European Commission, Horizon 2020 Programme

MORE-CONNECT

Final selection of favourable concept based on LCA

Country: Czech Republic

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Date: 21 November 2018

This document has been prepared within the framework of the EU Horizon 2020 project MORE-CONNECT, Work Package 6 "Market and Replication", Task 6.2.

Methodological guidelines and feedback on the selection of the favourable concept were provided by Roman Bolliger and Walter Ott, econcept, Switzerland.

For more information about the MORE-CONNECT project see the project website:

http://www.more-connect.eu

This project has received funding from the European Union's H2020 framework programme for research and innovation under grant agreement no 633477.The sole responsibility for the content lies with the authors. It does not necessarily reflect the opinion of the European Communities. The European Commission is not responsible to any use that may be made of the information contained therein.

This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0001. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government.

1 The reference building

1.1 Description of the reference building

Fig. 0. MORE-CONNECT – the reference building in Milevsko, Czech Republic

The reference building taken into account for the final selection of the favourable concept was the same as for the pre-selection: A residential house built in 1958 as a part of a social housing settlement in Milevsko, South-Bohemian Region. This particular building has 24 studios (room, kitchen, bathroom, hall), 31 m^2 each, in three upper stories. Technical or housing facilities and cellars were put in the basement. The building has a central hall, flats are oriented either to the east or to the west, every flat has two windows. The building has gable roof (33°), attic space is currently unused. The building has a longitudinal wall structural system made of brick (450 mm), ceilings are made of reinforced cast concrete. Façades are plastered, original windows and exterior doors have already been replaced with insulating double-glazed windows with plastic frame. The building uses a district heating system, which is utilized also for hot water preparation. The typical problems of the reference building are unsatisfying winter thermal comfort, overall energy performance, ruptures in plaster, devastated common shared areas, and insufficient ventilation supporting a mould growth mostly in the basement floor or even in the bathrooms or kitchens. Such type of building covers about 5 % of complete multi-family housing stock and belongs to the most frequent multi-family residential building in the Czech Republic.

1.2 Dimensions and characteristics of the reference building

The following table summarizes the dimensions and characteristics of the reference building.

Tab. 1: Dimensions and characteristics of the reference building

Parameter	Unit	Data	Parameter	Unit	Data
Building period		1946–1960	Typical indoor temperature	°C	20
Gross heated floor area	m^2	993.3	Average electricity consumption per year and m^2 (excluding heating, cooling, ventilation and user (plug-in) electricity)	kWh/(a*m^2)	8.8
Wall area (excl. windows)	m^2	776.9			
Roof area pitched	m^2	-	*U*-value wall	W/(m^2*K)	1.4
Roof area flat	m^2	-	*U*-value roof pitched	W/(m^2*K)	-
Attic floor (if attic is unheated)	m^2	410.4	*U*-value roof flat	W/(m^2*K)	-
Area of ceiling of cellar	m^2	369.1	*U*-value attic floor	W/(m^2*K)	0.9
Area of windows to North	m^2	11.1	*U*-value ceiling of cellar	W/(m^2*K)	2.2
Area of windows to East	m^2	51.8	*U*-value windows	W/(m^2*K)	1.2
Area of windows to South	m^2	17.7	g-value windows	Factor	0.67
Area of windows to West	m^2	51.8	Energy need hot water	kWh/m^{2}a	35.2
Average heated gross floor area per person	m^2	40.1/20.7[1]	Energy need for heating	kWh/m^{2}a	186.6
			Airflow rate	m^3/(h*m^2)	0.78

[1] higher value: national declarative calculation; lower value: expected real occupancy density

2 The MORE-CONNECT solution

MORE-CONNECT tries to solve the renovation issue by developing prefabricated, multifunctional renovation elements for the total building envelope (façades and roof) and installation building services that will enable modular retrofitting of residential buildings. These elements can be combined, selected and configured by the end-user, based on his specific needs. This information can be used as input into advanced Building Information Modelling systems to control and steer the further production process of these elements. In this way, unique series of one can be made in a mass production process for the same reduced price of mass production.

In detail, the MORE-CONNECT solution is described in a separate report prepared in the MORE-CONNECT project [5].

3 Investigated renovation packages

For the identification of favourable concepts, an assessment of possible renovation variants (packages) was carried out with respect to greenhouse gas emissions, primary energy use, and costs.[1]

The investigated renovation packages covered partly solutions commonly used in the Czech Republic, partly environmentally friendly solutions focused on natural materials and sources used. The renovation packages also included the MORE-CONNECT solutions. It was expected that the commonly used solutions would be generally favourable as they have been pre-selected by the market, while the environmentally friendly solutions created a target boundary from the environmental point of view. Comparison of packages covering these approaches allowed an evaluation of how far or close the environmentally friendly concepts are from the market pre-selection.

The renovation packages were assessed within the framework of different heating systems that were possible in case of the reference building. The heating systems taken into account were:

- District heating (current heating system),
- Heat pump,
- Natural gas,
- Wooden pellets.

The process of the assessment was multi-step (see also Fig. 1). Each renovation step improved certain part of a building and consisted of several variants of given improvement. The variants were delimited by material or technology used and/or by level of improvement. From each renovation step, a partial optimum was selected. That subsequently advanced to the next step as a basis. Assessment steps were:

- Firstly, the "anyway" renovation was considered as the basic case. It comprised the restoration of the functionality of the renovated building elements, yet without improvement of their energy performance.
- Second, additionally, a change of heating system was considered. No other improvement was supposed. This case served as a reference for further renovation steps.
- Step 1: External walls were provided with additional thermal insulation.
- Step 2: Ceiling of the last storey (attic floor) and basement ceiling were provided with additional thermal insulation.
- Step 3: Triple-pane glazing windows were used.
- Step 4: Mechanical ventilation system with heat recovery was used (considering either mechanical ventilation only or warm-air heating system within).
- Step 5: PV panels of various sizes were added (applied to both variants from the previous step).
- Step X-ven: Mechanical ventilation system with heat recovery was added to the selected variants of wall insulation from Step 1 and to anyway renovation case.

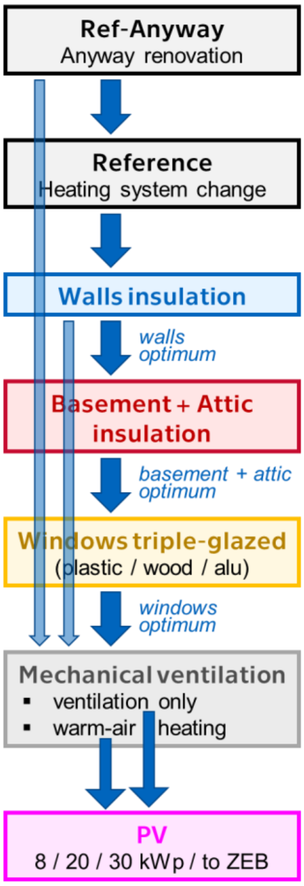

Fig. 1: Assessment steps

[1] For a description of the assessment methodology, a separate document is available which has been prepared within the MORE-CONNECT project [6]

The detailed description of the investigated renovation packages is stated in the Tab. 3.

Note: Most of investigated renovation packages were adopted from the Pre-selection of favourable concept document (D6.1). Besides those taken into account in the pre-selection, four additional packages were considered:

- Windows renovation was added to walls insulation using ETICS: In case of the assessed reference building, windows have already been replaced by plastic ones with double glazing recently; however, it need not to be a starting point in case of all buildings intended for renovation. Therefore, the case was added to make the MORE-CONNECT and ETICS solutions better comparable as MORE-CONNECT solution includes windows replacement in it.
- Anyway renovation and two wall insulation variants in combination with mechanical ventilation: as a standard sequence of renovation steps, ventilation system was considered to be added to completely insulated envelope; however, contribution of ventilation providing higher indoor air quality in combination with just basic wall measures was of interest.

Embodied environmental parameters' data of the materials and technologies used were taken from the Ecoinvent 3.3 database [1], [2]. Particular inputs used for cost and environmental impact calculation are provided in Appendix 1. Conversion factors of non-renewable primary energy and greenhouse gas emission factors ($CO_{2,ekv.}$) related to operational energy consumption were taken from the Czech Gemis database (2009) [3], [4] as factors from this database are expected to represent better the energy mix in the Czech Republic than the official factors set for the purpose of declarative calculations. The factors used in the calculations are listed in Tab. 2.

Tab. 2: Conversion and emission factors of operational energy consumption [3], [4] and energy prices

Energy carrier	**Primary energy** [kWh/kWh]	**$CO_{2,ekv}$** [kg $CO_{2,ekv}$/kWh]	**Energy price** [EUR/MWh]
District heating	2.23	0.79	75.0
Electricity from the grid	3.16 (2.84, 2.53, 2.21)*	0.75 (0.67 ,0.60, 0.52)*	149.3
Natural gas	1.46	0.32	48.2
Pellets	0.11	0.03	46.4
Electricity produced (PV)	-3.16 (-2.84, -2.53, -2.21)*	-0.75 (-0.67 ,-0.60, -0.52)*	16.1 (0–21.4)**

* used within the sensitivity analysis
** range taken into account within the purchase electricity price sensitivity analysis

Notes to comparability of MORE-CONNECT solution and ETICS

In the following assessment, the MORE-CONNECT solutions with ETICS are compared. Both are referring to two insulation thicknesses: 10 cm and 20 cm. However, the MORE-CONNECT solution and ETICS are not fully compatible – neither in total thermal insulation thickness, nor in *U*-value. ETICS contains just single thermal insulation layer while the MORE-CONNECT panel contains three thermal insulation layers in total. The thickness referred to in the report concerns the main insulation layer, which is possible to be varied. The total thickness of the thermal insulation is bigger in case of MORE-CONNECT panel compared to ETICS and the MORE-CONNECT panel also has lower *U*-value even though the thermal conductivity of each insulation layer is higher (compared to ETICS) due to systematic thermal bridges in a shape of timbers. Referred insulation layer thicknesses correspond to *U*-values:

- 10 cm ~ 0.16 W/(m^2K) (MORE-CONNECT) / 0.26 W/(m^2K) (ETICS)
- 20 cm ~ 0.12 W/(m^2K) (MORE-CONNECT) / 0.15 W/(m^2K) (ETICS)

Tab. 3: Renovation packages taken into account within selection of favourable concept

Step	Renov. Pack.	Description
Step 1	Ref-anyway	In the reference case (“anyway” renovation), the façades plasters are refurbished and repainted, the water-proofing failures in the basement and the attics are refurbished. These measures do not improve the energy performance of the building.
	Ref	Additionally to Ref-anyway, considering change of heating system
	P1	Additionally to Ref , Walls are provided with ETICS with 10 cm of EPS (windows retained the existing ones since they were already replaced by plastic ones with double glazing recently)
	P2	Additionally to Ref , Walls are provided with ETICS with 20 cm of EPS (windows retained the existing ones since they were already replaced by plastic ones with double glazing recently)
	P2+win	Ditto P2 but windows assumed to be replaced (to assess the potential of such combination in cases where windows have not been renovated yet)
	P3	Additionally to Ref , Walls are provided with a MORE-CONNECT panel including 10 cm of mineral wool, new double-glazed windows with plastic frames as a part of the panel
	P4	Additionally to Ref , Walls are provided with a MORE-CONNECT panel including 20 cm of mineral wool, new double-glazed windows as a part of the panel (furthermore, windows frame material impact was investigated for plastic, wooden and aluminium frames)
	P5	Additionally to Ref , Walls are provided with a MORE-CONNECT panel including 20 cm of mineral wool and vacuum insulation, new double-glazed windows with plastic frames as a part of the panel
Step 2	P6	Additionally to step1 optimum, ceiling of the last storey (attic floor) are provided with 20 cm of mineral wool, basement with 6 cm of mineral wool
	P7	Additionally to step1 optimum, ceiling of the last storey (attic floor) are provided with 40 cm of mineral wool, basement with 14 cm of mineral wool
	P7x9	Additionally to step1 optimum, ceiling of the last storey (attic floor) are provided with 40 cm of wood blown insulation, basement with 14 cm of mineral wool
	P8	Additionally to step1 optimum, ceiling of the last storey (attic floor) are provided with 20 cm of wood blown insulation, basement with 6 cm of wood-fibres insulation
	P9	Additionally to step1 optimum, ceiling of the last storey (attic floor) are provided with 40 cm of wood blown insulation, basement with 14 cm of wood-fibres insulation
Step 3	P10	Additionally to step2 optimum, the windows are replaced with new 3-glazed windows with plastic frames and U-value for the entire window of 0.7 W/(m2K)
Step 4	P11	Additionally to step3 optimum, mechanical ventilation system with heat recovery is installed for ventilation
	P12	Additionally to step3 optimum, mechanical ventilation system with heat recovery is installed for both ventilation and warm air heating
Step 5	P13	Additionally to P11, PV panels of 8 kWp are installed
	P14	Additionally to P11, PV panels of 20 kWp are installed
	P15	Additionally to P11, PV panels of 30 kWp are installed
	P16	Additionally to P12, PV panels of 8 kWp are installed
	P17	Additionally to P12, PV panels of 20 kWp are installed
	P18	Additionally to P12, PV panels of 30 kWp are installed
	P19	Additionally to P11, PV panels of such power to reach net zero primary energy
	P20	Additionally to P12, PV panels of such power to reach net zero primary energy
Step X-ven	P0 +vent	Additionally to Ref-anyway, mechanical ventilation system with heat recovery is installed for ventilation
	P2+win +vent	Additionally to P2+win, mechanical ventilation system with heat recovery is installed for ventilation
	P4 +vent	Additionally to P4, mechanical ventilation system with heat recovery is installed for ventilation

4 Assessment of investigated renovation packages and final selection of favourable concept

4.1 Final-selection methodology notes

4.1.1 Differences between final-selection and pre-selection calculations

This document presents and discusses results of final selection of favourable concept calculations. The basic approach and methodology concur with those used for the pre-selection of favourable concept. However, compared to calculations made for the pre-selection, several changes have been made:

- Input data have been given higher precision: embodied environmental parameters, lifetimes, maintenance costs, operational costs, and purchase electricity price have been updated and incorporated in higher detail.
- Four more packages have been assessed for wider representation of various possible choices (in case of district heating only which was sufficient for illustration of trends).
- Simple sensitivity analysis of operational environmental parameters and cost trends has been added:
  - To estimate impact of higher share of renewable energy in electricity mix, decrease of conversion and emission factors of electricity consumption was considered (10 %, 20 %, and 30 %).
  - To estimate impact of mass production and technology automation of MORE-CONNECT solution, decrease of MORE-CONNECT production costs was considered (10 %, 20 %, and 30 %).

4.1.2 Notes regarding costs

Costs were established based on market prices and in some cases by expert estimation after consultation with builders. Prices of the MORE-CONNECT solution thus do not reflect particular cost of the project partner RD Rýmařov based on his manufacturing. In the price of MORE-CONNECT solution, only the material used, assembly and construction expenses are covered. Expenses needed for business kick off are not included. Transportation costs are not included in any variant.

Prices for energy vary depending on the locality and an energy distributor. Also purchase electricity price is fluctuating and is not guaranteed so it may happen that the price is almost zero or the produced electricity is not purchased. Therefore, results comparison between different energy sources and conclusion about PV profitability are burdened with high level of uncertainty.

4.2 Consecutive selection of favourable variant per each step

The step-by-step evaluation was carried out for the case with district heating (it is the current heating system in case of the Czech reference building and is expected to be probably maintained). The evaluation and favourable package selection substantiation is provided below.

4.2.1 Step1: External walls insulation

Comparison of wall insulation variants to each other and to the reference case (“anyway” renovation) is shown in Fig. 2. Compared to the reference case, any variant of wall insulation decreased the environmental burden by about 40 %. An external thermal insulation composite system (ETICS) is the most frequent way of wall insulation in the Czech Republic and both ETICS cases (P1, P2) had the lowest cost from all investigated variants. The variant with thinner insulation (P1) had higher impact on both primary energy and greenhouse gas emissions since environmental parameters related to operational energy consumption had bigger influence than the embodied quantities. Package with 20cm ETICS including the windows replacement (P2+win) shows higher costs by about 3 % compared to the case without windows renovation (P2). The MORE-CONNECT solution with 10 cm of main insulation layer (P3) had similar environmental impact as 20 cm ETICS (P2, P2+win) and showed only slightly higher costs (by about 3 % compared to P2+win). The MORE-CONNECT solution with 20 cm of main insulation (P4) showed slightly lower environmental impact than the 10cm MORE-CONNECT solution with subtly lower cost (P4pl, the variant uses plastic-frame windows). Aluminium frames (P4alu) were connected with costs increase by 4 %, wooden frames (P4wd) were the most expensive ones (costs higher by 12 % compared to plastic frames). The MORE-CONNECT solution containing vacuum insulation layer through out the panel (to reach better insulation parameters without significant increase in thickness) (P5) showed higher cost by about 14 % compared to P4pl with approximately the same primary energy use.

Comparison of the two corresponding solution from ETICS and MORE-CONNECT family (variants having the same thickness of thermal insulation (20 cm) and both with renovated windows – P2+win and P4pl) brought findings that the MORE-CONNECT solution should be competitive on the market. The results indicate that MORE-CONNECT solution for walls may be comparable to ETICS with EPS. The prices were found only slightly higher in the case of MORE-CONNECT panels, while ETICS resulted with slightly higher environmental burden. Moreover, the MORE-CONNECT solution can provide higher standard of living as thermal insulation is accompanied by other services in one solution, which is not quantitated in the results. Such other services comprise for example a possibility of mechanical ventilation, new heating piping (for case of heat source change), electrical wiring including wi-fi router, etc. Therefore, **MORE-CONNECT panel with 20 cm of main thermal insulation and plastic-frame windows (P4pl) was considered to the optimal**

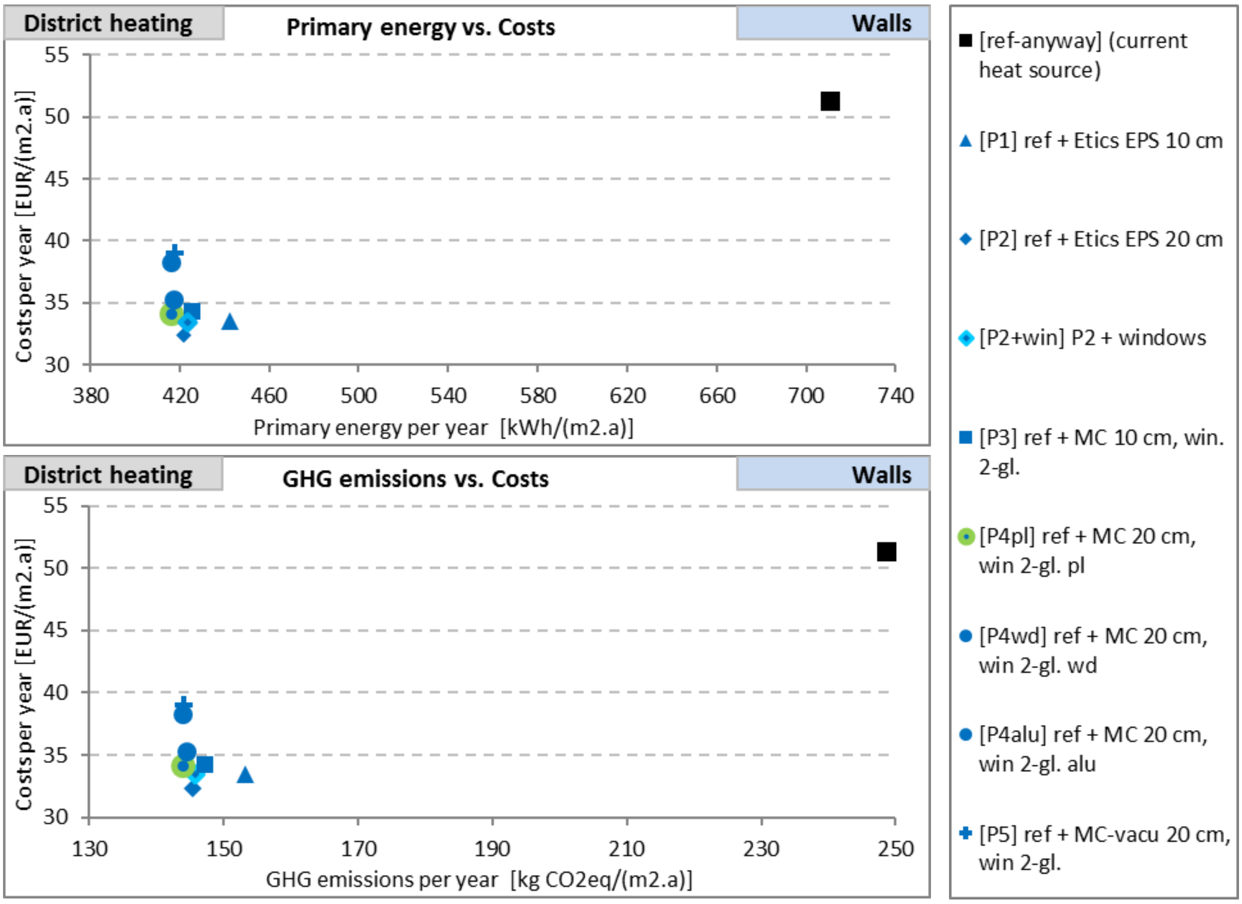

Fig. 2: Selection of favourable concept – step 1: walls insulation (district heating); selected variant marked with green circle (top – primary energy vs. costs impact, bottom – greenhouse gas emissions vs. costs impact)

solution for walls in this step. This solution means approx. 42% reduction of primary energy and GHG emissions and 34% save of yearly costs compared to the reference case (“anyway” renovation).

4.2.2 Step 2: Attic and basement insulation

In step 2, attic floor and basement ceiling insulation were added. The results of the variants taken into account are in Fig. 4. Compared to an initial point (pre-selected variant from the previous step – P4pl), addition of basement ceiling and attic floor insulation reduces environmental burden by about 38 % and costs by approx. 28 % in average. Higher insulation levels led to better results in all criteria. The variants with similar insulation level had almost the same environmental impact and only slightly differed in costs – wood wool insulation is connected with slightly higher costs. Variants P7 and P7x9 hardly differ. Mineral wool for basement is the safest option among the considered materials in relation to possible higher relative air humidity risks in the basement. Regarding the attic floor, blown wood fibre insulation was considered as more favourable due to easier application at complicated geometric conditions around attic beams. Therefore, **variant with 14 cm of mineral wool at basement ceiling and 40 cm of blown wood fibre insulation on attic floor (P7x9) was considered as optimal within this step**.

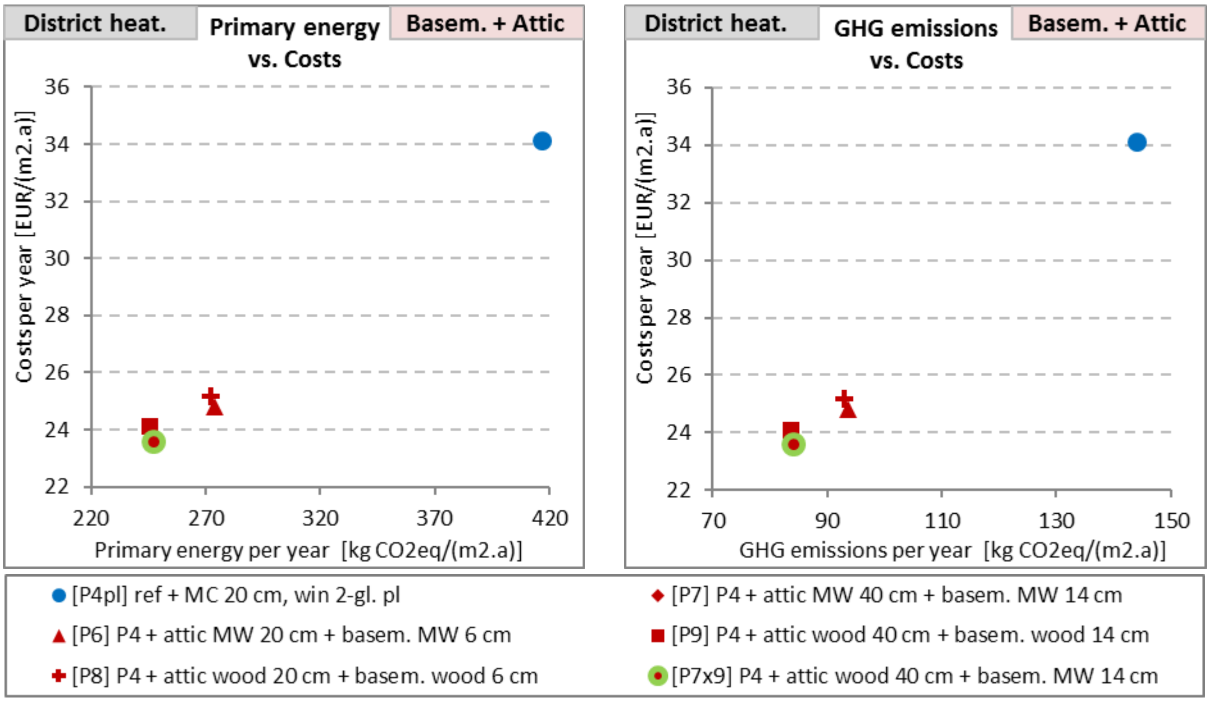

Fig. 3: Selection of favourable concept – step 2: basement and attic insulation (district heating); selected variant marked with green circle
(left – primary energy vs. costs impact, right – greenhouse gas emissions vs. costs impact)

4.2.3 Step 3: Triple-pane glazing windows

As a subsequent step, windows with triple-pane glazing were used instead of double-pane glazing. Variants differ in window frame material. The results are shown in Fig. 4. Use of triple-glazed windows decreased primary energy use and greenhouse gas emissions compared to double-glazed ones (initial case), regardless of the material of frames. The differences between environmental impacts of frame material are rather small. On costs, the window frame material has, however, significant impact. Only windows with plastic frames (P10pl) led to a cost reduction. Wooden frames (P10wd) showed the highest cost, aluminium frame cost (P10alu) lies between wooden and plastic frames. **Plastic-frame triple-glazed windows variant (P10pl) was considered as optimal in this step**.

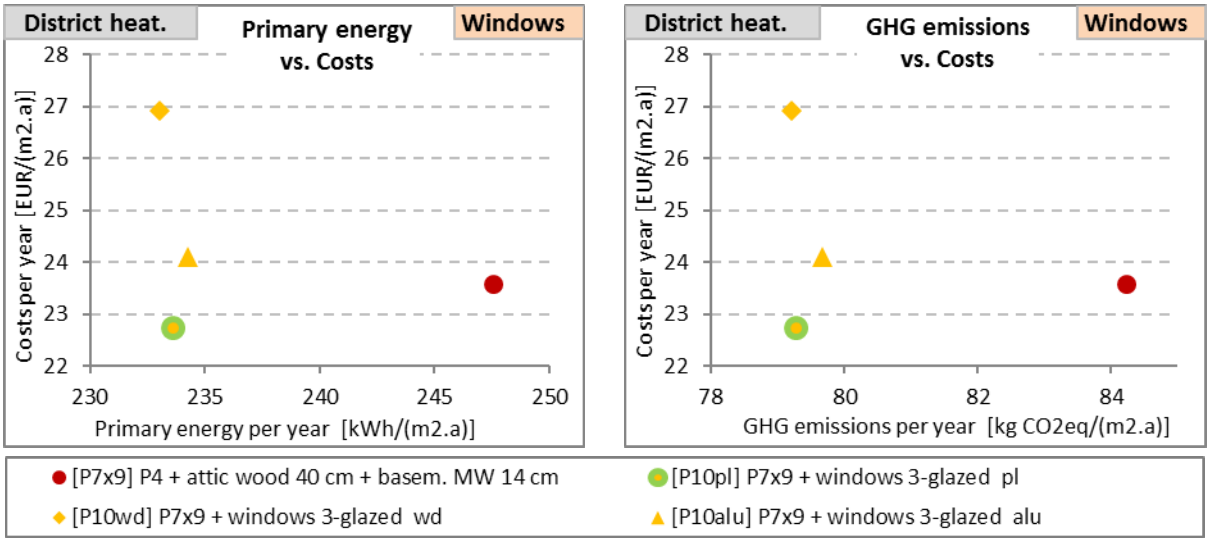

Fig. 4: Selection of favourable concept – step 3: triple-pane glazing windows (district heating); selected variant marked with green circle (left – primary energy vs. costs impact, right – greenhouse gas emissions vs. costs impact)

4.2.4 Step 4: Mechanical ventilation

This step comprised of an addition of a mechanical ventilation system with heat recovery to the variant selected in the previous step. One variant counts with mechanical ventilation only (P11), another one counts with mechanical ventilation combined with worm air heating system (P12). Comparison is provided in Fig. 5. Both variants resulted in decrease of environmental impact compared to naturally ventilated initial case (reach 76 % and 88 % in case of P11 and P12 respectively, compared to initial naturally ventilated level). Internal air quality improvement, although not covered by this analysis, is another argument in favour of the mechanical ventilation system installation. The system designed for ventilation only is more favourable solution in all the assessed criteria than the system combining ventilation with warm-air heating, which increases the cost by about 12 % compared to ventilation-only system. Therefore, **variant with mechanical ventilation only was considered as favourable**. However, decision whether to preserve original hot-water heating system or to replace it by warm-air heating system depends on factors beyond the scope covered by the performed optimization analysis. For that reason, both variants using mechanical ventilation proceed as a basis for further step.

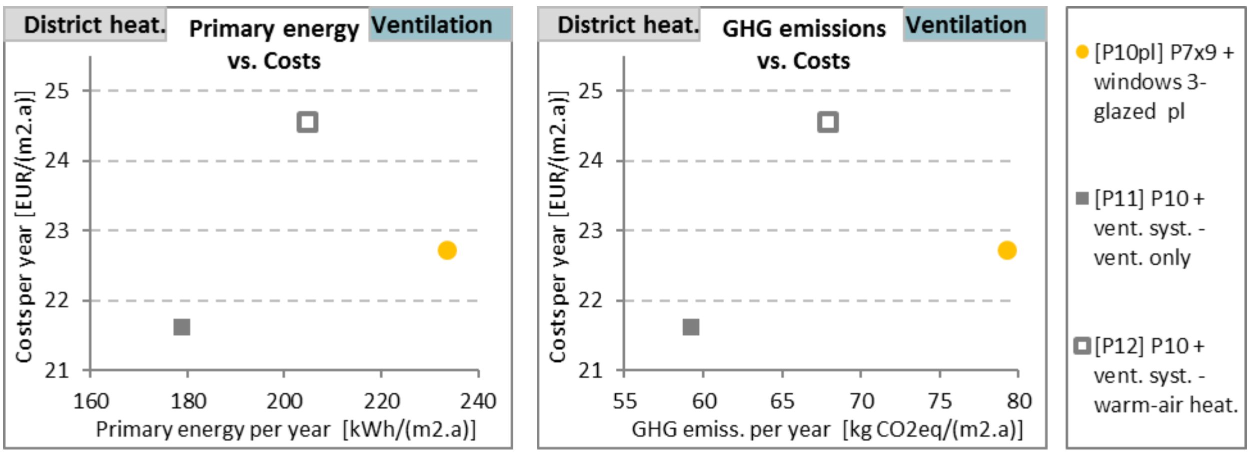

Fig. 5: Selection of favourable concept – step 4: mechanical ventilation (district heating); (left – primary energy vs. costs impact, right – greenhouse gas emissions vs. costs impact)

4.2.5 Step 5: PV panels installation

The last step involved installation of PV panels onto the reference building (no battery storage was considered). Areas available for installation were: pitched roof (south and west orientation, slope 32°, 180 m² + 180 m²), south gable wall (90 m²), and west and east façades (80 m² + 80 m²). Environmental impact of exported electricity is accounted in yearly balance by using minus conversion and emission factors (see Tab. 2). The variants taken into account differed in installed power.

Purchase electricity price was included within cost evaluation. However, the price is fluctuating and is not guaranteed, hence, it may happen that the price is almost zero or the produced electricity is not purchased, or, on the contrary, that maximal price is collected. Therefore, as a basic value of purchase electricity price, 0.016 EUR/kWh was assumed, and in addition to that, a range of purchase electricity price was considered between 0 EUR/kWh and maximal price which is approx. 0.021 EUR/kWh.

Results are depicted in Fig. 6. Installation of PV panels led to primary energy and greenhouse gas emission decrease (the higher the installed power, the higher the decrease). The profitability of the PV installation strongly depended on purchase electricity price and it may happen that PV shows to be unfavourable from the costs point of view.

The final decision about favourable installed power lies beyond the scope of this study as it depends on actual energy set-up, real electricity consumption profile, possibility to build a smart grid with some other buildings, purchase electricity price, etc.

To reach net zero primary energy level with district heating, for the variant with mechanical ventilation only (P19) installed PV power of 81 kWp would be needed which corresponds to the following size of the PV installation: fully covered roof and gable wall (i.e. 180+180 m² on roof, 90 m² on gable wall) and 15+15 m² on façades. Variant assuming warm-air heating (P20) would not reach net zero primary energy even with fully utilized available area for PV which produced 103 kWp. Current legislation in the Czech Republic, however, restricts installed power to maximum 30 kWp if connected to a grid (the limit was not taken into account as far as purchase electricity price is concerned).

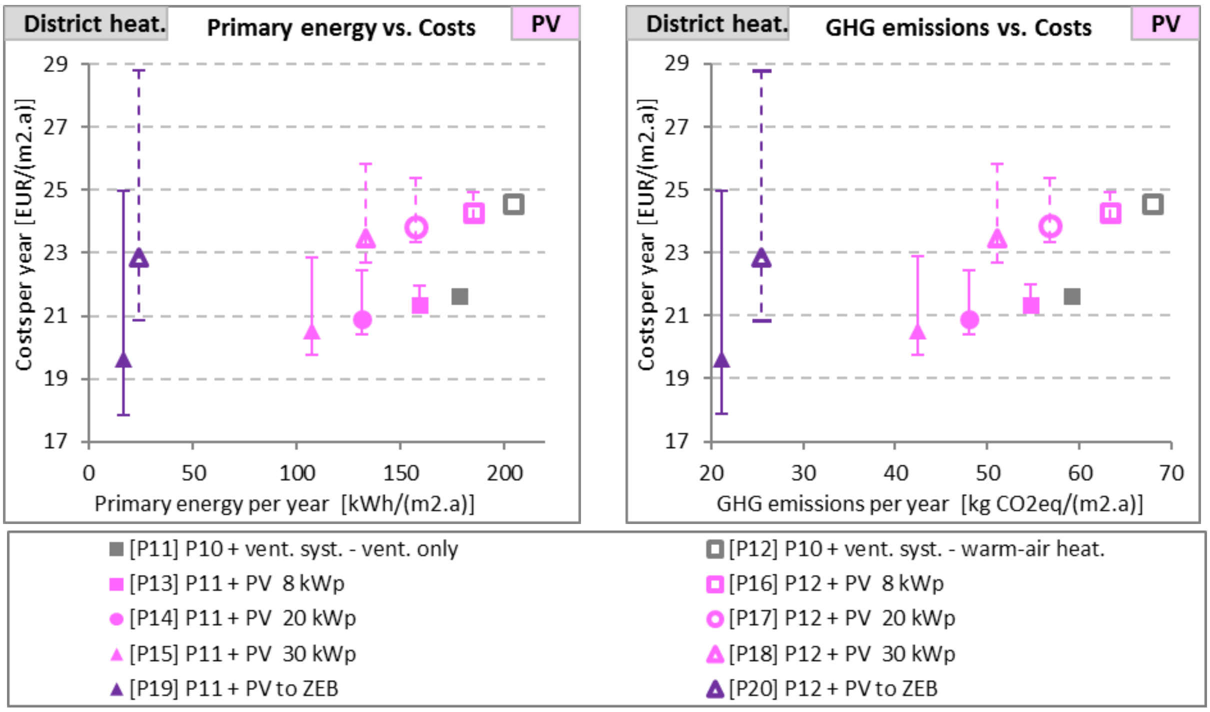

Fig. 6: Selection of favourable concept – step 5: PV installation (district heating); (left – primary energy vs. costs impact, right – greenhouse gas emissions vs. costs impact)

4.2.6 Step X-ven: Mechanical ventilation added to only wall-related measures

In this step, mechanical ventilation system with heat recovery was added to the selected variants of wall insulation from Step 1 (both ETICS and MORE-CONNECT solution with 20cm thermal insulation (P2+win, P4pl)) and to anyway renovation case to see how internal air quality improvement stands. These variants were investigated since it might be of interest for investors aiming to improvement of indoor air quality but for whom complex renovation would exceed their budget. The calculations of this step were made only for district heating system. Results are shown in Fig. 7. In all cases renovation enhancement by ventilation system resulted favourable from both environmental and cost point of view. Compared to naturally ventilated cases, mechanical ventilation decreased environmental burden by about 15 % in cases with insulated walls, and approx. 10 % in case of anyway renovation. Costs savings connected with mechanical ventilation addition (owing to operational energy consumption decrease) range around 3–5 %. Indoor air quality improvement is not quantified within the results. It can be concluded that also the combination of wall insulation only and mechanical ventilation can be advantageous in case of lack of funding, especially when the accent is put on indoor environment quality. However, the overall favourableness is lower compared to complex renovation. Furthermore, combination of mechanical ventilation with anyway renovation may be unreasonable especially in connection with original windows and generally poor airtightness, which need to be considered in each particular case.

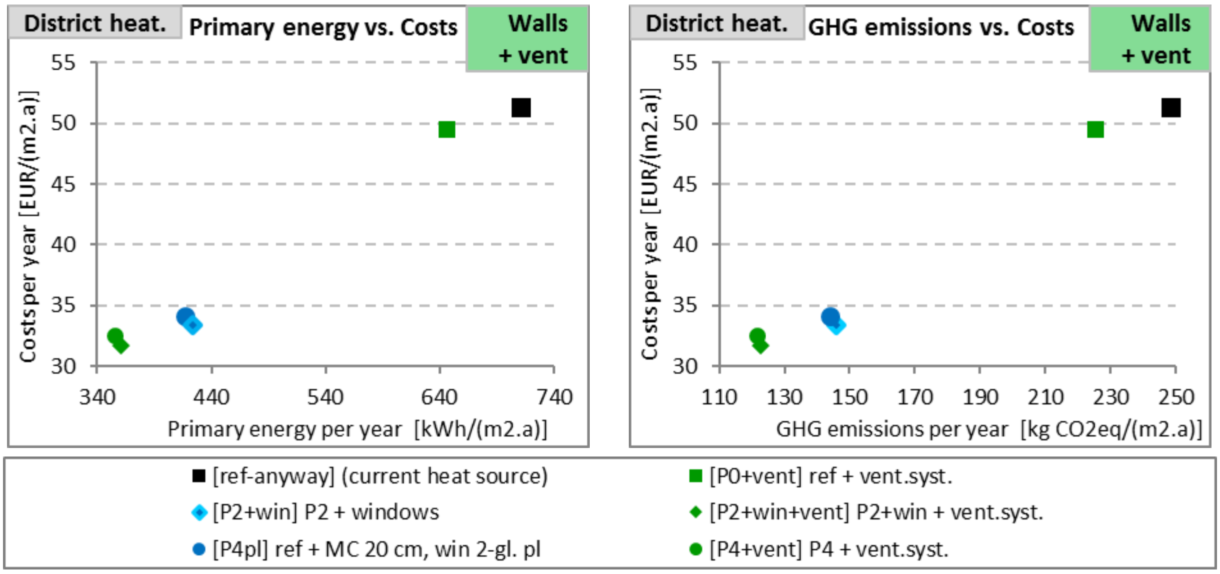

Fig. 7: Selection of favourable concept – step X-ven: mechanical ventilation added to only wall measures (district heating); (left – primary energy vs. costs impact, right – greenhouse gas emissions vs. costs impact)

4.3 Overview graphs

The expected impacts of the investigated renovation packages of the Czech reference building, taking into account different heating systems are shown in Fig. 8 and Fig. 9. It should be noted that the environmental assessment strongly depends on conversion and emission factors. These factors usually reflect current energy mix and/or the political convention. Therefore, the results are valid for the Czech Republic current conditions and are not generalizable. Analysis of electricity factors variation impact is presented in section 4.3.2.

Absolute criteria values differ among the heat sources. District heating is the current heat source in case of the reference building. District heating in the Czech Republic is mainly based on brown coal which is reflected in conversion factors and, therefore, environmental burden with this source is the highest from all considered sources. The lowest environmental burden is connected with pellets; environmental impact is at about 1/5 to 1/10 compared to other sources. Heat pump and natural gas cases lie between them; the heat pump shows slightly lower environmental impact than natural gas.

Prices for energy vary depending on the locality and an energy distributor. However, as far as considered costs are concerned, natural gas would be the most favourable source, followed by pellets and a heat pump at almost the same level, while preservation of district heating system would be the least favourable solution. Without regard to the heat source, almost each of the consecutive renovation steps shows advantageous compared to the previous step. Only mechanical ventilation combined with warm air heating shows slightly higher cost in comparison to the previous step. Further, in case of natural gas, costs subtly rose with addition of mechanical ventilation system even without warm air heating.

To reach net zero primary energy such power and areas of PV are needed:
(P19 is package with mechanical ventilation only; P20 assumes warm-air heating):

- District heating
  - Package P19: 81 kWp; fully covered roof and gable wall (i.e.180+180 m^2 on roof, 90 m^2 on gable wall) and 15+15 m^2 on façades
  - Package P20: did not reach net zero primary energy even with fully utilized available area for PV which means 180+180 m^2 on roof, 90 m^2 on south gable wall and 80+80 m^2 on west and east façades producing in total 103 kWp
- Heat pump (COP = 2.6 is considered)
  - Package P19: 42 kWp; 124+124 m^2 on roof
  - Package P20: 48 kWp; 143+143 m^2 on roof
- Natural gas
  - Package P19: 50 kWp; 148+148 m^2 on roof
  - Package P20: 58 kWp; 171+171 m^2 on roof
- Pellets
  - Package P19: 15 kWp; 44+44 m^2 on roof
  - Package P20: 17 kWp; 50+50 m^2 on roof

Since only the renovated and newly added components are included into the embodied quantity, it occupies minority of total environmental impact in the calculations. For the reader’s idea, the share for packages with mechanical ventilation (P11, P12) is as follows: in case of district heating the embodied parameters comprise about 5 % of the total, in case of heat pump it is about 9 %, for natural gas it is about 7 %, and the largest share is occupied by embodied part in case of wooden pellets (which, as an environmentally friendly heat source, have low primary energy conversion factor), where it comprises slightly above 20 % of the total. That is why the ZEB variants (P19 and P20) do not reach the zero environmental impact in the charts as the ZEB approach takes into account the operational impact only.

The analyses thus proved that complete renovation is reasonable under the condition assumed within the calculation: renovation investment costs, energy prices, embodied and operational environmental parameters. Favourableness of renewable energy sources (extent of PV installation area) is strongly dependent on actual situation of the building: possibility of smart grid connection, purchase electricity price and other factors.

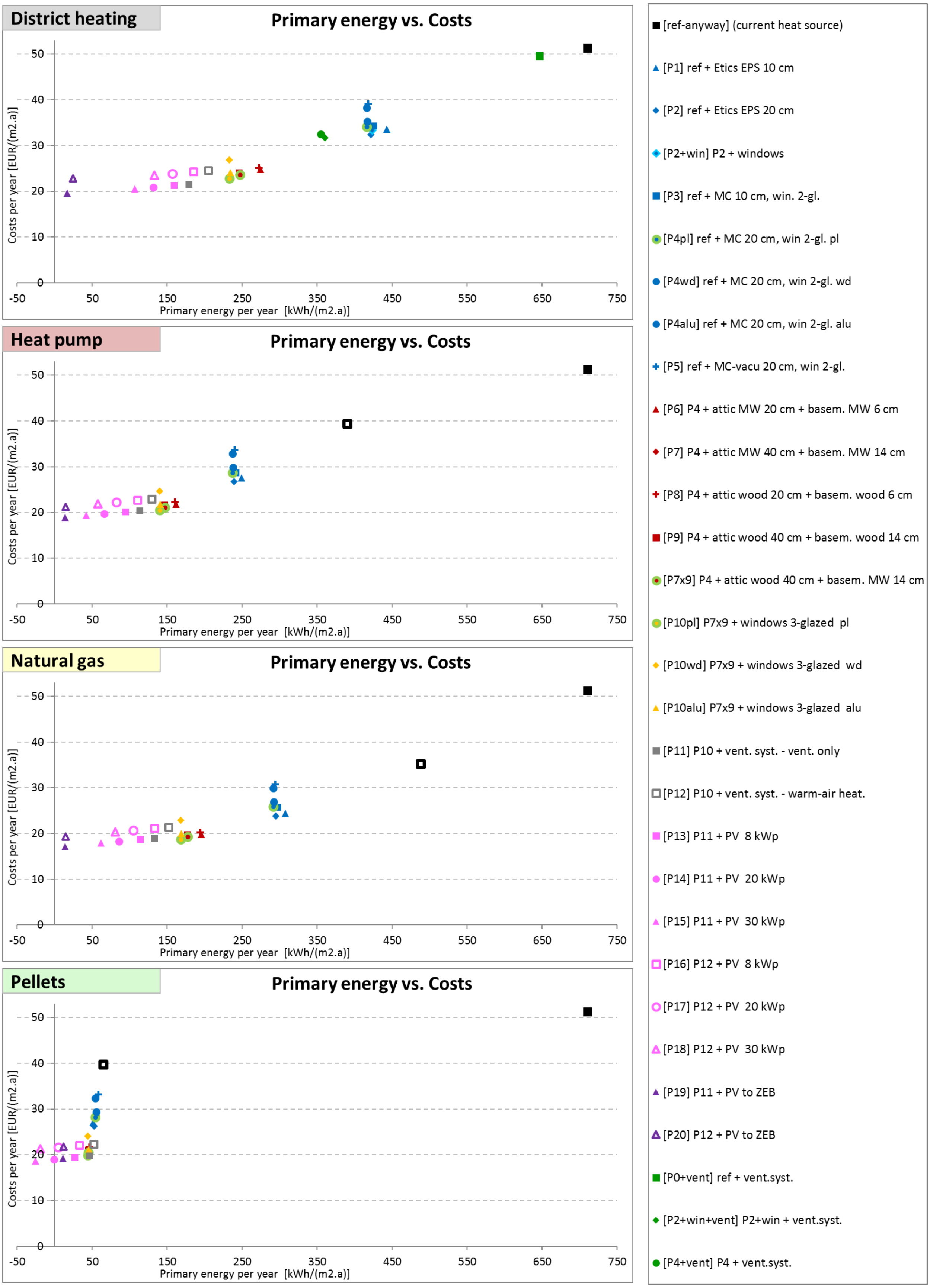

Fig. 8: Impacts on primary energy use and costs of various renovation packages for the MORE-CONNECT reference building in the Czech Republic, in combination with various types of heating systems

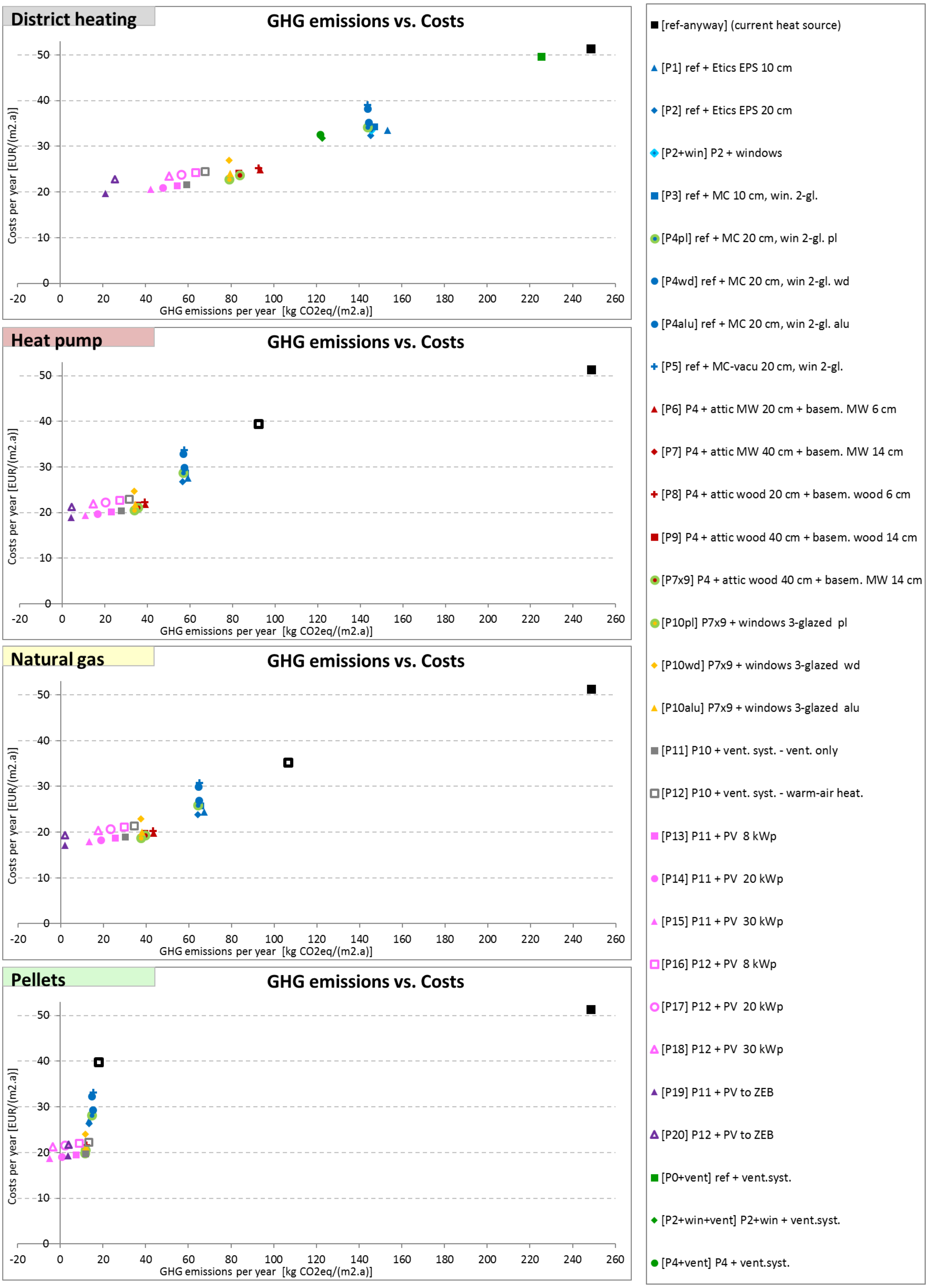

Fig. 9: Impacts on greenhouse gas emissions and costs of various renovation packages for the MORE-CONNECT reference building in Czechia, in combination with various types of heating systems

4.3.1 Sensitivity of the results on MORE-CONNECT solution investments costs changes

To estimate impact of higher mass production and technology automation of MORE-CONNECT solution, decrease of MORE-CONNECT production costs was considered. The decrease was considered in levels of 10 %, 20 %, and 30 %. The results can be seen in Fig. 10. If the production costs decreased by at least 20 %, renovation using the MORE-CONNECT solution (P4pl) reached the same total costs as with ETICS (P2+win) in case of 20 cm insulation and windows replacement. Costs connected with renovation using MORE-CONNECT solution with vacuum insulation layer (P5) are higher than those using ETICS even at 30% price decrease. In case of solutions using 10cm main insulation thickness, a decrease in production costs by approx. 25 % would be needed to get renovation using MORE-CONNECT (P3) to the same costs level as if using ETICS without windows replacement (P1). However, the differences in costs are generally relatively small, which led to the finding mentioned above according to which even in the absence of reductions in production costs, the MORE-CONNECT solution can be considered to be competitive with a renovation based on ETICS and new windows, if the building needs new windows anyway. It should also be kept in mind that the MORE-CONNECT solution can provide higher standard of living and internal air quality as thermal insulation layer is accompanied by other services in one solution, which is not quantitated in the results. It can therefore be concluded that even without further decreases in production costs, the MORE-CONNECT solution is nearly competitive with a renovation based on ETICS and new windows; the MORE-CONNECT solution becomes fully competitive when a decrease in production costs of 20% can be achieved, assuming a wall insulation with a thickness of 20 cm.

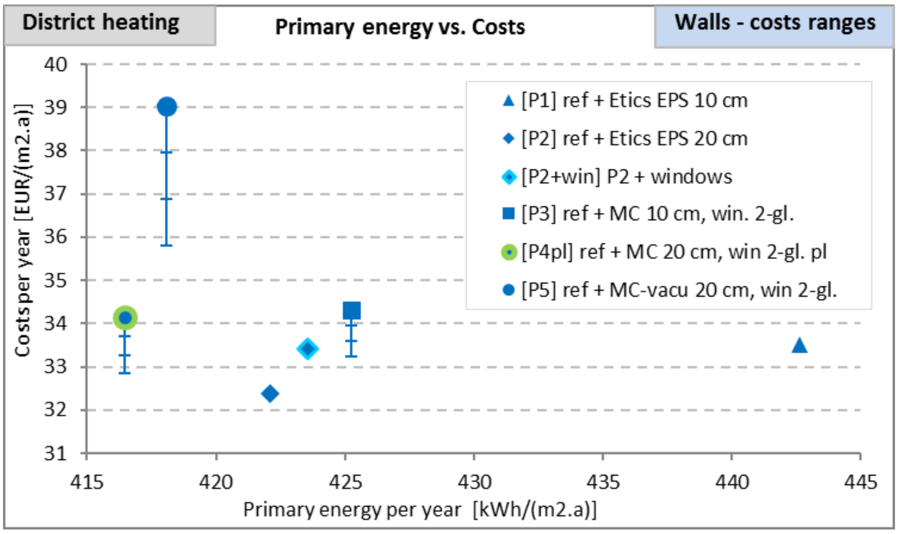

Fig. 10: Selection of favourable concept – step 1: walls insulation (district heating) – Sensitivity of the results on changes of the MORE-CONNECT solution investments costs

4.3.2 Sensitivity of the results on conversion and emission factors changes

Environmental assessment depends on conversion and emission factors setting. These factors usually reflect current energy mix and/or the political convention. In this task, conversion factors of non-renewable primary energy and greenhouse gas emission factors ($CO_{2,ekv.}$) related to operational energy consumption were taken from the Czech Gemis database (2009) [3], [4] since factors from this database are expected to represent better the energy mix in the Czech Republic than the official factors set for the purpose of declarative calculations. However, share of renewable energy rises. Therefore, the analysis was performed to verify sensitivity to changes in electricity conversion factors as this energycarrier is affected the most by increasing portion of renewable energy sources. The decrease of the factors was considered in levels of 10 %, 20 %, and 30 %. The results can be seen in Fig. 11.

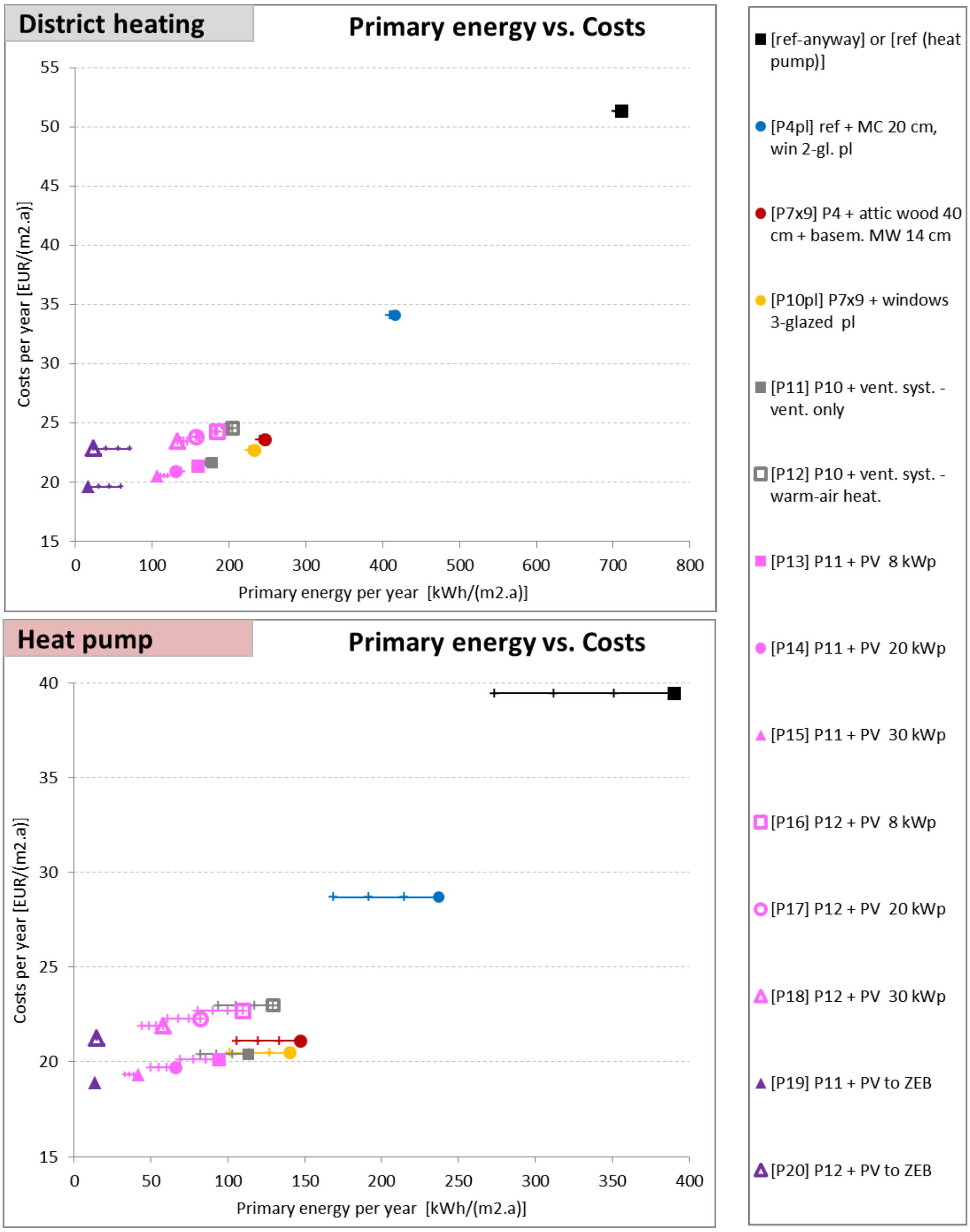

Fig. 11: Sensitivity of the results on changes of primary energy conversion factors for district heating (top) and heat pump (bottom)

In case the heat source is not electricity-based (district heating in Fig. 11, top), the impact of the conversion factor change is rather small as only the lighting and ventilation electricity consumption is taken into account (in the calculations according to Czech regulations). The impact ranges from 1 % to 5 % for 30% decrease of the conversion factor (the higher operational energy consumption, the lower impact). However, as soon as the PV is added, the reduced conversion factors cause that the PV becomes less advantageous as the subtracted primary energy produced by the PV is also reduced. The larger the PV installation, the less advantageous it is. Similar tendencies can be found also in case of natural gas and wooden pellets. This tendency thus make reaching of ZEB level from the primary energy consumption point of view more difficult.

In case of electricity-based heat source such as heat pump, for example, the impact of the conversion factor change is much more substantial and has the opposite tendency. The largest impact can be perceptible in packages with the greater energy consumption, without regard to existence of PV. With 30% decrease of the conversion factor, the impact ranges from 43 % in case of “ref” package (“anyway renovation” with the heat source change) to 26 % in case of P15 package (30kWp PV added to the mechanical ventilation package P11). With 10% decrease of the conversion factor, the impact ranges from 11 % to 7.5 % for the same packages.

Generally, reduction of conversion factors influences the favourableness of certain energy-saving measures if assessed from the point of view of primary energy consumption or GHG emission. Lower electricity conversion factors privileges electricity-based heat source, while in case of non-electricity based heat sources make PV installation less effective from the point of view of primary energy consumption.

4.4 Aspects related to reuse of materials, embodied energy and indoor environment

The embodied environmental parameters (the embodied primary energy and the embodied greenhouse gas emissions) were calculated and taken into account for all variants. The simplified life cycle analysis was performed using the Ecoinvent 3.3 database which can fit for the local Czech conditions. The more localized general data are not available for the Czech Republic. However, the environmental data carries unspecified uncertainties that relativize the overall results. The presented values should be only used to compare the variants in the set.

The possible reuse of the materials was not specifically assessed, but some relation can be found in both environmental parameters – embodied emissions and embodied energy. Lower values relate to the reusable, recycled or renewable materials used in the design. The recycled materials carry lower environmental burden thank to the life cycle system borders that cut off the burden from the material’s primary production.

The environmental assessment shows the ways which can be taken in the near future to move forward to the zero emission buildings and quantifies the cost of the measures needed to reach the environment saving targets.

4.5 Conclusions

The presented graphs showed numerous renovation packages, involving different building elements, different materials, and different energy efficiency levels, in combination with various heating systems. For each renovation package and for each combination with a heating system, the impacts on primary energy use, greenhouse gas emissions, and costs differ. In order to select a favourable concept, a choice has to be made taking into account these three dimensions.

The analysis proved that complex renovation does make sense. Each step grouping a set of renovation packages led to decrease in environmental impact compared to the previous step. The differences between environmental burden of the last step and of the reference case are significant. As far as costs are concerned, not all investigated packages brought costs reduction compared to the previous case, but a variant connected with lower costs was almost always available.

Comparison of the two corresponding solution from ETICS and MORE-CONNECT family (variants having the same thickness of main thermal insulation and both with renovated windows) brought findings that the

MORE-CONNECT solution should be competitive on the market. The differences in costs between ETICS and MORE-CONNECT solutions are generally relatively small, which led to the finding mentioned above according to which even in the absence of reductions in production costs, the MORE-CONNECT solution can be considered to be competitive with a renovation based on ETICS and new windows, if the building needs new windows anyway. The MORE-CONNECT solution becomes fully competitive when a decrease in production costs of 20% can be achieved, assuming a wall insulation with a thickness of 20 cm. It should also be kept in mind that the MORE-CONNECT solution can provide higher standard of living and internal air quality as thermal insulation layer is accompanied by other services in one solution, which is not quantitated in the results.

The analysis presented used the annuity method transforming investment costs into average annualized costs, yielding constant annual costs during the life span of the investment considered (50 years in case of this study). However, the initial (acquisition) cost may pose an obstacle for investors.

Based on the assessment carried out and the experience of the pilot project, the selected favourable concept is chosen as follows:

- Walls are provided with a MORE-CONNECT panel including 20 cm of mineral wool as a main insulation layer. Vacuum insulation is not used apart from local weakened details where there is no other way how to sufficiently insulate the structure. *U*-value of walls provided with the panel is 0.12 W/(m^{2}K).
- Attic floor is provided with 40 cm of blown wood fibre insulation, *U*-value is 0.11 W/(m^{2}K). There are used 14 cm of additional mineral wool insulation in the basement, *U*-value reaches 0.27 W/(m^{2}K).
- Windows are new, triple-glazed with plastic frames and *U*-value for the entire window of 0.7 W/(m^{2}K).
- If there is no need or interest to replace current heating system with the warm-air heating for some reason, mechanical ventilation only was found as favourable concept. However, decision whether to preserve original hot-water heating system or to replace it by warm-air heating system depends on factors beyond the scope covered by the performed optimization analysis.

Installation of PV panels led to a decrease in primary energy and in greenhouse gas emissions. Cost favourableness strongly depends on purchase electricity price. The final decision about suitable installed power lies beyond the scope of this study as it depends, besides purchase electricity price, on actual energy set-up, real electricity consumption profile, possibility to build a smart grid with some other buildings etc. Current legislation in the Czech Republic restricts installed power to maximum 30 kWp. If the goal was to reach a zero-energy building level (in annual balance) at current legislation limits, the goal is only achievable with the biomass as a heat source.

As far as heating system and heat source are concerned, the situation strongly depends on the local conditions. In case of the Czech reference building in Milevsko, district heating is the current source and the possibility of the heat source change is not expected (both the building and the district heating system is owned by the same owner – the municipality – which pushes rather on improvements in environmental parameters of district heating than disconnecting the consumers). In general case, conversion to natural gas can be expected as the most probable – when not giving a special consideration to the reduction of the environmental impact – due to accessibility of such source, low space demands, almost maintenance-free solution and low costs. Taking into account the environmental impact, wooden pellets appear as most favourable heat source while connected with reasonable costs. However, certain complication can be found regarding the need of pellets supply and storage. Heat pump solution has at the moment with the current electricity mix in the Czech republic similar advantages as natural gas, however, results in higher initial costs and, with respect to the socio-economic situation of inhabitants, it can therefore be seen as unfavourable under current framework conditions. However, it can be expected that heat pump solutions become more favourable for cost-effectively reducing non-renewable primary energy use and greenhouse gas emissions when the share of renewable energy sources in the electricity mix increases.

It should be kept in mind that the environmental assessment strongly depends on conversion and emission factors and also on the embodied environmental data available. The factors at the disposal reflect current energy mix in the Czech Republic and partially also the political convention. The embodied environmental data carries unspecified uncertainties. Both relativize the overall results. The presented results are therefore not generalizable; they are only valid for the Czech Republic and should only be used to compare the variants in the set.

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Appendix 1: Inputs used for cost and environmental impact calculation

Tab. 4: Inputs related to building envelope components

Building envelope	**Costs**	**Life-time**	**Embodied primary energy (non-renewable)**	**Embodied greenhouse gas emissions**	***U*-Value (incl. orig. struct.)**	**Maintenance costs**
	[EUR/m^2]	[years]	[MJ/m^2]	[kg CO_{2eq}/m^2]	[W/m^{2}K]	[EUR/m^2 /year]
Walls insulation						
ETICS – EPS 10 cm	40.15	30	373.4	15.9	0.26	
ETICS – EPS 20 cm	52.52	30	742.7	31.6	0.15	
MORE-CONNECT – mineral wool (10 cm + 4 cm)	72.01	30	686.0	57.7	0.16	
MORE-CONNECT – mineral wool (20 cm + 4 cm)	85.08	30	878.8	73.0	0.12	
MORE-CONNECT – mineral wool (20 cm + 4 cm) + vacuum insul. (2 cm)	216.23	30	1386.1	102.4	0.11	
Attic insulation						
mineral wool 20 cm	9.70	25	101.1	8.1	0.21	
mineral wool 40 cm	19.41	25	202.2	16.1	0.11	
wood blown insulation 20 cm	10.44	25	10.0	0.6	0.21	
wood blown insulation 40 cm	20.89	25	20.0	1.2	0.11	
Basement insulation						
mineral wool 6 cm	19.96	35	97.1	7.7	0.54	
mineral wool 14 cm	39.30	35	226.5	18.0	0.27	
wood fibres 6 cm	31.55	20	17.2	1.0	0.51	
wood fibres 14 cm	52.41	20	40.2	2.4	0.25	
Windows						
double-glazed window – Wood	203.70	30	743.42	58.73	1.2	34.07
double-glazed window – Aluminium	337.04	30	1764.33	163.81	1.2	5.93
double-glazed window – Plastic	159.26	30	1194.24	71.77	1.2	5.93
triple-glazed window – Wood	225.93	30	1011.34	80.19	0.7	34.07
triple-glazed window – Aluminium	385.19	30	2032.25	185.28	0.7	5.93
triple-glazed window – Plastic	177.78	30	1462.16	93.23	0.7	5.93

Tab. 5: Input related to heating system change

New heating system	**Costs**	**Lifetime**	**Embodied primary energy (non-renewable)**	**Embodied greenhouse gas emissions**
	[EUR/m^2]	[years]	[MJ/m^2]	[kg CO_{2eq}/m^2]
New natural gas heating system	5500	10	5400.37	464.03
New air/water heat pump	10000	10	22167.01	5291.7
New wood pellet heating system	6000	15	25200	2116

Tab. 6: Inputs related to PV installation and electricity production

On-site renewable electricity production		**Costs**	**Lifetime**	**Embodied primary energy (non-renewable)**	**Embodied greenhouse gas emissions**	**Installed power**	**Annual electricity production**	**Area of PV collectors**
		[EUR/full system]	[years]	[MJ/m^2]	[kg CO_{2eq}/m^2]	kWp	kWh/a	[m^2]
8 kWp		11 000	51	2749	203.7	8	6 200	48
20 kWp		26 000	51	2749	203.7	20	15 500	118
30 kWp		39 000	51	2749	203.7	30	23 250	178
District heating	pack 19	104 223	51	2749	203.7	81	62 775	480
	pack 20	132 381	51	2749	203.7	103	79 825	610
Heat pump	pack 19	54 307	51	2749	203.7	42	32 550	248
	pack 20	61 986	51	2749	203.7	48	37 200	286
Natural gas	pack 19	64 546	51	2749	203.7	50	38 750	296
	pack 20	74 785	51	2749	203.7	58	44 950	342
Pellets	pack 19	19 750	51	2749	203.7	15	11 625	88
	pack 20	22 310	51	2749	203.7	17	13 175	100