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Long-Term Economic-Ecological Assessment of Optimal Local Heat-Generating Technologies for the German Unrefurbished Residential Building Stock on the Quarter Level

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***Abstract*—**In order to reach the long-term national climate goals of the German government for the building sector, substantial energetic measures have to be executed. Historically, those measures were primarily energetic efficiency measures at the buildings' shells. Advanced technologies for the on-site generation of heat (or other types of energy) often are not feasible at this small spatial scale of a single building. Therefore, the present approach uses the spatially larger dimension of a quarter. The main focus of the present paper is the long-term economic-ecological assessment of available decentralized heat-generating (CHP power plants and electrical heat pumps) technologies at the quarter level for the German unrefurbished residential buildings. Three distinct terms have to be described methodologically: i) Quarter approach, ii) Economic assessment, iii) Ecological assessment. The quarter approach is used to enable synergies and scaling effects over a single-building. For the present study, generic quarters that are differentiated according to significant parameters concerning their heat demand are used. The core differentiation of those quarters is made by the construction time period of the buildings. The economic assessment as the second crucial parameter is executed with the following structure: Full costs are quantized for each technology combination and quarter. The investment costs are analyzed on an annual basis and are modeled with the acquisition of debt. Annuity loans are assumed. Consequently, for each generic quarter, an optimal technology combination for decentralized heat generation is provided in each year of the temporal boundaries (2016-2050). The ecological assessment elaborates for each technology combination and each quarter a Life Cycle assessment. The measured impact category hereby is GWP 100. The technology combinations for heat production can be therefore compared against each other concerning their long-term climatic impacts. Core results of the approach can be differentiated to an economic and ecological dimension. With an annual resolution, the investment and running costs of different energetic technology combinations are quantified. For each quarter an optimal technology combination for local heat supply and/or energetic refurbishment of the buildings within the quarter is provided. Coherently to the economic assessment, the climatic impacts of the technology combinations are quantized and compared against each other.

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***Keywords*—**Building sector, heat, LCA, quarter level, systemic approach.

I. Introduction

THE building sector shares a significant part of the whole energy demand particularly in developed countries. Germany is here no exception with roughly forty percent of its end energy demand consumed by buildings [1]. Primarily already existing and not refurbished buildings are responsible for this high energy demand. The most important energy form in the building sector is heat. To decrease the fossil energy carrier consumption, two principle pathways are thinkable: Firstly, the heating demand of the buildings themselves can be lowered by improving the energetic state of the envelope. Secondly the heating generation type can be altered.

Historically, the spatial dimension of a single building was the scope of measures. With the spatially larger area of a quarter different synergies and possible effects can be conducted in contrast to one single building. A quarter is not a completely defined term. Coherent buildings that are most commonly "socially constructed" are described as quarters. Furthermore, a quarter is substantially larger than one single building but smaller than a town district [2]–[7]. In conjunction with energetic technologies, a quarter can conduct several synergies and positive effects compared to single buildings: At first, technologies that are not economically feasible for one single building can be implemented much more easily on the quarter level (e.g. combined heat and power (CHP) power plants). In addition, the energetic refurbishment of a high number of individual buildings at the same time can both increase the total number of refurbishments as well as enabling business models for advanced energetic technologies on a spatially larger scale since the heating demand in a refurbished quarter is likely to stay stable in the time period after the refurbishment

Literature provides a large number of both scientific as municipal energetic concepts at the quarter level [8]-[10]. However, all of those studies work with a specific quarter and therefore unique setups. There is no systematic long-term assessment imaging the complete building stock and assessing the impacts of different energetic technology combinations on a comparative basis. The present paper seeks to provide both the methodology as well as the model for the case study of unrefurbished residential buildings in Germany. Subsequently the developed methodology is presented in full detail.

II. Methodology

Fig. 1 shows the working steps in the present paper. They can be subdivided generally into an input stage, an assessment stage and finally a result section.

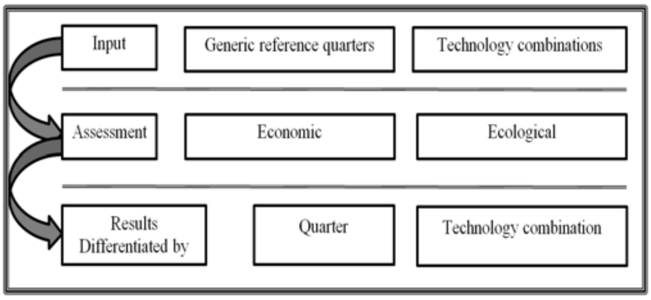

Fig. 1 Methodology schematic overview

A. Input Data

The first necessary input for the subsequent assessment are generic reference quarters that represent substantial parts of the German residential building stock. Their central differentiation is made by different construction time periods since this is a significant variable for the actual heating energy demand of the respective quarter. Since the development of those quarters is not the core aspect of the present paper only a short introduction is provided here: The quarters represent the German unrefurbished building stock at the quarter level. The following parameters are considered: Sizing of the quarters, ratio of cultivated area, distribution of buildings and orientation of buildings.

Existing generic reference buildings with the following building types are used: single family house, two-family house, small apartment building (6 residential units) and large apartment building (40 residential units) [11] [12]. In general about 400 buildings per quarter can be assumed.

For the available paper four generic quarters are used: Residential quarter (RQT) with buildings constructed before 1948 (RQT B48), between 1948 and 1978 (RQT B79), between 1979 and 1994 (RQT B95) and between 1995 and 2009 (RQT B10). The respective energetic standards concerning the buildings' envelope are estimated accordingly to [12]. Concluding the input data for the subsequent assessment are four generic quarters that represent different building ages and consequently different heating demands. Fig. 2 shows the end energy demand of the generic quarters for heating purposes in the unrefurbished state subsequently dissolved on a monthly basis.

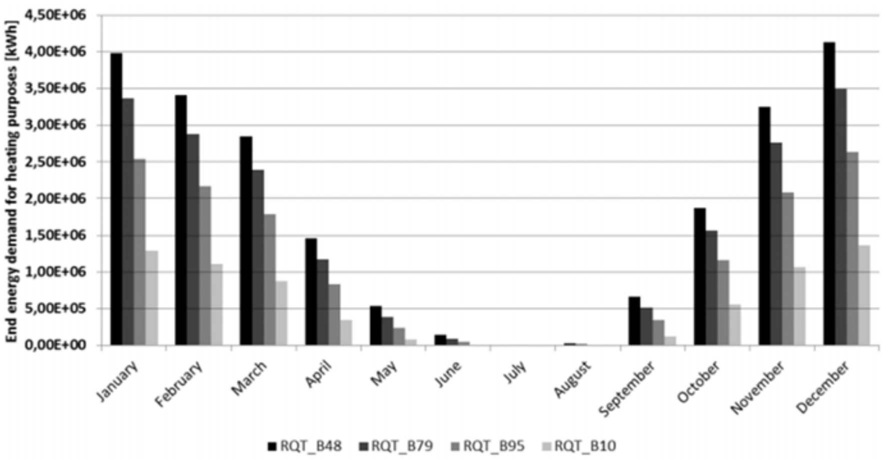

Fig. 2 End energy demand for heating purposes of the generic quarters

After the description of used generic quarters as the first input data, the investigated technology combinations at the quarter level are discussed. For the present paper the following technology combinations are elaborated:

Technology combination ***BAU| BAU*** investigates the impacts without any energetic measures at the buildings themselves or changes of the heat provision infrastructure of the quarters; hence retention of the current situation.

The technology combination ***A|CHP*** analyses the energetic refurbishment of the buildings according to [14] in combination with the installation of a central heat-operated CHP plant for the quarter.

Thirdly the technology combination **A| HP** investigates the economic-ecological impacts of an energetic refurbishment according to [14] of the buildings with individual electrical air-water heat pumps in the buildings of the quarter

Fourthly **BAU|CHP** investigates the impacts of unrefurbished buildings combined with a central CHP power plant.

The last technology combination **BAU|HP** analyses unrefurbished buildings with individual electrical air-water heat pumps. Table I shows the technology combinations.

TABLE I
TECHNOLOGY COMBINATIONS

Symbol	Description
BAU| BAU	No measures, comparing reference
A|CHP	Energetic refurbishment of the buildings according to EnEV 2016, installation of a heat-operated CHP plant, local heating network
A | HP	Energetic refurbishment of the buildings according to EnEV 2016, installation of air-water heat pumps
BAU | CHP	No energetic refurbishment of the buildings, installation of a heat-operated CHP plant, local heating network
BAU | HP	No energetic refurbishment of the buildings, installation of air-water heat pumps

B. Assessment

The described technology combinations are subsequently assessed both economically as well as ecologically. Formula (1) provides the basis economic calculation rule:

$$C_{TC_i} = \sum_{t=1}^{N} \left\{ \sum_{t=1}^{k_{ZRK,TE_j}} C_{ANN,TC_i} + C_{MAI,TC_i} + C_{FUE,TC_i}^{(t_j)} + C_{ELE,TC_i}^{(t_j)} \right\} [€] \quad (1)$$

The cumulated costs for each technology combination C_{TC_i} are quantified and dissolved on an annual basis. The cost components are: Repayment cost and interest rates for the necessary technologies (C_{ANN}). Annuity loans and debt capital are assumed therefore. C_{ANN} is restricted to the repayment period of the credit (assumption: 20 years). General time boundaries are set to 2016-2050. Furthermore, facultative maintenance costs are quantified within the model (C_{MAI,TC_j}). Concluding the costs for fuel and possibly necessary electricity for heating purposes are quantified with $C_{FUE,TC_j}^{(t_j)} and\ C_{ELE,TC_j}^{(t_j)}$.

In order to take into account the dynamic energy carrier prices a price prediction for future energy prices based on [16]-[20] is conducted. Fig. 3 shows the assumed energy carrier price development in the time boundaries of the present paper.

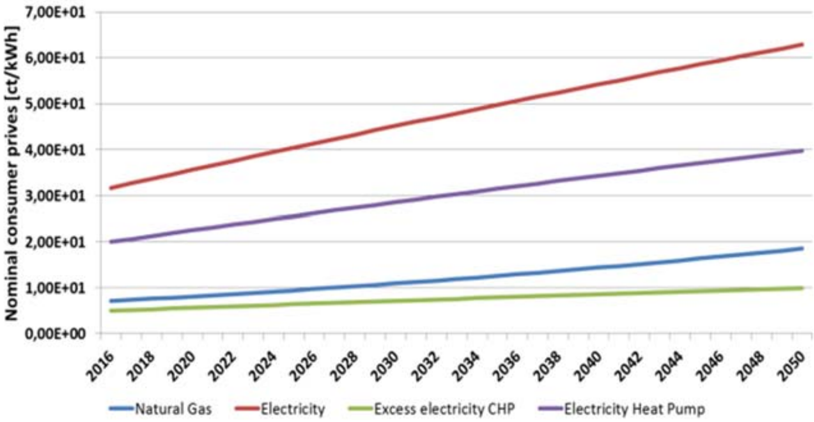

Fig. 3 Assumption for energy carrier price development within temporal boundaries of the study

In order to reflect the current situation in Germany, two "special prices" are introduced: Firstly, electricity that is used for electrical heat pumps is calculated with a reduced electricity price of currently 20 $\frac{ct}{kWh}$ [15]. Secondly, excess electricity of CHP power plants is assumed to be worth 5 $\frac{ct}{kWh}$ currently. The predicted future development of those prices is assumed to be proportional to the development of the electricity prices in general (compare Fig. 3).

Finalizing the economic assessment seeks to quantify full costs for different heat energy supplies for the described generic quarters and consecutively for different ages of residential quarters in Germany.

Besides the economic assessment, also the long-term climatic impacts are quantified within the present paper. Methodological framework is the Life Cycle Assessment (LCA) approach according to [21] and [22].

Coherently to the presented economic Assessment all technology combinations are assessed concerning their emissions dissolved on an annual basis.

Formula (2) provides the general calculation rule therefore:

$$E_{TC_i} = \sum_{t=1}^{N} \left\{ E_{T_i} + E_{FUE,TC_i} + E_{ELE,TC_i}^{(t_j)} \right\} [€] \quad (2)$$

The emissions for each technology combination E_{TC_i} in the considered time period (t =1-N) are composed of the emissions that are generated by the production, installation and running of the different technologies E_{T_i} (insulation, window replacement, CHP power plant, HP etc.) and the amount of fuel and electricity that is required for each technology combination and quarter in the time boundaries ($E_{FUE,TC_i} + E_{ELE,TC_i}^{(t_j)}$).

The specific emissions for electricity are subjected to dynamic changes since the electricity mix in Germany is likely to change in future. Therefore a prediction for the emissions for electricity in the time boundaries of the study (2016-2050) based on [19] is used to mirror the dynamic emissions for electricity:

$$E_{ELE}^{(t_j)} = \frac{-9{,}9589 * t_j + 20586}{1000} \qquad [\frac{kg\ CO_2-eq.}{kWh}] \quad (3)$$

A special case with potentially significantly impacts on the overall emissions for the quarters is the treatment of excess electricity in the technology combinations that include (heat-operated) CHP power plants. In the present paper, this electricity is credited ecologically with the emissions for the

German electricity mix valid for the respective year t_j. To quantify the potential impact on the results a sensitivity analysis without crediting is presented as well.

C. Results

The long-term economic and ecological impacts of each technology combination (compare Table I) and generic quarter (RQT B48, RQT B79, RQT B95, RQT B10) are quantified for the time boundaries 2016-2050. Cumulated cost and climatic impacts are presented to find the optimal refurbishment strategy in dependency of the quarter type.

III. Results

Results are differentiated to an economic and ecological result section. The following general boundary conditions are set:

- Point of time of energetic refurbishment: 2016
- Time boundaries: 2016-2050
- Annual inflation: 2.0% [23]
- Annual debt interest rate: 3.2% [24]
- Repayment period of loans: 20 years

The energetic refurbishment of the quarters in some of the described technology combinations (compare Table I) is conducted according to the legislative boundary conditions of [14]. The following heat transmission values are estimated after energetic refurbishment:

TABLE II
HEAT TRANSMISSION VALUES AFTER ENERGETIC REFURBISHMENT [13], [14]

Building component	Heat transmission value $[\frac{W}{m^2*K}]$
Roof	0.2
Outer Wall	0.24
Window	1.3
Ground against soil	0.24
Thermal bridges	+ 0.05

K: Kelvin (absolute Temperature) W: Watt

The economic Assessment for the generic quarters and different TC is executed subsequently.

A. Economic Assessment

Introducing the important parameters for the considered technologies are listed in Table III.

TABLE III
ECONOMIC PARAMETERS TECHNOLOGIES [25]-[38]

Component	Techno-logy	Lifetime [a]	Investment cost (C_{INV})	Annual maintenance cost
Insulation	Mineral wool (roof) Expanded Polystyrene (EPS) (Outer walls)	50	Outer wall: 2,431*d +87,35 $[\frac{€}{m^2}]$ Pitched Roof: 2,702*d + 172,82 $[\frac{€}{m^2}]$ Flat Roof: 0,638 *d +158,6 $[\frac{€}{m^2}]$ Cellar Ceiling: 1,0405*d +26,506 $[\frac{€}{m^2}]$	0
Window	Triple-glazed insulation glass	50	Single family house | two-family house: 389 $[\frac{€}{m^2}]$ Small/ large multi-family house: 334 $[\frac{€}{m^2}]$	0
Ventilation system	Multi-split exhaust fan	20	$356{,}9 * A^{-0{,}39}$	0
Radiator	Low-temperatur raditators	50	$325\ [\frac{€}{Piece}]$	0
Heat pump	Electrical air-water heat pumps	20	$1{,}243\ \frac{€}{kW_{thermal}}$	$0.002 * C_{INV}$
CHP	Heat-operated gasoline engine	20	100– 1,000 kW_{el}: = $4.907 * P_{CHP,EL}^{-0{,}352}$ > 1,000 kW_{el}: = $460.98 * P_{CHP,EL}^{-0015}$	100– 1,000 kW_{el}: = $6.2728 * P_{CHP,EL}^{-0{,}283}$ > 1,000 kW_{el}: = $8.6275 * P_{CHP,EL}^{-0{,}317}$
Peak load boiler	Gasoline fired boiler	20	$207.23 * P^{-0.1276}$	0
Local heating network	Radiation-net	50	House connection: 4,500 $\frac{€}{Piece}$ Pipe network:1.554*D +185,94 $\frac{€}{m}$	$0.005 * C_{INV}$

d: Thickness of insulation [cm] A: Living area [m²] kW: Kilowatt P: Power [kW] D: diameter [m]

All costs are full costs with labor cost and potential cost for secondary constructions (e.g. scaffoldings). Fig. 4 shows illustratively the annual nominal cost for the technology combination A|CHP and the quarter RQT B48.

As described in Section II, the repayment period for all technologies is set to 20 years. Energetic refurbishment measures have a lifetime greater than 20 years and therefore after 20 years the annual economic burden decreases. Note however that the financial burden for CHP power plants will not disappear since after 20 years a second CHP is necessary to replace the first one at the end of its lifetime.

For each generic quarter (RQT B48, RQT B79, RQT B95 and RQT B10) and each technology combination (BAU|BAU, A|CHP, A|HP, BAU|CHP, BAU|HP) the cumulated costs from 2016 until 2050 are provided. Fig. 5 shows the cumulated costs for RQT B48.

In contrast to the current energetic state (BAU|BAU) only the implementation of heat pumps without energetic refurbishment of the quarter (technology combination BAU|HP) generates more costs on the long-term. The lowest cumulated costs for old quarters that are constructed before 1948 (RQT B48) are generated with the combination of energetic refurbished buildings and an integrated CHP power plant as well as a local heating network. The cumulated costs of the second considered quarter RQT B79 are shown with Fig. 6.

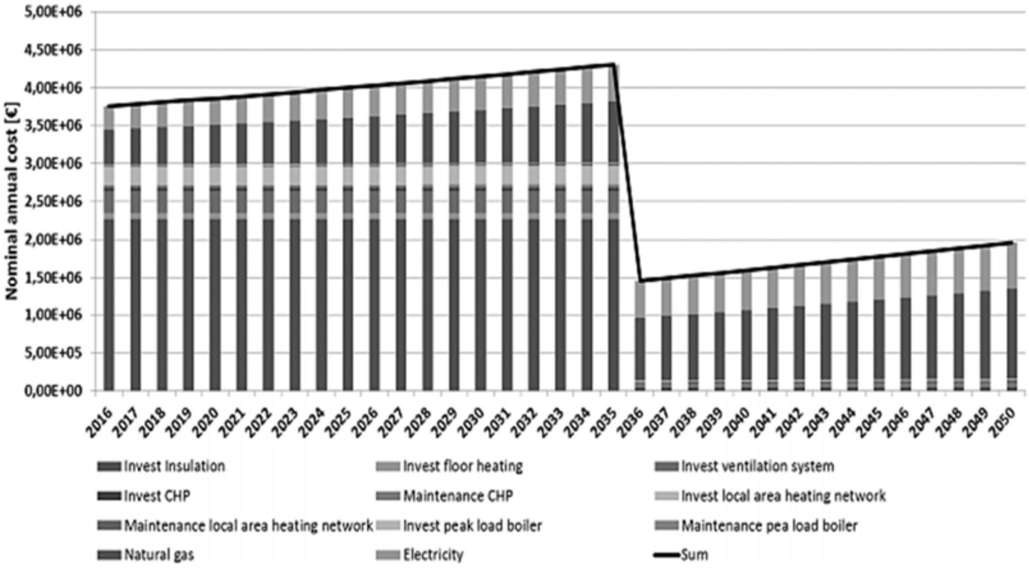

Fig. 4 Annual cost technology combination A| CHP RQT B48

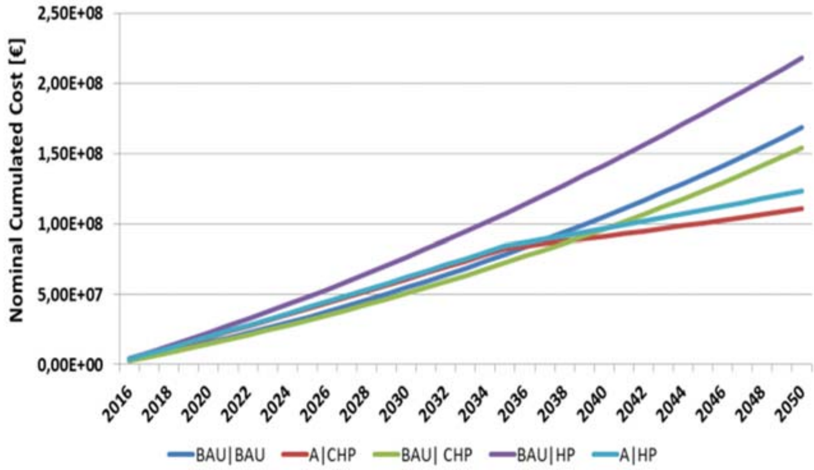

Fig. 5 Cumulated cost RQT B48

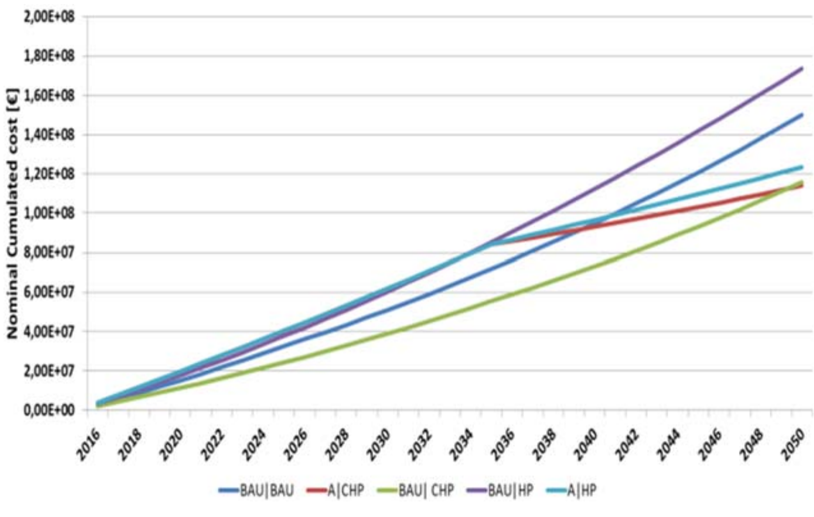

Fig. 6 Cumulated cost RQT B79

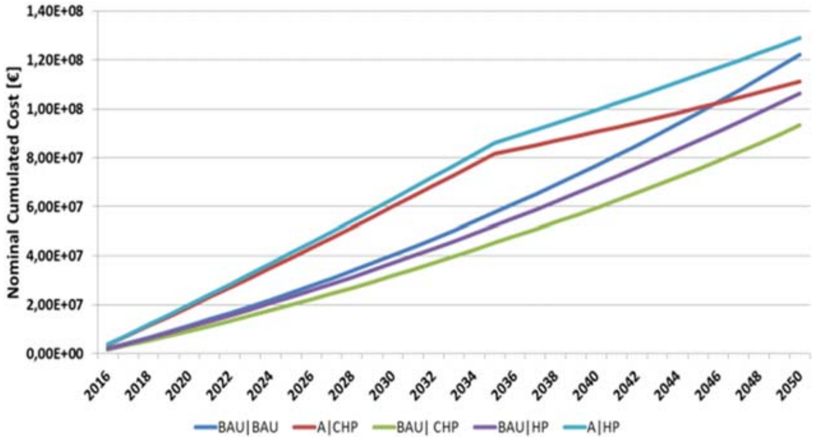

Fig. 7 Cumulated cost RQT B95

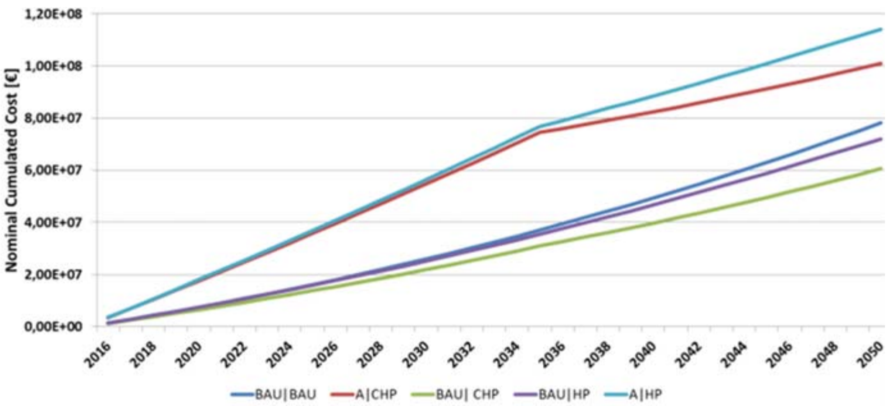

Fig. 8 Cumulated Cost RQT B10

Also here the technology combination BAU|HP generates the highest cumulated costs whereas in contrast to RQT B48 BAU|CHP generates the lowest cumulated costs in conjunction with A|CHP. With Fig. 7 the cumulated long-term cost for RQT B95 are visualized.

Interestingly, for the residential quarters that are constructed between 1979 and 1995 (RQT B95), the most expensive technology combination is A|HP respectively the energetic refurbishment of the buildings in the quarter in combination with the installation of air-water heat pumps. The integration of a CHP power plant (BAU|CHP) without energetic refurbishment is the least expensive technology combination – over the whole observed time period. Fig. 8 shows the cost for RQT B10.

For RQT B10, the technology combinations that contain an energetic refurbishment of the quarter (A|CHP and A/HP) result in the highest overall cost. Also here the technology combination BAU|CHP results in the lowest cost.

B. Ecological Assessment

Coherently to the economic Assessment the long-term climatic impacts of the described technology combinations and generic quarters are quantified. Initially the specific emissions of all investigated technologies are listed subsequently with Table IV.

The specific emissions of the insulation components are quantified including necessary secondary components like e.g. anchors and glue for mounting purposes. All technical components are identical to Table III.

TABLE IV
ECOLOGICAL PARAMETERS TECHNOLOGIES [25]-[40]

Component	GWP 100
Insulation	Mineral Wool147.46 $[\frac{kg}{m^3}]$
	EPS 157.81 $[\frac{kg}{m^3}]$
	Secondary components 1.4794 $[\frac{kg}{m^2}]$
Window	135.3 $[\frac{kg}{m^2}]$
Ventilation system	0.358 $[\frac{kg}{m^2 * a}]$
Radiator	129.56 $[\frac{kg}{Piece}]$
Heat pump	48.58 $[\frac{kg}{kW_{thermal}}]$
CHP	3177.2 * $P_{CHP,EL}^{0,661}$ $[\frac{kg}{kW_{elect.}}]$
Peak load boiler	49.564 $[\frac{kg}{kW}]$
Local heating network	1.0905*D² - 9.6715D +22.119

Secondary components: Composite fiberglass anchors | adhesive glue, D: Diameter pipes [m]

Following the long-term climatic impacts of all technology combinations and generic quarters are executed. Incipiently RQT is illuminated with Fig. 9.

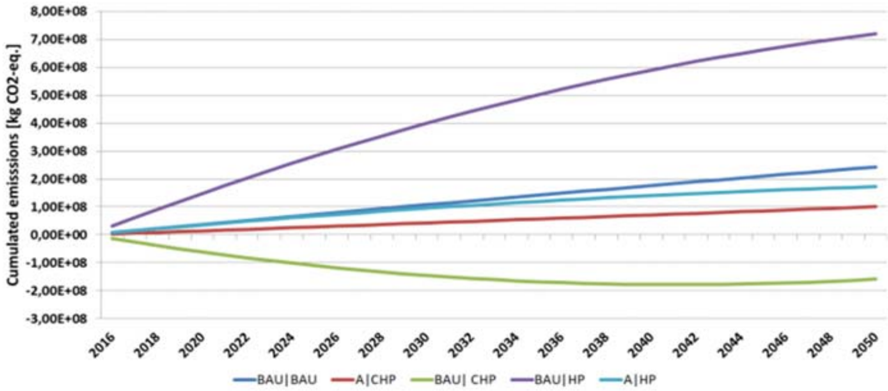

Fig. 9 Cumulated emissions RQT B48

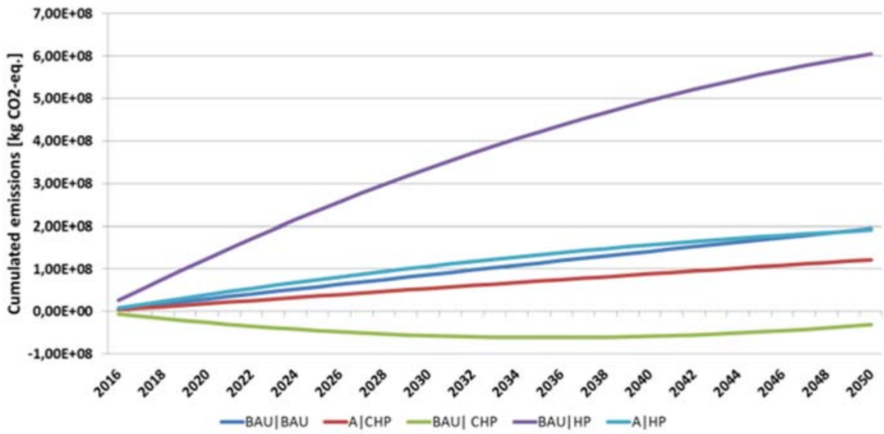

Fig. 10 Cumulated emissions RQT B79

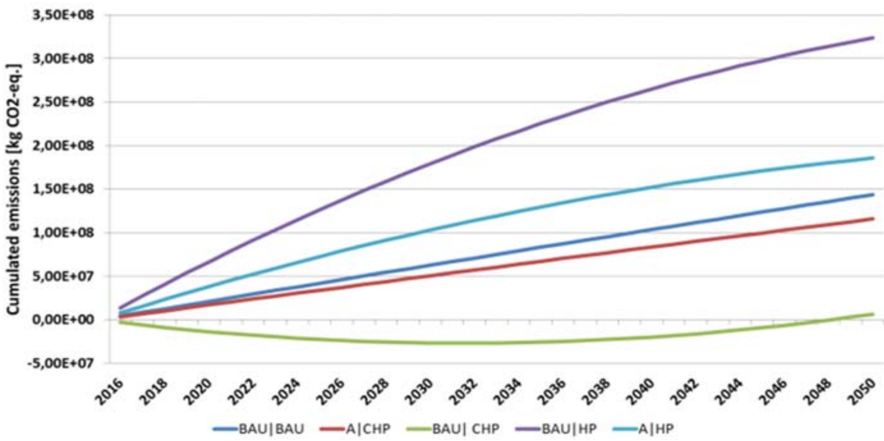

Fig. 11 Cumulated emissions RQT B95

By far the most emissions occur through the technology combination BAU|HP. In simple words, the heating of old unrefurbished quarters results in a very high electricity demand for the electrical heat pumps and due to the high specific emissions for electricity in high overall emissions.

A special case is BAU|CHP. Because of the ecologically credited export of excess electricity that is transferred outside the quarter's borders negative emissions occur in this case. Central reason for this is a very large CHP power plant in order to heat the energetically poor buildings in RQT B48 and therefore also high amounts of electricity as a by-product. Nevertheless it has to be taken into account that the energetic refurbishment of a quarter results in a significantly decreased heating demand and therefore in lower overall emissions. The impact of the emission credit for electricity exchange is examined in greater detail in the discussion part. Fig. 10 shows the climatic impacts for RQT B79.

Also, for quarters with the construction time period between 1948 and 1978 (B79), BAU|HP results by far in the most overall emissions. The described phenomena of calculative negative emissions for the technology combination BAU| CHP is also apparent in RQT B79, albeit in a weakened shaping. Interestingly A|CHP results in higher emissions compared to the current energetic state BAU|BAU. With Fig. 11, the climatic impacts valid for RQT B95 are presented. Again, BAU|HP shows by far the most emissions whereas the technology combinations that contain CHP power plants show the least emissions. A central cause for this is the already explained credit for electricity export out of the quarters themselves. In contrast to RQT B48, BAU| BAU generates fewer emissions compared to A|HP. The emissions for RQT B10 is provided with Fig. 12.

Most important due to a lowered heating energy demand and following lowered electricity production and ultimately lowered excess electricity, BAU|CHP generates positive emissions for RQT B10. Interestingly A|CHP accounts for higher emissions than BAU|BAU. The already low heating energy demand for the unrefurbished quarters in this construction time period is the central reason for this. For quarters with construction time periods after 1994 therefore no energetic refurbishments of the buildings themselves are advised from an ecological point of view.

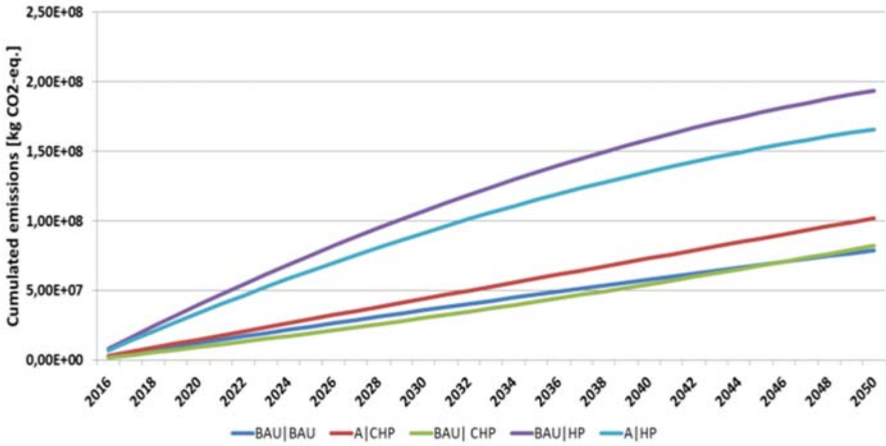

Fig. 12 Cumulated emissions RQT B10

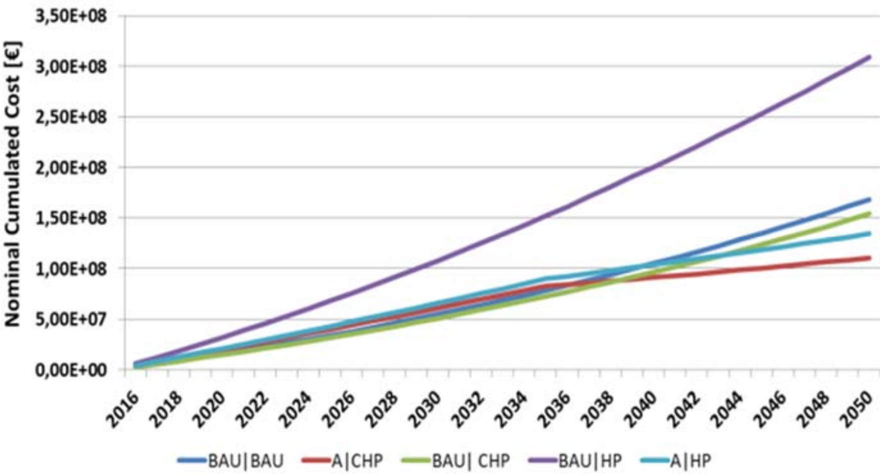

Fig. 13 Cumulated cost RQT B48 with full price accounting for HP electricity

IV. Discussion

Two core aspects are to be discussed: The sensitivity of the most important economic and ecological parameters:

- Economy: Full cost accounting of heat pump electricity (compare section II)
- Ecology: No positive ecological credit for excess electricity of CHP

A. Economic Sensitivity Analysis: Full Cost Accounting of Heat Pump Electricity

The discounted electricity cost accounting for heat pumps can be a crucial aspect in the overall economic assessment since especially in old unrefurbished quarters significant amounts of electricity can be consumed by the installation of heat pumps. Therefore subsequently the economic Assessment is executed once again with full cost accounting for heat pump electricity consumption this time. Fig. 13 shows the cumulated cost in the time boundaries for RQT B48.

Compared to the initial results (compare Fig. 5), the full cost for BAU|HP increase even further which makes the installation of heat pumps without energetic refurbishment of old quarters even less economically feasible. Fig. 14 demonstrates the economic Assessment with full HP cost accounting for RQT B10.

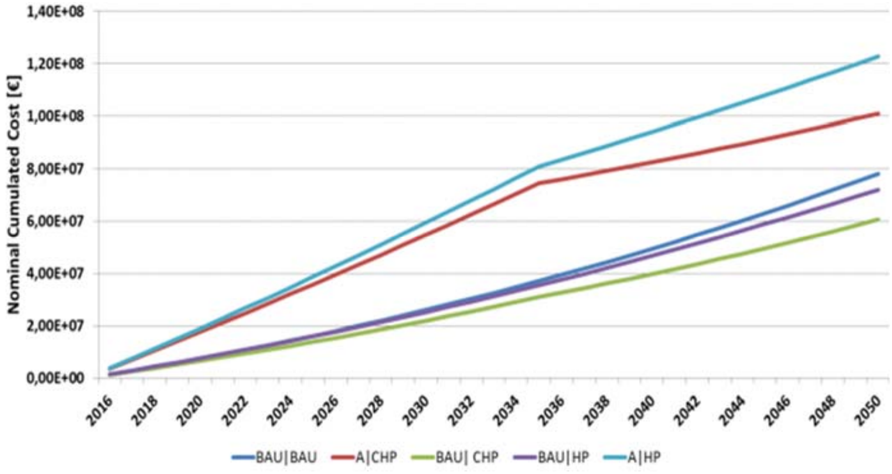

Fig. 14 Cumulated cost RQT B10 with full price accounting for HP electricity

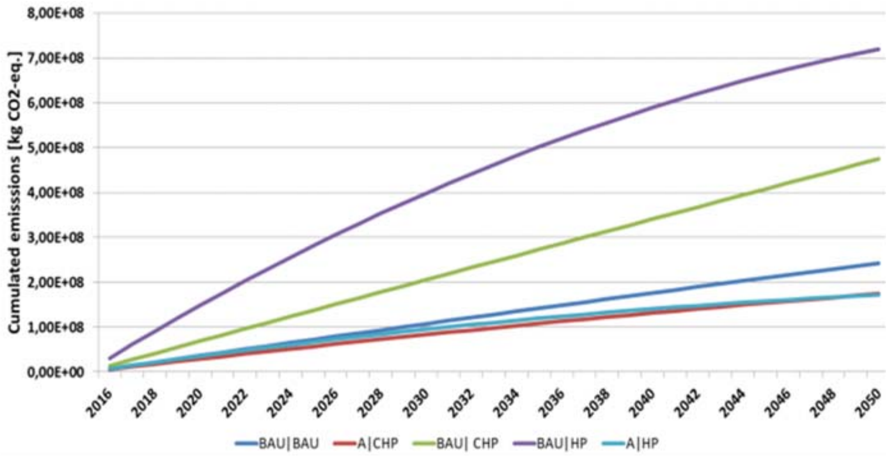

Fig. 15 Cumulated emissions RQT B48 without crediting excess electricity of CHP

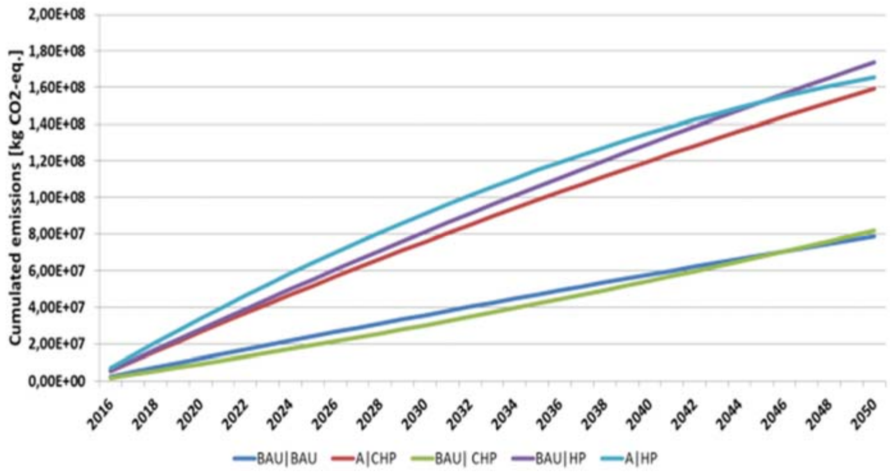

Fig. 16 Cumulated emissions RQT B10 without crediting excess electricity of CHP

Compared to the initial economic assessment with discounted price accounting for HP electricity in RQT B10, no systematic differences are apparent. Nevertheless the overall cumulated costs for A|HP for instance increase about 8.7% in the time boundaries from initially 1.15E+08 € to 1.25E+08 €. The ecological sensitivity analysis is conducted subsequently.

B. Sensitivity Analysis: Ecological Point of View

The positive ecological credit for excess electricity out of CHP power plants can have a significant impact on the overall climatic impacts of the different technology combinations, thus potentially resulting in overall negative emissions. Therefore the ecological Assessment is conducted once again for RQT B48 and RQT B10 without any credit to illustrate the significance of this parameter. With Fig. 15, the cumulated emissions for RQT B48 without crediting are visualized.

In contrast to the initial results a clear alteration of BAU|CHP is evident. The negative emissions (compare Fig. 9) alter and become positive. Therefore, the awareness of potential crediting and the possible impact out of this is of utmost importance for a correct ecological Assessment for buildings and quarters specifically and all energetic purposes in general. Fig. 16 visualizes the cumulated emissions for RQT B10.

Since the excess electricity of an unrefurbished quarter B10 is significantly less than for an older quarter B48, the alteration of emissions is also significantly lower. Nevertheless the emissions specifically for A|CHP increase compared to the initial calculation substantially.

V. CONCLUSION

Concluding for a holistic assessment of energetic refurbishment of quarters specific parameters can have a significant impact on the actual performance of the precise technology combination.

One central parameter is the construction time period of the buildings in the quarter. The present paper demonstrated the significance and differences in the economic and ecological performance on older and newer quarters. For example the installation of heat pumps without energetic refurbishment of the buildings' envelope can be an economically feasible option for a modern quarter (RQT B10) whereas the electricity costs in older quarters make the same technology combination very unattractive from an economic point of view. Also, the long-term emissions for the same technology combinations differ for different quarter ages. In modern quarters (B10) the current energetic state can be ecologically more beneficial than some technology combinations which increase the energy efficiency but not always the ecological performance. Furthermore, the long-term performances can differ significantly from the short-term performances.

Finalizing the boundary conditions and used methodology that do not necessarily have to have a physical reason can change the result drastically. Two examples (different energy prices and crediting for emissions) showed this in the present paper. The influence and interaction between the investigated system and its surrounding is therefore a crucial aspect that has to be considered for a holistic and sophisticated assessment.

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