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Published in:
E3S Web of Conferences

DOI:
10.1051/e3sconf/202339604014

Published: 16/06/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Võsa, K. V., Kurnitski, J., Felsmann, C., Meinsenbach, A., Carli, M. D., Tonon, M., & Iivonen, M. (2023). National methods fail to calculate standardized deep renovation concepts for dwellings : Benchmarking in three EU climates. *E3S Web of Conferences*, *396*, Article 04014. https://doi.org/10.1051/e3sconf/202339604014

National methods fail to calculate standardized deep renovation concepts for dwellings: benchmarking in three EU climates

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Abstract. Renovation of existing buildings has been highlighted as an essential action in the European Green Deal and in the latest revision of the EPBD to achieve energy efficiency targets. Renovation Wave strategy aims to double the deep energy renovation rate in EU by 2030, while specifically targeting the worst-performing segment of the existing building stock. The objective of this study was to assess the energy performance of deep renovation concepts on single and multi-family houses in three different geographical settings – Germany, Italy and Estonia. Typical German 1970s buildings were used as a baseline reference, and it was shown that very similar renovation concepts can be successfully applied across Europe that provides good bases to develop standardized solutions. Energy performance of two common renovation concepts was assessed both with national calculation methodologies and dynamic simulation with harmonized inputs and detailed heat pump plant models. The renovation concepts included improved envelope insulation and airtightness, switched to heat pump systems and heat recovery ventilation as well as incorporated on-site PV while complying with nearly zero-energy requirements for major renovations in all three countries. National energy calculation methodologies showed good accuracy for before the renovation situation but failed in many cases to calculate adequately NZEB renovation concepts with heat pumps and PV, indicating the development needs towards hourly calculation and more detailed treatment of heat pumps.

1 Introduction

As part of the European Green Deal, The Renovation Wave strategy has set an objective of at least doubling the annual energy renovation rate in the EU by 2030, focusing on tackling energy poverty and worst-performing building stock, public buildings and social infrastructure, as well as decarbonising heating and cooling [1]. As of 2019, the average annual deep renovation rate in EU stood at only 0.2% [2]. To achieve the climate targets set for 2030 and climate-neutrality by 2050, the annual deep energy rate must however be increased to at least 3 % by no later than 2030 and maintained at that level up to 2050 [3].

As shown in the previous study [4] of apartment buildings, nearly-zero energy building requirements in different EU climates can be achieved while implementing similar standard renovation solutions. However, the corresponding national energy performance calculation procedures often have significant differences, which complicates fair benchmarking of the buildings and renovation solutions across countries. Efforts were made to harmonise the calculation inputs and additional simulation results were compared to highlight the differences arising not only from the different climates but also from the different methodologies applied in the member states. In this study, we go a step further and model the technical systems in detail, to better describe the dynamic behaviour of the heating plant with heat pumps, self-use of PV and to further enhance the accuracy of the simulation models. We also address the cooling system as a part of renovation concepts.

The objective of this study is to analyse the energy performance of deep renovation solutions of typical single- and multi-family houses with heat pumps in three different European climates. National calculation methods as well as detailed energy simulations with hourly time-step are carried out to make this assessment. Special attention is given to the modelling of dynamic performance of the heat pumps, as well as local PV production and on-site use of renewable energy. Comparison of these results enables to check the robustness of assumptions and simplifications made in the national calculation methods as well as providing a calculation example of specified deep renovation solutions in the context of the Renovation Wave and latest framework of EPBD amendments.

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2 Methods

Energy performance calculations were conducted according to Estonian, German, and Italian national methodologies. Primary energy factors were normalised to 2.0 for electricity and 1.0 for natural gas.
National energy calculations were done with IDA ICE 4.8 for Estonia, Hottgenroth Energieberater 18599 3D PLUS for Germany and EDILCLIMA EC700 v. 11.22.14 for Italy. In the comparison of national methods calculation results, detailed simulation results with validated models of IDA ICE were considered as a baseline.

The following local climate data files were used for the three locations:

- Estonia→Estonian TRY
- Germany→DEU_POTSDAM_093790 (IWEC2)
- Italy→ITA_MILANO-LINATE_160800 (IWEC2)

The renovation concepts with heat pumps were further analysed with a detailed simulation model of the heating plant and heat pumps.

2.1 Single-family house

Fig. 1. View of the single-family house

2.1.1 Existing building

The reference building is a typical detached single-family house (SFH) in Germany. It has a saddle roof, an unheated basement and two residential floors, see **Fig. 1**. This type of construction with a solid wall made of high perforated bricks was typical in Germany during the period 1970-1990. Heating and domestic hot water is produced with locally installed natural gas boiler. Mechanical exhaust ventilation is used with intake air compensation through the envelope and/or fresh air intake valves. The intake air is therefore unheated and heated up with the space heaters. Radiators are used for space heating (typically 90/70 °C or 80/60 °C design supply/return air temperature). Buildings from this era have high heat losses through the envelope, especially through the external walls (U >1.0 W/(m^{2}K) and windows (U$_w$ >2.0 W/(m^{2}K).

2.1.2 Deep renovation concept 1 - AWHP

This renovation concept includes insulation of building envelope, installation of new windows, installation of new heating distribution system and installation of a new ventilation system. Installed ventilation system is mechanical supply and exhaust ventilation with heat recovery. The technical details of the renovation solutions are as follows:

- Additional insulation of external walls
- Additional insulation of roof
- Installing new triple-glazed windows
- Installing an air-to-water heat pump that delivers heat both to the hydronic system and DHW loop (55 °C set-point). Different SCOP values used in the calculations depending on the country.
- Installing a new underfloor heating system with thermostats (design supply/return temperatures of 35/28 °C)
- Installing a new supply-exhaust mechanical ventilation system with heat recovery:
  - Heat recovery temperature ratio 80%
  - Ventilation system SFP – 1.5 kW/(m3/s).
- Installing PV-panels with nominal power of 8 kWp
- Installing a split-type AC unit for cooling (SEER = 8.0 according to EN 14825)

2.1.3 Deep renovation concept 2 - EAHP

Compared to the previous renovation concept, the building HVAC systems have a different renovation solution. Ventilation system is mechanical exhaust ventilation from which heat is recovered with an exhaust air heat pump. Exhaust fan and air to brine heat exchanger unit is on the roof and the water-to-water heat pump is in the basement. Details that are different from concept 1:

- Installing a new two-pipe heating system with ventilation radiators (45/35 °C) and thermostats
- Installing a new mechanical exhaust ventilation system with exhaust air heat pump for heat recovery

2.2 Multi-family house

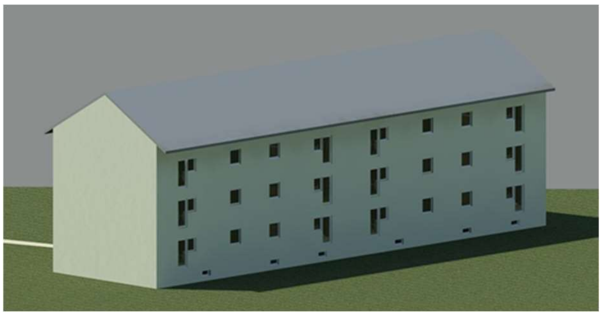

Fig. 2. View of the multi-family house.

2.2.1 Existing building

The reference multi-family house from 1970s consists of 12 residential units (**Fig. 2**). The flats are identical and have a floor area of approximately 95 m^2, with 6 rooms each. The building also has an unheated basement and attic.

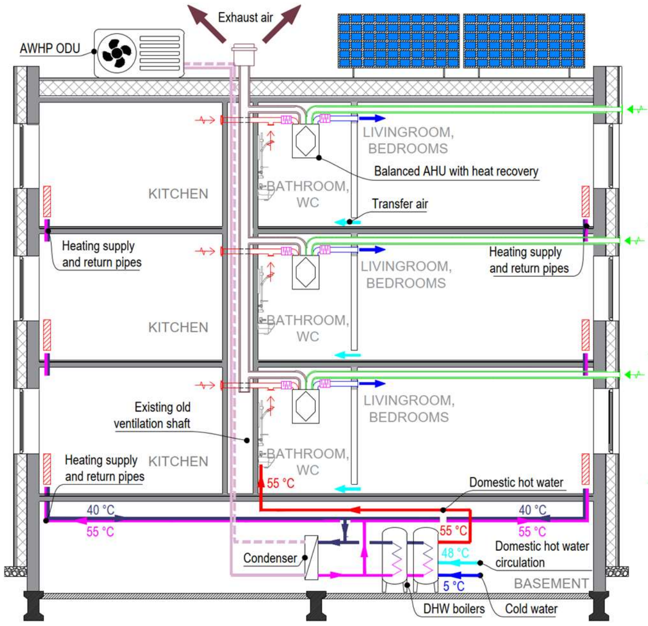

Fig. 3. Schematic view of the air-to-water heat pump solution of the multi-family house.

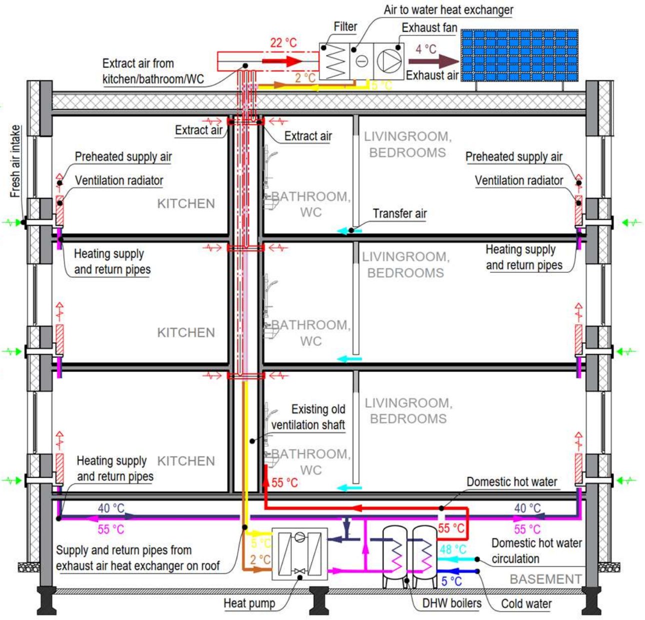

Fig. 4. Schematic view of the exhaust air heat pump solution of the multi-family house.

2.2.2 Deep renovation concept 1 - AWHP

Renovation concept includes insulation of building envelope, installation of new windows, installation of new heating distribution system and installation of new ventilation system. Ventilation system is decentralized mechanical supply and exhaust ventilation system with heat recovery, see **Fig. 3**

Renovation technical details are as follows:

- Additional insulation of external walls
- Additional insulation of roof
- Installing new triple-glazed windows
- Installing a central air-to-water heat pump for heating and DHW loop with circulation
- Installing new radiators (45/35 °C) with thermostats
- Installing a new apartment-based supply-exhaust mechanical ventilation system with heat recovery
    - Heat recovery temperature ratio 80%
    - Ventilation system SFP – 1.5 kW/(m^3/s).
- Installing PV-panels with nominal power of 30 kW
- Installing ceiling panels for cooling (15/18 °C) + dehumidifier for Italy
- Installing a central chiller (SEER 3.5) for chilled water

2.2.3 Deep renovation concept 2 - EAHP

Compared to the previous renovation concept, the building HVAC systems have a different renovation solution. Ventilation system is mechanical exhaust ventilation from which heat is recovered with an exhaust air heat pump. Exhaust fan and air to brine heat exchanger unit is on the roof and the water-to-water heat pump is in the basement floor (**Fig. 4**).

Renovation concepts include installation of photovoltaic (PV) panels on the roof of both the SFH (8 kWp) and MFH (30 kWp). Detailed description of different properties of the buildings can be found in **Table 1**-**Table 4**.

Table 1. Characteristics of the considered buildings.

	SFH	MFH
Year of construction	1977	1977
Number of floors	2	3
Net area (m^2)	177	1229
Heated area (m^2)	177	1117
No of rooms	17	85

Table 2. Building envelope properties

Property/object	Existing	Renovated	
		EE/DE	IT
Thermal transmittance W/(m^{2}K)			
External walls	1.39	0.14	0.23
Cellar wall	0.53	0.15	0.23
Windows U_w	2.34	0.80	1.30
g-value	0.68	0.50	0.50
Roof (insulated)	0.27	0.11	0.20
Roof (uninsulated, attic)	0.85	0.85	0.85
Attic floor (insulated)	0.40	0.10	0.20
Ground floor to cellar	0.56	0.18	0.25
Floor on ground	0.49	0.49	0.49
External door	1.75	1.75	1.75
Linear thermal transmittance W/(mK)			
External wall - external wall	0.22	0.040	0.040
External wall - internal wall	0.16	0.010	0.010
External wall – internal slab	0.16	0.010	0.010
External wall – roof	0.30	0.010	0.010
External wall – external slab	0.25	0.203	0.203
Window – external wall	0.10	0.070	0.070
External door perimeter	0.10	0.050	0.050

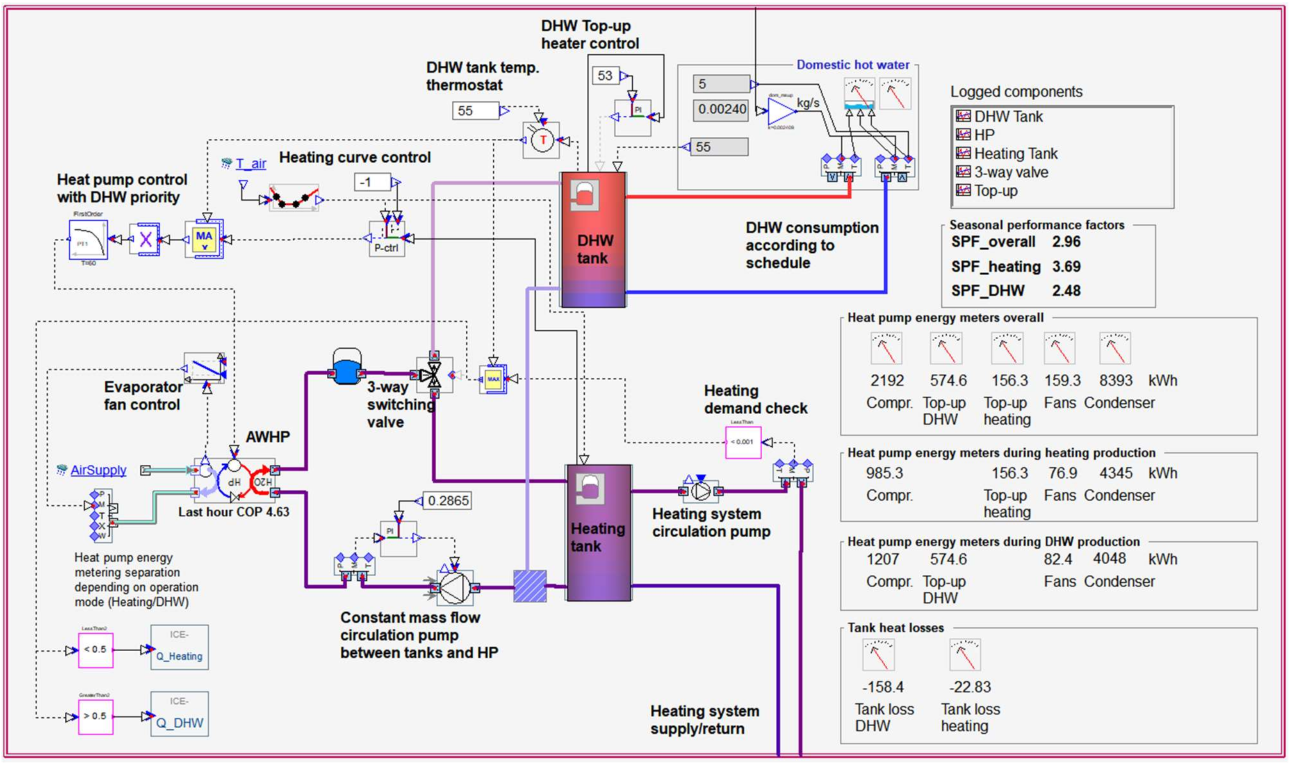

Fig. 5. Schematic view of the detailed plant simulation model in IDA ICE.

Table 3. Characteristics of the HVAC systems

System	Original	DR1 AWHP	DR2 - EAHP
Efficiency/SCOP[1]			
Heating (EE/DE/IT)	0.80	3.0/3.2/4.1	3.5
DHW (EE/DE/IT)	0.80	2.0/2.1/2.9	3.0
Cooling SEER	-	8.0	8.0
SFH	-	8.0	8.0
MFH	-	3.5	3.5
SFP (kW/(m^3/s))	-	-	-
Mech. exhaust	0.80	-	0.80
Mech. supply and exhaust	-	1.50	-

[1] SCOP values are used only in national energy calculation (detailed modelling in the simulation)

Table 4. Standard use input data, mostly from [5].

Parameter	SFH	MFH
Occupant, m^2/person	28.3	42.5
Appliances, W/m^2	2.4	3.0
Lighting, W/m^2	6.0	8.0
Usage time	0:00-24:00	0:00-24:00
Ventilation operation hour	0:00-24:00	0:00-24:00
Lighting usages rate	0.10	0.10
Occupancy usages rate	0.6	0.6
Appliance usages rate	0.6	0.6
DHW use, kWh/m^2 a	25	25
Ventilation rate, 1/h	-	-
Heated rooms	0.50	0.50
Basement	0.15	0.15
Fixed infiltration rate	0.30	0.10
Heating set point, °C	20	20
Cooling set point, °C	26	26

2.3 Detailed plant simulation model

IDA ICE 4.8 was used for the detailed simulations. Schematic view of the plant model can be seen in **Fig. 5**. The performance of the heat pump is modelled dynamically, depending on the fluid temperatures and mass flows through the evaporator and condenser. The instantaneous coefficient of performance is derived from a standardized compressor performance map. Heat pumps in the models were sized according to results from design heat load calculations, taking into account the limited heating capacity of the exhaust air heat pump. This limitation arises from the fact that the leaving air temperature in the exhaust air stream must be limited to avoid frost build-up on the heat exchanger coil. Flow through the heat exchanger was controlled so that the exhaust air temperature does not drop below 3 °C. This corresponds to flow temperatures of 2/5 °C in the water-glycol mixture between the exhaust air heat exchanger and heat pump evaporator. Nominal COP of 3.80 for the AWHP (+7/+45 °C)[1] and 3.17 (+20/+55 °C) were used in the detailed simulations.

Heating and DHW tanks were modelled as insulated cylindric vessels (U = 0.4 W/m^{2}K) with stratification between 10 fluid layers, with heat loss to ambient space (cellar). Heat transfer from the heat pump to the building was modelled with inlet and outlet streams at specified heights of these tanks. Tank sizes of 2.0 m^3 for DHW and 0.5 m^3 for heating were used in the MFH and 0.15 m^3 and 0.10 m^3 for SFH.

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[1] OAT/LWT – outdoor air temperature and leaving water temperature at nominal conditions

Table 5. Energy performance calculation results with national methodologies and normalised inputs (white background) and detailed heat pump plant simulations (grey background) - single-family house.

	ESTONIA					**GERMANY**					**ITALY**				
Energy use, kWh/(m2a)	OR	AWHP		EAHP		OR	AWHP		EAHP		OR	AWHP		EAHP	
Heat for space and vent. heating	325	-	-	-	-	212	-	-	-	-	164	-	-	-	-
El. for space and vent. heating	-	16.3	12.2	27.7	36.5	-	16.7	5.8	12.3	21.7	-	9.2	4.3	9.9	14.2
Heat for DHW	31.3	-	-	-	-	17.1	-	-	-	-	17.0	-	-	-	-
Electricity for DHW	-	14.1	10.6	11.2	11.6	-	5.4	9.9	4.4	10.6	-	5.4	9.0	7.5	10.0
Electricity for cooling	-	0.6	0.6	0.4	0.3	-	1.7	0.7	0.5	0.5	-	2.1	2.2	4.1	2.0
El. for fans and pumps	3.9	7.2	5.2	3.9	2.9	2.6	0.9	5.2	1.7	2.9	0.3	5.0	5.2	2.7	2.9
Delivered energy	361	38.2	28.5	43.2	51.3	232	24.7	21.6	18.9	35.6	182	21.7	20.7	24.2	29.2
Primary energy	365	76.4	57.0	86.4	103	235	49.4	43.2	37.8	71.3	182	43.4	41.4	48.4	58.4

Hot water tapping from building users is modelled according to [6], with two distinct consumption peaks at morning and evening. Temperature of 55 °C is maintained with an ON/OFF controller with a deadband of 2 °C (55±1 °C). Electric top-up heater is modelled in the top third of the DHW tank, which is switched on if the water temperature drops below 53 °C.

3 Results and discussion

3.1 Single-family house

National methodology calculation results for the single-family house can be seen in **Table 5**. The primary energy presented accounts for energy used for EPBD services only and does not include local PV production. The two renovation concepts provide significant energy performance improvements in all three climates. There is a primary energy reduction of at least 70 % in all cases. According to national calculation methodologies, concept DR1 AWHP offered better energy performance in Estonia and Italy, while in Germany DR2 with exhaust air heat pump resulted in lower energy consumption.

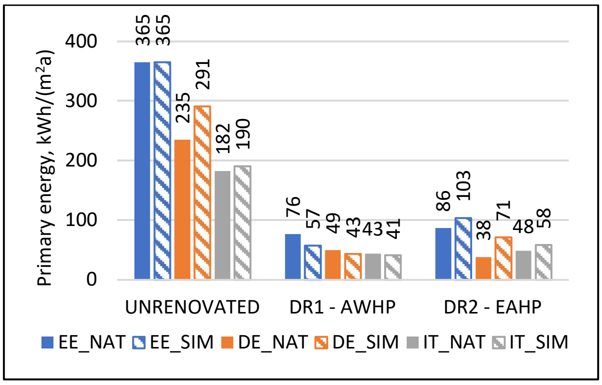

Fig. 6. Primary energy consumption of single-family house (EPBD uses). Comparison of national methodology calculations vs detailed plant simulation.

Results and comparison between the national methodology calculation results and dynamic simulations with a detailed heating plant can be seen in **Fig. 6**. Concept DR1 results show that the assumptions made in the national methodologies are in line with dynamic simulation results, with Estonian calculation results being on the conservative side (76 vs 57 kWh/(m^{2}a)). For the exhaust air heat pump (DR2) however, the results from the detailed simulation showed higher energy demand in all three countries. This difference was especially noticeable in the German case, where the primary energy demand is nearly twice as high in the dynamic simulations. In the Estonian national methodology, the tabulated values for the fraction of heat provided with the exhaust-air heat pump are not differentiated for apartment buildings and single-family houses, while the actual performance can be significantly different. Most likely, the national methodologies over-estimate the limited heating capacity of heating available from the exhaust air due to finite air flow rates. Consequently, electric top-up heater energy is under-estimated, and the difference in primary energy consumption is further amplified with by the primary energy factor.

Fig. 7 and **Fig. 8** further show the differences in the performance of the heat pumps and electric top-up heater. For the air-to-water heat pump, the differences in the use of electric top-up heater between the three locations are insignificant, with the top-up heater providing 7-8 % of the heat with direct electric heating. There is still of course a difference in the seasonal performance factor (SPF) due to higher evaporation temperatures in the warmer climates, with Italy predictably having the highest SPF of 3.22. There is a significant performance difference for the exhaust air heat pump, with electric top-up heater providing a third of the required heat in Estonia. The proportion is lower in the other two climates, but for Italy it is still a 125 % increase of direct electric top-up heater use when compared to the air-to-water heat pump (17.6 vs 7.8 %). Consequently, the SPF of such a system is between 1.98 and 2.58 in the simulated climates, which indicates that for the single-family house, concept DR1 with air-to-water heat pump is superior.

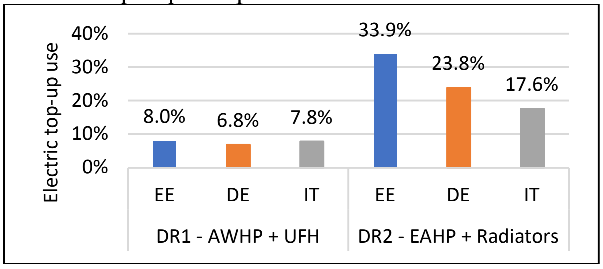

Fig. 7. Single-family house electric top-up heater use.

Table 6. Energy performance calculation results with national methodologies and normalised inputs (white background) and detailed heat pump plant simulations (grey background) - multi-family house.

	ESTONIA					**GERMANY**					**ITALY**				
Energy use, kWh/(m2a)	OR	AWHP		EAHP		OR	AWHP		EAHP		OR	AWHP		EAHP	
Heat for space and vent. heating	228	-	-	-	-	157	-	-	-	-	120	-	-	-	-
El. for space and vent. heating	-	10.5	8.8	23.2	19.6	-	8.9	3.7	4.6	12.3	-	3.9	2.3	7.2	8.4
Heat for DHW	35.3	-	-	-	-	33.7	-	-	-	-	24.0	-	-	-	-
Electricity for DHW	-	17.3	10.8	13.7	16.9	-	20.5	10.0	18.6	14.4	-	6.4	8.8	9.7	12.4
Electricity for cooling	-	0.8	0.7	0.4	0.4	-	2.9	1.1	2.2	0.6	-	6.4	3.9	8.3	3.5
El. for fans and pumps	3.5	5.2	5.1	3.5	3.0	4.7	6.3	5.1	2.8	3.0	1.0	0.9	5.2	0.7	3.0
Delivered energy	266	33.8	25.4	40.8	39.9	195	38.6	19.9	28.2	30.3	145	17.6	20.2	25.9	27.3
Primary energy	270	67.6	50.7	81.6	79.9	200	77.2	39.8	56.4	60.6	146	35.2	40.4	51.8	54.5

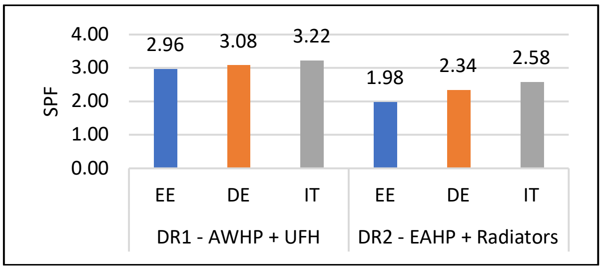

Fig. 8. Single-family house heat pump seasonal performance factors

3.2 Multi-family house

National methodology calculation results for the multi-family house can be seen in **Table 6**. The proposed renovation concepts provide a primary energy reduction of at least 60 % when considering EPBD services and no local PV production. AWHP solution achieved 17 and 33 % lower primary energy consumption than EAHP in Estonian and Italian calculations, respectively, while in the German case the AWHP had a lower primary energy consumption by 37 %.

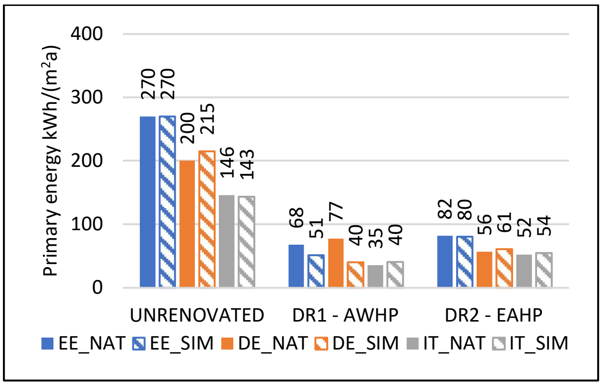

Fig. 9. Primary energy consumption of multi-family house (EPBD uses). Comparison of national methodology calculations vs detailed plant simulation.

Results and comparison between the national methodology calculation results and dynamic simulations with a detailed heating plant can be seen in **Fig. 9**. For Estonia and Germany, the AWHP results with the national methodologies were conservative (68 vs 51 kWh/(m^{2}a) in Estonia and 77 vs 40 kWh/(m^{2}a) in Germany). Renovation solution with EAHP showed consistent results between the national calculations and detailed plant simulations. Better matching of primary energy consumption likely arises from the fact that it is far more common to have this type of heat pump installed in a MFH, therefore the calculation methodology is better tailored for this application.

There is a significantly lower electric top-up heater use in the MFH. For the EAHP, it ranges between 16.3 % in Estonia down to only 4.5% in Italy, while for the AWHP, the top-up heater demand is 2.2 % in Estonia and negligible in Germany and Italy, as can be seen in **Fig. 10**. Consequently, the SPF values, shown in **Fig. 11**, are higher for the MFH, even in case of the AWHP, which has a higher supply temperature curve for radiators (45/35 °C) than the SFH, which has under-floor heating (35/28 °C). The difference in SPF is highest in the Estonian case (2.35 in MFH vs 1.98 in SFH), as the reduction in proportion of electric top-up heater use is also highest, from 33.9% to 16.3 %.

As expected, the primary energy demand for the MFH is somewhat lower than in the SFH, due to the more efficient form factor and lower ratio of external envelope area to heated area. This was more significant for Estonia and Germany, where there was about 10 % difference in the primary energy demand between the MFH and SFH after deep renovation. There was no significant difference for the Italian case.

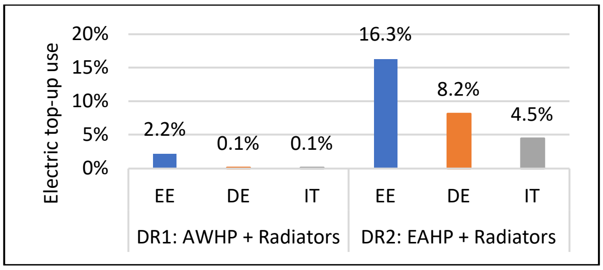

Fig. 10. Multi-family house electric top-up heater use.

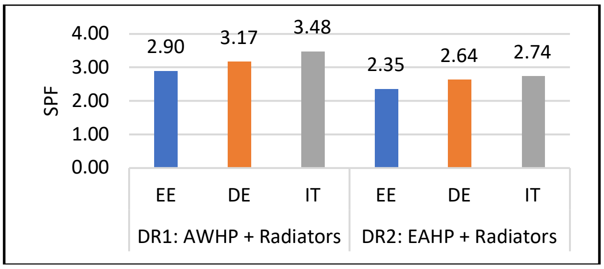

Fig. 11. Multi-family house heat pump seasonal performance factors.

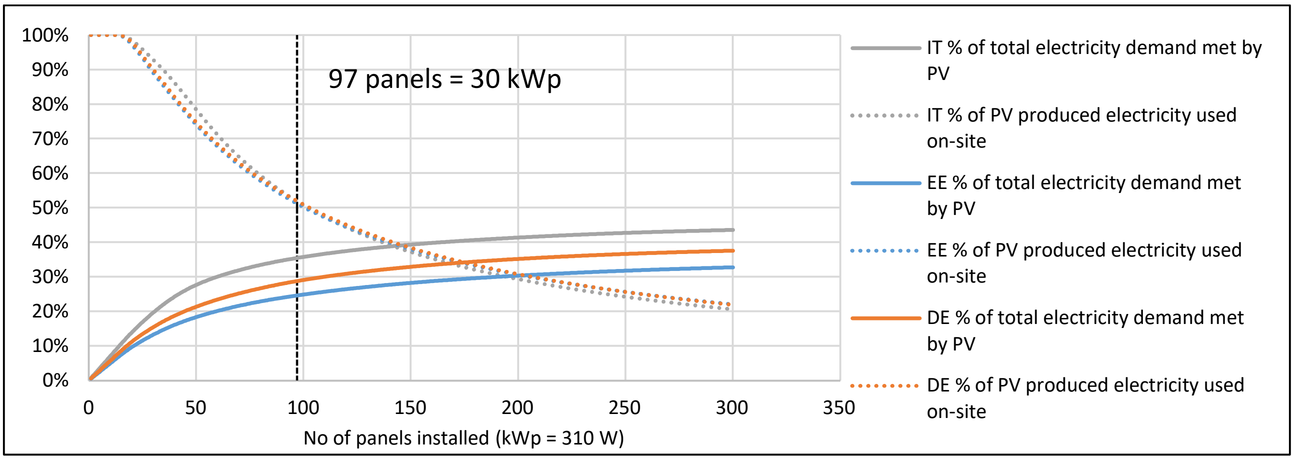

Fig. 12. Photovoltaics self-use fraction and coverage ratio of multi-family house (EPBD services + appliances and lighting).

3.3 Local PV electricity production

Additional analysis was carried out to assess the energy performance impact of local renewable energy production by photovoltaic panels in the MFH. In **Fig. 12**, the effects of proposed installation of 30 kWp solar panels (dashed line) can be seen. At this level of installation and considering both EPBD services together with standard appliances and lighting use outlined in **Table 4**, the proportion of used on-site electricity translates to roughly half of the total production in all three countries. Naturally, the annual electricity generation is highest in Italy, covering a total of 36% of the annual electricity demand of the building, followed by 29% in Germany and 25% in Estonia. It is also evident that further increasing the installed power has diminishing returns on the coverage ratio due to mismatch in the on-site electricity production and demand curves. For example, in Estonia, there is typically a 3-month period of practically no PV production during the winter coinciding with highest electricity demands, especially with heat pump solutions.

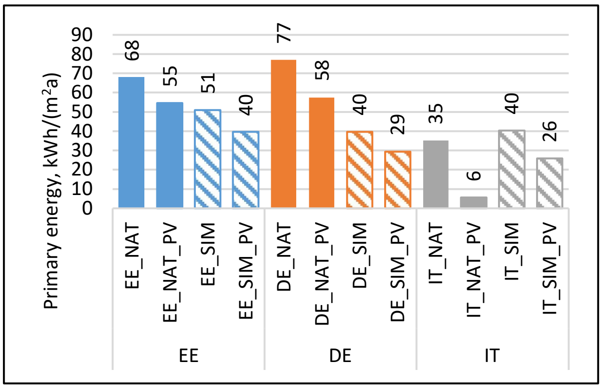

Fig. 13. Comparison of primary energy consumption with and without accounting for local PV production (EPBD services only) in MFH with AWHP.

The effect on the primary energy delivered to the building site can be seen in **Fig. 13**. For the simulated values, hourly PV production and electricity use were compared. Hourly PV electricity production was distributed proportionally between the EPBD services and appliances+lighting electricity uses, and exported electricity was not considered in the primary energy balance. This is similar to the calculation process in the Estonian national methodology. It must be taken into account that in Germany, only a maximum of 30% of the annual primary energy demand of the reference building according to the GEG may be deducted from the annual primary energy demand due to PV use. For Italy, the calculation is based on monthly energy balances.

In the simulation results, the primary energy reduction was 11 kWh/(m^{2}a) in Estonia and Germany, and 14 kWh/(m^{2}a) in Italy. More electricity use could be offset with local production as there is a considerable cooling load with coinciding solar production during the summer in the warmer climate. Together with self-used renewable energy, the primary energy reduction with renovation concept 1 (AWHP) from the original building becomes 85 % for Estonia, 86 % for Germany and 82 % for Italy, when considering EPBD services only.

There are considerable differences between the simulated PV self-use and for the German and Italian national methodologies. Notice that for Italy, the primary energy reduction is 29 kWh/(m^{2}a) in the national calculation, while with the hourly simulation analysis it was only 14 kWh/(m^{2}a). Such differences highlight the importance of accurate assessment of both the annual performance of heat pumps as well as locally generated electricity production.

4 Conclusions

In this study, we have highlighted the importance of accurate prediction of the energy performance of heat pumps in deeply renovated buildings. We show that by implementing either an AWHP or EAHP as the heat generator of a deep renovation concept, primary energy savings of at least 70 % can be achieved for reference single-family house and at least 60 % for the multi-family house, when comparing the building services listed in the EPBD. Together with on-site PV production, the AWHP solution was shown to save over 80 % of primary energy on a similar basis, accounting for self-used electricity only, which is in line with the goals set in the Renovation Wave.

Results from the detailed modelling of the heat pumps revealed significant deviations when compared to national methodology results. The greatest differences were seen for EAHP of the single-family house, for which all three national methodologies underestimated the energy use. The results were in much better agreement for the multi-family house, which indicates that the methodologies might not handle the limited heating capacity of such systems sufficiently accurately for smaller dwellings. Results show that highly energy efficient buildings are more sensitive to the calculation methods imposed when assessing the energy performance. In this case, even low proportions of electric top-up heater use have a significant impact on the energy use of the heating system and the whole building. The development needs towards hourly calculation and more detailed treatment of heat pumps are evident.

This research was supported by Purmo Group and Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE (grant 2014-2020.4.01.15-0016) funded by the European Regional Development Fund.

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