Systemic challenges of Germany's heat transition – a measure and policy roadmap for a climate neutral building stock

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Abstract
To reduce Germany's total GHG emissions by 95 % by 2050, the building sector must be completely decarbonised. Due to the inertia of the sector, it is necessary to significantly accelerate the renovation of buildings and the transformation towards climate-neutral heat supply technologies. Our analysis identifies which measures need to be implemented by which date at the latest, to achieve the long-term target of full decarbonisation. Based on this we develop a consistent set of policy instruments that would enable the building stock becoming climate neutral in 2050. For both, measures and policies, a roadmap for the heat transition in Germany is developed with short- (2020–2025), medium- (2025–2035) and long-term (2035–2050) guidelines and recommendations. The roadmap of measures is based on an analysis of potential risks and how they could be compensated. Potential risks include for example failing to achieve the refurbishment rates and renovation standards required to realize climate neutrality; or failing to get renewable heat quickly enough into the heating market. Options to offset resulting gaps include an additional use of domestic renewable energy, increased efficiency efforts or the import of renewable energy. The roadmap is divided into four blocks addressing the overall regulatory framework, demand reduction in buildings, heat supply technologies and district heating. The roadmap of measures is "translated" into a roadmap of policy instruments. The policy roadmap includes regulatory approaches, support programs as well as informative instruments. The policy roadmap is designed to provide sufficient incentives for target achievement while avoiding lock-in effects that would undermine meeting the long-term goal.

Introduction
In recent years, several studies have identified visions for the buildings sector, the whole energy system of Germany in 2050 and possible transformation pathways to achieve these long-term visions. The visions and goals differ amongst the studies. Those focusing on the buildings sector without considering interactions with other parts of the energy system often analyse paths to achieve the goal of an almost climate neutral buildings sector as defined in the energy concept of the Federal Government (Bundesregierung 2010). This goal is the basis of the government's Energy Efficiency Strategy for Buildings (Prognos et al. 2015). It is operationalised as a reduction of the non-renewable primary energy demand by 80 % until 2050 compared with 2008 levels. However, this target is not compatible with the commitments within the Paris Agreement. More ambitious scenarios also considering other elements of the energy system and interactions between them seek a reduction of the greenhouse gas (GHG) emissions of at least 95 % compared with 1990 levels. In these scenarios usually an optimisation parameter, e.g. the overall economic costs in the target year or for the entire transformation, is defined and it is examined which contribution each sector must achieve to fulfil the overall goal.

In most scenarios the buildings sector plays an important role for achieving the overall emission reduction targets. To achieve a climate neutral buildings sector, a strong increase in refurbishment rates and qualities is often assumed or is a result of the optimization. Furthermore, heat supply technologies in buildings are changing dramatically. While oil and especially gas boilers are dominating today, they only play a minor role in the future. Instead, electric heat pumps and district heating (DH) become the leading heat supply options. However, the refurbishment rate in Germany has remained at very low levels of approx. 1 %/a for years and the overall heating energy demand has stagnated for several years as well. In addition, it is often criticised that new constructions built today are not yet compatible with long term goals. Another challenge in this context is that even though heat pumps are the dominating heating technology in small new buildings, yet they play only a minor role in existing or large buildings. To realise the required fuel-switch in the buildings sector, heat pumps must also be used in these buildings soon. On 16th March 2021, Germany's Federal Environment Ministry (BMU) presented the sector specific GHG emissions of 2020, for which sector specific reduction targets are defined in the Federal Climate Change Act. The buildings sector is the only sector amongst the sectors covered by the Climate Change Act that did not meet the defined reduction targets. And the defined targets do not yet consider the decided target tightening for 2030 on European level. This clearly shows that additional actions are needed in the very near future to come back on track for the 2050 targets. In addition, a sector-specific long-term target should be clearly defined to develop a consistent pathway towards a climate neutral building stock, including different measures and policies. In this paper one possible solution for a successful heat transition is developed and presented.

Methodology

The major goal of the presented work is the definition of a consistent roadmap for the heat transition in Germany. To develop this roadmap, four steps are carried out, which are described in the following.

CROSS-ANALYSIS OF EXISTING STUDIES

The basis for the results presented in this paper is a cross-analysis of relevant studies and included scenarios for a 95 % reduction of the overall GHG emissions in Germany's energy system. The analysed parameters are the final and primary energy demand by energy carrier, GHG emissions, renovation rate, electricity demand (final energy), biomass and environmental heat for heating purposes, share of DH, as well as the use of synthetic fuels (power-to-gas (PtG) and power-to-liquid (PtL)) in the energy system. Thereby, key measures and technologies for achieving the long-term target are identified. They are comparable to measures and technologies in other European countries. Ten studies, in which scenarios for a GHG emission reduction in Germany of at least 95 % are developed, are assessed focusing on the described parameters. The studies considered are:

- (Gerbert et al. 2018): Climate pathways for Germany (BDI-Study)
- (geea and dena 2017): Scenarios for a market-based climate and resource protection policy 2050 in the buildings sector (dena building study)
- (Fraunhofer ISI et al. 2017b, 2017a): Long-term scenarios for the transformation of the energy system in Germany (LFS)
- (Fraunhofer IWES and Fraunhofer IBP 2017): Heat transition 2030 (Agora study)
- (Öko-Institut e. V. and Fraunhofer ISI 2015): Climate protection scenario 2050 (2nd edition)
- (Umweltbundesamt 2014): GHG-neutral Germany
- (Umweltbundesamt 2017): Shaping the path to a greenhouse gas-neutral Germany in a resource-conserving manner
- (dena and ewi 2018): Lead study: Integrated energy system transformation
- (Nitsch 2016): The energy system transformation after COP 21 – Current scenarios of the German energy supply
- (NOW GmbH 2019): Integrated Energy Concept 2050 – Electricity, Heat, Transport, Industry

RISK AND DEFICIT ANALYSIS

With the risk and deficit analysis challenges for achieving 2050 targets in the buildings sector are identified and assessed by defining a target scenario (based on the above mentioned studies), in which a complete avoidance of energy related CO_2-emissions is pursued. This scenario was processed in an energy-system model at Fraunhofer ISE (REMod[1]). The model only considers CO_2-emissions and therefore only these emissions and not CO_2-equivalents are adressed. The model optimises the transformation pathway of the whole energy system to find the solution with minimum costs. For the sensitivities and remaining CO_2-emissions, compensation possibilities are defined and quantified. The energy related emissions must be zero in 2050 (-100 % compared with 1990 levels) in order to achieve the target of -95 % in overall emissions reduction in Germany, also taking into account emissions, which are not energy related, as there are sectors which will most likely not be able to avoid all emissions (e.g. agriculture).

We define a target pathway that adequately takes into account both energy efficiency and decarbonisation of the heat supply. For the risk and deficit analysis, this is considered the reference path. Based on this target pathway, different sensitivities are parametrized to systematically evaluate the risks and sensitivities quantitatively. The analysis focuses on effects on/in the buildings sector, but consideres the overall energy system. The major risks and sensitivities analysed are:

- Sensitivity 1: Failing to achieve the necessary refurbishment rate needed for the reduction of the energy demand (Insufficient refurbishment rate)
- Sensitivity 2: Insufficient refurbishment depth leading to lower-than-needed energy demand reductions
- Sensitivity 3: Missing the renewable targets in buildings (fuel switch)

For the simulation of the sensitivities, the energy system configuration (installed technologies and capacities etc.) are not changed compared with the target pathway despite the specific

1. REMod – National Energy System Model with Focus on Intersectoral System Development – Fraunhofer ISE.

parameters defined for each sensitivity. However, due to the changes in the buildings sector, energy flows, emissions and costs within/of the entire energy system change. For each sensitivity, three compensation options are defined and quantified. Compensation options are designed and parameterized in such a way that they can be used to compensate for the target shortfall. The assessed options are:

- Compensation option 1: Increased use of domestic renewable energies (due to limited potentials an additional use of biomass in buildings is not considered as an option):
  - PV + heat pump (option a)
  - Solar thermal collectors (option b)
- Compensation option 2: Import of additional synthetic fuels produced from renewable electricity (PtG/L).

ROADMAP DEVELOPMENT

Two roadmaps are developed, (1) a roadmap with measures from a technical and economic perspective and (2) a roadmap with instruments from a policy perspective. For the development of the roadmaps, a common understanding of the terms "measures" and "instruments/policies" is essential. The terms are not used consistently in the literature. In our study, the term "measure" refers to activities to reduce GHG emissions, e.g., energy retrofitting, construction of buildings with high energy efficiency, replacement of a heating system, etc. "Instrument" refers to a policy intervention that aims to stimulate/support the necessary measures.

The developed roadmaps are a synthesis of the analysis carried out. In the roadmaps, techno-economic as well as political necessities are translated first into measures, that are required, and second into policies supporting the required measures and assuring that long-term goals in the buildings sector are achieved. Besides translating results of the analysis, existing and proposed policies were assessed in detail to integrate and/or adjust them for meeting the target. Key measures and required technologies for the heat transition are derived from the analysed studies. They are the centre of the developed measures roadmap and are complemented by findings from the quantification of risks and compensation options (see above).

Cross-analysis of existing scenarios

EXISTING SCENARIOS FOR THE DECARBONISATION OF THE ENERGY SYSTEM

The differences between the scenarios regarding the developments in the buildings sector until 2050 are shown in Figure 1: the final energy demand and distribution of final energy sources. In Figure 1, reference scenarios extrapolate past and current developments (comparable to business as usual), while target scenarios aim at achieving the goal of 95 % GHG reduction until 2050. It is noticeable that gaseous and liquid fuels still have a significant share in the energy mix of the buildings sector in the reference scenarios compared with the target scenarios. However, in the reference scenarios the achieved GHG emission reductions are only 58 % to 89 %. To achieve the goal of a 95 % emission reduction in Germany, the buildings sector must make a higher contribution, which can be seen in the target scenarios: the buildings sector is expected to emit virtually no or only very low GHG in 2050 (e.g. 6 million t CO_2-eq/a in KS95). The high emission reduction in the buildings sector is achieved by reducing the finale energy demand and switching to low emission renewable heating technologies.

In the target scenarios heat pumps or other electricity-based heat supply technologies are dominating. Heat pumps (electricity + ambient heat) in final energy supply is between 24 % and 86 %. Besides electric heating applications, DH becomes a central heat supply technology for buildings in almost all scenarios. The share of DH in the overall final energy demand for heating ranges from 15 % to a maximum of almost 40 % in (Nitsch 2016). The high share in (Nitsch 2016) is not directly visible in Figure 1 as only fossil CHP and industrial excess heat are summarised under DH, but not the energy from other energy carriers supplying heat to DH systems (e.g. most of the biomass is used for the supply of DH). The role of biomass strongly differs and ranges in 2050 from 11 TWh/a in BDI_KPf (Gerbert et al. 2018)) to approx. 100 TWh/a in (Nitsch 2016). The potentials are comparably high, but the allocation of biomass in the energy system differs; in most scenarios biomass is mainly used for high temperature processes in the industry sector as well as for transport fuel supply. PtG/L only play a subordinate role and only few scenarios consider their use in the buildings sector (in most scenarios PtG/L is not used at all). However, for the overall energy system in some scenarios large amounts of PtG/L are needed (in some scenarios up to over 1,000 TWh per year by 2050; most of which must be imported).

The scenarios strongly differ in achieved final energy demand reduction and thereby achieved efficiency improvements in buildings by refurbishment activities. The demand reduction achieved is a result of the rate of energy-related refurbishment and the targeted refurbishment depth. In some scenarios the energy demand is strongly reduced by efficiency measures, in others the demand reduction is minimal. In 2008 the final energy demand of Germany's buildings stock was 896 TWh (Bundesministerium für Wirtschaft und Energie 2021). In the reference scenarios, the final energy demand is reduced by 29 % to 58 % and in the target scenarios by 54 % to 76 % until 2050. The only exceptions are the IEK2050 scenarios (cf. (NOW GmbH 2019)), in which the final energy demand is only reduced by 1 % to 2 % until 2050. Reasons are comparably low renovation rates (only 1.1 % between 2031 and 2050) and fuel cells are used to a relatively large extent, which have a low thermal, but high electrical efficiency. In the analysed scenarios the equivalent full refurbishment rates range from 1.4 % up to 3.9 % per year and is in most scenarios well over 2 % in the whole period from 2020 to 2050. This means that the current refurbishment rate of approx. 1 %/a must at least double or even quadruple in the coming years.

KEY MEASURES, TECHNOLOGIES, AND POLICIES

From the assessed studies key measures, technologies and policies are derived, which are essential for achieving the 2050 goals and are necessary in the short-run to avoid lock-ins. In addition to measures in the buildings sector, it is essential to increase the energy efficiency in all sectors (e.g. efficiency improvements in processes, energy supply and transport) as the potential for expanding renewable energies is limited. Further-

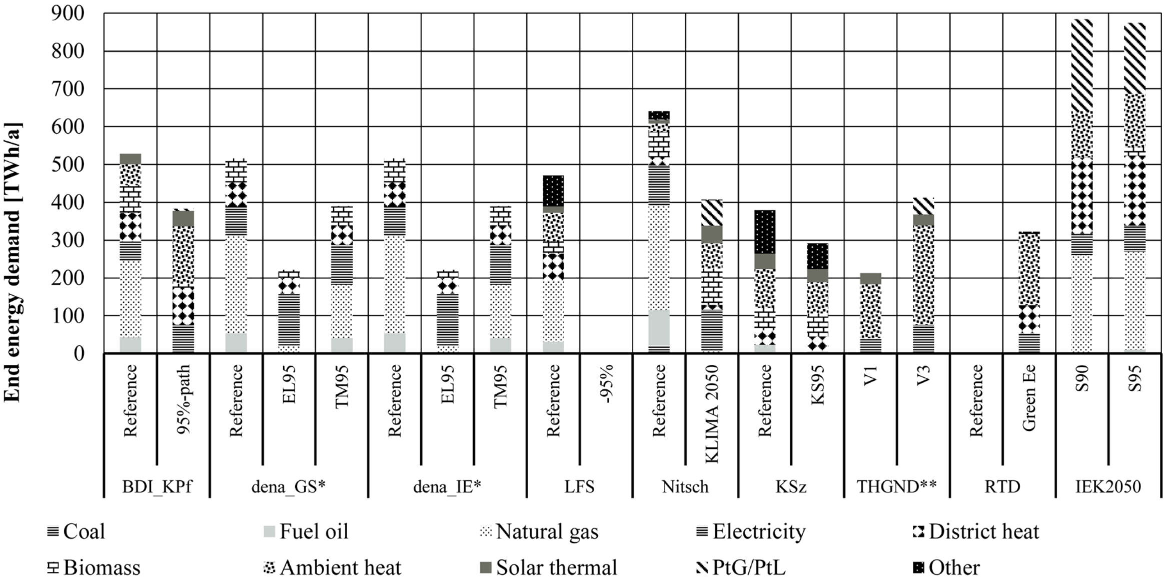

Figure 1. Final energy demand in the buildings sector in 2050 in different scenarios assessing a GHG-emission reduction of -95 % in Germany. Own illustration based on the assessed studies.

**) Fuel oil/natural gas = fossil, synthetic, biogenic.*

***) Natural gas completely renewable in 2050; in case of base V1 only heat demand for space heating and DHW (hot water) in residential buildings, as no data on LWG are available; environmental heat not accounted for.*

more, PtG and PtL play an important role for the overall energy supply for achieving a GHG emission reduction of 95 %. Key measures, technologies and policy instruments in the buildings sector must fulfil the following functionalities:

- Demand reduction by energetic renovation: increase renovation rate and refurbishment depth;
- Fuel-switch to heating technologies based on renewable heat sources (especially heat pumps);
- Biomass allocation for processes and applications with high temperature requirements (up to 500 °C);
- Fully decarbonise DH and develop needed infrastructure for the heat transition (mainly heating networks)
- Meet interim GHG emission reduction targets to achieve long-term targets;
- Rapid decarbonisation of energy sector: Expansion of renewable electricity generation, fast coal phase-out;
- Transformation strategy for gas infrastructure: in most scenarios not required anymore in buildings sector;
- Develop global PtG/L markets and infrastructure for import/ domestic generation from 2030 at the latest.

The identified key measures and technologies are similar in many European countries as Member States face similar challenges (reduce the final energy demand and switch to renewable, emission free heating technologies). The similar needs and challenges can be seen in the Renovation Wave and other European initiatives.

Risks for a successful heat transition in Germany

Amongst others, major energetic indicators like final and useful energy demand for space heating and domestic hot water as well as CO_2-emissions of the overal energy system are analysed. The refurbishment rate assumed in the taget pathway (our reference pathway for the risk analysis) is derived from the cross-analysis of existing scenarios (see above). The average rate for residential and non-residential buidlings is between 2.3 and 2.5 % during the whole period (see Table 1). The refurbishment rates are average values for a ten years period. In REMod, a continuous increase of the rate is implemented to avoid extreme leaps from one year to another.

There are three refurbishment depths defined in the model: "unrefurbished", "fully refurbished" (comparable to currently valid national standard for new buildings) and "fully refurbished plus" (comparable to passive house). The share of unrefurbished buildings in 2050 results from the simulation and defined refurbishment rates. The distribution of refurbishment depths is based on (Bürger et al. 2017): In our reference pathway 34 % of refurbished buildings achieve the level "fully refurbished" and 66 % "fully reurbished plus". The parametrisation of the sensitivities is summarised in Table 1. The refurbishment rates in sensitivity 1 are comparable to today's level. In sensitivity 3, the maximum share of heat pumps in 2050 is set to 15 %, which leads to an increase of heating technologies using gaseous fuels. In the target pathway, by 2050 every building (residential and non-residential) is renovated to a level meeting at least the requirements for new buildings according to the current building code. Over 50 % of the buildings have the level "fully refurbished plus". The useful energy demand of the sector is reduced by almost 50 % until 2050. Heat supply in buildings is dominated by DH supplying 45 % of the heat demand in 2050 and heat pumps with a share of 32 %. In the target pathway oil boilers disappear until 2042 and the share of gas boilers decreases to 18 % in 2050. The share of biomass decreases to 2 %.

The differences in the final energy demand and supply structure of the sensitivities compared to the reference pathway are shown in detail in Figure 2. Compared to the reference pathway, the final energy demand increases in all sensitivities as the energy demand reduction is lower (sensitivity 1 and 2) and alternatives for heat pumps have lower thermal efficiencies (sensitivity 3). The increased energy demand is supplied by the same technology mix as in the reference pathway in sensitivity 1 and 2. The increasing share of DH, electricity and ambient heat as well as the decreasing share of oil and gas is clearly visible in all assessed scenarios. In sensitivity 3 it can be seen that limiting the share of heat pumps in 2050 leads to a strong increase of PtG in the buildings sector due to an already high share of DH and missing alternatives for decentralised heat generation in buildings.

The resulting deviations from the CO_2-emissions reduction targets are summarised in Table 2. The presented values only reflect the status in 2050 and do not include the cumulative emissions of the whole transformation period. These additional emissions might be even higher. The deviations are based on the following assumption: For supplying the additional demand for gaseous and liquid fuels in the energy system resulting from missing the targets in the buildings sector, fossil fuels (natural gas, fuel oil) must be imported. The additional emissions, which must be compensated are between 8 and 57 Mio. t CO_2 in 2050.

Compensation measures

Due to the insufficient refurbishment rate in sensitivity 1, the useful energy demand in the buildings sector is 107 TWh/a higher than in the target pathway. In sensitivity 2, the additional demand is twice as high (approx. 214 TWh/a).

For compensation option 1 (increased use of domestic renewable energies) an average COP of 3 for the additionally installed

Table 1. Parametrisation of the target pathway and the sensitivities 1, 2 and 3.

Risk	Target pathway (our reference pathway for the risk analysis)	Parametrisation of sensitivity
Sensitivity 1: Insufficient refurbishment rate	2021–2030: 2.3 % 2031–2040: 2.5 % 2041–2050: 2.6 % Refurbishment depth: 34 % of refurbished buildings “fully refurbished“, 66 % “fully refurbished plus”	2021–2030: 1.0 % 2031–2040: 1.1 % 2041–2050: 1.2 % Refurbishment depth like reference pathway
Sensitivity 2: Insufficient refurbishment depth	Refurbishment depth: 34 % of refurbished buildings “fully refurbished” and 66 % “fully refurbished plus”	Refurbishment rate like in reference pathway, but lower refurbishment depth: useful energy demand reduction of 13 % in buildings currently unrefurbished
Sensitivity 3: Insufficient fuel switch	Share of electrical heat pumps 32 % (result of optimisation)	Share of heat pumps 15 %

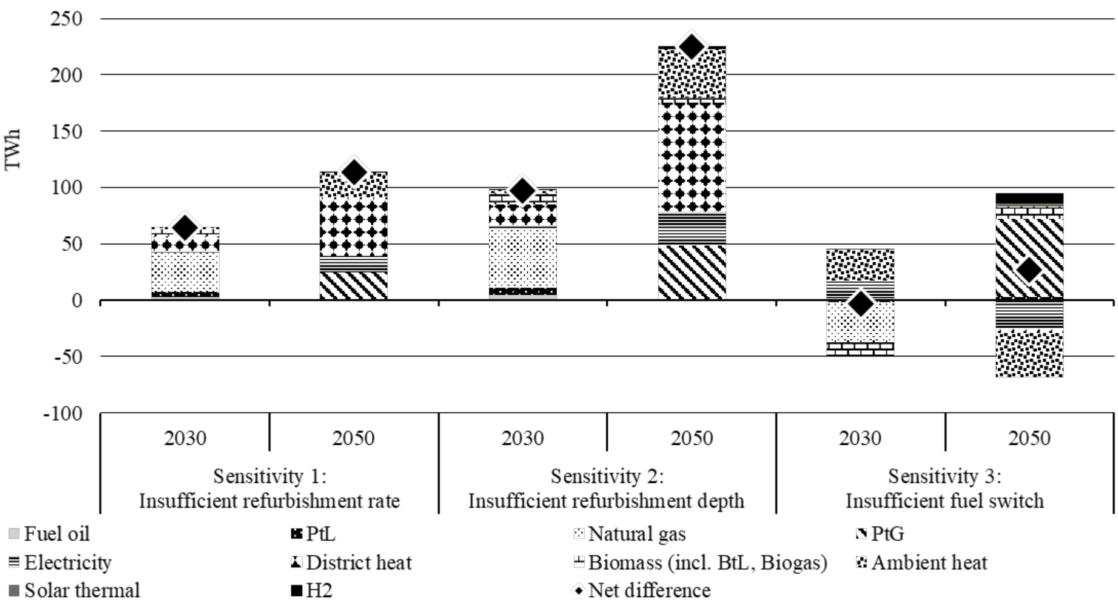

Figure 2. Difference in the final energy demand and supply of the sensitivities compared with the target pathway. Own illustration based on simulation results.

Table 2. Energy related CO_2-emission reduction and deviation from target in 2050.

Scenario	Achieved emission reduction in %	Deviation from target in %	Deviation from target in Mt CO_2
Sensitivity 1: Insufficient refurbishment rate	98 %	1.7 %	16.6
Sensitivity 2: Insufficient refurbishment depth	94 %	5.7 %	56.5
Sensitivity 3: Missing renewable targets in buildings (fuel switch)	99 %	0.8 %	8.2

Table 3. Additional demand for synthetic gaseous and liquid fuels and associated additional costs in the assessed sensitivities compared with the target pathway.

Scenario	Synthetic CH_4 [TWh]	Synthetic liquid fuels [TWh]	Additional costs [bn €]
Sensitivity 1: Insufficient refurbishment rate	418	1,414	286
Sensitivity 2: Insufficient refurbishment depth	872	2,194	472
Sensitivity 3: Missing the renewable targets in buildings (fuel switch)	157	60	24

heat pumps is assumed resulting in an additional electricity demand of 35 and 70 TWh_{el} respectively. To provide the additional electricity from PV (assumed full load hours of 1,000) an additional PV capacity of 35 and 70 GW_{el} respectively is needed, leading to additional costs of €21 and 42 billion (€600/kWp see (Sterchele 2019)). An alternative to PV and heat pumps is the energy supply from solar thermal collectors. Assuming an annual heat supply of 600 kWh/m² (408 to 711 kWh/m²; cf. (Lämmle 2019)), this would lead to an average additional collector area per building of about 7 m² in sensitivity 1 and 13 m² in sensitivity 2. In sensitivity 3 compensation by installing additional heat pumps and PV is not possible (maximum share of heat pumps is limited). For supplying the additional heating demand by solar thermal collectors, approx. 3 m² must be installed on each building (same assumptions as described above). For comparison: in the target pathway a total of 225 GW PV capacity and approx. 3 m² solar thermal collectors per building are already installed. The capacity and collector area increase, needed to compensate for the non-achievement of energy efficiency improvements and fuel-switch, is high. An increase of PV capacity of 14 % to 28 % and of solar thermal collector area of 110 % to 480 % would be required compared with the already ambitious reference pathway.

The second compensation option for achieving the CO_2-emissions reduction target is the import of synthetic gaseous (methane) and liquid fuels. To calculate the additional demand, each sensitivity is simulated again, but the possibility to import synthetic fuels is increased. The assumptions to estimate the associated additional costs are based on (Pfenning et al. 2017). For imported green CH_4 and liquid fuels they are €155/MWh in 2030, €137/MWh in 2040 and €118/MWh in 2050. During the considered period from 2025 to 2050, the imported amount of synthetic fuels strongly increases compared with the target pathway. The results are summarised in Table 3. The additional costs range from €24 to 472 billion for the period.

From the analysis of sensitivities and possible compensations several conclusions can be drawn:

1. If efficiency contributions of the reference pathway are missed, the target of zero emissions is missed by 1.7 % to 5.7 %. The additional final energy demand will be mainly covered by DH and heat pumps.
2. A complete decarbonisation of electricity and DH supply is essential to meet the target. If the sectors do not completely decarbonise, heat provided by heat pumps and DH must be covered by other renewable sources (including synthetic green fuels). However, if decarbonisation of DH and electricity generation is not achieved, the emissions reduction target cannot be met even if the remaining fossil fuels in all other sectors (except electricity and DH) are completely replaced. In other words, even if PtG/L is used to a large extend, an ambitious national expansion of renewable electricity generation is indispensable.
3. DH is dominating the heat supply in buildings with a share of 44 % in 2050. To provide this share free of emissions, the right boundary conditions for the transformation of the sector must be set soon to stimulate the required investments in the network infrastructure and heat generation.
4. Besides DH, heat pumps are of major importance, both decentralised in buildings (share of 28 % in target pathway) and for generating DH (share of 64 % in DH generation). Overall, 56 % of the total final energy for space heating and domestic hot water is provided by heat pumps in the target pathway. If the efficiency targets in buildings are not met, additional renewable electricity supply of 35–70 TWh is needed to run the heat pumps compensating for the efficiency gap.
5. As the biomass potential is very limited and biomass is required in other sectors of the energy system, solar thermal collectors are one of the few remaining renewable heat supply options for buildings. To compensate for the additional emissions from the sensitivities, between 3 m² and 13 m² of solar thermal collectors must be installed on average on each building.
6. Compensating for missed targets in the buildings sector by importing additional green synthetic fuels leads to additional costs of €24 and 472 billion between 2025 and 2050 and large amounts of PtG and PtL, which must be imported (157–872 TWh more PtG, 60-2,194 TWh more PtL).

Measure and policy roadmap for Germany's heat transition

Based on the results presented above two roadmaps are developed: first a roadmap of measures, and second a policy roadmap. The roadmaps present a comprehensive and consistent set of measures and policy instruments, which allow for achieving the target in the buildings sector within the framework of the Germany's overarching climate protection goals. Together with the roadmaps, strategic guidelines and recommendations are formulated, which address required political decisions and actions. The roadmaps are divided into different time horizons: 2020–2025 (short-term), 2025–2035 (medium-term) and 2035–2050 (long-term). For achieving a 95 % GHG mitigation target by 2050, ambitious measures and policies are needed at an early stage to avoid lock-in effects. The roadmaps are shown in Figure 3 (measures roadmap) and Figure 4 (policy roadmap). It must be noted that several necessary developments like increasing the share of renewable in the electricity and gas sectors are outside the scope of the presented study and are thus not integrated in the roadmaps. It is essential that all energy carriers used in the buildings sector and other sectors are decarbonised. This holds true for electricity and DH, but also for all liquid and gaseous fuels still used in 2050.

The measure roadmap focuses on technical measures and is based on the cross-analysis of existing scenarios, the identified key measures and technologies as well as the assessment of risks for a successful heat transition and possible compensations. The leading question for the roadmap development is: How can a target-oriented and economic transition process be designed? The addressed areas are building refurbishment, local use of renewable energies/ fuel-switch as well as DH. The measure roadmap is divided into four parts: "regulatory framework", "demand reduction", "supply technologies" and "district heating".

The refurbishment rate must more than double in the coming years. At the same time, the energetic quality/ standard of new constructions and refurbishments must considerably increase to be compatible with the long-term targets. The analysis concludes that a minimum standard for new constructions at KfW-55 level is needed until 2025, and KfW-40 level beyond that date. For refurbishments KfW-70 level is required by 2025 and KfW-55 level thereafter[2]. Both levels (new construction and refurbishment) are much more ambitious than the current minimum standard defined in the German Building Energy Law.

It is foreseeable that oil boilers disappear from the market comparably soon and gas boilers will/must lose shares in the heat supply mix in buildings. Therefore, an early ban for the installation of new monovalent fossil fuel boilers is suggested and oil boilers should also not be installed as bivalent systems after 2025. The role of biomass in the buildings sector and the whole energy system is discussed controversially. Biomass is on the one hand a limited renewable energy source and on the other hand needed in other sectors than the buildings sector in the future. Consequently, no new biomass boilers should be installed in the period after 2025. Due to the fact that most heat supply technologies in buildings have a technical lifetime of 20 years and are often used even longer, it is absolutely necessary to define a clear target regarding the future supply structure in buildings by 2025 to avoid lock-ins and thus increasing costs for the heat transition and the *Energiewende* as a whole.

DH generation must be decarbonised, and the DH infrastructure must be extended and densified from now on. Furthermore, adjustments to the infrastructure itself (flow temperatures, thermal storages etc.) are needed to integrate renewable and excess heat. To a limited extend, also "green" gas (PtG) is needed to operate CHP-plants in DH systems. These plants can also provide benefits and services to the electricity system.

The policy roadmap is designed as to "translate" the roadmap of measures into specific policy interventions (which policy instruments would be appropriate to activate the required measures). In the policy roadmap the specific needs and challenges of the various stakeholders in the buildings sector are considered to ensure that all or at least most relevant stakeholders are addressed adequately. It must be noted that the proposed set of policy instruments is an example how a policy roadmap could look like. The heat transition might probably also be achieved by a different set of policies. The policy roadmap is divided into four parts as well: "other instruments", "demand reduction", "supply technologies" and "district heating".

The policy set is developed to support the target-oriented heat transition in Germany in a coordinated way. To meet the climate targets and to ensure a successful heat transition, a mix of strategic, advisory and information, regulatory as well as target-oriented subsidies and instruments is necessary.

Adapting energy prices is essential. Electricity must become cheaper, fossil fuels much more expensive, e.g. by introducing effective CO_2-pricing. Strategic municipal heat planning plays an important role and should be incorporated in policy immediately. On a strategic level, a dialogue on the allocation of the limited biomass resources must be started and completed by 2025. The analysis of scenarios and of risks associated with the heat transition also emphasises the importance to increase the rate and depth of refurbishments and thus reduce the energy demand. Immediate adjustments to existing policies are therefore needed and should be accompanied by the introduction of additional regulation and funding programmes. Legislation on the building energy demand and supply must be adjusted to the long-term goals and should include bans on certain technologies as well as a reduction of exceptions (e.g. on the existing obligation to replace old fossil fuelled boilers). Continuous reviews are needed to assess whether the buildings sector is on track. This permanent monitoring should cover renovation activities and qualities as well as achieved effects in terms of GHG emission reduction. Thereby, policymakers are enabled to adjust the policy set at any time to meet the targets.

Summary and conclusion

The work presented in this paper clearly shows that a complete decarbonisation of the heat supply in Germany is possible. The transformation of the sector will lead to enormous changes in the heat supply structure, both decentralised in single build-

2. KfW levels describe efficiency levels of refurbishments. The indicated number refers to the percentage of the maximum allowed primary energy demand of the applicable building law (e.g. a KfW-55 building only needs 55 % of the primary energy compared with a reference). For each level, also typical requirements for the building envelope are described. In this paper, KfW-levels only refer to the envelope requirements and not to the primary energy demand.

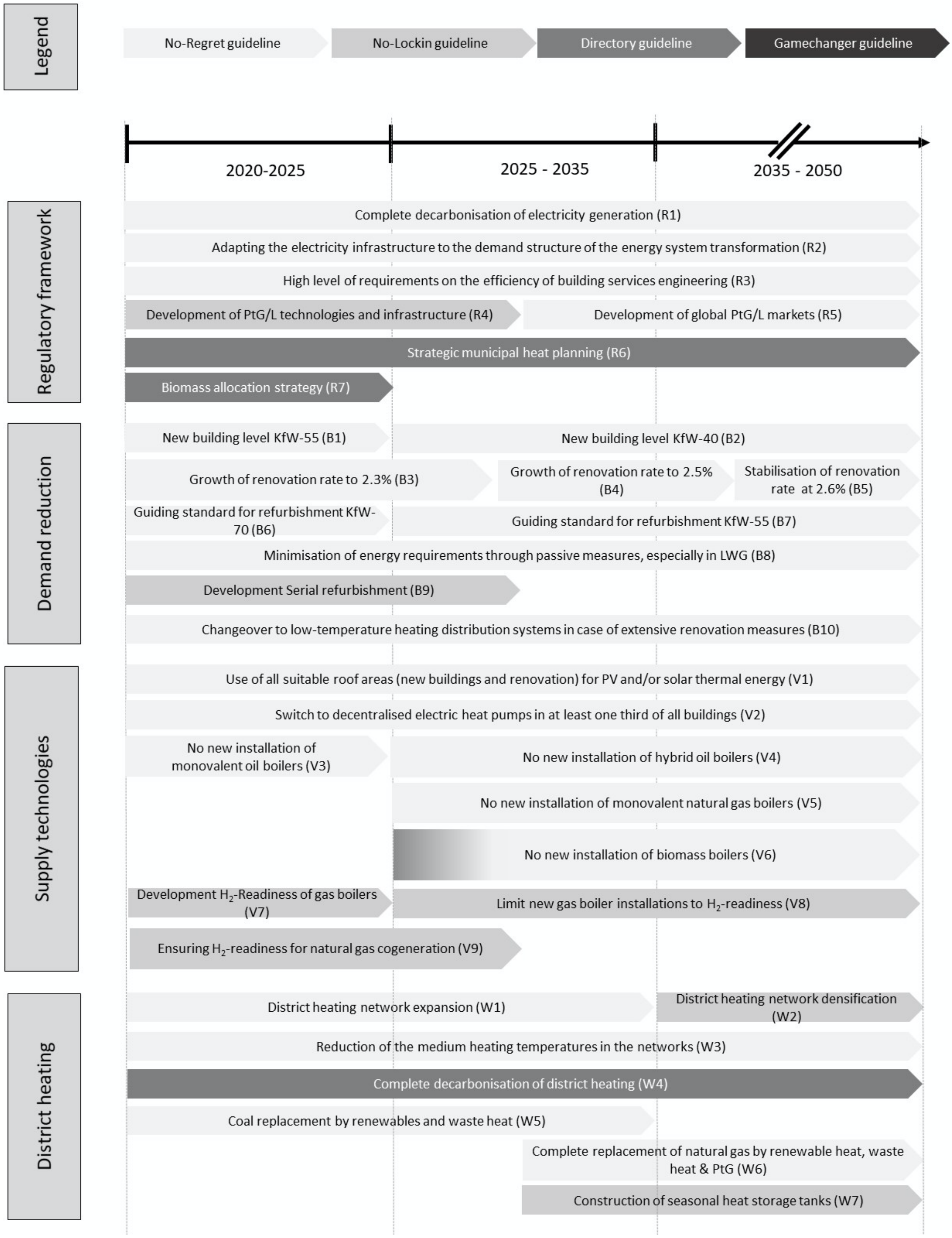

Figure 3. Measures roadmap to achieve the target of a GHG reduction by 95 %; own illustration.

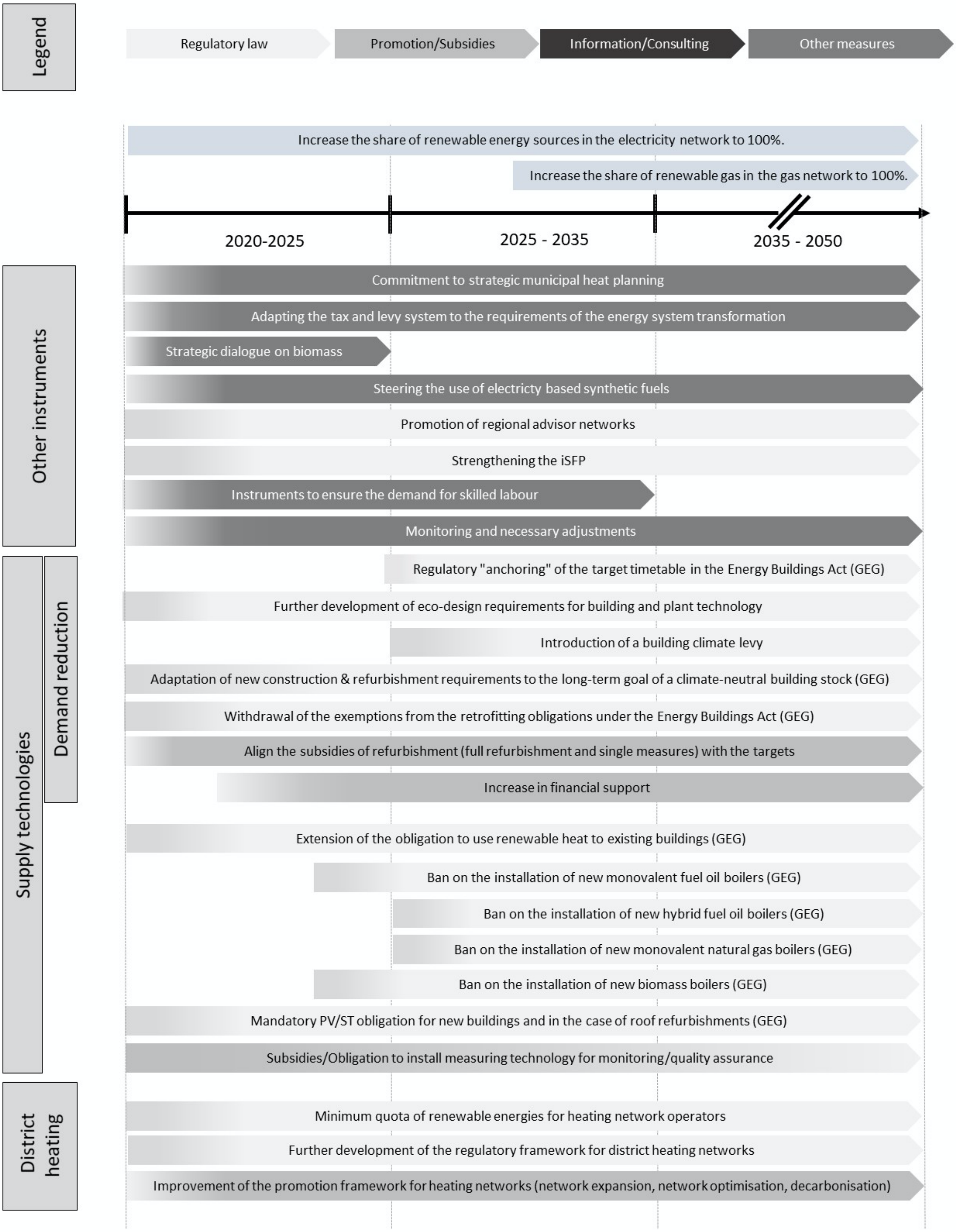

Figure 4. Policy roadmap to achieve the target of a GHG reduction by 95 %; own illustration.

ings and in district heating. To achieve the long-term target of a completely emission free heating sector in a cost-effective way, the cross-analysis as well as the risk and deficit analyses show that there are several options on the supply side, which achieve the target. However, our analysis shows that there are many robust measures, which are reflected by almost all scenarios:

- It is necessary to strongly decrease the heating energy demand in buildings. Consequently, the refurbishment rate must be increased significantly already in the short-term. In addition, the refurbishment depth and quality must be increased. As the investment cycles in the buildings sector are long, the average refurbishment depth (for a building as a whole or single building components) must already today be compatible with the target of a climate neutral building stock in 2050. Accordingly, the average level should be comparable to the KfW-55 level as soon as possible.
- The key technologies for providing space heating and domestic hot water will be heat pumps and DH. Also, in DH systems, large heat pumps will play an important role for the decarbonisation of the sector. The share of boilers burning gaseous and liquid fuels, which are currently dominating the decentralised heat supply, will drop dramatically and therefore must be removed swiftly. To support and foster this development, bans on installing these boilers can be an effective and target-oriented option.
- The future heat supply structure is strongly depending on local conditions. To use local renewable and waste heat potentials in a cost-effective way and to avoid lock-in effects and investment decisions, which are not compatible with long-term targets, (mandatory) municipal heat planning – at least for large municipalities – is essential. It should be established as soon as possible.
- To support and accompany the target-oriented heat transition, a clear vision of the future structure is helpful. Furthermore, the heat transition needs a consistent policy framework. The policy framework must consist of strategic, advisory, and informative and regulatory instruments, which need to be complemented by target-oriented subsidies.

The derived set of policy instruments is an exemplary set and must be interpreted accordingly. It can and should also be accompanied by effective CO_2-pricing. In the developed roadmaps, CO_2-pricing is reflected by the need to adapt the tax and levy system to the needs of the energy system transformation. Furthermore, social distribution effects and social hardship must always be considered when designing a policy mix, which on the one hand is able to support the heat transition and on the other hand assures a socially just transition. However, instruments balancing the social impact were not assessed in the study and should be addressed in future projects.

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