Energy and cost optimization in the life cycle of nearly zero energy buildings using parametric calculations

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Abstract. Possible cost saving potentials in the planning and construction of future building standards are often not sufficiently assessed, as only a few possible variants are considered in the traditional planning process. Often planning and analysis are not carried out in parallel, and the various possibilities are discarded at an early stage. If, on the other hand, several variants are realistically compared in the planning phase, including life-cycle costs, a profound decision can be made. Therefore parameter studies were carried out as part of the national research project "KoPro LZK+" (cost and process optimization in the life cycle of nearly zero energy buildings) for seven buildings, five multi-family buildings, a school and an office building. For this purpose, a VBA macro was programmed in MS-Excel®, which automatically carries out energy demand calculations in the "Passive House Planning Package" (PHPP) and life-cycle cost calculations in the tool "econ calc". A total of more than 216,000 variants were investigated in this way, whereby on the one hand a variety of technologies, such as insulation of the building envelope, ventilation or electricity and heat supply, and on the other hand a variation of the boundary conditions (such as observation period, user behaviour, energy price increases or CO₂ costs) were carried out. The results were analysed energetically and economically over the life cycle (separately from each other and combined) with the objectives of identifying coherences, deriving trends and optimizations over the life cycle.

1. Methodology

In the traditional planning process client, architect and technical planners develop a building with the relevant technical equipment and building services. In many cases, everyone optimizes in "his/her" area, and thus the building project as a whole is being lost out of sight. Thus, it can happen that at the end a building is built and in operation, it turns out that, e.g. the running costs are extremely high. If, on the other hand, several variants are being compared in the planning phase, including life-cycle costs (LCC), a sound decision can be made already in advance. Research and demonstration projects show that it is already possible today to construct new or to renovate buildings to near zero and plus energy standards that achieve extremely low energy consumption and CO₂ emissions and can be operated economically. [1]

The term "parametric analysis" in this paper defines a method in which series of calculations are run by a computer program, systematically changing the value of parameters associated with one or more design variables. The key feature of this approach is that it allows evaluating the effect of individual design variables on energy, costs and environmental parameters in one step. This so-called multi-objective optimization analysis has become more popular in recent years. [2]
The multi-objective approach is based on the concept of Pareto frontier: a solution is optimal when no other feasible solution improves one of the objectives without affecting at least one of the other. In that case, the multi-objective algorithms generate a set of solutions, known as the Pareto front. If the problem includes only two objectives, the Pareto front is a two-dimensional curve. This concept can also be applied to three or more objectives, although the results are more difficult to analyse. This approach seeks to explore a set of optimal solutions rather than to find a single optimal solution. [3]

The difference between a conventional optimization method and the parametric optimization is clearly shown in following figure 1. With the conventional method, only selected technology combinations are checked and compared with each other. The optimization, therefore, takes place within this selection but does not include all possible combinations. This is the big difference between the conventional method and the parametric analysis and optimization. Here, all possible combinations are calculated, analyzed and the optimal variant is determined.

Figure 1. Comparison of conventional optimisation method vs. parametric optimisation [4]

The method of parametric analysis and energy-economic optimization in the research project “KoPro LZK+ - cost and process optimization in the life cycle of nearly zero energy buildings” (https://nachhaltigwirtschaften.at/en/sdz/projects/kopro-lzk-plus.php) follows the order below:

- Design
- Determination of target values and goals
- Determination of the parameters to be varied and their levels e.g. envelope quality, heating system, window size, window quality.
- Energy demand calculations with the “Passive House Planning Package (PHPP)”
- Calculation of the life cycle costs of each variant, taking into account operating costs, maintenance, replacement investments and residual values, using the LCC tool “econ calc”
- Evaluation and presentation of the results.

With this method, more than 216,000 different variants could be calculated in a manageable amount of time for seven prototypical case studies.

2. Investigated Case Studies
In the KoPro LZK+ project, seven buildings were investigated in detail. These case studies were selected so that they reflect a limited cross-section over different uses (multi-family residential, office and school) and include new as well as renovated buildings.

All buildings have already been completed and are in operation, except for one multi-family building, which was still in the construction phase at the beginning of 2019. The investigation of the buildings was therefore carried out after completion of the building. This procedure was chosen
because in the short time of the project duration it was not possible to find several real buildings, which were in the planning phase at this time and that can be managed within the research project. However, the examples can be used to show the potentials and commonalities of the projects and to identify the levers and influencing variables. In future construction projects, however, the method shown should be used in the planning process of the building.

To give a short overview of the investigated case studies, Table 1 summarizes some facts and figures of the buildings. Table 1 also gives some information about the investigated parameters.

### Table 1. Overview of the case studies and the investigated parameters.

| parameter                      | case study 1 | case study 2 | case study 3 | case study 4 | case study 5 | case study 6 | case study 7 |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| use                            | residential  | residential  | residential  | residential  | residential  | office       | school       |
| gross floor area [m²]          | 1,495        | 589          | 1,822        | 2,845        | 1,450        | 1,283        | 3,243        |
| treated floor area [m²]        | 1,212        | 432          | 1,421        | 2,091        | 1,025        | 822          | 2,580        |
| year of completion             | 2019         | 2013         | 2017         | 2014         | 2015         | 2012         | 2013         |
| utilisation units              | 15           | 6            | 19           | 32           | 16           | 28           | -            |
| investigated parameters in all case studies | | | | | | | |
| building envelope              | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| ventilation                    | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| heating system                 | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| solar thermal system           | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| PV                             | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| energy tariffs                 | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| observation period             | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            | ✓            |
| investigated parameters in selected case studies | | | | | | | |
| user behaviour                 | ✓            | ×            | ×            | ✓            | ✓            | ✓            | ✓            |
| heat distribution              | ✓            | ✓            | ✓            | ×            | ×            | ×            | ×            |
| heat emission                  | ×            | ×            | ✓            | ×            | ×            | ×            | ×            |
| construction                   | ×            | ×            | ✓            | ×            | ×            | ×            | ×            |
| household electricity          | ✓            | ×            | ×            | ×            | ×            | ×            | ×            |
| PV credit                      | ✓            | ✓            | ✓            | ×            | ×            | ✓            | ✓            |
| battery storage                | ×            | ✓            | ×            | ×            | ×            | ×            | ×            |
| electricity tariff model       | ×            | ✓            | ×            | ×            | ×            | ×            | ×            |
| funding model                  | ×            | ✓            | ×            | ×            | ×            | ×            | ×            |
| CO₂ follow-up costs            | ×            | ×            | ×            | ✓            | ×            | ×            | ×            |
| number of investigated variants| 53,000       | 49,000       | 75,000       | 7,300        | 5,800        | 23,000       | 3,500        |
The construction costs for the seven example buildings were provided by the project partners. The costs for the investigated technology options were provided directly by the property developers or building services planners or derived from other reference projects. The costs for the PV systems were derived exclusively from current market prices, as there has been a significant cost reduction in recent years. All costs are stated as net costs, excluding VAT. Furthermore, land costs were not taken into account in all projects, as they can strongly distort the life cycle cost analysis.

As the buildings were built between 2013 and 2017, the costs cannot be directly compared. To ensure some comparability, the costs for all case studies have been index-adjusted to the year 2017. Since the costs in the KoPro LZK+ project are viewed more from the buyer's or user's point of view, the construction price index was used. The indices are given with different reference years (2015, 2010, 2005, 2000, 1996...).

The interest rate for the bank rate has been set at 3.0% nominal for the 25 year credit period. The current rate for the 10-year fixed rate is around 1.8%. The inflation rate is set at 1.7%. The principal or discount rate is set at 3.0% nominal, similar to the bank rate.

3. Example multi-family building “+ERS” (case study 5)

3.1. Description of the case study. The project “Plus Energy Network Reininghaus Süd (+ERS)” is an integral part of the "Energy City Graz-Reininghaus (ECR)” project and follows the specifications of the overall urban planning framework. The project is divided into two sections: part 1 is an office and business complex with residential use on the upper floors, part 2 consists of 12 multi-family houses with 162 residential units in total. In the national research project KoPro LZK+, one of the 12 multi-family buildings was investigated in detail. All results in chapter 3.3. refer to this building, which is shown in figure 2.

![Figure 2: +ERS - Plus Energy Network Reininghaus Süd (source: Martin Grabner)](image)

3.2. Variants and sensitivity analysis. Table 2 shows an overview of the investigated technologies. For each technology, different parameters were varied, which can be classified into a maximum of three levels.
Table 2. Overview of the investigated technologies and parameters.

| Parameter                  | level 1                              | level 2                              | level 3                              |
|----------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| building envelope          | passive house standard               | national regulation                  | -                                    |
| ventilation                | mechanical ventilation with heat     | window ventilation                   | -                                    |
| heating system             | ground source heat pump + earth      | ground source heat pump + ground     | air source heat pump                 |
|                           | piles                                 | collector                             |                                       |
| photovoltaics (PV)         | no PV                                 | medium-sized PV                       | large-sized PV                       |
| solar thermal system       | no solar thermal system               | solar thermal system for DHW          | solar thermal for DHW + heating       |

In addition to the technologies also some boundary conditions were varied like user behaviour, the energy tariff, energy tariff increase, the calculation period and CO₂ follow-up costs. Table 2 shows, for example, the assumptions for the investigated user behaviour.

Table 3. Investigated user behaviour and assumptions.

| user behaviour | room temperature in winter | DHW demand (60°C) | additional shading in winter due to misuse of external blinds | additional window ventilation in winter due to misuse |
|----------------|----------------------------|-------------------|---------------------------------------------------------------|-----------------------------------------------------|
| ideal          | 21°C                       | 25 L/pers/d       | + 0%                                                          | +0,00 1/h                                           |
| standard       | 22°C                       | 30 L/pers/d       | +10%                                                         | +0,05 1/h                                           |
| inefficient    | 23°C                       | 35 L/pers/d       | +20%                                                         | +0,10 1/h                                           |

3.3. Results. This chapter contains some selected results of the many calculations available. All results with detailed descriptions can be found in the final report of the national research project under the link: [https://nachhaltigwirtschaften.at/en/sdz/projects/kopro-lzk-plus.php](https://nachhaltigwirtschaften.at/en/sdz/projects/kopro-lzk-plus.php) and on the website of AEE INTEC ([https://www.aee-intec.at/index.php?params=&lang=en](https://www.aee-intec.at/index.php?params=&lang=en)).

To analyse the energy performance in combination with cost efficiency scatter plots were used. Each technology was analysed separately and in combination with other technologies.

For every single technology, the net present value was compared to the balanced CO₂ emissions and the balanced primary energy demand. The results of this analysis are shown in following figure 3. “Balanced” in this case means that the self-consumption of the PV system was considered, transferred into CO₂ emissions (and in into primary energy) by the conversion factors for electricity and then subtracted from the calculated CO₂ emissions (respectively primary energy demand).

Written as a formula, the balanced CO₂ emissions were calculated as follows:

\[
CO_2_{balanced} = CO_2_{[\frac{kg}{m^2a}]} - PV \text{ self consumption} \times electricity \text{ conversion factor}_{[\frac{kg}{kWh}]} \times \frac{kWh}{m^2a}
\]
Figure 3. Analysis of the influence of the building envelope on the net present value, the balanced CO$_2$ emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO$_2$ and PE factors OIB RL-6 2015 / without consideration of subsidies / no CO$_2$ or PE credit for electricity fed into the grid).

Figure 3 shows the influence of the building envelope on the net present value, the balanced CO$_2$ emission and the balanced primary energy demand. The analysis shows that the improvement of the insulation from level 1 to level 2 leads to a reduction of the CO$_2$ emission and the primary energy demand, and also to a reduced net present value. Looking at the whole life cycle of the building it is, therefore, advisable to improve the quality of the building envelope, in this case to passive house standard.

In further consequence, the sensitivity of the individual technologies to the indicated performance indicators “balanced CO$_2$ emission”, “balanced primary energy demand”, “financing costs” and “net present value” was investigated. For this purpose boxplots were produced to show the sensitivity of all investigated technologies on the named indicators. These results indicate the sensitivity of the investigated performance indicators for the multi-objective building life-cycle cost and performance optimisation.

The analysis was done in two parts:
- Part 1: Technologies that could be counted as “energy efficiency measures” or “passive measures”, like insulation of the building envelope or mechanical ventilation.
- Part 2: Technologies counted as part of the “energy supply system” or “active measures”, like heating system, solar thermal installation and PV system.

When the difference in median value and the standard deviation is small, it is assumed that the indicator is not sensitive.

Figure 4 shows as an example the sensitivity of the energy supply measures on the defined indicators.
Figure 4. The sensitivity of the financing costs, the net present value, the balanced primary energy demand and the balanced CO₂ emissions to the energy supply measures (heating system, PV and solar thermal system)

All results from the project were integrated into an interactive web-based guideline for zero and plus energy buildings, which makes it possible to evaluate all variants individually. This means that estimations of cost and energy reduction potentials can be analysed at an early stage of the project using the example buildings (see https://www.aee-intec.at/kostenreduktion-plusenergiegebaeude-n-koprolzk-p218).

4. Lessons learned
Determining the best global solutions for nearly zero energy buildings design variables, in terms of energy, environmental and cost performance, is not an easy task, mainly because the variables affect each other through processes that are often not linear, and the optimisation goal of each variable can change significantly based on the optimisation goal and the importance of the key performance indicators (e.g. financing costs, net present value, primary energy demand, CO₂ emissions).

The assumption that the additional costs of energy efficiency measures are so low that energy efficient buildings have the lowest life-cycle costs can now be confirmed by the investigation of seven example buildings (with different use / new constructions and renovations). Energy efficiency measures have only a small percentage influence on construction costs but can save many times more CO₂ emissions. Regarded over the whole life cycle of the building, these efficiency measures are then usually cost-neutral or even economical.

In detail the results of the evaluations within the national research project KoPro LZK+ can be summarized as followed:

- The energy efficiency level has only a small influence on building and construction costs. Energy efficiency is therefore not a significant cost driver.
- For most technologies, the additional construction costs of energy-efficient variants are compensated over the life cycle of the building even without subsidies.
- Considering the life cycle costs, the primary energy demand and the CO₂ emissions the optimum is in the range of passive houses. Passive house envelopes and highly efficient
windows are in most cases economical even without subsidies. This is due to the long service life of these components in comparison to the building services.

- The optimum for life-cycle costs and CO₂ emissions are very flat. Low emissions and energy consumptions can, therefore, be achieved with different energy concepts as long as the building envelope is very efficient. This allows creative and conceptual freedom.

It is shown that energy efficiency and economic efficiency are not contradictory strategies, but can complement each other very well. The selection of variants according to life-cycle costs, therefore, makes sense and should be increasingly used as a decision criterion.

References

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