Methodology for the calculation of energy scenarios to achieve carbon neutrality in the building stock

Alice Tosatto[1], Fabian Ochs[1], Wolfgang Streicher[1], Mara Magni[1], Elisa Venturi[1]
[1]Unit of Energy Efficient Building, Universität Innsbruck, Innsbruck, Austria

Abstract

The building sector is a major contributor to CO_2 emissions and, due to its inertia to change, is easily subject to lock-in effects. This paper presents the methodology to implement a target-oriented scenario. The model uses a detailed statistical base of Austria's building stock, from which a hybrid bottom-up approach is used to assess energy consumption trends, considering possible renovation paths and energy carrier allocation. Two scenarios (one 'Business as Usual' and one 'Best') are presented, which differ in terms of the ambition of renovation measures. Equivalent CO_2 emissions are evaluated by considering different scenarios for the energy system.

Highlights

- methodology to implement a scenario for the building stock decarbonisation
- role of energy demand reduction measures
- role of heat pumps and district heating
- impact on energy consumption and CO_2 emissions

Introduction

Achieving the decarbonisation of the building sector by 2050 requires a drastic reduction in CO_2 emissions: this can be reached by improving the efficiency of the building stock and increasing the integration of renewable energy sources (RE) (UNEP (2021)).

The necessity to provide a good depiction of the existing building stock as well as a good prediction of its development is important to have a global overview which allows to study and develop targeted policies to support the energy transition (Johansson et al. (2021); Fernandez-Luzuriaga et al. (2021)). In this perspective, energy scenarios emerge as an important tool since they allow the study of the impact of different measures with different boundary conditions. Several studies are available and provide a global depiction of the current European building stock, the characteristics of the different countries and the relative applicable efficiency measures (among others Dascalaki et al. (2016), Olkkonen et al. (2021)). A quantitative analysis of the measures allows to consider the required adaptation of the market and of the energy system. For example, the increasing demand for thermal insulation materials may represent a bottleneck that hinders the increase of building refurbishment rates. Along the same line, the anticipated increasing demand for new efficient heating systems like heat pumps (HPs) (Abbasi et al. (2021)) would find the European producers unable to meet this demand without a drastic increase in the production rate. The extension of the district heating (DH) grids, which can ensure a faster and efficient phase-out of inefficient decentral systems, is another challenge which should be considered since it requires deep structural interventions on the city-level (Jodeiri et al. (2022)).

However, the mutual impact between the building sector (energy demand), and the energy sector (energy supply) is often overlooked. As pointed out by Ochs et al. (2023), energy efficiency measures taken on the building level do not lead to a corresponding impact in terms of CO_2 emissions, if a decarbonized energy system (electric and DH) is not reached. However, due to the scarce availability of RE, the decarbonisation of the building sector cannot overlook the reduction of the energy demand.

Therefore, the present work addresses the methodology for the definition of an energy scenario to ensure the decarbonisation of the building stock. The building stock of Austria is presented as case study, considering that goal of the Austrian government is to achieve carbon neutrality in the energy system by 2050 (BMNT (2018)). Concerning the building sector, this goal will be achieved through a full transition of the electricity production system and the complete phase-out of fossil-based HVAC systems by 2040 and is actively supported by the thermal renovation of the building stock to reduce its energy demand. Starting from the analysis presented by Steininger et al. (2021), the study of the development of the Austrian building stock is presented. Two scenarios, differing in terms of ambitiousness of the building efficiency measures, are presented to provide an overview of their impact on the final energy demand and energy carriers. Moreover, a sensitivity analysis of the CO_2 emissions is conducted, using emissions factors that account for the possible paths towards the decarbonisation of the energy production, i.e. for electricity and DH.

Methods

In the development of the building stock scenario a bottom-up approach is followed.

The tool implementation starts from the model developed in Excel environment by Dobler (2016) for the city of Innsbruck (Tyrol, Austria) and it extends it to the entire Austria.

https://doi.org/10.26868/25222708.2023.1489

The tool considers the status of an existing building stock and studies its yearly development until 2050 in terms of gross floor area (GFA) and final energy demand. Being the target of the study the decarbonisation of the building stock, specific measures are implemented in the tool concerning the renovation, the HVAC change and the type of technology used. These measures are introduced through specific parameters that can be set by the user:

- thermal renovation depth;
- thermal renovation rate
- HVAC change type;
- HVAC change rate.

Different building categories are taken into consideration to account for the different specific space heating (SH) and domestic hot water (DHW) energy demand and for the type of associated energy carriers. A first distinction is between residential and non-residential buildings, considering the size and the intended use. In this work, the focus is on the residential buildings, therefore the building categories considered are single family houses (SFH) and small- and large multifamily houses (MFH). Within each building category, buildings are further clustered according to their construction period, in order to account for the progressive improvement of the envelope quality in the last years and for the consequent different distribution of the energy carriers.

In the section *Baseline definition*, the process for the definition of the initial building stock is described, while section *Scenario definition* presents the measures applied to evaluate its evolution.

A scheme of the followed method is provided in Figure 1.

Baseline definition

As basis data the model uses the description of the Austrian building stock in 2019 in terms of total GFA and number of buildings (STATcube (2020)) and the corresponding energy consumption (Statistik-Austria (2019)). The available base year is 2018 for energy statistics, therefore an extrapolation was made to 2020 (the actual start of this scenario).

The data concerning the specific energy demand for SH, DHW and household electricity are available from Austrian databases (Tabula (2020)) and from previous studies (Pfeifer (2017)).

A noteworthy aspect in the definition of the energy consumption of the existing building stock is the prebound effect: several studies on existing building stocks have observed that buildings with high (calculated) heating energy demand present in reality lower heating energy consumption (Sunikka-Blank and Galvin (2012); Dermentzis et al. (2017)). To take this phenomenon into account, and since many buildings have already been renovated, an analysis of the available data concerning the quality (i.e. the heating demand used as input in the model) of the Austrian building stock was conducted. Figure 2 shows the measured heating energy demand values (Q_M) of the analysed building types with the prebound correction (according to the Loga's correlation by Loga et al. (2011) versus the calculated ones (Q_C) (available from Tabula). Additionally the heating demand values available from the Tabula Web Tool for the same building types and construction years are presented. The values selected to be used in the tool to describe the quality of the existing building stock are those pf the Tabula Web Tool, as they correspond better to the total energy demand of residential buildings available in the statistics.

However, the total final energy demand of the residential building stock obtained applying the defined energy demands to the building stock is higher than the one derived from the statistics. In order to account for non-occupied buildings and non-heated spaces, additional calibration factors are used on the existing building stock energy demand to match the one available from Statistik-

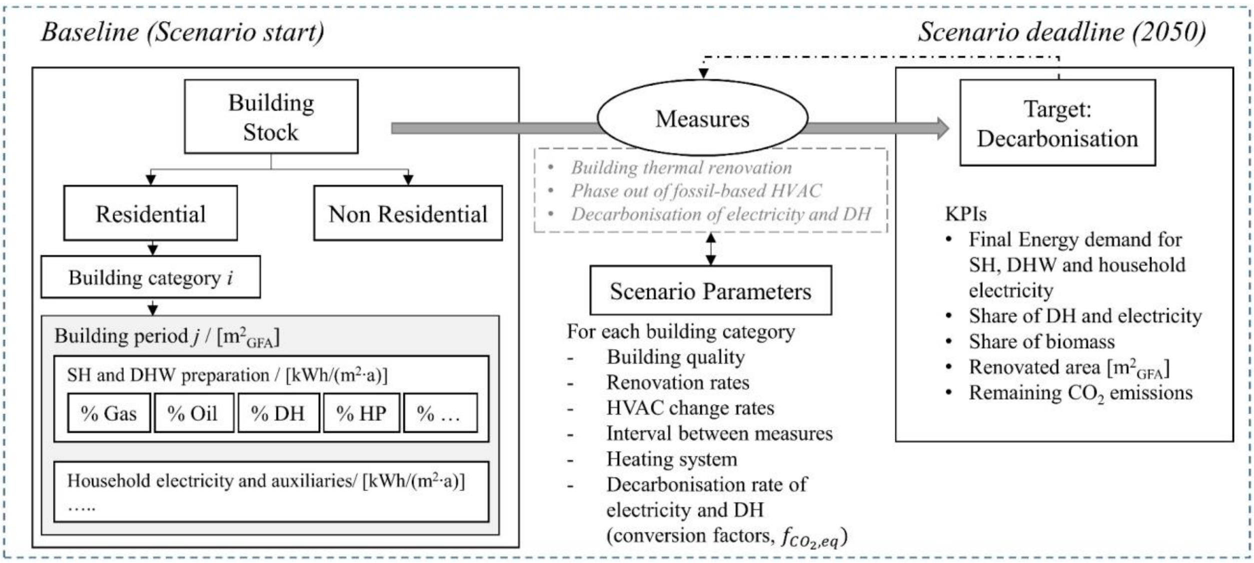

Figure 1: Scheme of the Scenario methodology. Building categories and respective data are defined for both residential and non residential buildings, although only the former are presented in this paper, with categories SFH, small MFH and large MFH.

https://doi.org/10.26868/25222708.2023.1489

Austria (2019): 0.82 for SH, 0.75 for DHW and 0.65 for household electricity.

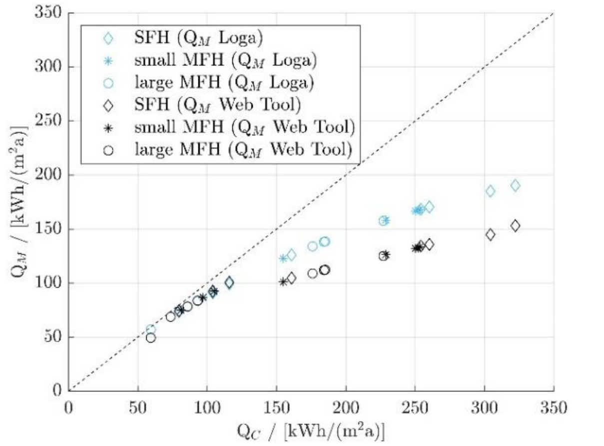

Figure 2: Calculated (Q_C) from Tabula and measured (Q_M) SH demand according to the Loga's correlation (in blue) and to the Tabula Web Tool data (in black) for the residential buildings. The different points are related to the different building periods.

Table 1 presents the heating demand of the existing residential building stock defined from Tabula (2020), while Table 2 shows the share of energy carriers according to the construction period derived from the analysis of the work of Lechinger and Matzinger (2020). Table 3 presents an overview of the residential building stock.

Scenarios definition

In this work two different scenarios are presented, both aiming at achieving the phase-out of fossil-based systems, with the main difference being the level of ambition of thermal renovation, both in terms of rate and quality. The two scenarios are defined *Business as Usual* (BAU) and *Best*, according to the distinction presented by Tosatto et al. (2021).

Building renovation and HVAC change ensure a reduction of the specific energy demand of the building thanks to the higher envelope quality and the improved efficiency of the newly installed HVAC, respectively. Two possible measures are therefore introduced in the tool: a full thermal renovation (which includes both envelope renovation and HVAC change) and HVAC

Table 1: SH demand and final energy demand for DHW preparation of the existing building stock used as input in the scenario model with respect to the gross floor area (GFA), considering prebound effects and pre-renovation.(most likely an inconsistency in the database).*

[kWh/m2/a]		**SH demand (useful energy)**			**DHW demand (useful energy)**		
Building Period		SFH	small MFH	large MFH	SFH	small MFH	large MFH
	1919	108.6	101.1	87.1	23	24.2	20.8
1920	1944	122.5	106.7	100.1	24	25.2	20.7
1945	1960	107.4	106	89.8	23.8	25.9	20.6
1961	1970	115.8	105.7	89.6	23.6	25.6	22.7
1971	1980	115.8	105.7	89.6	23.5	25.6	23.7
1981	1990	83.7	80.9	39.5	23.8	25.5	23.4
1991	2000	80.6	74.2	67	23.9	25.6	23.5
2001	2010	59.4*	60.0*	55.0*	23.5	25.3	23.7
2011	2019	74	69.6	62.7	24.4	27.4	25.5

Table 2: Energy carrier distribution for SH with respect to the total energy demand for the existing SFH and large MFH based on year of construction.

Building Period	Oil	Gas	Coal	Wood	Wood chips	Pellets	DH	DE	El. (HP)	Amb. (HP)	Solarth.
	SFH										
1919	0.47	0.14	0.01	0.23	0.06	0.02	0.03	0.02	0	0	0.01
1920 -1970	...	...	...	...	...	...	...	...	...	...	...
1971 -1980	0.18	0.26	0	0.32	0.05	0.04	0.04	0.02	0.03	0.06	0.01
1981-2010	...	...	...	...	...	...	...	...	...	...	...
2011-2019	0	0.32	0	0.37	0.04	0.06	0.04	0.02	0.05	0.09	0.01
	small MFH										
1919	0.3	0.18	0.01	0.2	0.02	0.03	0.19	0.07	0	0	0
1920 -1970	...	...	...	...	...	...	...	...	...	...	...
1971 -1980	0.11	0.28	0	0.22	0.01	0.03	0.21	0.07	0.02	0.03	0
1981-2010	...	...	...	...	...	...	...	...	...	...	...
2011-2019	0	0.35	0	0.23	0.01	0.03	0.22	0.07	0.03	0.06	0.01
	large MFH										
1919	0.2	0.26	0.01	0.04	0	0.02	0.41	0.06	0	0	0
1920 -1970	...	...	...	...	...	...	...	...	...	...	...
1971 -1980	0.08	0.31	0	0.05	0	0.04	0.43	0.06	0.01	0.01	0
1981-2010	...	...	...	...	...	...	...	...	...	...	...
2011-2019	0	0.34	0	0.06	0	0.06	0.44	0.06	0.01	0.02	0

https://doi.org/10.26868/25222708.2023.1489

change only. These measures are applied in terms of yearly rates of renovated GFA and buildings' GFA with HVAC change.

Table 3: Summary of the status of the Austrian residential building stock in the base year (2019).

Building category		
SFH	*small MFH*	*large MFH*
GFA / [m²]		
331,622,094	102,158,915	135,747,626
n. of buildings		
1,846,670	187,981	79,970
Final energy demand [MWh/a]		
SH		
33,685,522	9,395,771	10,303,882
DHW		
5,886,496	1,955,608	2,310,226
Household electricity		
7,150,056	1,924,065	2,651,368

BAU and *Best* scenarios consider different levels of ambition in the renovation depth (see overview on Table 7). Moreover, in the *Best* scenario, in new buildings and renovated buildings, an increased household electricity consumption of 2.5 kWh/m^2/a is considered to account for the presence of mechanical ventilation systems and related auxiliaries.

The energy demand for DHW production is also changed whenever a renovation occurs and in new buildings as from Table 4.

Table 4: Useful energy demand for DHW preparation related to the GFA in new and existing buildings after efficiency measures.

	SFH	*small MFH*	*large MFH*
	[kWh/m^2/a]		
E_{DHW}	13.1	11.8	13.4

The HVAC change involves the change of the heating and DHW production system used in the building; in order to achieve the phase-out of fossil-based systems, it is assumed that no gas, coal or oil boilers are installed starting from 2020. Different energy carriers' shares are considered depending on the building type and on whether the building is already existing or is newly built.

Considering the transition to RE sources and the wide possibility offered by the improvement of these technologies, HPs and DH are assumed to cover the largest share of energy carriers. Table 5 presents the distribution of the different energy carriers for SH with respect to the GFA, in the studied building types. In particular, it is assumed that HPs are more likely to be the most common system in rural SFH, while DH is going to play a major role in MFH. This hypothesis is supported by the fact that there is currently no solution on the market for the substitution of decentral traditional fossil-based systems with HPs (Ochs et al. (2023)). On the other hand, biomass boilers will be mostly employed in renovated SFH, rather than in new buildings, whose better envelope quality will make the application of HPs more convenient.

Table 5: Energy carrier share for SH with respect to the GFA for the studied building types in case of new construction and energy efficiency measures.

	Biomass	*DH*	*DE*	*HP*
SFH				
HVAC change	0.44	0.04	0.03	0.49
new	0.03	0.03	0.04	0.91
Small MFH				
HVAC change	0.22	0.23	0.02	0.53
new	0.02	0.18	0.03	0.77
large MFH				
change	0.05	0.48	0.03	0.44
new	0.01	0.43	0.04	0.52

The efficiency of the newly installed HVAC is assumed to follow a linear increase along the time, as presented in Table 6, which shows the efficiency values at the beginning and at the end of the analysed period for both SH and DHW systems. For the latter, also storage and distribution losses are added. As highlighted by Lämmle et al. (2022), the seasonal performance factor (SPF) of HPs depends strongly on the operation temperature. Therefore two different SPFs are considered in the two scenarios to account for the better operation in presence of a high quality building envelope: 2 for the *BAU* scenario and 3 (increasing to 3.5 by 2050) for the *Best*. In the evaluation of the HP electricity demand for SH, the SPF considers the distribution losses.

Table 6: Efficiency of the installed HVAC systems.

	SH		**DHW**	
	2020	2050	2020	2050
Oil	0.89	0.9	0.87	0.89
Gas	0.92	0.93	0.96	0.97
Coal	0.7	0.72	0.68	0.7
Biomass	0.72	0.75	0.72	0.75
DH	0.91	0.92	1	1
DE	1	1	1	1
storage and distribution	-	-	0.6	

Different time intervals between the different measures (i.e. demolishment, construction, renovation, HVAC change) are considered for the two scenarios (see overview on Table 7).

Currently, the rate of subsidized renovations of residential buildings in Austria is around 1 % comprehensive renovation equivalent (Amann et al. (2020)). However, the total renovation rate (including both subsidized and non-subsidized renovations) is 1.3 % for Tyrol (Ebenbichler et al. (2018)), and is assumed to be approximately 1.3 % for Austria in the *BAU* scenario. More ambitious rates are assumed for the *Best* scenario.

An overview of the parameters applied in the two scenarios are presented in Table 7.

https://doi.org/10.26868/25222708.2023.1489

*Table 7: Scenario parameters (GFA: Gross floor area, *: in relation to unit area).*

Parameter		
*Demolishment rate of buildings / [%pa]**		
Built prior to 1980	0.7	
Built between 1980 and 1990	0.3	
*Building GFA increase / [%pa]**		
linked to population increase and useful GFA pp	0.54 (average)	
Scenario	**BAU**	**Best**
Heating demand (renovated) / [kWh/m²/a]		
SFH	56	29.6
small MFH	47	24.1
large MFH	39	21.2
Heating demand (new) / [kWh/m²/a]		
SFH	30	10
small MFH	25	9
large MFH	21	9
Energy efficiency measures in existing buildings		
Renovation and HVAC change /[%pa]*	1.3	2.4
HVAC change only / [%pa]*	1.4	1.6
Time interval between measures / [a]		
	25	22
Heat Pumps		
SPF / [-]	2	3-3.5
Domestic appliances efficiency improvement		
η / [%pa]*	0	+1

CO_2 emissions

The CO_2 equivalent conversion factors used in the analysis are presented in Figure 3. While for fossil fuels and biomass a constant factor is considered, a progressive decarbonisation of the energy mix for DH and electricity generation should be accounted. Two different paths are in this case considered: a less ambitious one (with a 50 % emissions reduction, *Sz50 %*) and one with a more optimistic decarbonisation (Net Zero, *SzNZ*).

Results

The scenario allows to estimate for the investigated building categories the final energy demand for SH, DHW preparation and household electricity (appliances and auxiliaries).

Table 8 shows the total energy demand for SH and DHW preparation for the residential building stock in the base year and in 2050. It is possible to observe that a high rate of renovation of the building stock determines an increase in the share of energy demand for DHW with respect to SH in relative terms. It is important to remark that the thermal renovation allows to reduce the energy demand for SH, while the energy required for DHW preparation cannot decrease because it is related to the population and building GFA increase and the specific requirements.

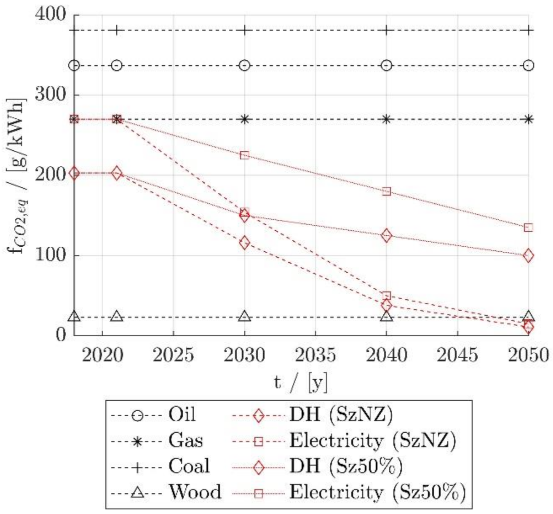

Figure 3: CO_2 conversion factors defined for the analysis: low ambition decarbonisation Scenario (Sz50%), Net Zero Scenario (SzNZ).

Table 8: Thermal energy demand for SH and DHW preparation in the residential buildings according to the studied scenarios.

year	*Energy / [GWh/a]*		
	SH	**DHW**	**Tot.**
2018	53,385	10,152	63,537
	84%	16%	
2050 (BAU)	41,446	14,442	55,889
	74 %	26 %	
2050 (Best)	24,460	14,714	39,175
	62%	38%	

Table 9 presents an overview of the building stock at the beginning of the study (i.e. 2020) and in the year 2050 for the studied scenarios.

Table 9: Building stock overview (in terms of number of buildings) across the scenario.

	[Number of buildings]		
	SFH	*small MFH*	*large MFH*
2020	1,846,670	187,981	79,970
2050 BAU			
new	414,799	44,601	18,931
renovated	758,964	86,011	36,653
HVAC ch.	856,096	78,311	33,373
2050 Best			
new	381,748	40,914	17,260
renovated	1,312,729	134,373	56,866
HVAC ch.	934,310	93,746	39,793

Figure 4 presents the resulting final energy demand associated to the different energy carriers for the first year, and for the two studied scenarios in years 2030, 2040 and 2050.

https://doi.org/10.26868/25222708.2023.1489

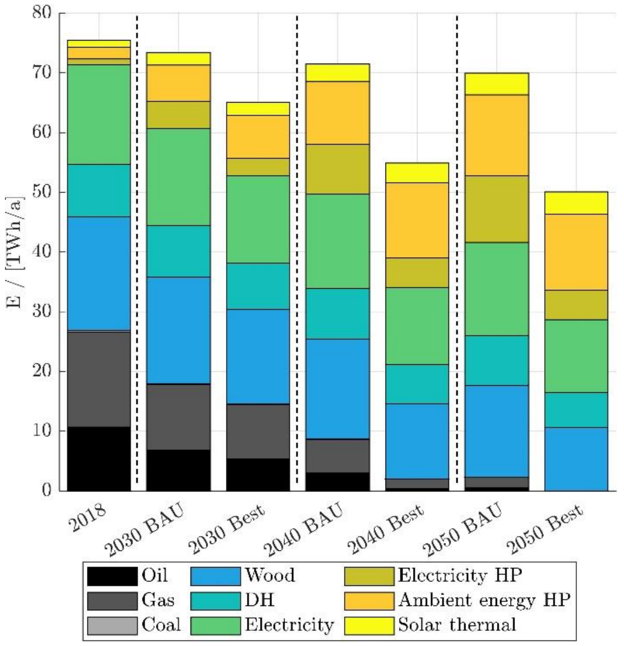

Figure 4: Energy demand (SH, DHW preparation and household electricity) and energy carriers' distribution of the residential building stock in the two scenarios.

In both scenarios, it is possible to observe that the phase out of fossiles starting from 2020 allows to reach a minimal share of oil and gas in case of the *BAU* scenario in 2050, while the higher HVAC change rate (thanks both to renovation and single measure, see Table 9) allows to remove entirely fossil systems in the *Best* scenario. The most significant difference between the two scenarios is observed in the total energy demand, which shows a slow decrease in the *BAU* scenario and a significative decrease in the *Best* scenario with respect to the starting year.

The importance of reducing the energy demand is further highlighted in Figure 5, which shows the total electricity demand and the share required by HP operation (for both SH and DHW) in the two scenarios. The high share of HPs assumed to be installed in new and renovated buildings results in an increase of the respective energy demand, but the efficiency measures (i.e. reduced building SH demand) applied in the *Best* scenario allow to keep the total electric energy demand almost constant.

In the *BAU* scenario instead, the high share of installed HPs meets a building stock with higher energy demand and results therefore in a significant increase of the total electricity demand (+60 % with respect to the *Best* scenario, considering an SPF of 2). This has an important effect on the actual feasibility of the energy mix and its decarbonisation.

A similar path is observed on the DH energy demand (see Figure 6). The timid renovation measures assumed in the *BAU* scenario result in a slight decrease of the DH demand, while the *Best* scenario shows a significant decrease, considering the given assumptions regarding the energy carriers distribution in the scenarios (see Table 5).

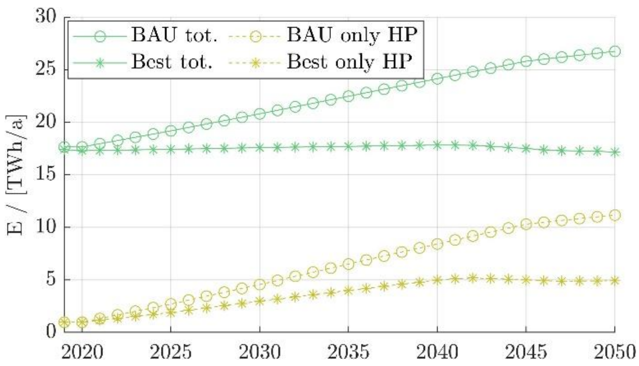

Figure 5: Total electrical energy demand and HP electric demand in the studied scenarios.

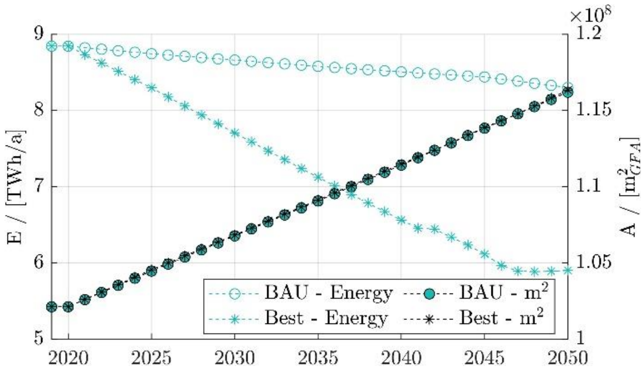

Figure 6: DH energy demand and variation of the residential area supplied with DH.

CO_2 Emissions

In order to highlight the challenge of achieving decarbonisation in the presence of a building stock with high electricity demand, a simplified comparison is here presented considering the number of football fields of PV needed to provide the required electric energy. To estimate the yearly solar radiation available, the reference climate for Austria is used (Meteonorm (2023)). The global radiation on a 45° tilted south-oriented PV panel (with conversion efficiency η=0.26, estimated for 2050 by Energistyrelsen (2022)) is derived (see Figure 7).

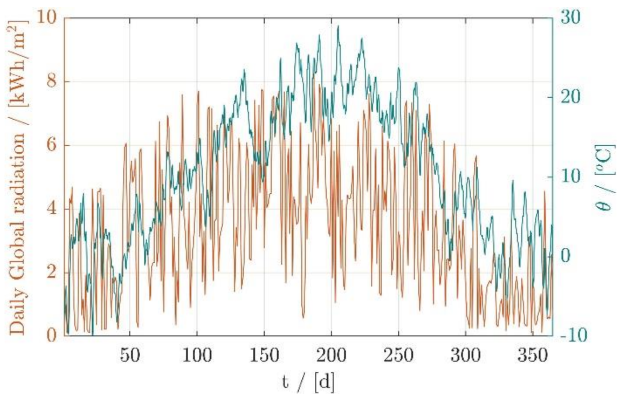

Figure 7: Daily specific global radiation and moving average temperature for Austria.

The number of football fields (90 m x 45 m) required to produce the total electricity demand required in the two scenarios is then derived and is presented in Table 10. The difference between the two scenarios in terms of the size

https://doi.org/10.26868/25222708.2023.1489

of the needed RE generation systems is clear and shows how the use of the same CO_2 conversion factors cannot guarantee a correct interpretation of the scenario results since they would require a significantly different generation system structure.

Table 10: Number of football fields PV.

	BAU	Best
Football fields	29000	18000

For the evaluation of the equivalent CO_2 emissions, two scenarios were considered also for the energy system, as introduced in Figure 3. Figure 8 shows thereby the equivalent CO_2 emissions for the residential building stock for the two scenarios presented in Figure 4. The area between the two curves for each building stock scenario represent the possible range of the CO_2 emissions with the given energy system assumptions.

In the presence of a fully decarbonised energy system (*SzNZ*), demand-side measures seem to have no impact: from the point of view of CO_2 emissions, both *BAU* and *Best* scenarios appear to have low emissions. However, given the higher energy demand of the *BAU* scenario compared to the *Best* one, a less optimistic decarbonisation scenario for the energy system (*Sz50 %*), could be taken into account. In this case, the difference in CO_2 emissions between the two scenarios is significantly higher. From the brief analysis presented in this paragraph, it can be inferred that energy reduction measures have an important impact on achieving the 2050 decarbonisation target.

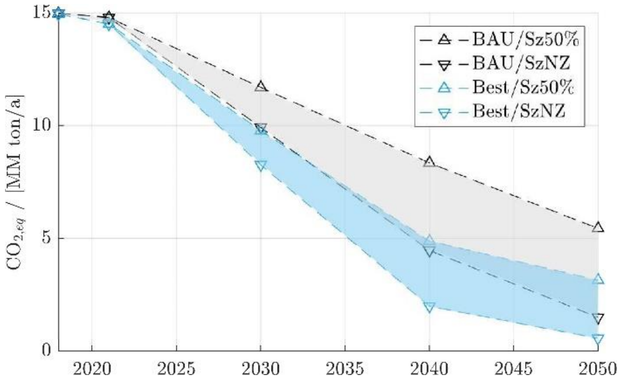

Figure 8: Equivalent CO_2 emissions for the two building stock scenarios (BAU and Best) according to two decarbonisation scenarios of the energy system (Sz50% and SzNZ).

Conclusion

This paper presented the methodology to define energy scenarios of the building stock in Austria, considering different ambition levels in the applicable measures. Both energy reduction solutions (i.e. building renovation) and energy carriers shifts (i.e. HVAC change) were considered in the definition of the scenarios. To capture the complexity of the building stock, the buildings were distinguished by typology and period of construction. Hence, it was possible to assign the different energy carriers on the basis of the buildings' characteristics.

Considering the increased role played by the electric system and the DH, the structure of the energy system was also taken into account in terms of equivalent CO_2 emissions.

The results showed that, while the HVAC change is a fundamental step to achieve the phase-out of fossil-based systems, this measure must be supported by a significant reduction of the final energy demand. The massive electrification of the energy system, driven by the installation of HPs (both in single buildings and in DH grids) can lead to a significant increase of the total electricity demand, thus forcing the energy system to follow with high investments to be able to cover the demand with RE.

It is important to remark that the energy demand of the building sector has a strong seasonal pattern, linked to the heating load. In a RE scenario dominated by HPs, this pattern will be translated to the electric energy demand. Considering the seasonal and daily fluctuation of RE, storage systems will play a fundamental role in the effective decarbonisation of the energy system in order to cover the winter gap between energy demand and RE availability. Further studies are ongoing to determine the role of storage systems in supporting the decarbonisation of the building sector, taking into account its seasonal profile.

Acknowledgement

This research was carried within the framework of the project INTEGRATE (Project Nr.: 370232), financed by the Austrian “Klima- und Energiefonds”. Therefore, the authors wish to acknowledge the financial support for this work.

References

Abbasi, M. H., B. Abdullah, M. W. Ahmad, A. Rostami, and J. Cullen (2021, 12). Heat transition in the european building sector: Overview of the heat decarbonisation practices through heat pump technology. *Sustainable Energy Technologies and Assessments 48*, 101630.

Amann, W., A. Storch, and W. Schieder (2020). Definition und Messung der thermisch-energetischen Sanierungsrate in Österreich.

BMNT (2018). #mission2030 die österreichische Klima- und Energiestrategie.

Dascalaki, E. G., C. A. Balaras, S. Kontoyiannidis, and K. G. Droutsa (2016). Modeling energy refurbishment scenarios for the Hellenic residential building stock towards the 2020 and 2030 targets. *Energy and Buildings 132*, 74–90.

Dermentzis, G., J. Schnieders, R. Pfluger, D. Pfeifer, W. Feist, and F. Ochs (2017). An overview of energy district tools in Europe and the importance of an equivalent heating reference temperature for district simulations. *Bauphysik 39*, 316–329.

Dobler, C. (2016). Theoretische Grundlagen von Prognosemodellen für die energetische Stadtentwicklung angewandt auf das Beispiel Innsbruck. Masterarbeit.

Ebenbichler, R., A. Hertl, W. Streicher, D. Fischer, C. Richtfeld, M. Mailer, I. Anton, A. Hofmann, and C. Pöham (2018). Ressourcen- und Technologieeinsatz-Szenarien Tirol 2050 Bericht.

Energistyrelsen (2022). Technology data for energy plants. url: https://ens.dk/en/ourservices/ projections-and-models/technology-data (Last accessed 16.03.2023).

Fernandez-Luzuriaga, J., L. del Portillo-Valdes, and I. Flores-Abascal (2021, 6). Identification of costoptimal levels for energy refurbishment of a residential building stock under different scenarios: Application at the urban scale. *Energy and Buildings 240*, 110880.

Jodeiri, A. M., M. J. Goldsworthy, S. Buffa, and M. Cozzini (2022, 4). Role of sustainable heat sources in transition towards fourth generation district heating – a review. *Renewable and Sustainable Energy Reviews 158*, 112156.

Johansson, M., D. Langlet, O. Larsson, Åsa Löfgren, N. Harring, and S. Jagers (2021, 12). A risk framework for optimising policies for deep decarbonisation technologies. *Energy Research & Social Science 82*, 102297.

Lechinger, V. and S. Matzinger (2020). So heizt Österreich - Heizungsarten und Energieträger in österreichischen Haushalten im sozialen Kontext. Wirtschaftspolitik Standpunkte No.36.

Loga, T., N. Diefenbach, and R. Born (2011). Deutsche Gebäudetypologie, beispielhafte Masnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden.

Lämmle, M., C. Bongs, J. Wapler, D. G¨unther, S. Hess, M. Kropp, and S. Herkel (2022). Performance of air and ground source heat pumps retrofitted to radiator heating systems and measures to reduce space heating temperatures in existing buildings. *Energy 242*, 122952.

Meteonorm (2023). Meteonorm software. https://meteonorm.com/.

Ochs, F., A. Tosatto, M. Magni, E. Venturi, W. Monteleone, and G. Dermentzis (2023). Strategies to overcome the dilemma in renovating and integrating HPs and RE into the building stock. In *Heat Pump Conference 2023*. Chicago (USA), 15-18 May.

Olkkonen, V., J. Hirvonen, J. Heljo, and S. Syri (2021, 11). Effectiveness of building stock sustainability measures in a low-carbon energy system: A scenario analysis for Finland until 2050. *Energy 235*, 121399.

Pfeifer, D. (2017). Entwicklung, Untersuchung und Bewertung von Berechnungsmodellen zur Erstellung von kommunalen Energiebilanzen im Gebäudebereich. Ph.D. Dissertation, Universität Innsbruck.

STATcube (2020). Statistik-austria: Registerzählung 2011 - gwz: Gebäude. 2011. url: https://www.statistik.at/web de/services/statcube /index.html (Last accessed 10.11.2020).

Statistik-Austria (2019). Nutzenergieanalyse für Österreich 1993-2018.

Steininger, K. W., J. Mayer, G. Bachner, S. Duelli, E. Frei, W. Grossmann, R. Maier, S. Nabernegg, K. Williges, W. Streicher, F. Ochs, M. Magni, A. Tosatto, E. Venturi, A. Passer, H. Kreiner, M. Scherz, B. Truger, J. Vogel, and I. Offenthaler (2021). The Economic Effects of Achieving the 2030 EU Climate Targets in the Context of the Corona Crisis - An Austrian Perspective: Wegener Center Scientific Report 91-2021. Wegener Center Verlag.

Sunikka-Blank, M. and R. Galvin (2012). Introducing the prebound effect: The gap between performance and actual energy consumption. *Building Research and Information 40*, 260–273.

Tabula (2020). Tabula webtool. url: https://webtool.building-typology.eu/#bm (Last accessed 10.11.2020).

Tosatto, A., F. Ochs, W. Streicher, M. Magni, and E. Venturi (2021). Role of passive buildings in the achievement of the EU55 targets in Austria – energy scenario. In *PassivHaus Conference 2021*. Wuppertal (DE).

UNEP (2021). 2021 global status report for buildings and construction: Towards a zero-emissions, efficient and resilient buildings and construction sector. United Nations Environment Program, Nairobi (Kenya).

https://doi.org/10.26868/25222708.2023.1489