power (CHP) installation. Various calculation options have been proposed, with different assumptions regarding the allocation of the overall conversion efficiency between the heat and electricity output of the installation [37].

The debate on optimal PEF calculation methods also has a strong *political dimension*. As explained before, the methodological choices can have a significant impact on the relative attractiveness of different technologies used in the residential buildings sector. While industry associations representing the electricity generators lobby for a low PEF_E-value, players representing the biomass and micro-CHP industry lobby for a high PEF_E-value (and a low PEF_F value for the respective fuels that their technologies use). The political dimension in this debate does not limit itself to a dispute between private industries, but also between European Member States. Especially the PEF_F-values are disputed in this regard, as they can still be determined nationally (as opposed to the single EU-wide PEF_E-value). For example, Poland has chosen a low PEF_F-value for biomass used in residential heating. The country may have done so for political reasons because many Polish households use furnaces that allow for mixed fuel-use [38]. While these households may have 'biomass heating' on paper (achieving low emissions and a low primary energy use), they may in practice mostly be using fossil-based solid fuels in their furnaces. It could be politically difficult for Polish policy makers to make this common situation much less attractive by using a higher PEF_F for biomass. It would result in many residential buildings that currently achieve good energy efficiency levels (in terms of the theoretically calculated PE), to no longer do so in the future.

Another political dimension is found in the methodological choice regarding the production and grid-injection of electricity from on-site photovoltaic solar panels. It can be argued that self-generated electricity from solar PV should be attributed a PEF_E of 1, in line with the PEF_E for off-site non-combustible renewables. However, the question then arises how to deal with the surplus electricity that is injected into the electricity grid. If a high PEF_E is attributed to this exported electricity, the amount of primary energy that can potentially be deduced from the buildings' overall energy use is also high (making PV very attractive as a means of achieving a low primary energy use). It can then be argued that each kWh of electricity injected into the grid is 'displacing' a kWh of 'grid electricity' that has the average PEF_E of the national electricity system. It is clear that these methodological choices are not just a matter of objective science, especially in countries where the policy-influence on the attractiveness of residential PV is a sensitive subject.

In the 2018 recast of the EED, the average European PEF_E-value was updated from 2.5 to 2.1 to better reflect the increase in the share of renewables that has taken place in the European electricity production mix so far [5]. A review process was also established to update this value every four years, making sure that the continuing evolution of the European mix is taken into account. These updates to the policy framework are a step in the right direction to help ensure a correct trade-off can be made between demand- and supply-side measures in de residential buildings sector. However, there are at least two more potential improvements to the PEF_E-methodology that are desirable to better optimize the balance between different kinds of measures.

First of all, we know that the PEF_E can differ from season to season and even from hour to hour, depending on changes in the electricity generation mix throughout time. At the seasonal level, it is for example possible that the combination of a lower demand for electricity and a higher production from solar PV can significantly reduce the PEF_E during the summer. Conversely, a higher demand and a lower production from solar PV can increase the PEF_E in the wintertime. Even larger fluctuations in the PEF_E can take place at the hourly level. Due to the constantly changing availability of wind and solar as well as the activation and deactivation of regular power plants, the PEF_E may be very low during one part of the day and very high during another. These fluctuations can even be considerable in systems dominated by baseload nuclear energy. If the electricity consumption of residential buildings is also considered at the hourly level, the calculated primary energy demand could be significantly different from what would be estimated using the traditional 'yearly' methodology. This could be especially the case if the building in question uses an electrically-driven heating technology, which may consume most of its electricity during certain periods of the year and certain hours of the day.

A second methodological improvement that should be made to more accurately calculate the PEF_E and increase our understanding of the optimal balance between energy efficiency and renewables is to use a national PEF_E value (instead of the single European value) and to take into account the import and export of electricity in a given country. As the European internal market for electricity further develops, the cross-border trade of electricity is expected to increase. For some well-interconnected countries in the European network, this can mean that an increasingly large share of their electricity consumption is imported from other countries (or conversely, a large share of their locally produced electricity is exported). If the PEF_E-value used in the calculation of the primary energy use of a building is meant to reflect the production mix that has generated the electricity being consumed, these increasing cross-border flows should thus be fully taken into account. The Annex 56 project also supports using *consumption-based* PEF_E-values instead of *production-based* values that only consider the production of electricity in the country itself (ignoring import and export)[18].

The two improvements explained above can be relatively easily implemented within a modelling exercise where the European electricity grid is simulated on an hourly basis. In a traditional dispatch optimization model, the PEF_E can be calculated for each individual hour by considering the hourly changes in the electricity generation mix. The import and export of electricity across the European network can also be taken into account in such a model. Even projections taking into account the future evolution of the PEF_E could be generated, to take into account the changes taking place over the lifetime of an electrically-driven heating system. The *average* PEF_E is expected to decrease over the next 5-25 years (see table 1), but the increasing share of variable renewables like wind and solar will also increase the degree to which the PEF_E fluctuates on an hourly basis.

Table 1: Projected European yearly average PEF_E-values

Method	2000	2005	2010	2015	2020	2025	2030
Method 1	2.41	2.37	2.26	2.08	1.87	1.79	1.74
Method 2	2.41	2.36	2.14	1.90	1.59	1.46	1.35
Method 3	2.52	2.49	2.38	2.21	2.01	1.93	1.87
Method 4	2.65	2.61	2.49	2.30	2.09	2.00	1.93

Source: [37]

Note: The four mentioned 'methods' each represent different combinations of methodological choices regarding elements like the PEF_F for biomass and non-combustible renewables, taking into account lifecycle primary energy use related to extraction and transportation of fuels and dealing with CHP's. The largest difference is made by the choice regarding the PEF_F of non-combustible renewables, for which some advocates argue that it should be set to 0 (zero equivalency method) instead of 1 (physical energy content method). For more information regarding the different methods, see [37].

In comparison to a theoretical modelling exercise, it is much less straight-forward to implement an hourly PEF_E-calculation in policy practice. It is understandable that this has not yet been done. Generating 'official hourly PEF_E-profiles' for each European country and using them in the primary energy calculation methodologies for residential buildings would not be easy. When projections are made for the coming 5-25 years (to take changes across the lifetime of the system into account), difficulties would arise regarding which 'scenario' for the future of the European electricity system should be used. The current approach of using a single European average PEF_E when calculating the primary energy demand of a residential building is much less complicated. However, that should not necessarily be an excuse to continue ignoring the effects of hourly fluctuations and cross-border electricity trade. After all, the use of standardized weather variables is already common practice in energy performance calculations, even though these variables can be quite detailed as well (e.g. in terms of their temporal resolution). The use of detailed PEF_E-profiles is therefore not unimaginable. If they would be used, the most important precondition is they should be updated frequently. Not only because the ongoing transition in the electricity sector leads to changes in the PEF_E from year to year.

2.3. Carbon emissions calculation methodology

To find the optimal balance between demand- and supply-side measures, it is important to correctly calculate the carbon emissions for every renovation- or newly built scenario as proposed in section 2.1. Contrary to the calculation of the primary energy consumption (and the related PEF), there is currently no official methodology to calculate the carbon emissions of an individual residential building in the European policy framework[16]. There is a clear lack of attention for what could be considered the most important policy objective in the buildings sector. If an official methodology for the calculation of carbon emissions were to be developed in the future, the current shortcomings of the PEF_E should be avoided.

Like the PEF_E, carbon emissions related to the production of electricity also fluctuate on an hourly basis. The carbon intensity (g/kWh) of electricity withdrawn from the grid can be very low during hours when

---

[16] Official procedures do exist within the UN IPCC framework, where parties have to report building sector emissions. However, this does not entail making detailed assessments at the individual building level.

a relatively low national electricity demand is combined with a high generation of renewable energy (i.e. when it is both windy and sunny). Conversely, during hours with a very high electricity demand and a low amount of renewable energy, the carbon intensity can be much higher. How much the carbon intensity fluctuates on an hourly basis differs from country to country, depending on the national electricity mix. However, the fluctuations can be expected to increase as national electricity systems across Europe become more and more weather-dependent due to the continually rising share of wind and solar energy.

The question arises how the carbon emissions related to the electricity use of a residential building should be calculated. From a *physical perspective*, every building is withdrawing electricity from the same (national) grid and the carbon intensity of that electricity fluctuates as described above. The electrons injected into this grid by different electricity generators 'mix evenly' and cannot be traced in an exact manner from individual producers to individual consumers. From a *commercial perspective*, a homeowner can sign a contract with an electric utility[17] to buy electricity from a specific source. For example, it is possible to sign a contract for '100% green electricity from windmills'. The regulatory framework in European countries does not typically forbid a utility to offer this kind of contact, even if the electricity produced by the windmills does not temporally match with the consumption of its customer. The utility is typically only obliged to do two things: (1) guarantee *on an annual basis* that as much wind power is generated as is consumed by its customers[18] and (2) guarantee that on an hourly basis, no imbalances are caused on the electric grid. To guarantee the latter, electricity is sold to the electricity spot market when the utility's windmills are producing more than what is consumed by the portfolio of customers, and electricity is bought when they are producing less. This implies that the '100% green' contract is only feasible as long as *other* parties in the electricity market are willing to 'balance out' the inevitable shortages and surpluses that occur on an hourly basis.

In a closed system, it would be impossible to offer such a contract to all customers, as there would be no counter-parties to balance out the mismatch between production and consumption. For example, if two utilities on an island each have 100 GWh of annual electricity production and consumption, utility A could potentially offer a '100% wind' contract to its customers, as long as utility B could balance out the temporal mismatch between A's production and consumption. To guarantee an hourly balance between total demand and supply on the island, B would need to have the exact right amount of excess demand in its portfolio, whenever A is overproducing wind energy. Curtailing A's excess wind energy generation is not feasible, because the 100 GWh of wind energy *needs to be produced* by A in order to 'cover' its green energy contracts on an annual basis. Moreover, B should also have the exact amount of excess firm generation capacity (e.g. gas plants) available. This excess on B's side would be required to cover the hourly shortages faced by A, whenever its wind energy generation is lower than its demand. Clearly, A would be entirely dependent on B's (non-renewable) portfolio of electricity generation assets, in order to offer the '100% wind' contract. In this illustrative island system example, the 'green contract' offered to A's customers is made possible by B's portfolio of customers that have signed a contract for non-renewable electricity. Given the fact that this kind of 'green contract' system does not accurately reflect the technical need to balance a utility's demand and supply, we argue that –in the long term– the CO_2 emissions related to a building's electricity consumption profile should be calculated from a *physical* perspective. By measuring the hourly electricity consumption of each building and multiplying it with the average CO_2-intensity of electricity on the grid, a more technically

---

[17] For simplicity reasons, we ignore the difference between 'generators' and 'retailers', assuming that they are a single company. Due to the unbundling of the European electricity market, these are technically always separate companies (in a legal sense).

[18] I.e. the aggregated portfolio of customers that have signed up to this contract.

accurate bookkeeping can be made of building related emissions. It should be noted that we ignore the European emissions trading system (ETS) in this report. Within the bookkeeping logic of the ETS, renovation measures that reduce the heating demand of building that is heated with a heat pump, do not reduce CE at all. The reason for this is the fact that the same amount of emissions ("ETS cap") can still be emitted within the system. In other words, the renovation measures only create an opportunity to emit the same CO_2 elsewhere in the economic sectors covered by the ETS.

Another commonality with the calculation of the PEF_E is the fact that the import and export of electricity between countries in the European system can have a significant influence on the value that should be attributed to a particular residential consumption profile. As explained in section 2.2, the increasing interconnection capacity and cross-border trades between European countries is making it more important to consider imports and exports of electricity. Only considering the electricity produced within the borders of a single country is no longer sufficient. The electricity consumed by a residential building could be largely imported from another country during certain hours of the day. The same difference in perspectives (*physical or commercial*) then arises. We can either choose to identify the exact cross-border commercial trades made by each utility in order to calculate the carbon intensity of the electricity consumed by their customers. Or, we can calculate the carbon intensity of the electricity generation mix within every country and use 'flow tracing' algorithms to take into account the effects of cross-border trade. Given certain assumption like the 'even mixing' of electrons across a network, flow tracing allows us to determine how much higher or lower the electricity consumed in a given country is when it is importing electricity from another country with a different carbon intensity.

The carbon emissions related to the production of on-site solar energy and its injection into the grid can also be considered from a realistic physical perspective. Instead of assuming that injections and withdrawals from the grid are 'balanced out' on an annual basis – resulting in 'zero' carbon emissions as long as the PV installation is large enough – all electricity withdrawn from the grid should be attributed the appropriate hourly carbon intensity. Injections into the grid do not physically reduce the carbon emissions of a building, but can potentially still be subtracted from the overall building emissions. To be fully consistent from a physical perspective, the amount that can be subtracted should be calculated by considering the hourly carbon intensity on the grid when excess solar energy is being injected. Since this will most likely occur during sunny hours when many other buildings are also injecting into the grid (and utility-scale solar parks are also producing at their maximum), the carbon intensity can be expected to be lower than average and therefore the amount of emissions that can be subtracted will be relatively small.

Considering the (sub)hourly electricity consumption profile of a residential building and calculating its related carbon emissions with hourly carbon intensity values should result in a more accurate estimate than simply using the annual consumption and average carbon intensity[19]. It also opens the door to considering the impact of demand-side management in residential buildings, which is becoming increasingly important. As mentioned earlier in this report, the electricity consumption of residential buildings can in theory be more and more flexible. By shifting the consumption towards certain hours of the day and away from others, not only the electricity bill could be minimized but also the carbon emissions could be reduced. In fact, we can expect that an optimized consumption profile (making use of the demand-side management potential of the building) would result in a lower bill, a lower PEF_E and lower emissions.

---

[19] One example of the use of overly simplified average carbon intensity values in the context of calculating the carbon emissions of residential buildings can be found in [54].

Strictly speaking the demand-side optimization would most likely focus on minimizing the bill (shifting consumption to hours with a lower electricity price), but this would likely also result in a lower PEF_E and lower emissions because those values can both be expected to correlate with hourly electricity prices. Hours with a high share of renewable generation tend to have lower than average price levels, PEF_E value and emissions (and vice versa). It is obvious that these aspects should not be completely ignored when considering the optimal balance between renewable energy and energy efficiency measures in residential buildings, since both the hourly fluctuations and the potential for demand-side management are only increasing in the future (due to the continuing increase in the share of variable renewables in the electricity generation system). However, as is the case with more accurately calculating the PEF_E, generating and using hourly values in official calculation methodologies would undoubtedly be challenging to implement in policy practice.

Taking into account carbon pricing when calculating global costs

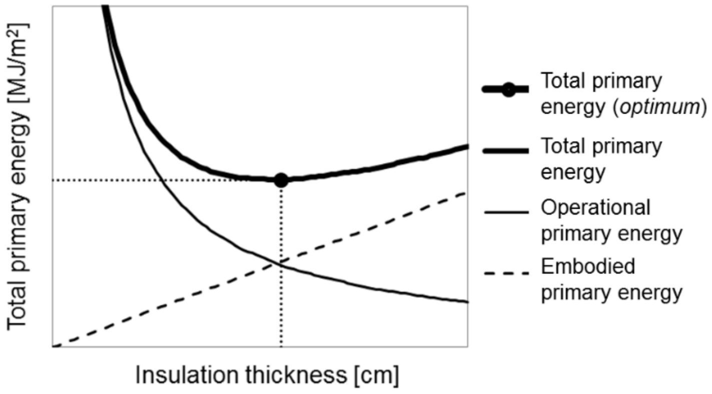
As explained in section 2.1, projections need to be made for future fuel prices when the global costs of a renovation or newly built project are calculated. In addition, we can argue that a similar trajectory is also necessary with regard to carbon-prices. While the importance of carbon pricing is still relatively limited in the context of the energy use of residential buildings, it can be expected to increase in the future. Already today, carbon pricing is in place for the entire European electricity generation system. The European emissions trading system (ETS) implicitly puts a price on the carbon emissions related to the electricity consumption of an electrically driven residential heating system. In the case of heating technologies that use combustible fuels (heating oil and natural gas), a carbon price is not yet in place in most European countries but that could change. A carbon tax or another carbon pricing policy could be introduced for traditional heating systems. Since the lifetime of these systems spans across many years, it becomes necessary to also project *those* future carbon prices if the global costs of all heating system technologies is to be evenly compared.

2.4. The importance of embodied energy and emissions from a life-cycle perspective

To correctly identify the cost-optimal renovation- or newly built scenarios (as explained in section 2.1), it can be important to consider the primary energy use and emissions from a life-cycle perspective. This means that the ‘embodied’ energy and emissions would also be taken into account, next to the conventional ‘operational’ energy use and emissions. These primarily consist of the energy use and emissions that were caused during the production process of the building materials (bricks, concrete, glass, insulation materials etc.)[33]. Other elements that can be taken into account in this type of analysis are the energy use and emissions related to the transport of materials, the construction of the building and even the eventual deconstruction and processing of the materials. Some life-cycle analyses even consider the energy use and emissions related to the transport needs that are required due to the geographical location of the building, although this is an especially difficult element to calculate from a methodological perspective [39,40].

Embodied energy and emissions are especially important in the newly built sector, where the most ambitious energy efficiency measures are generally taken. Beyond a certain point, energy efficiency measures like increasing the insulation thickness of a building can actually lead to an *increase* in energy use and emissions from a lifecycle perspective [33]. This principle is illustrated in figure 9, showing the basic idea behind an ‘optimal’ level of insulation. The trade-off illustrated in this figure has triggered a research interest in the relative merits of different levels of operational energy performance in residential buildings. It has for example been found that a ‘passive house’ standard does not have a large benefit in terms of lifecycle energy use in comparison to regular well-insulated newly built dwellings [41]. While the former has a slightly lower operational energy use, the latter has a lower amount of embodied energy.

Figure 9: Optimal insulation thickness from a lifecycle perspective



Source: [33]
Note: This figure only illustrates a theoretical principle. It is not based on a particular empirical dataset.

In the case of renovation, an important consideration from a lifecycle-perspective is the fact that much of the existing building materials can be reused in a renovation project. In comparison to fully demolishing an existing building and replacing it with a modern one, renovating existing buildings and reusing most of the structural elements can potentially lead to significantly lower lifecycle energy use and emissions [28]. To effectively limit the amount of carbon emissions in a given renovation scenario, it can thus be important to limit the use of new materials. However, even if a large part of the existing building is demolished and replaced with new materials, a careful design and selection of materials can already make a big difference in terms of embodied energy and emissions [11,41].

Next to the embodied energy and emissions related to demand-side measures (e.g. improvement of insulation), those related to supply-side measures can also be considered. The production, transport and installation of boilers, heat pumps and other equipment are also responsible for a certain amount of energy use and emissions [42]. A ground-sourced heat pump may for example have a higher level of embodied energy and emissions than a conventional gas boiler [28]. One type of installation on the supply-side that has received a lot of attention in academic literature is solar PV [42,43]. The production process of solar PV panels has historically been relatively energy-intensive, leading to a long ‘energy payback period’ if the panels are installed at a geographical location with a low solar irradiation. Recent analysis however shows that the embodied energy and emissions of solar PV have been significantly reduced over the past decade and are expected to continue to reduce in the future [44].

When the embodied energy and emissions of both the demand- and supply-side measures are aggregated, the question arises how large this total embodied part is in comparison with operational energy use and emissions. The share of embodied emissions in the total lifecycle energy use increases as the measures taken in a renovation or newly built project are more and more ambitious, but the exact size of this share is unclear in academic literature. Several such estimates can be found in literature, but they are very divergent due to differences in assumptions and calculation methodologies. Fenner et al. find that the share of embodied energy in conventional residential buildings that do not have a very high level of energy performance lies around 30%, while Koezjakov et al. estimates a share of only 10-12% for conventional residential buildings and a share of 31-46% for buildings with a high energy performance [40,45]. Meanwhile, Cabeza et al. estimate a share of 15-20% for regular buildings while Allacker finds a share of 15-30% for regular buildings and 40-65% for high energy performance buildings [46,47].

The European policy framework principally supports the use of a lifecycle perspective to achieve the cost-optimal transformation of the buildings sector, but there are no targets or methodologies that are imposed and actual policies remain heavily focused on the operational energy use [6,11,48]. There are also several initiatives both at the governmental and academic level to develop standardized methodologies for performing lifecycle analyses. At the governmental level, standards have been developed like ISO 14040, ISO 14067, EN15804 and EN15978 [33,40]. Meanwhile, initiatives like the development of the "TOTEM tool" (in Flanders) have been set up to evaluate an even broader range of environmental impacts of buildings from a lifecycle perspective (i.e. not limited to carbon emissions)[49].

A core issue of applying lifecycle analyses is the fact that there is still a large need to further develop methodologies and improve the availability and quality of the datasets that are necessary. Data quality needs to be improved both in terms of the average values for certain material and BITS, as well as in terms of specific values for products from specific manufacturers. Assumptions and calculation methodologies also still need to be harmonized and made more transparent. Recent reviews of academic literature on embodied energy and emissions pinpoint these and many other challenges that will still need to be solved before this type of analysis can become as broadly used and accepted as the conventional assessments of operational energy use [39,40,42,50–52]. We can therefore only recommend a minimal and pragmatic use of lifecycle methodologies when assessing the optimal balance between different kinds of measures at the individual building level, at least for the time being.

3. Identifying the cost-optimal approach at the societal level

3.1. Introduction

The cost-optimal balance between different kinds of measures to realize a decarbonized[20] residential building stock can not only be investigated at the individual building level (as discussed in chapter 2), but also at the societal level. We then consider the perspective of the policy maker, who can take a much broader set of measures than an individual homeowner. Several previously exogenous 'boundary conditions' then become endogenous decisions to be made in a cost-optimal approach. These lie mostly on the supply-side, where measures like the construction of district heating networks and the decarbonization of the electricity supply can now me included ('locations' 1 and 2 in figure 1a). The policy maker also has additional possibilities in terms of demand-side measures. For example, a decision can be made to insulate entire streets of terraced houses, instead of renovating individual buildings one by one. Although similar measures may then be taken as in the individual building level analysis, the cost per building may be lower due to economies of scale.

The inclusion of 'societal level' measures (each with their own costs and benefits) and the changes in the costs of some 'individual building level' measures, can together result in a *different outcome* in terms of the cost-optimal approach. This means that, for any particular building, the cost-optimal package at the individual level (chapter 2) may be different from what is the cost-optimal package 'for that building' from a societal perspective (chapter 3). It also means that, for each the three identified trade-off's (chapter 1), both levels of analysis will result in a different 'optimal balance'.

The scope of the 'societal level' can include different levels of government, like the city-, national- or even the European level. Some measures are typically considered by policy makers at the more local level, like building and expanding district heating networks or electricity distribution networks. Meanwhile, other measures like the decarbonisation of the electricity supply rather fall under the competence of policy makers at the national and European levels. Cost-optimally exploiting the potential of renewable resources at different geographical locations typically requires a very broad policy perspective and may include measures like improving the cross-border electricity transmission capacities between European countries.

Whenever the societal-level is considered, the question arises whether a green-field or brown-field analysis should be performed. In the former, the optimal system is designed 'from scratch', assuming that an entirely new system is built and ignoring the entire building stock and energy supply system that is already in place. In the latter, the calculation takes into account everything that is already in place today (the building stock in its current form, the current electricity generation system, existing electricity, gas and heating grids, etc.). The current situation is considered as a starting point, taking into account both the sunk costs and the costs of making changes to the existing system.

A brown-field analysis can result in an 'unfair' advantage for some kinds of measures over others. For example, taking into account the fact that gas-grids are already available and are (for the most part) already fully amortized, can create a relative disadvantage for district heating grids. In a greenfield analysis, the full investment cost of both the gas and district heating grids would have to be considered, but this is not the case in a brown-field approach. Likewise, areas that already have very strong

---

[20] In this chapter, we focus on the goal of reducing CE, which we perceive to be of primary importance. The alternative goal of reducing PE (cf. figures 1a and 1b) is left out of consideration. However, as explained in the introduction, measures aimed at realizing one goal will –in most cases– also result in a (partial) realization of the alternative goal.

electricity distribution networks could lean towards a heavier reliance on electrically-driven heating technologies in a brown-field analysis (and vice-versa). While a green-field analysis may be easier from a modelling perspective, a brown-field analysis most closely resembles the actual challenge faced by policy makers.

A similarity with the analysis at the individual building level is the fact that the *local climate* can heavily influence the optimal balance between different kinds of measures. Even when we consider the optimization challenge from the European level, the differences in climate across Europe need to be taken into account. For example, the cost-optimal balance will likely include more ambitious demand-side measures (better insulation) in countries with a colder climate. Moreover, the local climate does not only determine the heating demands (and the related optimal share of demand-side measures), but also the renewable energy potential. Relying heavily on the electrification of residential heating systems will likely make more sense in a country like Norway (where >90% of electricity can be generated with renewable hydropower) than in a country like Finland (where hydropower is much less abundant, but there exists a large potential for local biomass instead).

We explore the challenge of balancing different kinds of measures at the societal level more closely in the following sections. In Section 3.2 we discuss the additional considerations that need to be made for several supply-side technologies when looking at them from a societal perspective. In section 3.3 we discuss the current state-of-the art in modeling efforts that consider the societal level. Finally, we explore what might lie *beyond* the state-of-the-art in academic literature in section 3.4. We perform a thought-experiment about the necessary modelling efforts that *would be* required, if we were to *actually* determine what the cost-optimal decarbonization strategy for the residential buildings sector may be.

3.2. Renewable heating technologies from a societal perspective

Biomass

The large-scale use of biomass[21] is a potential pathway for the decarbonisation of the residential building stock. Especially in the case of existing buildings, a switch from traditional fossil fuel based heating technologies to biomass heating can seem attractive from a policy maker point of view. However, policy makers need to consider several elements that are less relevant at the individual building level. First, it should be recognized that there is only a limited amount of biomass resources available in each region and that they should be allocated carefully. Especially if biomass is to be sourced sustainably and within Europe, it should not be seen as a supply-side measure that can be realized at *any* scale. The optimal package of measures at the societal level can only rely on biomass up to a certain scale, which is especially limited if we restrict ourselves to the use of 'waste stream' biomass (i.e. excluding virgin biomass, which is arguably better used for other purposes). Therefore, biomass will most likely need to be combined with a heavy investment in energy efficiency measures, to avoid shortages on the supply-side [20]. It is feasible that in an optimal scenario biomass use is limited to those parts of the residential buildings stock that are particularly difficult to decarbonize. For example, specific rural dwellings that are both too costly to connect to a district heating network

---

[21] Some heterogeneity exists in the definitions of biomass used at the UN and EU level, as well as various national and sub-national governments. In this report, biomass broadly refers to all plant-based solid fuels used for electricity and heat generation. This is mainly traditional wood (from sustainable forestry), as well as various kinds of wood residues (e.g. from the construction sector) and specially farmed energy-crops.

or extraordinarily difficult to improve in terms of energy performance (i.e. to make them suitable for using a heat pump).

A second element that needs to be considered at the societal level is the debate on the actual merits of using biomass as a decarbonisation strategy. Not only is biomass a limited resource, but policy makers should also be careful when attributing a value to its carbon emissions[22]. As made clear by a recent analysis in the scientific journal Nature, the merits of burning American wood as a key measure in the European decarbonisation process can be seriously questioned [53]. Finally, a third consideration is the negative effect of biomass on local air quality levels. A policy maker with a holistic view on the cost of each supply-side technology could take into account the indirect health costs that can be caused by large-scale use of biomass. Especially in dense urban areas, 'low emission zones' where certain heating technologies like biomass cannot be used – as they already exist for cars in several European cities – can be part of the overall equation from a policy maker point of view.

Heat pumps

In the case of heat pump technologies, supplying the necessary electricity to match the (sub)hourly consumption profile and doing so in a renewable fashion is a considerable challenge. It is difficult to avoid a temporal mismatch between renewable energy generation and the electricity consumption of heat pumps, especially when they are deployed in the residential buildings sector on a very large scale. At the level of an individual building, it may be assumed that electricity can be freely withdrawn from and injected into the electricity grid. In fact, the use of the grid and the electricity it provides may even be ignored, in which case the consumption of a heat pump and the local production of solar energy is 'balanced out' on an annual basis. These simplifications are not possible when performing an assessment at the societal level. The continuous balance between demand and supply of electricity needs to be safeguarded and the *actual emissions* caused on the supply-side (the electricity system) are fully taken into account. The degree to which heat pumps can actually help decarbonize the residential building stock will to a large degree depend on the ability to decarbonize the electricity sector and the costs related to that.

Generating the right amount of low-carbon electricity during each hour of the year is not the only challenge that needs to be considered. The additional loads caused by residential heat pumps (and solar panels) on the distribution grids are also a major cause of concern. If a policy maker tries to find the optimal balance between different kinds of measures to decarbonize the residential building stock, the additional costs that are caused in terms of improving electricity grids (i.e. 'location' 2 in figure 1a) are also part of the optimization. As mentioned in chapter 2, utilizing the demand side management and local energy storage potential of residential buildings can avoid some of the additional grid investment costs, but integrating all of these aspects into a cost-optimization exercise at the societal level could prove to be very difficult [54,55]. What is clear however, is that the most cost-efficient solutions to this problem are most likely found at the societal level as opposed to the individual building level [56].

---

[22] As mentioned earlier, the PEF value for biomass is also a contested issue. However, we focus our discussion about the optimal balance between different kinds of measures at the societal level on the goal of reducing CE (for which the PEF values of different technologies are irrelevant).

District heating

District heating grids can potentially deliver significant cost savings when decarbonizing the residential building stock, especially if more of the 'waste heat' produced all across the economy (energy sector, industry, datacenters, etc.) could be successfully captured[23]. However, attributing costs to a roll-out of district heating grids within a societal-level assessment can be extremely difficult in practice. There is an inherent trade-off between the concentration of heating demand and the costs of building and running a district heating system [57]. In a scenario where the existing residential building stock is heavily renovated to achieve very high levels of energy performance, the economic attractiveness of deploying large-scale district heating can be significantly diminished. In fact, new district heating grids rarely present an attractive business-case for short- to medium-term investors. Their pay-back time easily exceeds 30 years in many cases, which may mean that some level of government support is always necessary[24].

Another reason why the consideration of district heating in societal level analyses is so challenging, is the fact that the associated investment costs can be highly uncertain depending on a variety of technical parameters. For example, the exact *configuration* of the underground network and the locations of the (different) heat source(s) can lead to large variations in the estimated investment costs [57].

3.3. State-of-the art in cost-optimal building sector transformation models

Traditional building stock models

In this section, we provide an overview of the current state-of-the-art in terms of identifying the cost-optimal combination of measures from the societal point of view. Most recent studies still focus exclusively on the building stock [58–64]. Electricity and district heating systems (both in terms of *grids* as well as electricity and heat *generation*) are then seen as exogenous boundary conditions, instead of being considered as (endogenous) elements that are part of the overall optimization.

In most cases, these traditional building-stock models are focused on the goal of reducing PE. CE reductions are sometimes calculated, but only as a output that is of secondary importance (i.e. not as the optimization objective). Regardless of the reduction goal (PE or CE), these models typically want to inform policy makers about one of two things. Either they want to identify the 'cost optimal' reduction level, or they want to identify which package of measures reaches a certain reduction *target* at the lowest cost.

To calculate PE and costs at the societal level, building stock models use one of two methods. Either the building stock is represented by a range of (fictional) 'representative buildings', or it is represented by a selection of (real) 'sample buildings' that act as a kind of case studies to be extrapolated from. In the representative buildings approach, all the building characteristics represent the (calculated) averages for each segment of the building stock. For example, an 'average terraced house of a certain age', an 'average apartment of a certain age', with 'average insulation levels' and using and 'average efficiency boiler' etc. The exact building taxonomy used in different studies – which divides the building

---

[23] Insofar as this waste heat supply is itself not severely diminished because of efficiency improvements in the energy and industrial sectors, which is likely to occur during the same decades as the decarbonization of the residential building stock.

[24] However, to reiterate, this allocation of costs between private and governmental players is out of scope for the societal-level analysis as conceptualized in this report.

stock into different representative segments – varies depending on the formulated research question, the available input data and the geographical scope of the study.

The total costs calculated in these models traditionally include both the investment costs (CAPEX) and operation costs (OPEX) for the entire building stock. Across the temporal scope of the studies – which often comprises of looking several decades into the future – costs are either summed up, or expressed in an annualized form. In both cases, discounting is usually applied. Certain models also disaggregate the total costs across the different building stock segments, to provide additional information about which segments require heavier investments than others. It may for example be found that, in the overall cost-optimal approach, a majority of measures and costs take place in the segment of the worst-performing buildings.

Traditional building stock models focusing on a reduction in PE are subject to several shortcomings. First of all, the treatment of electricity and district heating systems as exogenous boundary conditions clearly leads to a disproportionate focus on individual building level measures ("I" in figure 1b). In other words, the same measures that can be taken in any optimization for a single building, are simply 'scaled up' to the level of the entire building stock. Meanwhile, most societal-level measures ("S" in figure 1b) are left out of consideration. Secondly, the PE of buildings in different segments is often calculated in a highly inaccurate way. This applies both to the PE of buildings at the 'starting point' of the analysis (i.e. the description of the original state of the building stock in question), as well as their PE after certain measures are taken (i.e. the PE reduction effect of different measures).

Regarding the starting point, several studies at the individual building level have found that standard methodologies (which are also applied at scale in building *stock* models) frequently overestimate the energy consumption of inefficient buildings and vice versa [58,65]. Regarding the effect of measures in terms of reducing PE, inaccuracies occur for several reasons. Not only are the building energy simulations – which determine the physical impact of a certain measure in terms of the reduction in heat demand – overly simplified in many cases, but so are the assumptions and modelling with regard to *user behavior*, which is a major driver of residential energy consumption [58,59,64].

Finally, building stock models face severe constraints on the availability of input data. Available data is not only limited for the description of the current building stock itself, but also regarding the costs related to improving its energy performance. To deal with this issue, they often have to rely on a bottom-up approach where many pieces of available data from different sources are combined in a suboptimal fashion [59].

For all mentioned shortcomings of the traditional building stock models that focus on reducing PE, it should be noted that the more integrated models discussed in the next section (which also endogenize electricity and district heating systems) are also subject to them. The same building stocks need to be modelled after all, and the additional modelling of electricity and district heating systems may even exacerbate some of shortcomings. For example, even more input data may be required but not available. However, the limitations in terms of modelling, input data and computational demands, do not necessarily invalidate the generated insights. Policy makers should just be aware of these shortcomings, when designing their polities on the basis of these models.

Integrated societal-level models

Several recent studies have a larger modelling scope than the traditional building stock models. They take a more integrated approach, by considering at least one additional part of the energy system. For example, the national or European electricity generation system may be modelled as well, to analyze the interplay between a large scale roll-out of heat pumps in the building stock on one side, and the necessary increase in the generation of electricity on the other side. Note that, in this example, electricity distribution grids and district heating systems (both in terms of grids and in the generation of heat itself) are left out of consideration, potentially leading to misleading conclusions about where the societal cost-optimum lies.

By taking (some of) the additional parts of the energy system that are closely connected to building energy use into account, the PE, CE and total societal costs can each be better estimated. The overall cost-optimal approach (to reach a certain PE or CE target) will then take into account trade-off's and synergies across buildings, grids, electricity and district heating systems. In the following paragraphs, we discuss several state-of-the art studies in a sequential manner. It should however be stated upfront that *none* of the studies discussed below achieve a *fully comprehensive* (fully integrated) analysis. What such an analysis may have to consist of, is explored in the next section.

Several of the studies discussed below can be situated under the broader academic field of 'sector coupling' research. This young research field studies the interactions between the different parts of the energy system. Most of the studies performed so far under the banner of 'sector coupling research', focus their modelling primarily on the electricity sector. Opportunities to make use of flexibilities *outside* of the electricity sector – like the thermal buffering capacity of buildings, or the conversion of electricity to molecules – are then explored within the context of further increasing the share of intermittent renewables *inside* the electricity sector [66,67]. However, the majority of studies discussed below have a different focus. They tend to model the buildings sector in most detail, and perform additional modelling to include some of the connecting pieces in a less detailed manner.

A study by Agora Energiewende analyzes different scenarios for the future German building stock, combining energy efficiency improvements with the large-scale roll-out of district heating grids, heat pumps and power-to-gas (P2G) technologies [68]. One of the main conclusions of this study is the fact that the limits of feasible supply-side capacities (e.g. how much renewable electricity can be realistically produced in Germany) can easily be reached if demand-side measures are completely ignored. In other words, a drastic electrification of the heating supply in the German residential buildings sector would in any case *have to be* combined with some level of demand-side measures. In their P2G-focused scenario, they find that the large quantities of synthetic methane that would be needed to cover the heating needs of the German residential building sector, is likely to be produced outside of Germany at geographic locations where the cost of solar energy will become extremely low (e.g. Northern Africa).

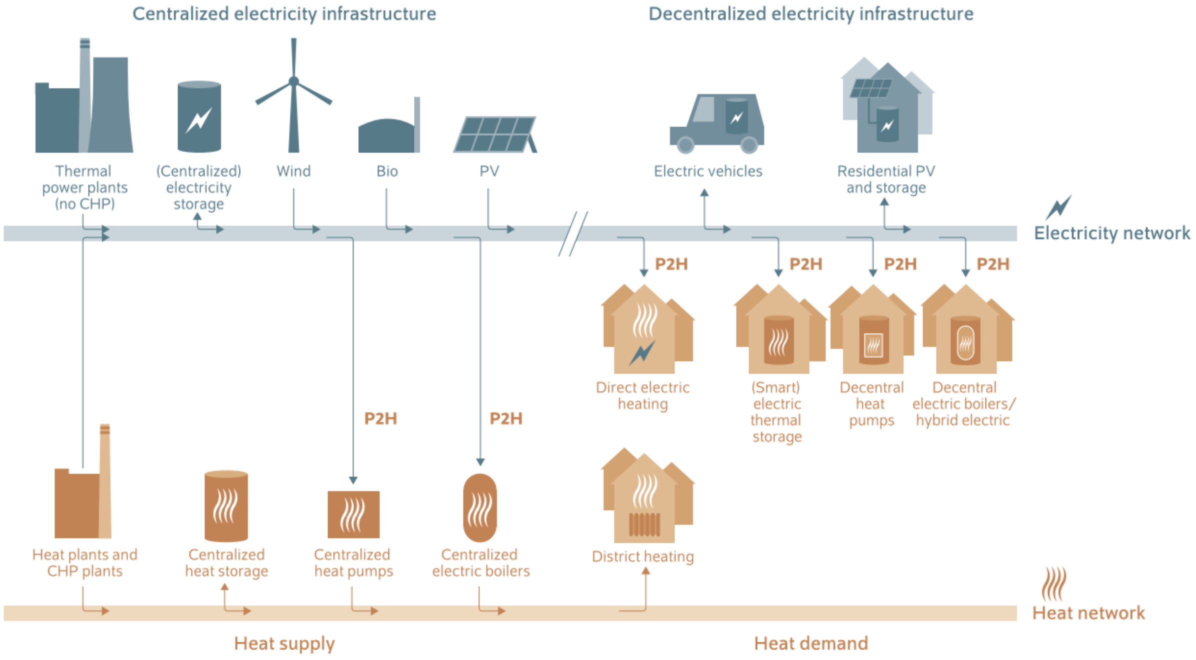
A study by Astudillo et al. uses a TIMES-model to analyze the building stock in Quebec (Canada) and estimates the impact of a large-scale rollout of heat pumps. The study finds that the rollout of heat-pumps on the supply-side can *decrease* the electricity peak demand (because the starting point is a building stock dominated by electrical resistance heating) and thereby generate significant cost savings [69]. Meanwhile, energy efficiency improvements on the demand-side can further reduce the peak demand, leading to additional cost-savings and together forming an attractive scenario from a societal point of view.

A study by Zvingilaite and Balyk considers the Danish residential building stock in combination with the heavily developed district heating grids [70]. They estimate that the most cost-optimal scenario for

Denmark is to improve building energy performance by only a moderate amount (12-17%) by 2050 and to instead invest heavily in the further expansion and decarbonisation of the Danish district heating grids. They only recommend more ambitious demand-side measures for some rural buildings, for which a connection to a district heating grid is either not technically feasible or highly uneconomical. A similar trade-off between energy efficiency measures and the development of district heating grids is found in a study by Nässén and Holmberg, which looks at the Swedish residential building sector [71]. They specifically consider the profitability of the CHP's that provide heating to the district heating grids. Assuming a rising carbon price in the future, they find that the electricity prices received by CHP's will be high in a scenario where the electricity sector decarbonizes only moderately. This enables the CHP's to sell their heat output at a lower price, which results in a bigger role for district heating in the buildings sector and a smaller role for energy efficiency measures.

Several other studies that focus on the German context stress the importance of considering sector coupling opportunities between the electricity and heating sectors [2,72–74], as illustrated in figure 10. Bloess et al. find that the smart and flexible use of P2H technologies can prevent a strong increase in electricity prices that could be expected when the residential heating sector is electrified [72]. By considering the electricity and heating sector in an integrated fashion, important synergies are identified. These include lowering the electricity peak demand, lowering the need for renewables curtailment and expensive storage technologies like batteries, and increasing the operational efficiency of thermal power plants.

__Figure 10: Sector coupling between the electricity and (residential) heating sectors__



Source: [72]

Two studies by Palzer and Henning consider the feasibility of a completely renewable electricity and heating sector in Germany [2,73]. They calculate the costs of reducing the building stock energy demand on one hand and increasing the generation of renewable energy on the other. Many aspects of this trade-off are dealt with in a highly simplified matter, and they acknowledge the fact that their cost-estimates for improving the energy performance of the German building stock are rather uncertain. However, they do find that a scenario that relies heavily on energy efficiency improvements has a *higher* total system cost than a scenario with milder energy efficiency improvements combined with a larger investment in renewable energy capacities. The scenario with the lowest total system cost is one where the investments in renewables are increased as much as possible, but the authors admit that the capacities are probably higher than what can feasibly be built within Germany.

A study by Brown et al. also takes into account the possibility of trading electricity across the German borders, and finds an inverse relationship between cross-border transmission capacities and the optimal level of energy efficiency in the building stock [64]. Generally speaking, increasing the capacity of interconnectors on the German border can lead to lower electricity prices and therefore reduce the cost-savings reached by demand-side measures. Especially the economics of *very ambitious* energy efficiency improvements – that have a relatively high cost in return for limited additional energy savings – can be affected by a change in cross-border transmission capacities.

The most recent study by Bloess incorporates the heat demand of the German building stock, as well as the heat demand of German industry, within an electricity system model for the entirety of Europe [75]. District heating systems are also represented in the model in a simplified way. The scenarios consist of exogenously determined changes to the total heat demand, which may take place in the future. The costs associated with, for example, the renovation of the German building stock (in order to realize this reduction in heat demand), are not included in the analysis. The author finds that the electricity demand in Germany may double or even triple in the long term, due to the heavy electrification of building and industrial heating. The endogenous optimization of the electricity generation capacities reveals the fact that, under a strict CE constraint, the investment in wind power increases substantially. In contrast the investment in solar PV increases to a much lesser extent, due to much of the additional electricity demand (for heating) taking place in the winter period. The author also notes that there are not yet any European-scale electricity system models available which accurately endogenize the heating sectors of all European countries. Input data and computational constraints are identified as potential barriers in this pursuit. It becomes clear from this study however, that even including the heating sector of a single (large) country within the broader European electricity system, can already have a significant effect.

A study by Patteeuw et al. considers the trade-off between conventional gas boilers and heat pumps for a variety of different segments of the future Belgian building stock [76]. Although they do not take into account the cost of improving the energy performance of the building stock, they do consider the additional operational- and investment costs in the electricity system when heat pumps are rolled out on a large scale. They also take into account the difference that can be made by applying a basic form of active demand response in the buildings using a heat pump. They find that, for the worst-performing segments of the building stock, improving their energy performance has a lower carbon abatement cost than the installation of a heat pump. On the other hand, for buildings with an average energy performance level, the abatement cost of switching to a heat pump combined with demand response is similar to the abatement cost of renovating to a very high energy performance. They also find that the additional costs caused in the electricity sector because of the large-scale rollout of heat pumps can be significantly limited by adding demand response capabilities to the buildings that use them.

A study by Drysdale et al. uses the well-known tool 'EnergyPlan' to assess whether the overall PE of the Danish building stock will in fact reduce as drastically as expected, when all new buildings are forced to reach an nZEB standard of energy performance [77]. They take into account the fact that the investments to reduce the buildings' heat demand will take place in a context where the PEF of electricity is continually decreasing (due to a further increase in the share of renewables) and where the supply-side efficiency of district heating grids is continually increasing. Perhaps unsurprisingly, they find that the nZEB standard will *not* result in the PE reductions that are projected by policy makers, due to the interaction effects with the supply-side. They also find that even more stringent energy performance requirements for newly built projects – as proposed by some stakeholders – are highly suboptimal from a total societal cost perspective. In their conclusions, the authors stress the fact that policy makers all across Europe will have to better take into account the complex interactions across the energy system, by relying more heavily on integrated models. Determining optimal building-code standards (e.g. nZEB) clearly requires an analysis with a scope that is much broader than the buildings sector alone.

Vandevyvere et al. analyzed the interplay between the cost of building district heating systems on one side, and the cost of renovating existing buildings on the other side, by integrating both in a single model [4]. The analysis is focused on (sub)urban districts in Flanders, and does not endogenize the electricity system. Both the additional costs that may be triggered by each scenario in electricity distribution grids, as well as in the (national/European) electricity generation system, are thus left out of consideration. Electricity and gas prices are taken as exogenous boundary conditions. The main trade-off that the study wants to analyze is increasing the energy efficiency of the existing building stock on one side, and supplying it with renewable energy and/or district heating on the other. To take into account the fact that renovations that improve the energy efficiency of buildings also have a range of non-energy related co-benefits (like the health, esthetics and market value improvements), they apply the rather unusual assumption of de-rating the building renovation costs by 50%[25].

They find that the societal cost-optimum does not reach the PE and CE targets that are desired by policy makers, mainly due to current electricity and gas prices (and the division of taxes between those two) providing insufficient incentives. In the scenario's where an ambitious CE target is imposed, the cost-optimal package that reaches that target usually includes deep retrofits on most buildings. This either enables low temperature heating through individual heat pumps, or through a low-temperature district heating network. It should however be noted that this finding changes considerably in the sensitivity where 100% of the renovation costs are included. In the main (non-sensitivity) results, the combination of district heating and mild renovations is only optimal in certain cases. Namely when a cheap, high-temperature renewable source of heat is available (close to the urban district), and the buildings cannot easily be renovated to enable low-temperature heating (for example because of heritage reasons). Finally, it is also found that the combination of building both a low-temperature district heating system *and* heating a large share of the buildings with independent heat pumps, is highly *suboptimal* from a societal cost perspective. If and when a district heating system is built, most if not all buildings should be connected to it – instead of being heated individually with a heat pump – in order to avoid expensive 'double infrastructure' and 'double costs'.

It should be noted that it is to some degree uncertain how many existing buildings are in fact unsuitable for low temperature heating without completely changing the existing heating system. In some buildings with a traditional central heating system, the radiators may be overdimensioned enough to be compatible with low-temperature heating. This has for example been found in some case-studies in the Netherlands [78]. However, this is not discussed in the study by Vandevyvere et al., and is very challenging to take into account in a societal-level modelling exercise. If the necessary building stock data (detailed to the level of the dimensioning of the heat dissipation systems) would become available, it could turn out to be the case that many existing buildings are suitable for low temperature

---

[25] Strictly speaking, they only de-rate the cost of renovation measures with regard to the *building envelope*. The reasoning is that other measures like the replacement of the heating installation, *can* only be attributed to the aspect of 'energy performance improvement'. For those measures, 100% of the costs are included.

heating (provided that the building envelope is improved to the appropriate degree). In that case, the cost-optimal share of low-temperature district heating or individual heat pumps may be higher than conventionally expected, for example in the study by Vandevyvere et al.

3.4. Thought experiment on a fully integrated model (FIM)

3.4.1. Introduction

Before we explore what potentially lies *beyond* the current state-of-the-art, a brief summary of what has been discussed so far in this report is in order. In chapter 1, we provided a framework to conceptualize the necessary transformation of the residential building stock. We proposed that this transformation should effectively pursue *either* the goal of reducing the primary energy use *or* the carbon emissions related to the building stock, even though the measures taken in this regard largely overlap and will often contribute to reductions on both fronts. Depending on the chosen goal, all potential measures are evaluated in terms of their costs on one side, and their contribution to the goal (e.g. emissions reduction) on the other. A wide range of measures can be considered, once a particular goal is chosen. As we discussed in chapter 1, each of them can be categorized in a number of ways, according to different trade-off's (cf. figure 1b). Both at the individual building level and at the societal level, a cost-optimal combination of measures can be identified, which realizes either a certain PE or CE reduction goal at the lowest possible cost.

In the current chapter, we discussed the state-of-the-art in terms of identifying this cost-optimal approach at the societal level. We found that the latest studies already achieve a partial 'integration' of – for example – the buildings sector and the national electricity generation system. However, a full integration of the key elements involved in the transformation of the building stock is still missing. By 'key elements', we specifically mean, each of the elements that are discussed at length in this report, as shown in figure 1b. Each of these have their own costs and benefits, and are therefore important to consider, if the societally cost-optimal approach is to be identified. Unfortunately, there are not yet any studies that incorporate all key elements in a single analysis. In many cases, there is a strong focus on energy efficiency and demand-side measures, while much less attention is paid to the full range of renewable energy and supply-side measures. Local electricity and district heating grids are also often excluded. In the few existing analyses where those elements *are* included, the (inter)national electricity system is excluded instead, and so forth.

Extrapolating from the recent surge in 'sector coupling' research, and considering the more established field of 'energy system models' like TIMES, this section explores what a 'fully integrated model' (FIM) – which endogenizes all of the key elements involved in a cost-optimal decarbonization of the building stock– may look like. The *goal* of such a FIM would be to identify the societal cost-optimal path towards a certain PE or CE reduction target. In terms of the chosen goal, we prefer a prioritization of emissions over primary energy use, since the former is arguably more important than the latter. Adequately reducing emissions in the face of climate change, while we miss an arbitrary goal in terms of PE, would be worse than reaching a PE goal without realizing the necessary emissions reductions. We therefore put forth a FIM that takes decarbonization as its goal, and identifies a cost-optimal approach to reach it. However, a FIM could in theory focus on the goal of reducing PE as well.

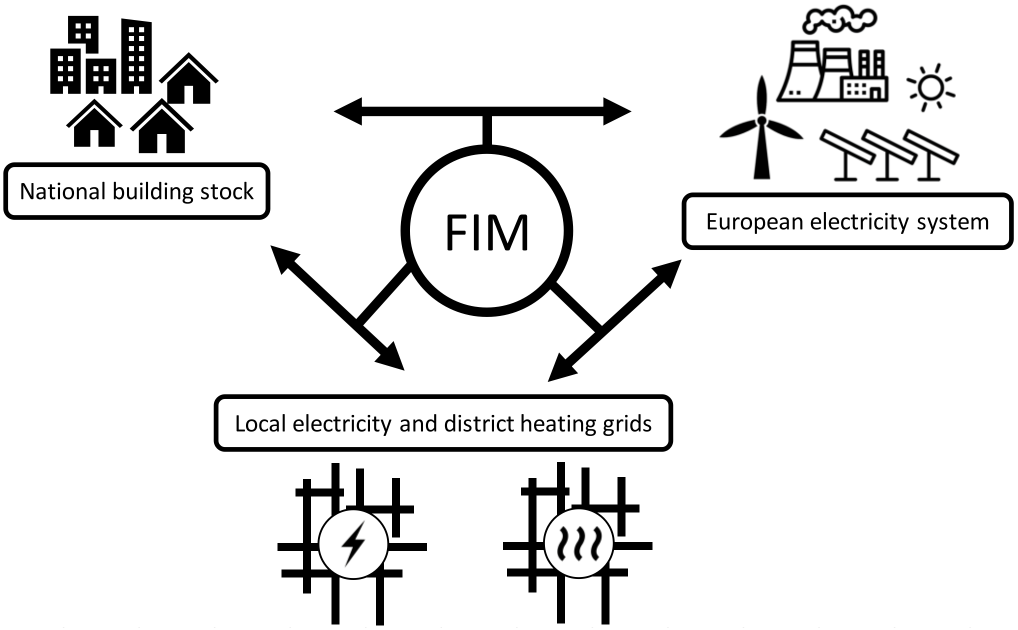
The bottom line in this report is that electrification is a *fundamental* principle in the process of decarbonizing the residential building stock, unlike many other aspects that can potentially be taken into account (health impacts, mobility impacts,…) . The electricity system – including both generation and (local) grids – should therefore be considered in an integrated model. We have also discussed the fact that district heating likely has an important role to play in an overall cost-optimal approach. It would therefore be inappropriate to exclude this from a FIM. Ultimately, the aim of a FIM is thus to capture the important interactions between buildings, the electricity system, and district heating systems.

The remainder of this section is divided into the following parts. We begin my clarifying the scope of the proposed FIM, not only in terms of the various sub-models (buildings, electricity generation and distribution, and district heating), but also in terms of the temporal and geographical aspects. Here we also discuss the sub-models in more detail, including their relation to the broader context (e.g. the simultaneous electrification of the mobility and industrial sectors). Finally, we discuss the challenges and barriers to the actual realization of the proposed FIM, and shed a light on the various aspects that remain *out* of its scope.

3.4.2. Model scope of a FIM

As the statistician George Box famously noted in 1976, "*All models are wrong, but some are useful*". In the case of our proposed FIM, the aim is therefore not to design an all-encompassing 'correct' model. Its usefulness – compared to traditional building stock models – would rather be that it would better take into account the costs and savings opportunities related to electrification and district heating systems. Insofar that this results in an improved understanding of how to achieve a cost-efficient decarbonization for the building stock, the FIM can already be valuable, even if several aspects still remain out of its scope. However, some questions remain with regards to *what exactly* should be contained within its scope. Although we know what the main ingredients of a FIM would be, determining the appropriate level of detail for each of them still forms an important challenge. A schematic overview of the proposed FIM is provided by figure 11.

Figure 11: Schematic overview of the FIM



Before we discuss the details of what might lie within scope of each of the sub-models, some general principals are important to consider. First of all, it should be determined whether a FIM would apply a green- or a brown-field perspective. A greenfield approach, where the entire building stock, electricity system and district heating grids would be designed 'from scratch' (to fit the needs of a particular population), would be more convenient from a modelling perspective. The main reason for this being the fact that much less input data would be required about the *current state* of each of the key elements. However, such an approach would fail to reflect the actual challenge faced by policy makers. Since the societal challenge mostly consists of decarbonizing an *existing* building stock, a brown-field perspective is most appropriate. This also applies to the electricity system and district heating grids. Within a brown-field approach, the fact that many assets *are already in place* can affect the cost-efficiency of investing in certain measures. For example, the presence of a strong electricity distribution grid that can easily accommodate a large penetration of heat pumps, could make an investment in a (new) district heating network much less cost efficient.

As a second general principle, the geographical and temporal scopes of the FIM need to be carefully considered. In terms of the geographical scope, each of the sub-models are conventionally modelled on a different level. For the electricity generation (and transmission) system, it is achievable and desirable to model at the European scale. This allows the FIM to take into account the increasingly important exchanges of electricity across country borders, which co-determine the PEF and CI of electricity consumed in any particular country (cf. sections 2.2 and 2.3). Meanwhile, building stock models are rarely modelled at the European scale. While European-level building stock models do exist, national models are much more common because a taxonomy of buildings at the European level unavoidable makes a few overly simplistic generalizations. Even more local are the models for electricity distribution and district heating systems. Existing models for these key elements are usually severely limited in their geographical scope, due to the highly specific characteristics of every local grid. Reconciling these differences in a FIM with a unified geographical scope, is perhaps the most difficult hurdle to overcome.

It is not realistic to lift each of the key elements of the FIM to the European level, whoever desirable it may be. That would require a representation of each of the national building stocks, and of the local electricity distribution and district heating grids all across Europe. An immense amount of input data would be required for such an endeavor. A more pragmatic choice would therefore be to focus the FIM on a single country. This means that the building stock would be modelled at the national level, and separate approaches would be used to link it with the other key elements.

To take into account the interaction between the building stock and the electricity system, the latter can still be modelled on the European level. The only simplification that would need to be applied, is to model the electricity system of other countries in a more exogenous way than the system at the national level. While the national buildings stock and electricity generation assets can be fully endogenized – i.e. they can be co-optimized to achieve the lowest-cost decarbonization of the national building stock – the electricity demand and generation in other European countries would be fixed. This means that assumptions about their electricity systems would have to be made, including the available electricity generation assets as well as the national electricity demands in each country. This implicitly means that assumptions would also have to be made about the degree to which the building stocks in other countries are renovated and electrified (e.g. with PV and heat pumps), since this will heavily influence the aggregated electricity demands in each country. The model would than take the perspective of national policy makers, which have no power to make changes to the building stocks or electricity systems in other European countries, but *can* apply policy to help steer 'their own' building stock and electricity system.

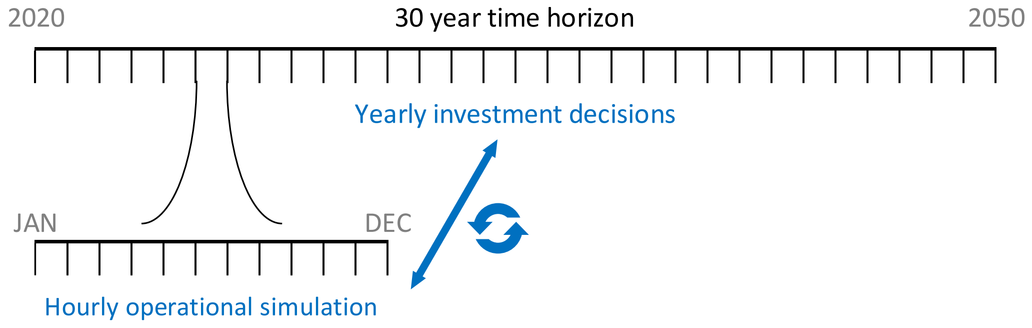
Meanwhile, the costs and benefits related to electricity distribution grids and district heating systems would somehow need to be extrapolated to the national level. This is particularly challenging because the physical- and cost-structure of each distribution grid can vary a lot from case to case. Differences in historic choices made with regard to the dimensioning of the network, the location and specifications of feeders and other technical equipment can all have an important impact. Each of these local and technical elements drives the supply-side costs of electrifying heating in residential buildings and increasing the local electricity generation with solar panels. Likewise, each district heating system is unique. Detailed analysis is often required to assess the costs related to its potential expansion. In fact, when new district heating networks are designed, technical parameters like the exact *routing of the pipes* from heat source(s) to heat demands (i.e. the network design), can heavily influence the investment and operational costs related to the system.

Extrapolating cost-estimates to the national level will inevitably result in some (over)simplifications with respect to the actual local circumstances related to these grids. However, it does seem to be the case that the goal of taking their costs and benefits into account in a cost-optimization at the national level could still be achieved in a satisfactory manner. This would however depend on further advances in the research field of ‘representative’ electricity distribution and district heating grids. Without a more solid understanding of how to extrapolate the costs related to distribution grids and district heating systems to the national level, it would be difficult to avoid excessively large errors in the national-level cost optimization.

In terms of the *temporal scope*, similar tensions between the different sub-models arise when designing a FIM. By temporal scope we mean both the total time period considered by the model (e.g. from a few years up to several decades), as well as the *temporal resolution* (i.e. the size of the timesteps over which the cost-minimization is performed). It is mostly for the latter, that tensions between the sub-models may become apparent. Most traditional building stock models use a yearly timestep when it comes to simulating the building energy use and the investments into various renovation investments. However, when modelling the electricity generation system, an hourly timestep is much more common. This higher temporal resolution is necessary to capture the dynamics of both electricity demand and supply, especially when the share of intermittent renewables like wind and solar is expected to increase further across the considered period. For the local networks, even higher temporal resolutions may be desirable. Both in the case of simulating electricity distribution networks and district heating networks, sub-hourly timesteps are often used to accurately capture dynamics in terms of voltages, line loading, mass flows, etc..

Similar to our reasoning for the geographical scope, a ‘middle road’ for the temporal resolution seems achievable and satisfactory. If we chose an *hourly* timestep for the part of the FIM that simulates the energy production, transport and consumption, most of the important dynamics will likely be captured. For example, hourly heat demands in the building stock will result in hourly electricity demands for each building using a heat pump, and the aggregated requirements in terms of electricity generation and distribution will be reflected in the simulation accordingly. Meanwhile, the investment decision cycle in the FIM simulation can be kept at a yearly timestep. Decisions to invest in the building stock, the electricity generation system, or any of the local networks, do not need to be evaluated at an hourly level. Such a ‘double temporal resolution’ (yearly and hourly) is already commonly applied in ‘simultaneous investment and dispatch optimization electricity system models’. These models simulate the production and consumption of electricity on an hourly timescale (e.g. for a single country), and use the outcomes of these ‘operational’ simulations to derive optimal investments on a yearly timescale. The least-cost mix of electricity generation assets to meet the hourly electricity demands is thereby identified.

Figure 12: temporal scope and simulation design of the FIM



In terms of the *considered period* in the FIM simulation, it seems more or less obvious to consider the entire remaining period up to the 2050 deadline, by which the decarbonization goal should be met. This roughly three-decade long time perspective leaves enough room for a lot of changes to be made to the existing state of each of the key elements. In terms of the building stock, many buildings can be renovated on this timescale, and a large amount of newly-built projects can be included in the analysis. Likewise, the electricity generation system can undergo a significant transformation across a period of 30 years. Many of today’s power plants will reach their end-of-life, and choices will need to be made about the technologies replacing them. It should be noted that a 30-year simulation period does introduce considerable uncertainties with regard to inputs like projected demographic evolutions, technology and fuel prices, just to name a few. However, the goal of the FIM – as stated before – is not to generate a perfect forecast. Rather, lessons can be learned by running the FIM with all the best information that we have at our disposal today, and the model can continue to be used as a tool as time goes on and the energy landscape continues to evolve.

Across the 30-year period simulated by the FIM, additional constraints can be added to deal with specific issues. For example, a maximum yearly renovation rate may be applied to the building stock sub-model. Such a constraint may be imposed if there are fundamental reasons why the building stock cannot be improved at a higher pace, like a limitation on the number of workers available in the renovation sector. The FIM may then be forced to invest more aggressively in some of the other sub-models, to reach the imposed CE reduction target by 2050. For example, heavier investments may occur in high temperature district heating systems, to cover the heat demands of the remaining (unrenovated) segments of the building stock. The imposed CE reduction target could thereby still be realized, without relying on an unrealistic yearly renovation rate. The net result of this kind of constraint may however be that the total costs related to reaching the CE target are somewhat higher.

Another constraint that may be added is to force the model to not only reach a CE reduction constraint by 2050, but also to reach certain intermediate targets (e.g. in 2030 ad 2040). This would avoid model behavior where the FIM ‘waits’ for the 2040’s to make all the investments in the last decade, when certain technologies are projected to become cheaper. Such an enormous concentration of investments in time would probably not be realistic. Another way to enforce this behavior in the FIM, is to introduce an overall remaining ‘carbon budget’ that can be spent in the 30 year simulation period. This will heavily incentivize the FIM to make investments as early as possible, because the current yearly emissions levels are very high and hence quickly ‘eat up’ the remaining carbon budget that needs to be respected.

The investment costs (and decarbonization benefits) related to measures in each of the three sub-models, can be *annualized* in the cost-optimization function. This allows the FIM to still make large new investments even in the year leading up to the end of the 2050 deadline (e.g. building a new district heating grid). If all measures taken by the FIM would have to be amortized before the end of the simulation period, many cost-effective investment opportunities could be missed. For example, it is well-known that investments in new district heating networks can only be amortized on a very long timescale of three or more decades . The model should however be just as ‘willing’ to invest in these technologies by the end of the simulation period as in the beginning. This implies that the 2050 system at the end of the simulation period would not necessarily be fully amortized yet (which is also not a necessary constraint from a policy perspective).

Additional considerations for each of the sub-models

For each of the three sub-models of the FIM, additional considerations need to be made in terms of their specific scope. Starting of with the *building stock sub-model*, for which we need to reflect on the modelling challenges discussed in sections 2.2 and 2.3. The FIM should not necessarily aim to advance the state of the art within the specific research field of building energy simulations, since its added value lies mostly in the *integration* of various research fields. However, it is still desirable for its building stock sub-model to incorporate – at least in a rudimentary fashion – user behavior, building integrated systems, demand response and energy storage capabilities. In terms of user behavior, perhaps the most important element to take into account is the recent research finding that households living in highly inefficient buildings tend to use less energy than traditionally predicted and vice versa. Adapting the building stock modelling to take this into account, will severely diminish the degree to which particular renovation investments result in actual energy and emissions savings. The FIM simulations can therefore avoid to overinvest in renovation measures (by avoiding an overestimation of their savings potential). The likely result of taking more realistic saving potentials into account, is that the ‘optimal approach’ identified by the FIM will more heavily rely on other types of measures to reach the targeted CE reduction.

In terms of including demand side management and energy storage capabilities in the building stock, it has become obvious over recent years that ‘smartness’ should be considered in the FIM to at least a minimum degree. As discussed in the previous chapter, various recent studies have found that electrochemical and heat storage technologies are important to consider (like batteries, thermal storage tanks, or even using the living space of the building itself as a thermal buffer). It is clear that the costs related to electrification in the building stock can be much broader than the investment and operational costs of the solar panels and heat pumps themselves. Many of the related costs also take place in the electricity generation and distribution systems, which may require large additional investments. However, smartness in terms of temporally shifting the heating-related electricity demands within and across days, can significantly reduce the need to build additional electricity generation capacities and upgrade existing electricity distribution networks. Taking the ability to temporally shift electricity demands into account at the building stock level, will likely affect the degree to which electrification plays a role in the overall cost-optimal decarbonization path. Therefore, the building stock model in the FIM should to some degree be able to simulate this smartness as well.

Similar to building stock models, the state-of-the-art in modelling the European electricity system still faces many methodological challenges, and they can be rudimentarily included in the respective sub-model. Some of the relevant topics still under investigation in this research field are industry-level demand side management (DSM) and utility-scale energy storage technologies. Without advancing the state-of-the-art on these topics, it could be important to adopt large-scale DSM and storage in the FIM because they co-determine the costs related to building sector electrification.

Finally, there are some additional considerations to be made with regard to the electricity distribution and district heating sub-model, which are closely interlinked with the building stock sub-model. To properly model the costs related to investments in electricity distribution networks and district heating system, the building stock sub-model would ideally make a distinction between rural and urban buildings. The reason for this is the fact that the costs related to the local networks are highly dependent on whether a rural or urban environment is considered. In the case of electricity distribution grids, rural area typically have a tree-like 'radial' network structure, while urban grids are often meshed. First of all, this can have a profound impact on the degree to which additional loads (e.g. from heat pumps) will trigger a need to upgrade the network. Secondly, it has an impact on the *costs* related to executing those upgrades. Similar distinctions are important to consider when it comes to district heating systems. These are usually only cost-effective when a large amount of buildings can be connected to the system within a relatively small area (i.e. in urban situations). For buildings in rural areas, which are more spread out from each other, district heating networks are much less likely to offer a cost-effective solution to decarbonize. The FIM building stock model should therefore include a rough delineation between urban and rural buildings. That way, the model can prevent an unrealistic overreliance on district heating systems and electricity distribution system upgrades in the identified cost-optimal approach.

Another consideration with regard to investment in district heating systems, is the fact that not only the building stock and its demands matter, but also the availability of heat sources to feed the networks. Cost-effective heat sources, especially if they should also be low-carbon, are relatively rare in many European countries. The FIM should be reasonably constrained in terms of how much district heating networks it can 'build', by introducing a limit to how much heat is actually available in each (rural and urban) segment of the building stock (which may have to be distinguished on a geographical basis). A 'heat map' that locates each of the potential heat sources for the country focused on by the FIM may therefore be required as input. Such a map would detail the costs related to exploiting each of the available heat sources, and where necessary, include an 'end date' to some of the heat sources. The latter may be necessary if some heat sources, for example those related to residual heat from industrial installations, may disappear at a certain point in time (before 2050). This could happen when an industrial player itself invests in improving the energy efficiency of its operations, thereby eliminating the residual heat that may still be available today.

Major boundary conditions to consider within the FIM

In addition to the three sub-models, there are two important boundary conditions that lie out of the scope of the FIM, but should at least be taken into account in a rudimentary fashion. First of all, projections need to be made with regard to the evolution in demographics and the total housing needs. Across the 30-year period simulated in the FIM, a considerable increase in the amount of residential buildings that are required may have to be taken into account. For example, it has been estimated that up to 400.000 new households will be in need of a dwelling in Belgium by the year 2050 [79]. The projection should also take into account other demographic evolutions like the increase in single-person households and the underutilization of available living space in many existing buildings (e.g. many elderly people living alone in buildings that are suitable for large families)[80]. By accounting for changes in the amounts and types of dwellings that are required in the next 30 years, the FIM will identify optimal approaches that are a better fit for the actual demographic context in which they need to be implemented.

Secondly, it is important that the FIM includes a rough estimation of the electrification of the industry and transport sectors, which will take place during the same 30-year period that will be simulated. Both in the country that is focused on, as well as in the other countries included in the European electricity system sub-model, the electrification of these other sectors can increase the total electricity demand by at least as much as the electrification in the buildings sector (or even more). In the case of Belgium, a back-of-the-envelope calculation indicates that the electrification of all road transport would roughly increase the current electricity demand (in TWh) by 25%, while a realistic partial electrification of the industrial sector (including the chemical sector) could easily increase it by 40-50%. Meanwhile, the impact on the peak electricity demand (in GW) could also be significant. If these trends were to be ignored in the FIM (e.g. because they are considered 'out of scope'), the total electricity demand may be drastically underestimated, which could heavily skew the calculation of the costs related to building sector electrification. For example, if a proliferation of charging infrastructure for electric vehicles triggers a need for a large upgrade to the electricity distribution grid, then the need to 'pay for' those upgrades solely from the perspective of enabling a higher penetration of heat pumps and solar panels may be somewhat diminished.

This brings us to a final point with respect to the scope of the FIM. Some measures that the FIM attributes to the decarbonization of the building stock, should not necessarily be attributed to that goal for 100%. As apparent in the previously given example with regard to EV's, it would be incorrect to attribute 100% of the costs related to upgrading the electricity distribution grid to the decarbonization of buildings. Therefore, a partial de-rating of that cost may be desirable within the FIM. Likewise, the costs associated with the many improvements to building shells in the FIM's cost-optimal approach, should not necessarily be included for 100%. Since the improvements to a building's windows, outer walls, roof, etc., can also be partially assigned to other purposes than the decarbonization of the building's energy use (e.g. improving the esthetics of the building), partially de-rating the costs related to those measures can be considered. Such an approach has already been applied in other studies, for example in the recent study by Vandevyvere et al., where the costs associated with improving the building shell are de-rated by 50% [4]. As is done in that study, the FIM can also use a sensitivity analysis on these de-rating parameters to identify their impacts on the cost-optimal approach.

3.4.3. Challenges and barriers for realizing a FIM

A number of challenges and barriers to realizing a FIM can help explain why it firmly lies beyond the current state-of-the-art in academic literature. First of all, a FIM would be extremely data-intensive. The unprecedented amount of input data that would be required to develop a FIM, especially considering its brownfield perspective, would be extremely challenging to collect. Examples of the necessary input variables are the costs related to specific energy performance improvements, the costs of technologies used at the building level like heat pumps and solar panels, and the cost of changes to electricity distribution systems. Although the input data needed for all sub-models is gradually becoming more available over time, current data constraints severely limit the feasibility of developing a FIM in the foreseeable future. As long as this remains the case, following the principle of 'garbage in – garbage out', any conclusions drawn from the FIM could be meaningless, even if the technical modelling itself is highly accurate.

Another important challenge for the FIM, would be the calibration and validation of the model. Before the results coming out of the FIM could be trusted, it should be demonstrated that the FIM generates results that are somehow in line with reality. In theory, this could be achieved by considering historic data and verifying that, using the same historic inputs, similar results come out of the FIM as the 'output' that has been observed in reality. However, this would be particularly difficult to do in the case of the FIM, because the historic counter-factual to compare to barely exists. The best the FIM could do, would be to calibrate and verify each of the sub-models separately. For example, by comparing the predicted decrease in building energy consumption after a particular set of renovation measures, to the observed reductions in buildings where those measures were realized in practice.

Other important challenges relate to the computational requirements and interpretation of the FIM results. In terms of computation, the FIM will likely be so co complex that it will not be possible to run hundreds or even thousands of iterations. This will make it impossible to identify the cost-optimal approach by generating a dense point-cloud of scenario results, as is done in simpler studies that consider the (much less complex) individual building level (see for example [16,17]). The FIM will not be able to rely on such 'brute force' techniques, and will instead have to rely on a more careful selection of scenarios to compute. If computational requirements turn out to be excessively challenging to manage, the FIM could potentially be adapted to work with soft-linked sub-models, instead of hard-linking them. This would avoid the computational load associated with co-optimizing all the costs and benefits simultaneously at *run time*.

In terms of *interpreting* the results coming out of the FIM, researchers developing this model would need to be wary of the fact that it could easily turn into a *black-box*. To the degree possible, the problem of not being able to explain differences between different suggested approaches coming out of the FIM should be avoided. For a more detailed discussion on the challenges and issues related to highly integrated models like the FIM, we refer to [81]. Although this publication focusses on integrated models at the scale of university campuses and city districts, many of the issues discussed are also applicable to our proposed FIM with a national and even partially European scope.

3.4.4. What a FIM would still leave out of scope

To clarify the fact that a FIM is by no means a fully 'complete' model that captures all the dynamics related to the decarbonization of the building stock, it is useful to examine in more detail what the FIM would still leave *out of scope*. The list of items discussed below is by no means an exhaustive one; it is only intended to give an indication. Some items are out of scope because, even though they could theoretically be included in a FIM without changing its fundamental structure, they are not thought to be of a great enough importance to identifying the cost-optimal approach. Other items are rather out of scope because they require a fundamentally different analysis, which is not in line with the core goal and structure of the FIM.

In the former category we can place several items, like the inclusion of the health-related benefits of renovation and the costs and emissions related to the mobility requirements of buildings located in various locations. Health benefits, for example related to an improvement of both the indoor and outdoor air quality, could to some degree be expressed in monetary values, and included in the objective function of the FIM. Similarly, the costs and emissions related to mobility could be included, but it would require a lot of additional analysis. The FIM would have to endogenize urban planning to a certain degree, whereby the *location* of buildings in the simulated 30-year period is co-optimized to help reduce societal costs and emissions.

Belonging to the same category, is the fact that the FIM would not include the costs of *non-action*, for example with regards to the increased climate damage and adaptation measures that would occur when emissions are *not* successfully reduced. These costs are notoriously difficult to quantify and depend largely on the action of countries outside of Europe. Finally, the FIM would not include highly detailed multi-zone modelling of buildings, or apply state-of-the-art and highly detailed modelling for the heating and ventilation systems in buildings. While these details are of interest within the research field of building energy performance simulations, the FIM will need to rely on more simplistic representations of building energy use in order for its complexity to remain manageable.

In the latter category, we can place items like the analysis of macro-economic impacts, or an analysis of the housing market over the coming 30 years. The measures taken in the cost-optimal approach proposed by the FIM, will undoubtedly have some impact on GDP, jobs, and transaction prices in the housing market, but if those aspects were to be analyzed as part of the FIM, they would distract heavily from its core purpose.

Finally, while the FIM *would* shed light on the cost-optimal decarbonization approach for the buildings sector from a broad societal perspective, it *would not* necessarily tell policy makers *how to turn that optimal approach into reality*, and neither would it make any claims about *how to divide its costs and benefits* across the various stakeholders. Policy makers will need to consider the various policy tools available at their disposal, like fiscal and regulatory measures, and assess their impact on different stakeholders like households, the construction sector, grid operators, electricity generators, and so forth. The FIM would also ignore whether the societal cost-optimal approach would provide attractive business-cases for various market parties. If the business-cases and investment opportunities are not attractive enough to make the identified approach a practical reality, the government may need to intervene accordingly. Ultimately, policy makers may need to adapt the approach proposed by the FIM to better fit the political realities, like having to get parliamentary approval for the many included measures.

4. Concluding remarks

To achieve our long term climate and energy policy targets, the buildings sector needs to be drastically transformed. This report has explored and reflected on the current literature about how to realize this transformation in the most cost-efficient way. The motivation behind this focus on cost-efficiency, is that it is a critical success factor. If the transformation occurs in an overly expensive and inefficient way, it is much less likely that the stated policy targets will be achieved, let alone in a timely manner. This is however not to say that identifying the cost-optimal approach is the only challenge that needs to be overcome. Other challenges include the design and implementation of the right policies (fiscal measures, regulations, etc.) to turn the cost-optimal approach into a reality, and deciding how to divide the related costs and benefits fairly across different stakeholders (households in different income segments, market parties, grid operators, etc.). These more political challenges are however not the focus of this report.

We have started our analysis at the individual building level, where the perspective of a single home owner is considered. Here we found that the European legislation (EPBD) has triggered a number of studies that try to identify the cost-optimal combination of renovation measures to reach a certain primary energy (PE) reduction target. The official EPBD calculation methodology is often used, although more advanced methodologies are sometimes used as well. These studies make up the majority of the current literature on the individual building level, and mostly focus on measures related to reducing the buildings' heat demands. Renewable energy measures like heat pumps and solar PV are purely looked at from the perspective of how they contribute to a buildings' PE. For example, the total yearly electricity production from a solar PV installation is multiplied by a PEF and subtracted from the buildings' annual primary energy demand. This ignores the actual impact of solar panels on CO_2 emissions, as well as the degree to which the electricity is consumed by the building itself.

The goal of reducing a building's PE is in line with the EU-wide energy efficiency objectives, but in this report we have widened our scope to consider also the goal of reducing CO_2 emissions (CE). Depending on the goal that is focused on, all potential measures like improving a building's insulation or replacing the heating system can be framed purely in terms of their costs on one side and their contribution to the end goal on the other side. In chapter 1, we laid out a framework where all conceivable measures are categorized according to a range of different trade-off's. For example, measures can be labeled either as 'demand side' of 'supply side' measures, depending on whether they aim to reduce the building's heat demand, or contribute to the stated goal in another way. Likewise, measures can be labeled as 'energy efficiency measures' or 'renewable energy measures'. The cost-optimal combination of measures – i.e. the one that reaches a stated PE or CE reduction goal at the lowest total cost – reveals the optimal balance for each of these trade-off's.

In search of a comprehensive and detailed methodology that explicitly considers emissions as part of the cost-optimization at the individual building level, we found only the 'Annex 56' methodology. This methodology was recently published in a series of reports under the IEA's EBC program. It largely overlaps with the EPBD methodology, but is less customized specifically to the European context (since it was co-developed by several non-European IEA members). After a careful inspection of both the EPBD and Annex 56 methodologies, we found that there is a lot of room for improvement in both. For example, their approaches with regard to the carbon intensity (CI) and primary energy factor (PEF) of electricity is overly simplified. While poorly-calculated 'yearly average' values are typically used, we showed that a higher temporal resolution is likely important if, for example, the PE related to a heat pump is to be accurately calculated (taking into account the hourly and seasonal fluctuations of the PEF). Other shortcomings of the EPBD and Annex 56 methodologies include the overly simplified calculation of electricity consumption costs (purely on a per kWh basis, while capacity pricing per kW will likely become more important in the future), the exclusion of an LCA perspective (i.e. ignoring the PE and CE embodied in the construction materials, etc.), and the exclusion of the demand response and energy storage capabilities of buildings.

The identification of a cost-optimal combination of measures at the individual building level is found to be useful for a small set of narrow applications, but ultimately an analysis at the societal level is required if policy makers are to be adequately informed. For a single home owner, it may be useful to identify the most cost-effective way to reach a certain regulatory target (e.g. a certain PE level), within a broad set of constraints and boundary conditions. But for a policy maker, the building stock in its entirety should be considered, as well as its interactions with the electricity system and district heating systems. Many of the most efficient solutions to reduce CE or PE lie at the societal level, where synergies can be exploited that are out of scope from a single homeowner's perspective. Moreover, many important costs related to rolling out particular measures on a large scale take place outside of the scope of a single-building analysis. For example, the need to produce more electricity and potentially to upgrade electricity distribution grids when a large scale rollout of heat pumps takes place.

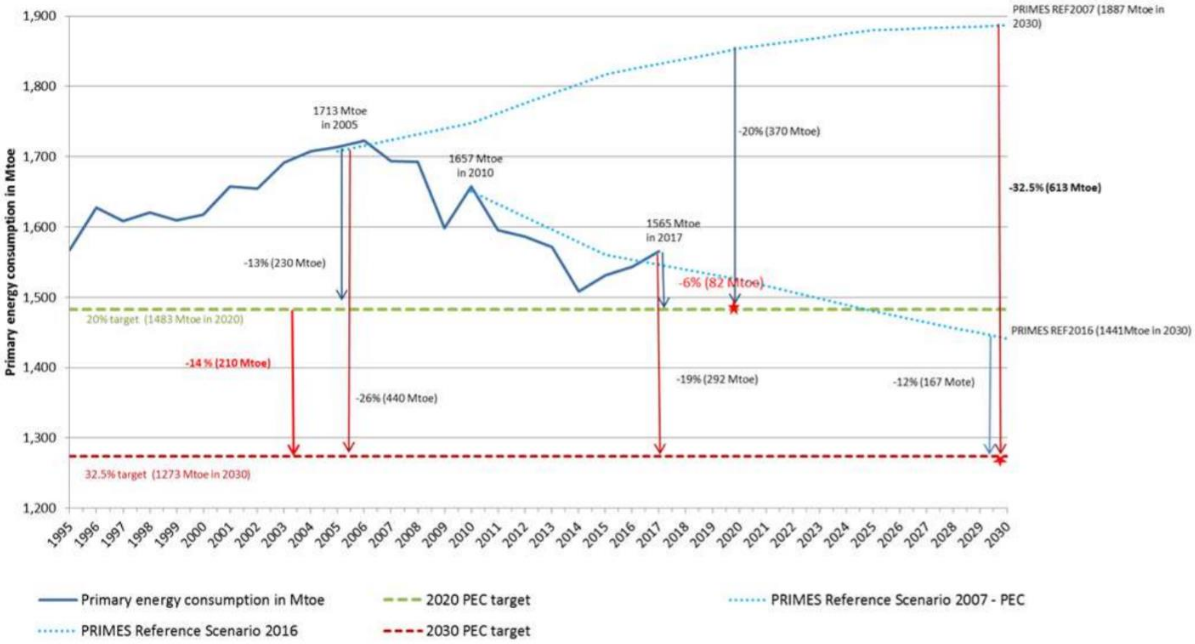
Identifying the cost-optimal approach to the decarbonization of the buildings sector at the societal level is much more complex. Considering the fact that the electrification of heating is likely to play a fundamental role in this process, the electricity system also needs to be taken into account (both in terms of electricity generation as well as local electricity distribution). It has also become clear that district heating can play a major role, so it should be considered as well. However, designing a single optimization approach that minimizes costs across the building stock, electricity system and district heating systems, turns out to lie beyond the current state of the art. Most societal-level models are limited to the building stock itself. They can therefore go no further than to calculate which segments of the building stock should be renovated in what way, to reach a certain CE target, while keeping many important variables (like the CI of electricity) exogenous. Many trade-off's are then ignored, like investing more in (renewable) electricity or heat, to reduce the need for some of the most-expensive kinds of building renovation.

A careful inspection of the latest literature shows that an increasing amount of studies goes beyond the traditional building-stock approach, and takes a more integrated approach instead. However, these studies are so far limited to the integration of some, but not all, of the major aspects related to electrification and district heating. For example, a state-of-the-art study may attempt to take the additional costs in the national electricity system into account, but still ignores opportunities in terms of district heating, or the costs related to electricity distribution networks. The fact that no 'fully integrated' studies exist as of today, unfortunately implies that – strictly speaking – we cannot yet be sure about which approach should be taken exactly by policy makers, to safeguard overall cost-efficiency at the societal level. Partial analyses, which is what the current literature is limited to, are likely to result in an inefficient decarbonization, which can ultimately jeopardize the timely realization of policy goals. We have thoroughly explored what a 'fully integrated model' (FIM) could potentially look like in the future. Our conceptualization of a FIM shows a potential way forward, but we also found that many challenges and barriers exist that make its actualization unlikely for the time being.

The following observation can ultimately be made on the basis of this report. In our thinking about the transformation of the building stock, we currently focus excessively on the wrong goal (PE instead of CE), only part of the potential means (demand-side and energy efficiency measures), and on the wrong level (individual buildings). This is reflected in the previous decade of research, which to a large degree stems out of the way in which the European policy framework for the buildings sector has been developed. In the coming decade, researchers should aim to focus on decarbonization, consider all the potential measures in and outside of the buildings themselves (as well as their related costs), and lift their analyses as much as possible to the more complex societal level.

5. Annex

Annex 1: Primary energy consumption target methodology



Source: [82]

Annex 2: Policy proposals made in the building sector transformation literature

In this annex, we summarize and reflect on the many policy recommendations that are made in the literature reviewed for this report. Many proposals try to refocus attention towards decarbonization instead of energy demand reduction, and towards the supply-side instead of the demand-side.

The main proposal made in literature is to introduce a carbon emissions target in addition to the existing primary energy targets at the individual building level [11,18,25,28,30,83]. There is no consensus on whether or not emissions targets should fully *replace* (primary) energy targets, but it is often cited that they should be at least *as* important (i.e. equally valued in the policy framework). To supplement the concept of nearly zero energy buildings (NZEB), some authors suggest an introduction of nearly zero *emissions* buildings (NZEmB). Appropriate values for the emissions target have rarely been proposed. An indicative target proposed by BPIE is <3 kg CO_2eq./m^2.a for newly built dwellings [18]. Some European countries have already experimented with carbon emissions targets, including Switzerland and the UK [18]. Over time, emissions targets may find their way in an increasing number of national regulations and calculation methodologies, or they could even be introduced at the European level in a future update to the EPBD. Such an increased focus on emissions could potentially coincide with a European framework for attributing a CO_2-price to direct building sector emissions (i.e. from the local combustion of heating oil and natural gas). Such a framework would supplement the European emissions trading system, which already puts a price on carbon implicitly for the electrified segment of building sector heating.

Some authors also argue that an LCA perspective should be used when setting carbon emissions targets (i.e. taking into account ‘embodied emissions’). However, this is a rather ambitious proposal considering the fact that targets for *operational* emissions have already been avoided historically due to the fact that it is difficult to calculate emissions (especially related to electricity use). Calculating lifecycle emissions would be even more difficult and is still a subject of much debate, as discussed in section 2.4.

There are also several proposals that allow the primary energy target to remain the centerpiece of the policy framework, but that try to adapt it in different ways in order to better align with the goal of achieving emissions reductions [20,25]. One such proposal is to remove renewable energy from the calculated primary energy consumption, replacing the conventional 'total primary energy' target with a 'non-renewable primary energy' target. Any substitution of non-renewable energy with renewable energy (e.g. replacing a gas boiler with biomass) would then be fully translated into a contribution towards the primary energy target. Some renewable energy technologies like a heat pump can already result in primary energy savings in the current framework (due to their higher efficiency), but their remaining primary energy use is then still included in the calculated primary energy consumption. This would no longer be the case under this proposal.

A second proposal in this category is to have separate primary energy targets for renewable and non-renewable primary energy use. The target for renewable primary energy could then be somewhat milder than the non-renewable target, increasing the flexibility to choose between demand- and supply side measures in a renovation or newly built project. Yet another proposal is to keep the current primary energy target in place, but to put the PEF value for renewable energy sources on zero. This would essentially remove renewable energy use from the 'total primary energy use' calculation, similar to introducing a 'non-renewable energy target'. Finally, there is a proposal to determine specific primary energy targets for residential buildings depending on their heating technology. Buildings using heating oil, gas boilers, heat pumps or biomass heating would then each have separate energy targets, providing incentives on a technology-by-technology basis.

Outside of the scope of energy and emissions targets, there are several other proposals that are made to increase the focus on emissions reductions in the residential buildings sector. It is for example possible to forbid the installation of certain heating technologies when an existing system has reached end-of-life and is in need of replacement [30]. It has often been argued that the end-of-life replacement of heating systems is an excellent 'trigger point' to steer building owners to less carbon intensive technologies. Other proposals try to alleviate the inconsistency of fiscal measures and subsidy schemes [83,84]. For example, there are very different tax levels imposed on heating and transport fuels. Across the European Union, the average tax on heating oil and natural gas is only 28% and 23% respectively, while the average tax on diesel and gasoline is 51% and 57% respectively [85]. A typical example of an inconsistency in the subsidy policy of many European countries is the subsidization for solar photovoltaic panels but not for solar thermal panels [83].

Across these diverse proposals a common nuance that is made by many authors is that policies to realize emissions reductions in the buildings sector should always remain sufficiently *flexible* and allow for certain 'exemptions' on a case-by-case basis [3,20,25,28]. For example, if a renovation takes place but the existing heating system is not even close to end-of-life, it would be suboptimal to obligate the premature replacement of that system only because energy efficiency improvements are being made to the building. It should also remain possible to be exempt from certain emissions-saving obligations if the home owner can prove that a certain measure would be highly cost-inefficient in the particular context of the building in question (or that *another* measure would be much more cost-efficient). The proposals discussed above should thus always be considered with great caution before being implemented, to avoid inflexible policies that trigger a range of unintended consequences.

6. References

[1] Buildings Performance Institute Europe. Factsheet 97% of Buildings in the EU Need to be Upgraded. 2017. doi:10.1038/nrg3033.

[2] Palzer A, Henning HM. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part II: Results. Renew Sustain Energy Rev 2014;30:1019–34. doi:10.1016/j.rser.2013.11.032.

[3] Ferreira M, Almeida M, Rodrigues A. Cost-optimal energy efficiency levels are the first step in achieving cost effective renovation in residential buildings with a nearly-zero energy target. Energy Build 2016;133:724–37. doi:10.1016/j.enbuild.2016.10.017.

[4] Vandevyvere H, Reynders G, Baeten R, De Jaeger I, Ma Y. The trade-off between urban building stock retrofit, local renewable energy production and the roll-out of 4G district heating networks. 2019.

[5] European Parliament and The Council of the European Union. Directive 2018/2002/EU on Energy Efficiency 2018.

[6] European Parliament and The Council of the European Union. Directive 2018/844/EU on the Energy Performance of Buildings 2018.

[7] Ferrara M, Monetti V, Fabrizio E. Cost-optimal analysis for nearly zero energy buildings design and optimization: A critical review. Energies 2018;11. doi:10.3390/en11061478.

[8] Hamdy M, Sirén K, Attia S. Impact of financial assumptions on the cost optimality towards nearly zero energy buildings – A case study. Energy Build 2017;153:421–38. doi:10.1016/j.enbuild.2017.08.018.

[9] Zangheri P, Armani R, Pietrobon M, Pagliano L. Identification of cost-optimal and NZEB refurbishment levels for representative climates and building typologies across Europe. Energy Effic 2018;11:337–69. doi:10.1007/s12053-017-9566-8.

[10] Ruá MJ, Guadalajara N. Estimating a threshold price for CO2 emissions of buildings to improve their energy performance level: case study of a new Spanish home. Energy Effic 2015;8:183–203. doi:10.1007/s12053-014-9286-2.

[11] Brinks P. Potential-analysis of grey energy limits for residential buildings in Germany. Energy Build 2016;127:580–9. doi:10.1016/j.enbuild.2016.06.025.

[12] Niemelä T, Kosonen R, Jokisalo J. Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings. Energy Build 2017;137:60–75. doi:10.1016/j.enbuild.2016.12.031.

[13] Longo S, Montana F, Riva Sanseverino E. A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. Sustain Cities Soc 2019;45:87–104. doi:10.1016/j.scs.2018.11.027.

[14] Van der Veken J, Creylman J, Lenaerts T. Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties van nieuwe residentiële gebouwen. 2013.

[15] Van der Veken J, Creylman J, Lenaerts T. Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties van gerenoveerde bestaande residentiële gebouwen. 2013.

[16] Van der Veken J, Creylman J, Lenaerts T. Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties van nieuwe residentiële gebouwen. 2015.

[17] Van der Veken J, Creylman J, Lenaerts T. Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties van gerenoveerde bestaande residentiële gebouwen. 2015.

[18] IEA Annex 56. Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation. 2017. doi:10.1007/12_003.

[19] IEA Annex 56. Factsheet. 2018.

[20] IEA Annex 56. Results of the Parametric Calculations with Generic Buildings and Case Studies. 2017.

[21] IEA Annex 56. Co-benefits of energy related building renovation. 2017.

[22] IEA Annex 56. Guidebook for Professional Home Owners. 2017.

[23] Almeida M, Ferreira M. Cost effective energy and carbon emissions optimization in building renovation (Annex 56). Energy Build 2017;152:718–38. doi:10.1016/j.enbuild.2017.07.050.

[24] Bolliger R, Ott W, Von Grünigen S. Finding the balance between energy efficiency measures and renewable energy measures in building renovation: An assessment based on generic calculations in 8 European countries. Energy Procedia 2015;78:2372–7. doi:10.1016/j.egypro.2015.11.191.

[25] Almeida M, Ferreira M. Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation. Build Environ 2018;143:15–23. doi:10.1016/j.buildenv.2018.06.036.

[26] IEA Annex 56. Evaluation of the impact of energy related renovation measures on selected Case Studies. 2015.

[27] IEA Annex 56. Shining Examples Brochure (2nd Edition). 2017.

[28] IEA Annex 56. Executive Summary for Policy Makers. 2017.

[29] IEA Annex 56. Tools and procedures to support decision making for cost-effective energy and carbon emissions optimization in building renovation. 2017. doi:10.1016/j.enbuild.2018.02.030.

[30] IEA Annex 56. Guidebook for Policy Makers. 2017.

[31] IEA Annex 56. Terminology and Definitions. 2017.

[32] IEA Annex 56. Owners and Residents Acceptance of Major Energy Renovations of Buildings. 2017.

[33] IEA Annex 56. Life Cycle Assessment. 2017.

[34] Buildings Performance Institute Europe. The Concept of the Individual Building Renovation Roadmap An in-depth case study of four frontrunner projects. 2018.

[35] Buildings Performance Institute Europe. Building Renovation Passports: Customised roadmaps towards deep renovation and better homes. 2016.

[36] European Parliament and The Council of the European Union. Directive 2012/27/EU on Energy Efficiency 2012. doi:10.3000/19770677.L_2012.315.eng.

[37] Fraunhofer ISI. Evaluation of primary energy factor calculation options for electricity. 2016.

[38] Buildings Performance Institute Europe. Is the Primary Energy Factor the right indicator for determining the energy performance of buildings? vol. 2. 2017.

[39] Vilches A, Garcia-Martinez A, Sanchez-Montañes B. Life cycle assessment (LCA) of building refurbishment: A literature review. Energy Build 2017;135:286–301. doi:10.1016/j.enbuild.2016.11.042.

[40] Fenner AE, Kibert CJ, Woo J, Morque S, Razkenari M, Hakim H, et al. The carbon footprint of buildings: A review of methodologies and applications. Renew Sustain Energy Rev 2018;94:1142–52. doi:10.1016/j.rser.2018.07.012.

[41] Himpe E, Trappers L, Debacker W, Delghust M, Laverge J, Janssens A, et al. Life cycle energy analysis of a zero-energy house. Build Res Inf 2013;41:435–49. doi:10.1080/09613218.2013.777329.

[42] Mirabella N, Röck M, Ruschi Mendes Saade M, Spirinckx C, Bosmans M, Allacker K, et al. Strategies to Improve the Energy Performance of Buildings: A Review of Their Life Cycle Impact. Buildings 2018;8:105. doi:10.3390/buildings8080105.

[43] Kneifel J, O'Rear E, Webb D, O'Fallon C. An exploration of the relationship between improvements in energy efficiency and life-cycle energy and carbon emissions using the BIRDS low-energy residential database. Energy Build 2018;160:19–33. doi:10.1016/j.enbuild.2017.11.030.

[44] Ludin NA, Mustafa NI, Hanafiah MM, Ibrahim MA, Asri Mat Teridi M, Sepeai S, et al. Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. Renew Sustain Energy Rev 2018;96:11–28. doi:10.1016/j.rser.2018.07.048.

[45] Koezjakov A, Urge-Vorsatz D, Crijns-Graus W, van den Broek M. The relationship between operational energy demand and embodied energy in Dutch residential buildings. Energy Build 2018;165:233–45. doi:10.1016/j.enbuild.2018.01.036.

[46] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew Sustain Energy Rev 2014;29:394–416. doi:10.1016/j.rser.2013.08.037.

[47] Allacker K. Sustainable building - The development of an evaluation method. KU Leuven, 2010. doi:10.1007/978-3-540-88546-7_81.

[48] European Parliament and The Council of the European Union. Directive 2010/31/EU on the Energy Performance of Buildings 2010. doi:10.1039/ap9842100196.

[49] Energyville.be. TOTEM: A new tool to improve the environmental performance of buildings 2018. https://www.ovam.be/materiaalprestatie-gebouwen-0.

[50] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Build Environ 2016;105:267–82. doi:10.1016/j.buildenv.2016.05.040.

[51] Fouche M, Crawford RH. Towards an Integrated Approach for Evaluating both the Life Cycle Environmental and Financial Performance of a Building: A Review. Procedia Eng 2017;180:118–27. doi:10.1016/j.proeng.2017.04.171.

[52] Azari R, Abbasabadi N. Embodied energy of buildings: A review of data, methods, challenges, and research trends. Energy Build 2018;168:225–35. doi:10.1016/j.enbuild.2018.03.003.

[53] Searchinger TD, Beringer T, Holtsmark B, Kammen DM, Lambin EF, Lucht W, et al. Europe's renewable energy directive poised to harm global forests. Nat Commun 2018;9:10–3. doi:10.1038/s41467-018-06175-4.

[54] Litjens GBMA, Worrell E, van Sark WGJHM. Lowering greenhouse gas emissions in the built environment by combining ground source heat pumps, photovoltaics and battery storage. Energy Build 2018;180:51–71. doi:10.1016/j.enbuild.2018.09.026.

[55] Baeten B, Rogiers F, Helsen L. Reduction of heat pump induced peak electricity use and required generation capacity through thermal energy storage and demand response. Appl Energy 2017;195:184–95. doi:10.1016/j.apenergy.2017.03.055.

[56] Lund H. Renewable Energy Systems. A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions (Second Edition). 2014. doi:10.1016/B978-0-12-410423-5.09991-0.

[57] Lake A, Rezaie B, Beyerlein S. Review of district heating and cooling systems for a sustainable future. Renew Sustain Energy Rev 2017;67:417–25. doi:10.1016/j.rser.2016.09.061.

[58] Brøgger M, Wittchen KB. Estimating the energy-saving potential in national building stocks – A methodology review. Renew Sustain Energy Rev 2018;82:1489–96. doi:10.1016/j.rser.2017.05.239.

[59] Naber E, Volk R, Schultmann F. From the building level energy performance assessment to the national level : How are uncertainties handled in building stock models. Procedia Eng 2017;180:1443–52. doi:10.1016/j.proeng.2017.04.307.

[60] Filogamo L, Peri G, Rizzo G, Giaccone A. On the classification of large residential buildings stocks by sample typologies for energy planning purposes. Appl Energy 2014;135:825–35. doi:10.1016/j.apenergy.2014.04.002.

[61] Mata É, Kalagasidis AS, Johnsson F. A modelling strategy for energy , carbon , and cost assessments of building stocks. Energy Build 2013;56:100–8. doi:10.1016/j.enbuild.2012.09.037.

[62] Mata É, Kalagasidis AS, Johnsson F. Contributions of building retrofitting in five member states to EU targets for energy savings. Renew Sustain Energy Rev 2018;93:759–74. doi:10.1016/j.rser.2018.05.014.

[63] Assoumou E, Marmorat JP, Roy V. Investigating long-term energy and CO2mitigation options at city scale: A technical analysis for the city of Bologna. Energy 2015;92:592–611. doi:10.1016/j.energy.2015.06.123.

[64] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 2018;160:720–39. doi:10.1016/j.energy.2018.06.222.

[65] Majcen D. Predicting energy consumption and savings in the housing stock : a performance gap analysis in the Netherlands. 2016.

[66] Guelpa E, Bischi A, Verda V, Chertkov M, Lund H. Towards future infrastructures for sustainable multi-energy systems: A review. Energy 2019;184:2–21. doi:10.1016/j.energy.2019.05.057.

[67] von Hirschhausen C, Gerbaulet C, Kemfert C, Lorenz C, Oei PY. Energiewende "Made in Germany": Low carbon electricity sector reform in the European context. 2018. doi:10.1007/978-3-319-95126-3.

[68] Agora Energiewende. The value of Energy Efficiency in Buildings for the Energy System. 2018.

[69] Astudillo MF, Vaillancourt K, Pineau PO, Amor B. Can the household sector reduce global warming mitigation costs? sensitivity to key parameters in a TIMES techno-economic energy model. Appl Energy 2017;205:486–98. doi:10.1016/j.apenergy.2017.07.130.

[70] Zvingilaite E, Balyk O. Heat savings in buildings in a 100 % renewable heat and power system in Denmark with different shares of district heating. Energy Build 2014;82:173–86. doi:10.1016/j.enbuild.2014.06.046.

[71] Nässén J, Holmberg J. On the potential trade-offs between energy supply and end-use technologies for residential heating. Energy Policy 2013;59:470–80. doi:10.1016/j.enpol.2013.03.059.

[72] Bloess A, Schill WP, Zerrahn A. Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. Appl Energy 2018;212:1611–26. doi:10.1016/j.apenergy.2017.12.073.

[73] Henning HM, Palzer A. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part I: Methodology. Renew Sustain Energy Rev 2014;30:1003–18. doi:10.1016/j.rser.2013.09.012.

[74] Merkel E, McKenna R, Fehrenbach D, Fichtner W. A model-based assessment of climate and energy targets for the German residential heat system. J Clean Prod 2017;142:3151–73. doi:10.1016/j.jclepro.2016.10.153.

[75] Bloess A. Impacts of heat sector transformation on Germany's power system through increased use of power-to-heat. Appl Energy 2019;239:560–80. doi:10.1016/j.apenergy.2019.01.101.

[76] Patteeuw D, Reynders G, Bruninx K, Protopapadaki C, Delarue E, D'haeseleer W, et al. CO2-abatement cost of residential heat pumps with active demand response: Demand- and supply-side effects. Appl Energy 2015;156:490–501. doi:10.1016/j.apenergy.2015.07.038.

[77] Drysdale D, Mathiesen BV, Paardekooper S. Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energy Effic 2019;12:37–55. doi:10.1007/s12053-018-9649-1.

[78] Vakbladwarmtepompen.nl. Warmtepomp op bestaande installatie zorgt voor nul-op-de-meter bij corporatiewoningen 2020:1–4. https://www.vakbladwarmtepompen.nl/projecten/artikel/2020/01/warmtepomp-op-bestaande-installatie-zorgt-voor-nul-op-de-meter-bij-corporatiewoningen-1015553.

[79] Vlaams Bouwmeester. De stadsrand herverkavelen. Wondelgem als casestudy voor verdicht wonen. 2018.

[80] Huebner GM, Shipworth D. All about size? – The potential of downsizing in reducing energy demand. Appl Energy 2017;186:226–33. doi:10.1016/j.apenergy.2016.02.066.

[81] Mavromatidis G, Orehounig K, Bollinger LA, Hohmann M, Marquant JF, Miglani S, et al. Ten questions concerning modeling of distributed multi-energy systems. Build Environ 2019;165:106372. doi:10.1016/j.buildenv.2019.106372.

[82] Goldstein K. News on Energy Efficiency EED and EPBD 2018. https://ec.europa.eu/info/sites/info/files/goldstein_2018_12_03_8th_ema_network.pdf (accessed March 4, 2019).

[83] Drummond P, Ekins P. Reducing CO2 emissions from residential energy use. Build Res Inf 2016;3218. doi:10.1080/09613218.2016.1180075.

[84] Laes E, Mayeres I, Renders N, Valkering P, Verbeke S. How do policies help to increase the

uptake of carbon reduction measures in the EU residential sector ? Evidence from recent studies. Renew Sustain Energy Rev 2018;94:234–50. doi:10.1016/j.rser.2018.05.046.

[85] International Energy Agency. Energy prices and taxes. 2015.

[86] VEA. Studie naar kostenoptimale niveaus van de minimumeisen inzake energieprestaties voor niet-residentiële gebouwen. 2017.

[87] European Commission. EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050. 2016. doi:10.2833/9127.