Controlling the power of the ground by integration

# D5.5

# Overall cost/benefit analysis for hybridGEOTABS buildings

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# Summary

We have performed a detailed cost/benefit analysis (CBA) for the four case study buildings of our project – Haus M, Líbeznice, Infrax/Fluvius and Ter Potterie. For the CBA, we followed the EC directive number 244/2012 (1), which brings templates and methods to calculate the global financial cost in the sense of the net present value. The CBAs have been calculated according to national price levels and specific parameters (such as discount rate or primary energy conversion ratio). For all the case study buildings, the hybridGEOTABS solution with MPC was recommended – with slightly higher global financial cost, this solution ensures much lower environmental impact than the baseline variants. In addition, a variant with added photovoltaic panels was also considered, and this brought additional decrease in both global financial value and environmental impact in terms of ETS.

In order to extend our CBA study on the EU level, we have used the models from D2.2 to calculate global financial costs and environmental impacts in a more general way. We have chosen a typical building, placed it into three climatic zones (represented by Madrid, Brussels and Warsaw) and modified the used technologies, which resulted in 36 variants in total. Based on the CBA of the case study buildings and the comparison study, we can conclude:

- The use of photovoltaics in hybridGEOTABS buildings decreases the global financial cost by 0.4–1.5 % (typical value 1 %) and decreases the $CO_2$ emissions by 20-50 % (typical value 30 %).
- The baseline variant is always cheaper than the hybridGEOTABS solution, but its environmental impact is higher. It is usually around 1-2 % cheaper than the hybridGEOTABS with photovoltaics but has 2–10 times higher environmental impact.
- Even for the worst-case scenarios, the hybridGEOTABS solution is only 3 % more expensive than the baseline, which makes the price difference negligible compared to the environmental impact.
- The more we invest into the building, the larger the environmental impact is. In terms of numbers, we have found in our study that for the increase in investments of about 7 %, we can decrease the $CO_2$ emissions from the operation of the building by more than 95 % (Warsaw scenario), 70 % (Brussels scenario) or 20 % (Madrid scenario).
- It appears from our study that hybridGEOTABS buildings have increased effect on the performance of buildings (in terms of the cost X environment dilemma) for harsher climates.

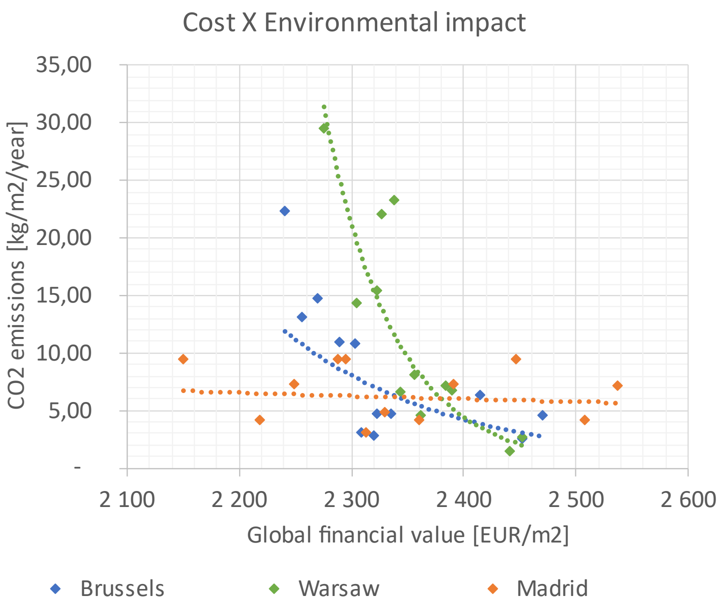


*Figure 1 – The effect of the global financial cost on the environmental impact of buildings.*

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# Nomenclature

## Acronyms

| | |
|---|---|
| *AB* | As-built |
| *AHU* | Ait Handling Unit |
| *ASHP* | Air Source Heat Pump |
| *BE* | Belgium |
| *CapEX* | Capital Expenditures |
| *CBA* | Cost Benefit Analysis |
| *CH* | Switzerland |
| *CHF* | Swiss Frank (currency) |
| *COP* | Coefficient of Performance |
| $CO_2$ | Carbon Dioxide |
| *CZ* | Czech Republic |
| *CZK* | Czech Crown (currency) |
| *DHW* | Domestic Hot Water |
| *EC* | European Commission |
| *EER* | Energy Efficiency Ratio |
| *ETS* | (European) Emission Trading System |
| *EU* | European Union |
| *EUR* | Euro (currency) |
| *FCU* | Fan Coil Unit |
| *FIAC* | International Federation of Construction Engineer (from French) |
| *GSHP* | Ground Source Heat Pump |
| *GSHX* | Ground Source Heat Exchanger |
| *HVAC* | Heating, Ventilation and Air Conditioning |
| *IEQ* | Indoor Environment Quality |
| *KPI* | Key Performance Indicator |
| *MPC* | Model Predictive Control |
| *NPV* | Net Present Value (value affected by discount rate) |
| *OpEX* | Operational Expenditures |
| *ppm* | Parts per million |
| *PV* | Photovoltaic (panel) |
| *RBC* | Rule-based Control |
| *ROI* | Return On Investments |
| *SCOP* | Seasonal Coefficient of Performance |
| *TABS* | Thermally Active Building System |
| *VAT* | Value Added Tax |

# 1. CBA Method

## 1.1. Methodology and assumptions

The calculation of the costs is primarily based on the EC Regulation No. 244/2012 (1). In order to provide consistent report for all the considered buildings, the templates and required data types were discussed among the partners that regularly work with cost estimates (Boydens, Lemon Consult and Energoklastr). First, a common data table was negotiated, and then it was checked against 244/2012 for compliance.

European Commission also issued a Guide to Cost Benefit Analysis of Investment Projects (2), which uses a general schematics for the CBA, and the EC Regulation No. 244/2012 can be used as one part of the wider CBA.

The directive requires the following cost categories to be evaluated:

- Initial investment costs;
- Running costs – these include costs for periodic replacement of building elements and might include, if appropriate, the earnings from energy produced;
- Energy costs – reflect overall energy cost including energy price, capacity tariffs and grid tariffs;
- Disposal costs if appropriate.
- Cost of greenhouse gas emissions. These reflect the quantified, monetised and discounted operational costs of $CO_2$ resulting from the greenhouse gas emissions in tonnes of $CO_2$ equivalent over the calculation period.

In practice, the initial investment costs are usually called CapEx, and the rest of the costs are called OpEx. In our analyses, we will follow this usual division into CapEx and OpEx, with a finer categorisation according to the Directive.

## 1.2. CBA outline

The grant agreement of the hybridGEOTABS project proposes the following KPIs of the CBA to be evaluated (C indicating Costs and B indicating Benefits):

i. Energy performance: overall energy use (C), primary energy savings (C), integration of renewables (or residuals) into the building's systems (B);
ii. IEQ: occupant comfort, health and productivity as a consequence of the thermal, acoustic, lighting and air quality conditions. (all B)
iii. Cost performance: engineering, investment, design, commissioning and operational costs, electricity sold to/bought from the grid; (all C)
iv. Environmental/resource intensity performance: GHG emissions and savings, resource use; (all B)
v. Other factors

To fulfill these requirements, we will organize the cost benefit analysis according to the structure proposed in the Guide to Cost Benefit Analysis of Investment Projects (2), and the methodology described by the EC Regulation (1) will be used for the cost performance.

The structure of the CBA described in (2) is illustrated by the following figure:

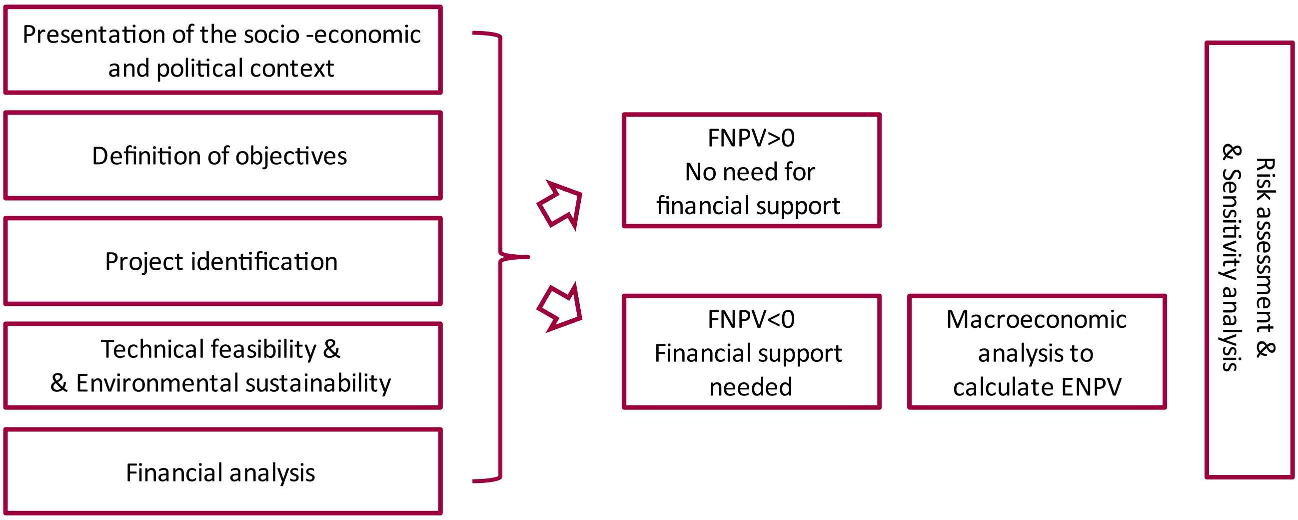



*Figure 2: Structure of the CBA according to Sartori et al.*

According to this figure, the structure of the CBA will be as follows:

1. Project identification
2. Presentation of the context – social, environmental, economic
3. Definition of objectives
4. Technical feasibility
5. Financial and environmental analysis
6. Financial net present value
7. Economic value
    a. Financial value
    b. Energies and Environmental impact
    c. Indoor environment quality
8. Sensitivity analysis and risk assessment
9. Conclusions

## 1.3. Scope

As already explained, the scenarios proposed in the project aim at comparison of various combinations of TABS, secondary system and MPC. As the other parts of the building (foundations, envelope, but also major part of the project and design) are common, they will not be evaluated. Only the differences between the scenarios will be evaluated.

## 1.4. Net Present Value concept

When determining the global cost of a variant for the financial calculation, the relevant prices are taken into account which are the prices paid by the customer including all applicable taxes including VAT and charges. No subsidies are included in the calculation.

Global costs for buildings and building elements are calculated by summing the different types of costs and applying to these the discount rate by means of a discount factor so as to express them in terms of value in the starting year, plus the discounted residual value as follows:

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i)\right) - V_{f,\tau}(j)\right]$$

where:

| | |
|---|---|
| $\tau$ | means the calculation period [years] |
| $C_g(\tau)$ | means global cost (referred to starting year $\tau_o$) over the calculation period [EUR, CHF or CZK] |
| $C_I$ | means initial investment costs for variant j [EUR, CHF or CZK] |
| $C_{a,I}$ (j) | means annual cost during year i for variant j [EUR, CHF or CZK] |
| $V_{f,\tau}$ (j) | means residual value of variant j at the end of the calculation period (discounted to the starting year $\tau_o$) [EUR, CHF or CZK] |
| $R_d$ (i) | means discount factor for year i [-] based on discount rate *r* to be calculated as: |

$$R_d(p) = \left(\frac{1}{1 + r/100}\right)^p$$

where p means the number of years from the starting period and r means the real discount rate.

## 1.5. Investment horizon

The directive (1) requires that the investment horizon is at least 20 years for administration buildings and 30 years for residential buildings. We will therefore consider the investment horizon of 30 years for all the case studies, in order to have consistent and comparable results.

Note that the investment horizon is not defined for schools (the case of Líbeznice), as there is no reason to calculate Return of Investment for state funded schools. The long-term cost indicators for the school building is thus academic and will be calculated for comparison purposes only.

## 1.6. Discount rates

The discount rates have to be defined for Belgium, Czech Republic, Switzerland and EU27. Due to the nature of long-term investments, average values for last couple of years cannot be used, as all considered markets have steadily falling discount rates (e.g., in Belgium, from more than 8 % in 1990s to virtual 0 % now). Following discount rates have been estimated for the 30 years investment horizon, based on indicative values suggested by the European Central Bank:

| Region | Discount Rate |
|---|---|
| Belgium | 1,5 % |
| Switzerland | 1,0 % |
| Czech Republic | 2,5 % |
| EU27 | 2,0 % |

## 1.7. Earning from produced energy

In our calculations, we will not consider the earnings from the energy produced within the buildings, as the MPC is tuned in such a way that all the energy produced by local sources is consumed within the building. The reason for this tuning is that we assume the market price for the energy supplied from the grid will always be higher than the buy-out energy price, thus consuming the energy inhouse is economically more viable.

## 1.8. Disposal costs

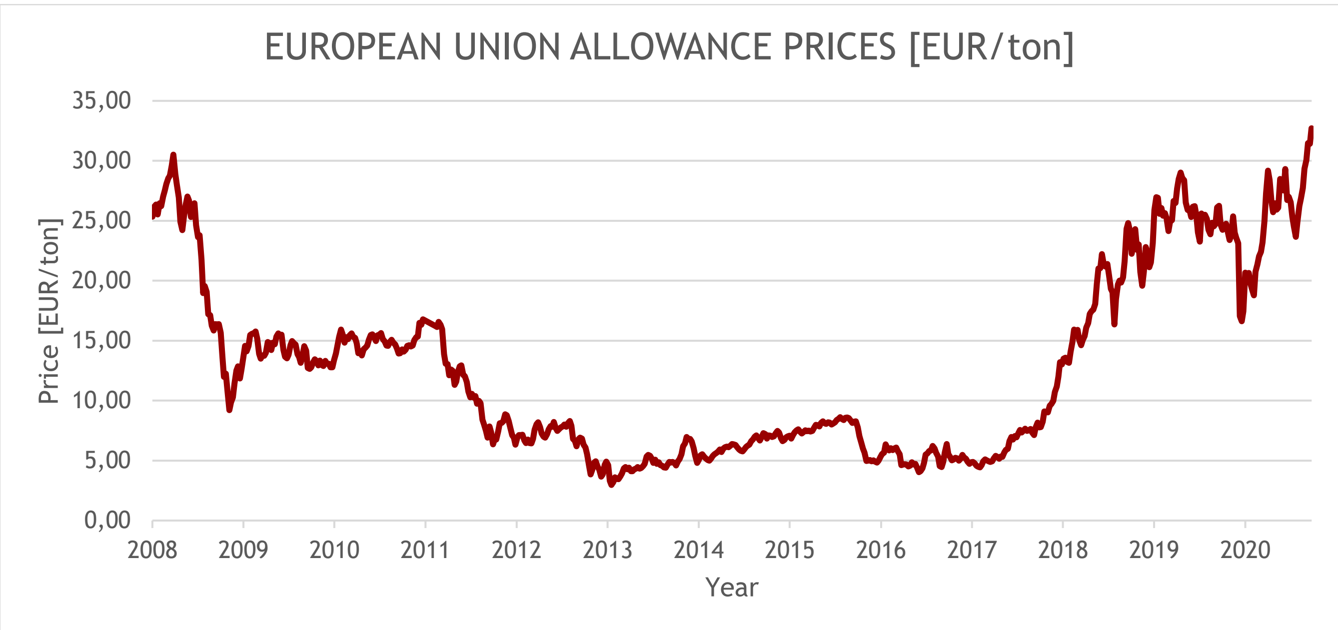
Furthermore, we will not consider the disposal costs, as they the differences between the considered scenarios (e.g. benchmark, TABS-RBC, TABS-MPC) will be insignificant. Most of the disposal costs apply to the disposal of structural elements (walls, windows, ...), which is the same for all the scenarios.

## 1.9. $CO_2$ emission costs

The $CO_2$ emission costs are calculated according to the EU Emission Trading System, which will enter into its Phase IV in 2021. The future prices of emissions are very difficult to estimate. The experience from the first three phases tells us that the market price for $CO_2$ emissions was much lower than expected, i.e. the costs for reducing the $CO_2$ emissions are in general lower than originally anticipated (which is of course a very good news).

The costs of $CO_2$ emissions plummeted in 2018, after the presentation of the "Winter package", from around 5 EUR/ton to the current 25 EUR/ton, as the market reflected the much more ambitious goals for the climate change mitigation. However, the publication of the European Green Deal in December 2019 seems to have little to none effect on the $CO_2$ emission prices. It may well be that the market is already on the level where the costs for the $CO_2$ reduction are settled.

From the above reasons, we will take the initial price of the CO2 emissions at 25 EUR/ton, and we will use the EU27 discount rate.




*CO2 emission prices (EUR/ton), 2010-2020.*

(Update February 2021) There was a significant increase in the $CO_2$ emission prices in late 2020, reaching estimated 50 EUR/ton in 2021[1]. Therefore, all the calculations were rerun with this price, as its impact on the final CBA was significant for some cases (see Sensitivity analysis for the case studies).

## 1.10. Investment costs

As already mentioned, only investments relevant for the comparison study will be considered. These include:

- Components of the primary production system
- Components of the secondary production system (if installed)
- Primary emission system
- Secondary emission system
- Control system
- Collaterals – devices not directly connected to above systems, but necessary for their function

Detailed list of components is provided for each of the case studies.

## 1.11. Running costs

We consider the life-span of all used structural components to be 30 years, i.e. no substantial component of the structure will need replacement. However, detailed maintenance costs has to be estimated, as maintenance is a significant part of total running costs. Some of the technologies will be replaced as follows:

- Batteries: after 10 and 20 years
- Heat pump, gas boiler or other secondary system, chillers, control system (including MPC): after 15 years
- Photovoltaics: no replacement within 30 years

Here the replacement rates are expert estimated based on the experience of consortium members and their business partners.

## 1.12. Energy costs

We will use the same structure of energy costs, as in Deliverable 4.9.

[1] https://ec.europa.eu/clima/sites/clima/files/docs/0094/thomson_reuters_point_carbon_en.pdf

## 1.13. Main parameters used in the CBA

For the CBA, we will use the following parameters, describing the environmental and financial impact of the building:

| **Name** | **Unit** | **Description** |
|---|---|---|
| Area | $m^2$ | Total floor area of the building |
| Nominal energy consumption | $kW/m^2/a$ | Simulated energy consumption (see Deliverable 4.9 for details) |
| Construction costs | EUR, CHF, CZK | Only elements not related to the variant are included in the construction cost, which includes walls, windows, roof, doors, water and electricity network, etc. |
| Control system cost | EUR, CHF, CZK | Costs for the automation and measurement, with or without MPC (based on the variant). |
| Borefield cost total | EUR, CHF, CZK | Total cost for the borefield and associated engineering (earth registers, pipes, valves, …) |
| Gas boiler cost | EUR, CHF, CZK | Total cost for the gas boiler and associated engineering (gas pipes, chimney, …) |
| Heat pump cost | EUR, CHF, CZK | Heat pump and associated engineering |
| End energy consumption | kWh | Total energy consumption (gas + electricity) |
| End energy price | EUR/kWh (CHF, CZK) | Average end energy price |
| PV cost | EUR, CHF, CZK | Cost for photovoltaic panels and associated engineering (wires, switchboard, inverter, …) |
| Installed kWp | kWp | Installed kWp of photovoltaic panels |
| Energy produced | kWh | Energy produced by photovoltaic panels |
| Energy in-house | kWh | Energy from photovoltaic panels used in-house |
| Energy sold | kWh | Energy sold to grid (assumed 0) |
| Energy income | EUR, CHF, CZK | Energy income (assumed 0) |
| $CO_2$ emissions nominal | $ton/m^2/a$ | $CO_2$ emissions, as calculated in Deliverable 4.9 |
| $CO_2$ emissions | ton/a | Total yearly emissions of the building |
| $CO_2$ price | EUR, CHF, CZK | Total price of $CO_2$ emissions according to the EU ETS |
| Technology extras | EUR, CHF, CZK | Extra technologies used for the specific variant (TABS, ventilation, chillers, secondary system, …) |
| Design fee | EUR, CHF, CZK | Design fee or the building variant |
| Maintenance | EUR, CHF, CZK | Yearly maintenance costs estimate |

## 1.14. Sensitivity analysis

The overall result of the cost performance is strongly dependent on various factors, mainly energy prices, discount rates, CO2 emission prices, etc. Sensitivity analysis enables the identification of the 'critical' variables of the project. Such variables are those whose variations, be they positive or negative, have the largest impact on the project's financial and/or economic performance. The analysis is carried out by varying one variable at a time and determining the effect of that change on the NPV (Net Present Value). As a guiding criterion suggested by (2), the general recommendation is to consider 'critical' those variables for which a variation of ±1 % of the value adopted in the base case gives rise to a variation of more than 1 % in the value of the NPV. The tested variables should be deterministically independent and as disaggregated as possible. Correlated variables would give rise to distortions in the results and double-counting.

| Variable | Variation of NPV due to a ± 1 % variation | Criticality judgement |
|---|---|---|
| **Energy tariff** | 2,6 % | Critical |
| **Total investment cost** | 7,0 % | Critical |
| **Yearly maintenance cost** | 0,3 % | Not critical |
| **Discount rate** | 1,8 % | Critical |

*Example of a sensitivity table*

## 1.15. Final cost performance overview

For the final cost performance overview, we will use the structure recommended by the Directive:

| Variant | Initial investment cost (referred to starting year) | Anuual running cost | | | Calculation period | Cost of greenhouse gas emissions | Residual value | Discount rate | Estimated economic lifetime | Disposal cost | Global cost calculated (NPV) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Annual maintenance cost | Operational cost | Energy cost by fuel with the medium energy price scenario | | | | | | | |
| [-] | EUR | EUR | EUR | EUR | years | EUR/ton | EUR | % | years | EUR | EUR |
| | | | | | | | | | | | |

# 2. Haus M

## 2.1. Project identification


*Figure 2: Haus M – Pictures (Photography courtesy of Johannes Marburg (left) and Ursula Meisser (right))*

| | |
|---|---|
| Number of spaces | 1 kindergarten (ground floor) & 29 apartments (1st-5th floor) |
| Number of occupants (design) | 97 (dwellings), 70 (kindergarten) |
| Gross floor area | 5,400 m² |
| Conditioned floor area (area that is heated) | 6350 m² (5,400 m² above ground, plus 950 m² basement) |
| Type of ground source | Ground source Heat pump (horizontal collectors) |
| Total annual thermal energy use | [40-60] kWh/(m²·annum) |
| Heating | Underfloor heating (Supply 30 °C / Return 24 °C) |
| Ventilation | Mechanical exhaust, heat recovery |
| Ventilation characteristics | Extraction fixed flow rate, decentral |
| Net volume | Total 13 800 m³ |
| Building envelope : floor area ratio | 0.86 (compact building) |

## 2.2. Presentation of the context – social, environmental, economic

The building is situated in Zürich, in an area with strong social and environmental culture. The Swiss regulations are very strict and require high energy standards for residential buildings. Haus M is a 5360 m² residential apartment building. It consists of 29 apartments over five floors centred around a large unconditioned atrium with staircase, a 950 m² day care centre (kindergarten) on the ground floor and a basement. The building is south-oriented and has shading systems that are manually controlled. It is a heavy-weight building and has a high insulation level with U-values lower than 0.15 W/m².a for the opaque elements and under 1.1 W/m².a for the glazing. The building is ventilated with natural supply (via openings above windows) and mechanical exhaust ventilation system. One heat pump recovers the heat from the extract air and uses it to deliver domestic hot water. Additionally, also the solar collectors do provide heat for domestic hot water. The other and bigger heat pump is connected to the GSHX (consisting of horizontal collectors) and delivers heating to the floor heating system (pipe depth 5 cm). The real building is not equipped with a cooling system.

## 2.3. Definition of objectives

The objective of the CBA is to compare for variants and present their financial value, with sensitivity analysis of important parameters. The IEQ will also be described.

## 2.4. Technical feasibility

For the analysis, we will compare four variants of the building:

| Variant | nonGEOTABS-RBC | hybridGEOTABS-RBC | hybridGEOTABS-MPC | hybridGEOTABS-MPC with PVs |
|---|---|---|---|---|
| **Weather** | Zurich | | | |
| **Ventilation** | Mechanical extraxion fixed flow rate + CO2 control | | | |
| **Primary heating** | FCU + Gas Boiler | Floor heating + GSHP | | |
| **Primary cooling** | FCU + Chiller | Floor cooling + GSHP | | |
| **Secondary cooling** | NO | FCU + Chiller | | |
| **Control** | RBC | | MPC | |
| **Renwables** | NO | GSHP | | GSHP + PV |

## 2.5. Financial and environmental analysis

For the four variants of the building, we will use the following numerical values of the parameters specified in part 1.13 Main parameters used in the CBA.

| Name | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV | Units |
|---|---|---|---|---|---|
| Area | 5 357 | 5 357 | 5 357 | 5 357 | m2 |
| Nominal energy consuption | 74,1 | 34,3 | 34,3 | 34,3 | kWh/m2/year |
| Construction costs | 16 071 000 | 16 071 000 | 16 071 000 | 16 071 000 | CHF |
| Control system cost | 101 783 | 101 783 | 132 318 | 132 318 | CHF |
| Borefield cost total | - | 246 286 | 246 286 | 246 286 | CHF |
| Gas boiler cost | 61 572 | - | - | - | CHF |
| Heat pump cost | - | 307 858 | 307 858 | 307 858 | CHF |
| End energy consumption | 396 954 | 183 745 | 146 996 | 104 996 | kWh/year |
| End energy price | 37 360 | 17 294 | 13 835 | 16 799 | CHF/year |
| PV cost | - | - | - | 48 000 | CHF |
| Installed kWp | - | - | - | 40 | kWp |
| Energy produced | - | - | - | 42 000 | kWh/year |
| Energy in-house | - | - | - | 42 000 | kWh/year |
| Energy sold | - | - | - | - | kWh/year |
| Energy income | - | - | - | - | CHF/year |
| CO2 emissions nominal | 12,48 | 1,15 | 1,15 | 0,82 | kg/m2/year |
| CO2 emissions | 66,86 | 6,16 | 6,16 | 4,40 | ton/year |
| CO2 price | 3 610 | 333 | 333 | 238 | CHF/year |
| Technology extras | 740 948 | 868 136 | 868 136 | 596 028 | CHF |
| Design fee | 112 353 | 170 674 | 170 674 | 170 674 | CHF |
| Maintenance | 12 000 | 16 000 | 16 000 | 16 000 | CHF |

The energy values are based on simulations performed on the virtual test bed, Deliverable 4.9. In the CBA, we will also assume the following constants and boundary conditions:

| Name | Basic value | Units |
|---|---|---|
| Consumption decrease for MPC | 0,80 | - |
| Electricity price per kWh | 0,16 | CHF/kWh |
| Gas price per kWh | 1,80 | CHF/kWh |
| Residual value | 0,25 | - |
| Calculation period | 30 | years |
| Discount rate | 1% | - |
| PV cost | 1 200 | CHF/kWp |
| Overall PV efficiency | 1 050 | kWh/kWp/year |
| In-house use ratio | 1,00 | - |
| CO2 price | 54 | CHF/year |

Local energy factors for Switzerland were used in the calculations, as described in Deliverable 4.9.

## 2.6. Financial net present value

When calculating the global net present value according to the above parameters, we get the results as shown in Figure 3 – Haus M, Global NPV. Only cumulative costs of the variant-specific technologies are shown.Figure 3. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

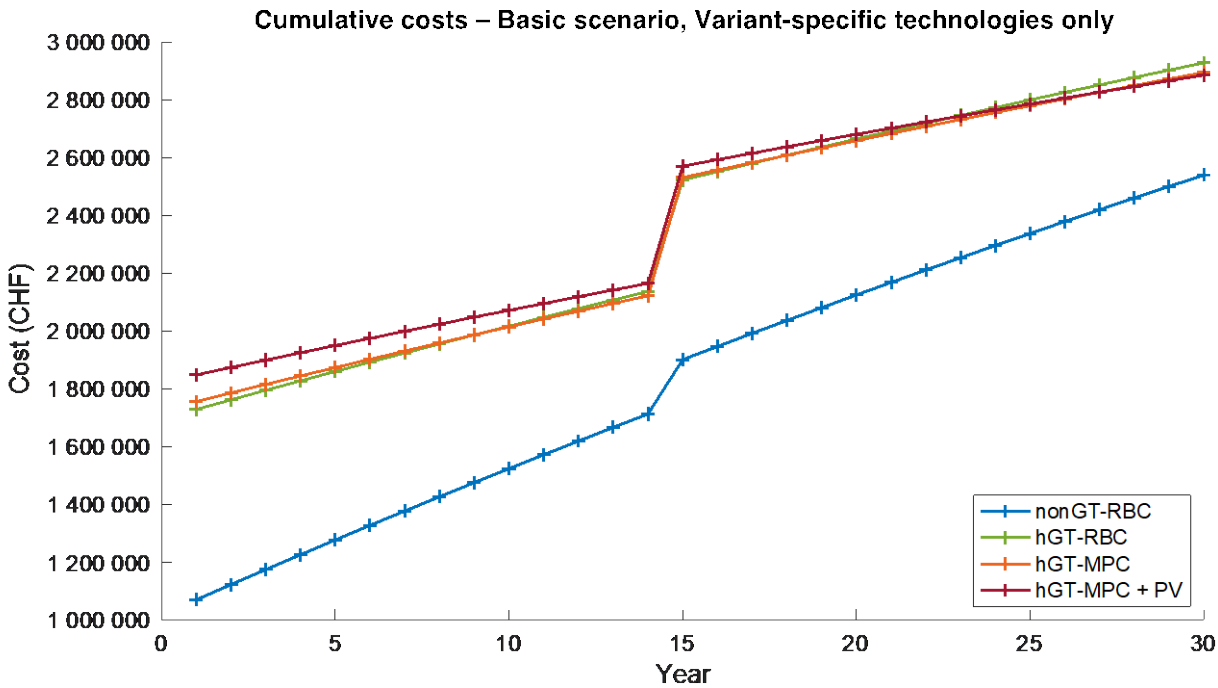



*Figure 3 – Haus M, Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

It is clear from the figure that the benchmark, i.e. non-GEOTABS, RBC version of the building is the most financially viable. However, this version is the least environmentally friendly and is not of our concern, we only use it as a benchmark. The step in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced. The final cost performance overview in the form required by the EC Regulation No. 244/2012 is shown in Table 1.

*Table 1 – Final cost performance overview of Haus M.*

| | | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV |
|---|---|---|---|---|---|
| | Variant | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV |
| | Initial investment cost | 16 924 301 CHF | 17 109 810 CHF | 17 109 810 CHF | 17 157 810 CHF |
| Annual running cost | Maintenance cost | 10 426 CHF | 13 902 CHF | 13 902 CHF | 13 902 CHF |
| | Operational cost (reinvestments) | 10 182 CHF | 33 743 CHF | 35 647 CHF | 37 247 CHF |
| | Energy cost by fuel with the medium energy price scenario | 32 461 CHF | 15 026 CHF | 12 021 CHF | 8 586 CHF |
| | Calculation period | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | 94 102 CHF | 8 671 CHF | 8 671 CHF | 6 194 CHF |
| | Residual value | 3 010 669 CHF | 3 010 669 CHF | 3 010 669 CHF | 3 010 669 CHF |
| | Discount rate | 1,00% | 1,00% | 1,00% | 1,00% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | 16 453 119 CHF | 17 026 747 CHF | 16 993 692 CHF | 17 032 178 CHF |

The baseline scenario has lowest global cost calculated, but it is out of our concern because of its high environmental impact. The other three variants are very similar, the results are within 0.5 % of the global cost and thus within an error of estimation.

*Table 2 – Minimum annual income from Haus M needed to achieve positive financial NPV.*

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV |
|---|---|---|---|---|
| Annual income needed to achieve positive financial NPV | 548 437 CHF | 567 558 CHF | 566 456 CHF | 567 739 CHF |

Table 2 shows the minimum income that the investor or owner needs to achieve from Haus M, should the building yield positive profit. Note that the residual value is not included in this calculation.

## 2.7. Economic value

### 2.7.1. Financial value

Comparing the four variants, the financial value (in the sense of net present value) is shown in Table 3. Without the benchmark variant (non GEOTABS, RBC), the financial value of the other three variants is very similar. The difference between the hybridGEOTABS, MPC and hybridGEOTABS, MPC + PV variant is less than 30 000 CHF, which is less than 0.3 % of the full price. It is therefore clear that other than financial considerations will play role in the decision process.

*Table 3 – Financial value of Haus M.*

| Variant | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV |
|---|---|---|---|---|
| Global cost (Net Present Value) | 16 453 119 CHF | 17 026 747 CHF | 16 993 692 CHF | 17 032 178 CHF |
| Difference between the variant and baseline (nonGT-RBC) | - CHF | 573 628 CHF | 540 573 CHF | 579 059 CHF |
| The varinat being more expensive than baseline in % | 0,00% | 3,37% | 3,18% | 3,40% |

### 2.7.2. Energies and Environmental impact

As already mentioned, the energy values are based Deliverable 4.9 – Concept and impact validation for the case-study buildings based on the virtual test bed. Here, in Table 4, we show the summary of the energies and environmental impact of Haus M.

*Table 4 – Haus M: Environmental impact and energy requirements.*

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC + PV | |
|---|---|---|---|---|---|
| **Nominal energy requirements** | 74,1 | 34,3 | 34,3 | 34,3 | kWh/m2/year |
| **End energy consumption** | 396 954 | 183 745 | 146 996 | 104 996 | kWh/year |
| **End energy price** | 37 360 | 17 294 | 13 835 | 9 882 | CHF/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 0 | 42 000 | kWh/year |
| **Total CO2 emissions** | 66,86 | 6,16 | 6,16 | 4,40 | ton/year |
| ***Nominal prices, not adjusted for inflation.*** | | | | | |

As the investor has the intention to build Haus M according to sustainability principles, the benchmark variant (nonGEOTABS, RBC) is not recommended because of significantly high $CO_2$ emissions. As can be seen, the carbon footprint of the other three variants is 10–15 times lower. The best environmental performance is for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 2.7.3. Indoor environment quality

The TABS system provides in general a very good comfort associated with radiant heating and cooling. The advantage of the radiant heating and cooling is the better human temperature sensing, and the inhabitants of the building with TABS system may feel comfortable with ambient temperature lower by ca. 1 °C compared to traditional heating and cooling systems, such as radiators or FCUs. This can result of additional energy savings of 5–10 %. In addition, MPC control can slightly improve the indoor environment quality by better maintaining the desired indoor temperatures.

The mechanical ventilation system is controlled by CO2 levels measured in the households, which provides excellent air quality and is in line with EU and Swiss standards.

In general, the advantages and disadvantages of the TABS system concerning the indoor environment quality are as follows:

- Advantages
  - Better space utilization – minimum of heating, cooling or ventilation equipment is present or visible inside the building occupation spaces, which allows the inhabitants to use the space more freely
  - Radiant heating and cooling – better perceived by some people
  - Lower ventilation rates in comparison with air-conditioned buildings, which results in less draught and infection spreading
  - High stability – indoor air quality is quickly restored e.g. after a window is opened and closed
- Disadvantages
  - Sensitivity to additional installations – one has to be careful to not pierce through the pipes
  - Worse acoustics
  - High thermal inertia, inability to change temperature quickly – this is partially compensated by the secondary system

## 2.8. Sensitivity analysis and risk assessment

The sensitivity analysis shows the variation of the global financial value in the sense of NPV due to ± 1 % variation of the analysed variable and a criticality judgement – if the change of global financial value is more than 1 %, the variable is considered critical.

| | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC+PV | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Variation** | **Criticality** | **Variation** | **Criticality** | **Variation** | **Criticality** | **Variation** | **Criticality** |
| **Discount rate** | 0.013 % | No | 0.01 % | No | 0.01 % | No | 0.01 % | No |
| **Energy tariff** | 0.06 % | No | 0.03 % | No | 0.02 % | No | 0.02 % | No |
| **$CO_2$ price** | 0.006 % | No | 0.0005 % | No | 0.0005 % | No | 0.0004 % | No |
| **PV price** | - | - | - | - | - | - | 0.003 % | No |
| **Heat pump price** | - | - | 0.03 % | No | 0.03 % | No | 0.03 % | No |
| **Borefield price** | - | - | 0.01 % | No | 0.01 % | No | 0.01 % | No |
| **MPC savings** | - | - | - | - | 0.5 % | No | 0.5 % | No |

We can see that there is no critical variable for Haus M. However, given very small differences in global financial values for the variants, energy tariff and MPC savings ratio can be considered as important parameters. We will also have a more detailed look on the variations of the discount rate. Let us have a look on discount rate first.

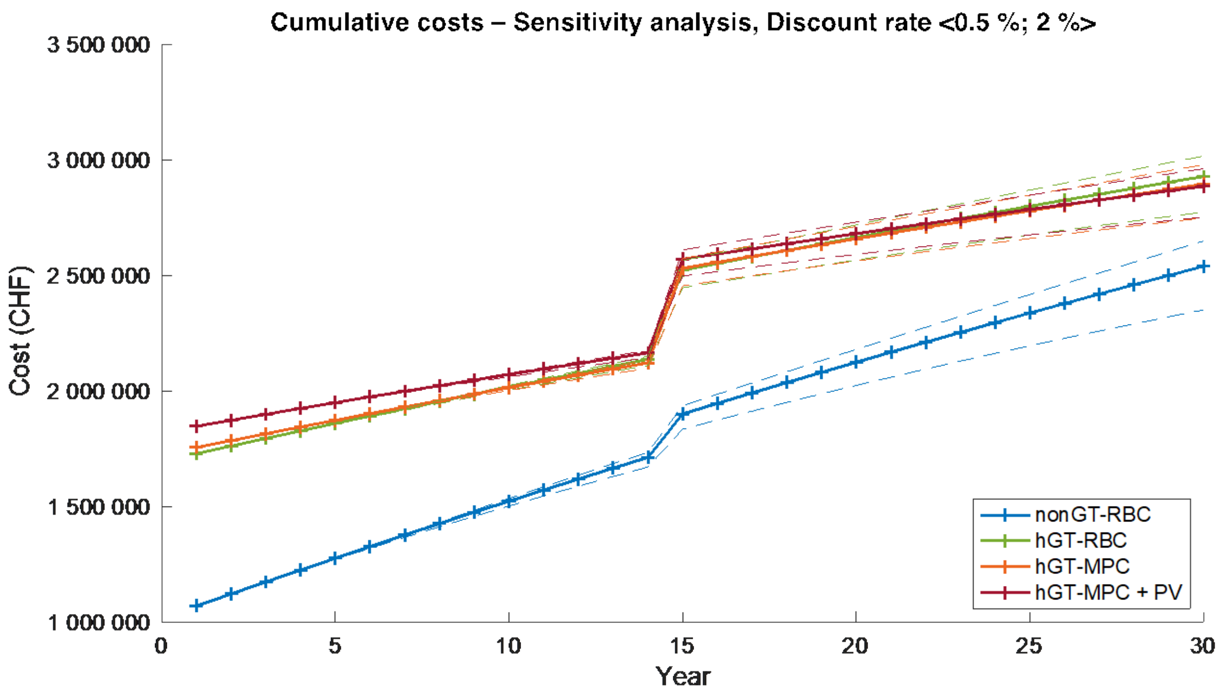



*Figure 4 – Haus M: Sensitivity analysis, discount rate.*

The global financial value is not very sensitive to variations of the discount rate for Haus M. The nominal value for discount rate is 1 %, we have performed the sensitivity analysis for half and double the value, i.e. for 0.5 % and 2 %. The three hybridGEOTABS solutions are still well separated from the benchmark case and are similarly influenced by the change in the discount rate.

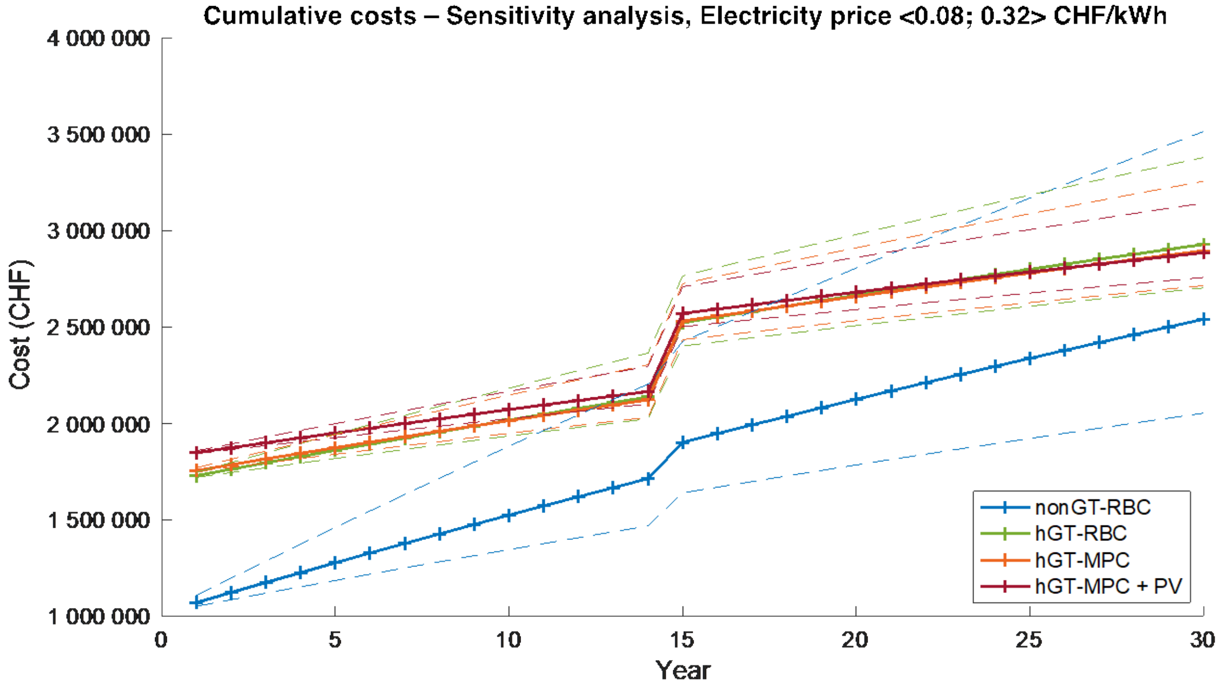



*Figure 5 – Haus M: Sensitivity analysis, electricity price.*

The electricity price has a more significant effect. Again, we took the half and the double of the nominal value. It can be seen that the benchmark case (nonTABS, RBC) is very sensitive to energy prices and can actually become more expensive than the hybridGEOTABS variants if electricity price increases by the factor of ca. 1.8 and more. The least sensitive variant is the hybridGEOTABS with MPC and photovoltaics.

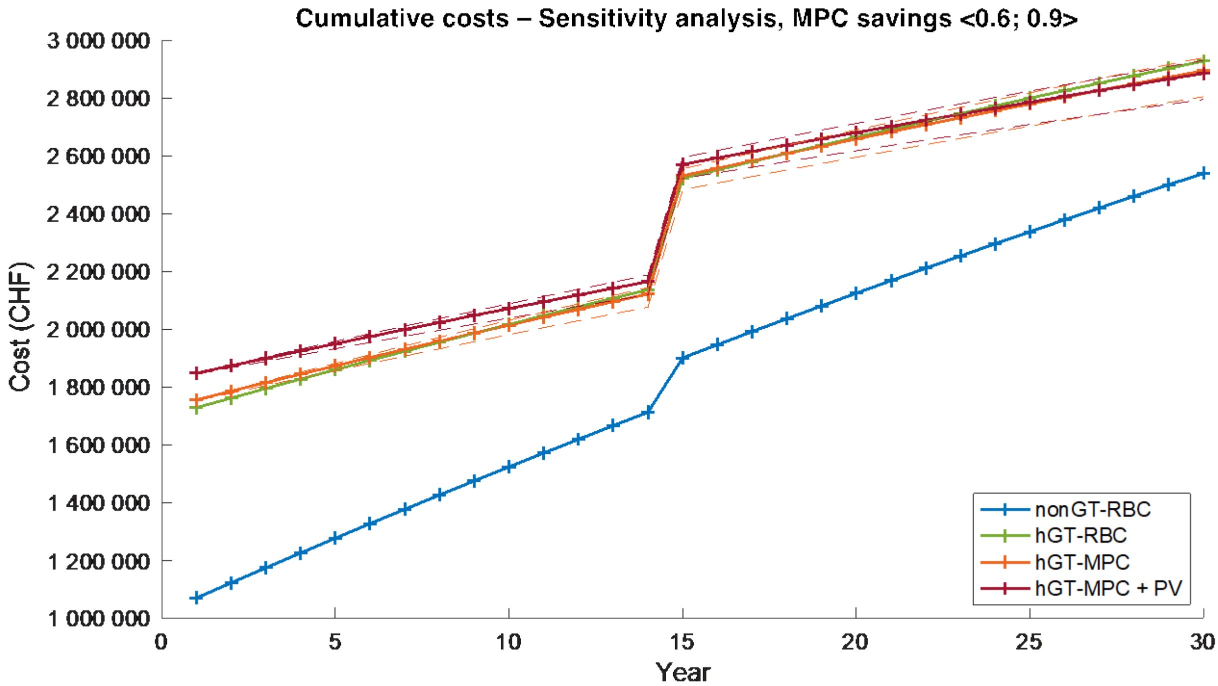



*Figure 6 – Haus M: Sensitivity analysis, MPC savings.*

The MPC savings have a very small effect on the last two variants, they still lay within the error of estimate.

## 2.9. Conclusions

For Haus M, the benchmark case is the cheapest one in the sense of global financial value. However, due to its high environmental impact and high environmental demands in the area of Zürich, it is not recommended. The other three variants are very similar, with the hybridGEOTABS variant with MPC and photovoltaics being slightly least expensive, least sensitive to variations of parameters and provides the best environmental performance.

For better decision-making process, Table 5 presents the summary of the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. The preferred variant (hybridGEOTABS, MPC and PV) is highlighted. It can be seen that it is about 3.40 % more expensive than the baseline variant, but that is out of our choice because of the environmental impact. It is 0.03 % and 0.23 % cheaper than the hybridGEOTABS + RBC, and hybridGEOTABS + MPC variant, respectively. Its environmental impact is only about 45.0 % of the baseline, and 61.4 % and 68.4 % of the other two variants.

The yearly revenue of the Haus M building, needed to pay-off the initial investment, is around CHF570 000, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 5 – Haus M: Summary of the CBA results.*

**Haus M**

**Global financial value (NPV) – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 0,00% | -3,49% | -3,29% | -3,52% |
| **hGT-RBC** | 3,37% | 0,00% | 0,19% | -0,03% |
| **hGT-MPC** | 3,18% | -0,19% | 0,00% | -0,23% |
| **hGT-MPC,PV** | 3,40% | 0,03% | 0,23% | 0,00% |

**CO2 footprint – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 100,0% | 136,6% | 152,1% | 222,3% |
| **hGT-RBC** | 73,2% | 100,0% | 111,4% | 162,8% |
| **hGT-MPC** | 65,7% | 89,8% | 100,0% | 146,1% |
| **hGT-MPC,PV** | 45,0% | 61,4% | 68,4% | 100,0% |

# 3. Líbeznice School

## 3.1. Project identification

*Figure 3: Líbeznice school building*

| | |
|---|---|
| Number of spaces | 8 classrooms, canteen and staff room |
| Number of occupants (design) | 240 pupils and staff |
| Gross floor area | 990 m² (690 m² net) |
| Conditioned floor area | 690 m² (area that is heated or cooled) |
| Type of ground source | Borehole Thermal Energy Storage (BTES) |
| Total annual thermal energy use | 92 MWh heating, 10 MWh cooling |
| Heating | Heat pump providing heat for both TABS and domestic hot water (DHW) |
| Ventilation | Decentral |
| Ventilation characteristics | Mechanical supply, mechanical exhaust, heat recovery |
| Net volume | 2,080 m³ |
| Building envelope:floor area ratio | 2.92 (gross), 4.19 (net) |

## 3.2. Presentation of the context – social, environmental, economic

An elementary school for 240 pupils in 8 classrooms, which also has after-school activities. The building is a single-storey annular shape with an eccentric round atrium, surrounded by a multifunctional foyer, integrating a corridor, children's lockers and a common area. The annular shape is inspired by the solar system. The school's cafeteria layout allows easy rearrangement, creating space for performances, or lectures with film screening. The building is equipped with TABS heating and cooling system (one circuit in the ceiling of the building), independent low-temperature ventilation units for each classroom and hot water circuit. The source of energy is ground coupled heat pump with heating power of 55 kW and cooling power of 65 kW. There are 6 boreholes on the primary side of the heat pump. The heat pump is operated in the three regimes i) heating, ii) passive cooling, iii) active cooling (compressor active). The GEOTABS system is controlled by a predictive controller (MPC) that takes into account weather forecast, model of thermodynamics of the heat pump and TABS. Moreover, spot market electricity prices are included in the MPC problem formulation which results in a higher consumption in situations when the price of electricity is low (surplus of the electricity in the grid) and lower consumption in other moments (demand side management). The algorithms benefit from the huge thermal capacity of the TABS system.

## 3.3. Definition of objectives

The objective of the CBA is to compare for variants and present their financial value, with sensitivity analysis of important parameters. The IEQ will also be described.

Given the requirements of the investor, the building is intended to have hybridGEOTABS as a mandatory condition. Unlike other case studies in the project, the focus of the CBA of the Líbeznice school building will be different. The four scenarios to be evaluated are:

- hybridGEOTABS, controlled by RBC
- hybridGEOTABS, controlled by MPC
- hybridGEOTABS, controlled by MPC, with PV panels added
- TABS with air source heat pump, controlled by MPC, with PVs and batteries added

The last variant will evaluate the economic possibility of substituting the expensive geothermal part by (also expensive) batteries, and thus to exchange long-term accumulation for highly efficient short-term accumulation.

## 3.4. Technical feasibility

For the analysis, we will compare four variants of the Líbeznice building:

| **Variant** | **hybridGEOTABS-RBC** | **hybridGEOTABS-MPC** | **hybridGEOTABS-MPC with PVs** | **TABS, MPC, PVs and batteries** |
|---|---|---|---|---|
| **Weather** | Prague | | | |
| **Ventilation** | Mechanical extraction variable flow rate + $CO_2$ control | | | |
| **Primary heating** | GSHP – TABS (ceiling) + AHU | | | ASHP – TABS (ceiling), AHU |
| **Primary cooling** | TABS (ceiling) – ground heat exchanger TABS, AHU | | | TABS (ceiling) – chiller, AHU |
| **Secondary cooling** | Independent FCUs | | | |
| **Control** | MPC | | | |
| **Renewables** | GSHP | | GSHP + PV | ASHP + PV + batteries |

## 3.5. Financial and environmental analysis

For the four variants of the building, we will use the following numerical values of the parameters specified in part 1.13 Main parameters used in the CBA.

| Name | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC, PV, Bat. | Units used |
|---|---|---|---|---|---|
| Area | 690 | 690 | 690 | 690 | m2 |
| Nominal energy consumption | 61,0 | 61,0 | 61,0 | 61,0 | kWh/m2/year |
| Construction cost | 38 640 000 | 38 640 000 | 38 640 000 | 38 640 000 | CZK |
| Constrol system cost | 2 490 000 | 2 801 000 | 2 801 000 | 2 801 000 | CZK |
| Borefield cost total | 629 000 | 629 000 | 629 000 | - | CZK |
| Heat pumpt cost | 712 000 | 712 000 | 712 000 | 560 000 | CZK |
| End energy consumption | 50 508 | 42 090 | 30 330 | 22 490 | kWh/year |
| End energy price | 62 164 | 51 803 | 37 329 | 27 680 | CZK/year |
| PV cost | - | - | 336 000 | 560 000 | CZK |
| Installed kWp | - | - | 12 | 20 | kWp |
| Battery capacity | - | - | - | 23 | kWh |
| Battery cost | - | - | - | 598 000 | CZK |
| Energy produced | - | - | 11 760 | 19 600 | kWh/year |
| Energy in-house | - | - | 11 760 | 19 600 | kWh/year |
| CO2 emissions nominal | 11,50 | 9,59 | 9,59 | 9,59 | kg/m2/year |
| CO2 emissions | 7,94 | 6,61 | 4,77 | 4,90 | ton/year |
| CO2 price | 10 714,91 | 8 929,09 | 6 434,29 | 6 621,01 | CZK |
| Technology extras | 5 400 000 | 5 400 000 | 5 500 000 | 5 100 000 | CZK |
| Design fee | 2 700 000 | 2 700 000 | 2 800 000 | 2 850 000 | CZK |
| Maintenance | 26 000 | 26 000 | 28 000 | 29 000 | CZK |

The energy values are based on simulations performed on the virtual test bed, Deliverable 4.9. In the CBA, we will also assume the following constants and boundary conditions:

| Name | Basic value | Units used |
|---|---|---|
| Electricity price per kWh | 3,20 | CZK/kWh |
| Residual value | 0,25 | - |
| Calculation period | 30 | years |
| Discount rate | 2,50% | - |
| PV cost | 28 000 | CZK/kWp |
| Battery cost | 26 000 | CZK/kWh |
| Overall efficiency | 980 | kWh/kWp/year |
| In-house use ratio | 1,00 | - |
| CO2 price | 1 350,00 | CZK/ton |

Local energy factors for the Czech Republic were used in the calculations, as described in Deliverable 4.9.

## 3.6. Financial net present value

When calculating the global net present value according to the above parameters, we get the results as shown in Figure 7. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

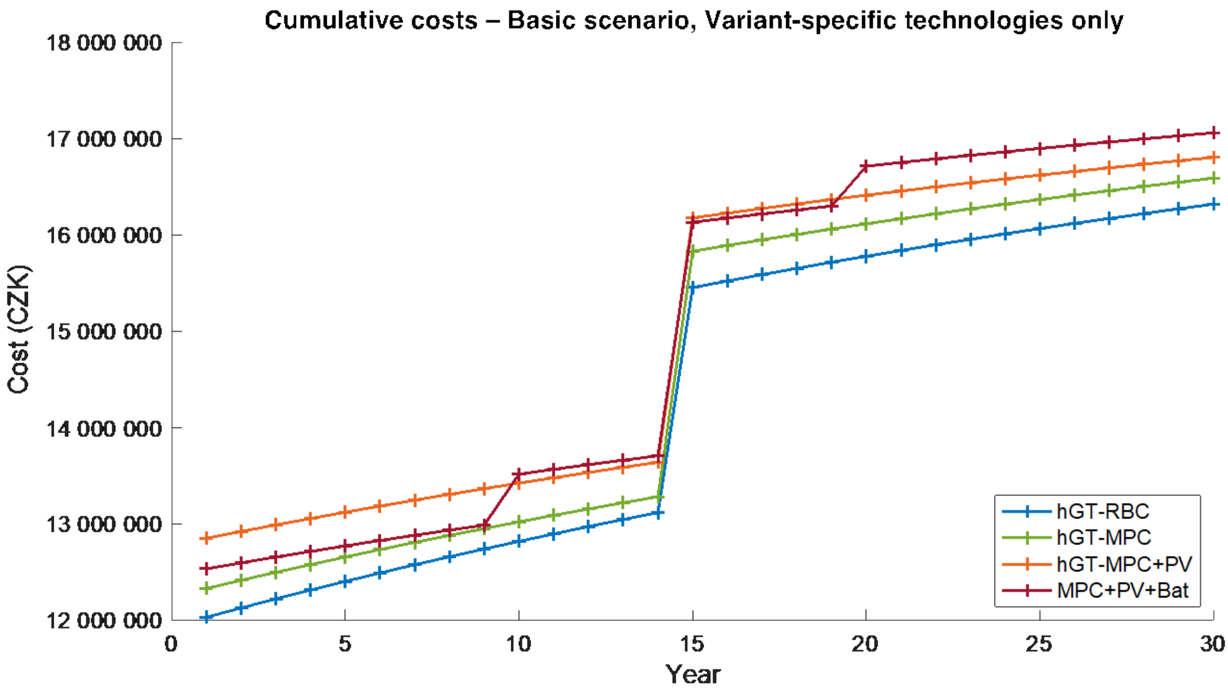



*Figure 7 – Líbeznice, Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

It is clear from the figure that the benchmark, i.e. hybridGEOTABS, RBC version of the building is the most financially viable. The step in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced. The batteries are replaced after 10 and 20 years. The final cost performance overview in the form required by the EC Regulation No. 244/2012 is shown in Table 6.

*Table 6 – Final cost performance overview of Líbeznice.*

| | | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC, PV, Bat. |
|---|---|---|---|---|---|
| | **Variant** | **hGT-RBC** | **hGT-MPC** | **hGT-MPC,PV** | **MPC, PV, Bat.** |
| | **Initial investment cost** | 50 571 000 CZK | 50 882 000 CZK | 51 418 000 CZK | 51 109 000 CZK |
| **Annual running cost** | **Maintenance cost** | 18 593 CZK | 18 593 CZK | 20 023 CZK | 20 738 CZK |
| | **Operational cost (reinvestments)** | 75 538 CZK | 82 875 CZK | 82 875 CZK | 107 719 CZK |
| | **Energy cost by fuel with the medium energy price scenario** | 44 454 CZK | 37 045 CZK | 26 695 CZK | 19 794 CZK |
| | **Calculation period** | 30 | 30 | 30 | 30 |
| | **Cost of greenhouse gas emissions** | 229 873 CZK | 191 561 CZK | 138 038 CZK | 142 044 CZK |
| | **Residual value** | 4 720 468 CZK | 4 720 468 CZK | 4 720 468 CZK | 4 720 468 CZK |
| | **Discount rate** | 2,50% | 2,50% | 2,50% | 2,50% |
| | **Estimated economic lifetime** | 30 | 30 | 30 | 30 |
| | **Disposal cost** | N/A | N/A | N/A | N/A |
| | **Global cost calculated (NPV)** | 50 237 972 CZK | 50 508 491 CZK | 50 723 360 CZK | 50 978 136 CZK |

The baseline scenario has lowest global cost calculated, but it is out of our concern because of its high environmental impact. The other three variants are very similar, the results are within 1.2 % of the global cost and thus within an error of estimation.

## 3.7. Economic value

### 3.7.1. Financial value

Comparing the four variants, the financial value (in the sense of net present value) is shown in Table 7. The financial value of all variants is very similar. The difference between the hybridGEOTABS, RBC and hybridGEOTABS, MPC + PV variant is 485 338 CZK (approx. €18 000), which about 1.45 % of the full price. It is therefore clear that other than financial considerations will play role in the decision making process.

*Table 7 – Financial value of Líbeznice.*

| Variant | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC, PV, Bat. |
|---|---|---|---|---|
| Global cost (Net Present Value) | 50 237 972 CZK | 50 508 491 CZK | 50 723 360 CZK | 50 978 136 CZK |
| Difference between the variant and baseline (hGT-RBC) | - CZK | 270 519 CZK | 485 388 CZK | 740 164 CZK |
| The variant being more expensive than baseline in % | 0,00% | 0,54% | 0,96% | 1,45% |

### 3.7.2. Energies and Environmental impact

As already mentioned, the energy values are based Deliverable 4.9 – Concept and impact validation for the case-study buildings based on the virtual test bed. Here, in Table 8, we show the summary of the energies and environmental impact of Líbeznice.

*Table 8 – Líbeznice: Environmental impact and energy requirements.*

| | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC, PV, Bat. | |
|---|---|---|---|---|---|
| Nominal energy requirements | 61,0 | 61,0 | 61,0 | 61,0 | kWh/m2/year |
| End energy consumption | 50 508 | 42 090 | 30 330 | 22 490 | kWh/year |
| End energy price | 62 164 | 51 803 | 37 329 | 27 680 | CZK/year |
| Renewable energy generation & self-consumption | 0 | 0 | 11 760 | 19 600 | kWh/year |
| Total CO2 emissions | 7,94 | 6,61 | 4,77 | 3,53 | ton/year |
| *Nominal prices, not adjusted for inflation.* | | | | | |

Because of the choice of variants for the Líbeznice school, the environmental impact of all three is very similar. The variants with photovoltaics are slightly better by about factor of two, but the values are very small. The best environmental performance is for the last variant, i.e. TABS with MPC, photovoltaic panels and batteries. The PV variants were calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 3.7.3. Indoor environment quality

The TABS system provides in general a very good comfort associated with radiant heating and cooling. The advantage of the radiant heating and cooling is the better human temperature sensing, and the inhabitants of the building with TABS system may feel comfortable with ambient temperature lower by ca. 1 °C compared to traditional heating and cooling systems, such as radiators or FCUs. This can result of additional energy savings of 5–10 %. In addition, MPC control can slightly improve the indoor environment quality by better maintaining the desired indoor temperatures.

The mechanical ventilation system is controlled by $CO_2$ levels measured in the classrooms, which provides excellent air quality and is in line with EU standards.

In general, the advantages and disadvantages of the TABS system concerning the indoor environment quality are as follows:

- Advantages
    - Better space utilization – minimum of heating, cooling or ventilation equipment is present or visible inside the building occupation spaces, which allows the inhabitants to use the space more freely
    - Radiant heating and cooling – better perceived by some people
    - Lower ventilation rates in comparison with air-conditioned buildings, which results in less draught and infection spreading
    - High stability – indoor air quality is quickly restored e.g. after a window is opened and closed
- Disadvantages
    - Sensitivity to additional installations – one has to be careful to not pierce through the pipes
    - Worse acoustics
    - High thermal inertia, inability to change temperature quickly – this is partially compensated by the secondary system

## 3.8. Sensitivity analysis and risk assessment

The sensitivity analysis shows the variation of the global financial value in the sense of NPV due to ± 1 % variation of the analysed variable and a criticality judgement – if the change of global financial value is more than 1 %, the variable is considered critical.

*Table 9 – Líbeznice: Sensitivity analysis*

| | hGT-RBC | | hGT-MPC | | hGT-MPC+PV | | MPC+PC+Bat. | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Variation** | **Criticality** | **Variation** | **Criticality** | **Variation** | **Criticality** | **Variation** | **Criticality** |
| **Discount rate** | 0.028 % | No | 0.028 % | No | 0.026 % | No | 0.030 % | No |
| **Energy tariff** | 0.027 % | No | 0.022 % | No | 0.016 % | No | 0.012 % | No |
| **$CO_2$ price** | 0.005 % | No | 0.004 % | No | 0.003 % | No | 0.002 % | No |
| **PV price** | - | - | - | - | 0.007 % | No | 0.011 % | No |
| **Heat pump price** | 0.024 % | No | 0.024 % | No | 0.024 % | No | 0.019 % | No |
| **Borefield price** | 0.013 % | No | 0.013 % | No | 0.013 % | No | - | - |
| **MPC savings** | - | - | 0.44 % | No | 0.44 % | No | 0.43 % | No |

We can see that there is no critical variable for Líbeznice. However, given very small differences in global financial values for the variants, energy tariff and MPC savings ratio can be considered as important parameters. We will also have a more detailed look on the variations of the discount rate and the battery price, which can be interesting for the last variant.

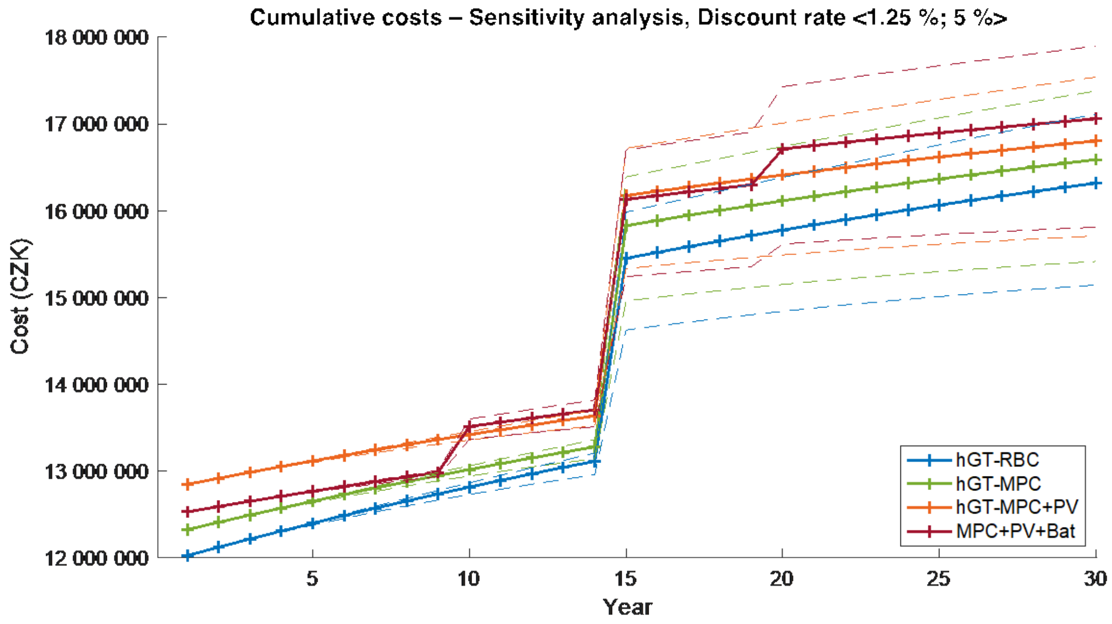



*Figure 8 – Líbeznice: Sensitivity analysis, discount rate.*

The global financial value is not very sensitive to variations of the discount rate for Líbeznice (Figure 8), but large differences can already have significant effect on the global financial value, as the discount rate for Czech Crown (CZK) is bigger than for Euro. The nominal value for discount rate is 2.5 %, we have performed the sensitivity analysis for half and double the value, i.e. for 1.25 % and 5 %. All variants keep their order with the change of the discount rate, but the variation can be significant. For higher discount rates, the variant with batteries can become competitive.

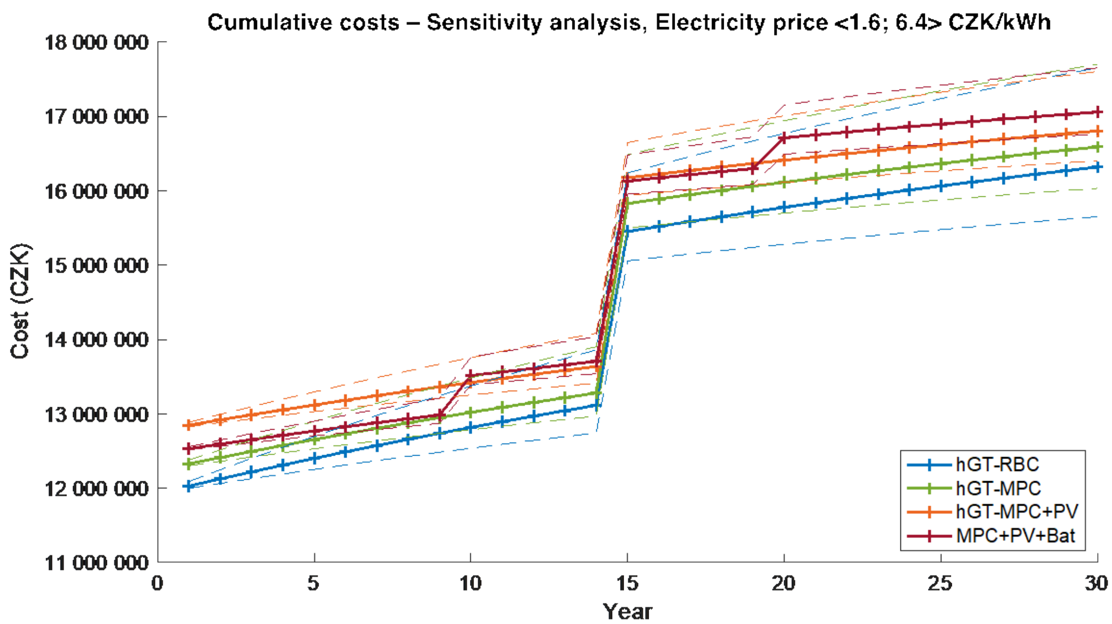



*Figure 9 – Líbeznice: Sensitivity analysis, electricity price.*

The electricity price has smaller effect (Figure 9). Again, we took the half and the double of the nominal value. For higher electricity prices, all four variants almost level, and the more advanced variants perform better.

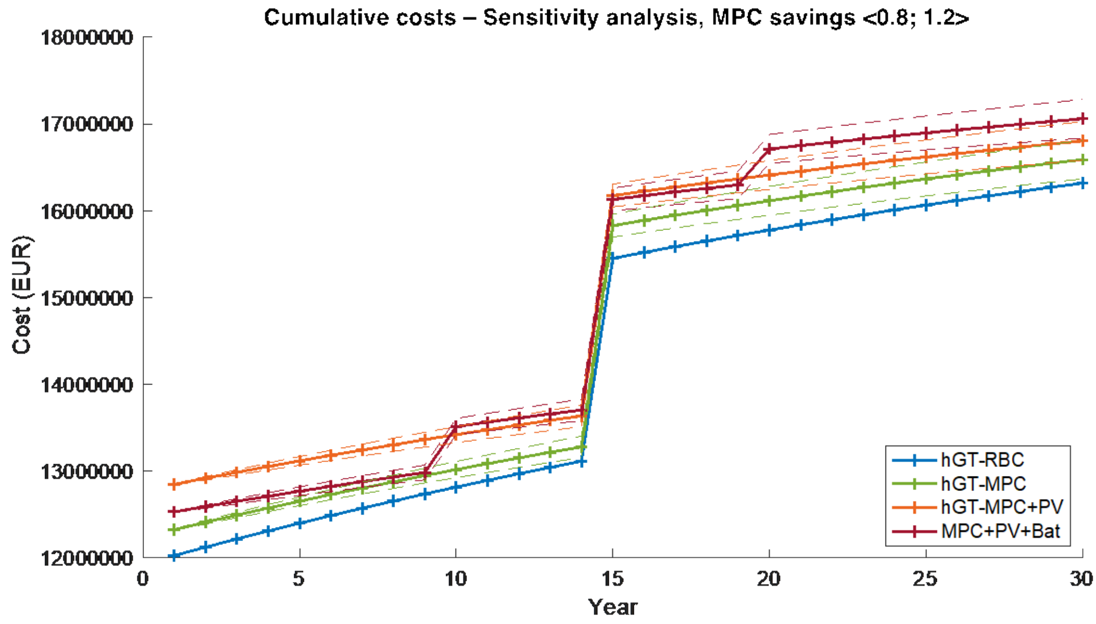



*Figure 10 – Líbeznice: Sensitivity analysis, MPC savings.*

The MPC savings have some effect on the RBC variant, which becomes more expensive if the MPC efficiency is increased by further 20 % (Figure 10).

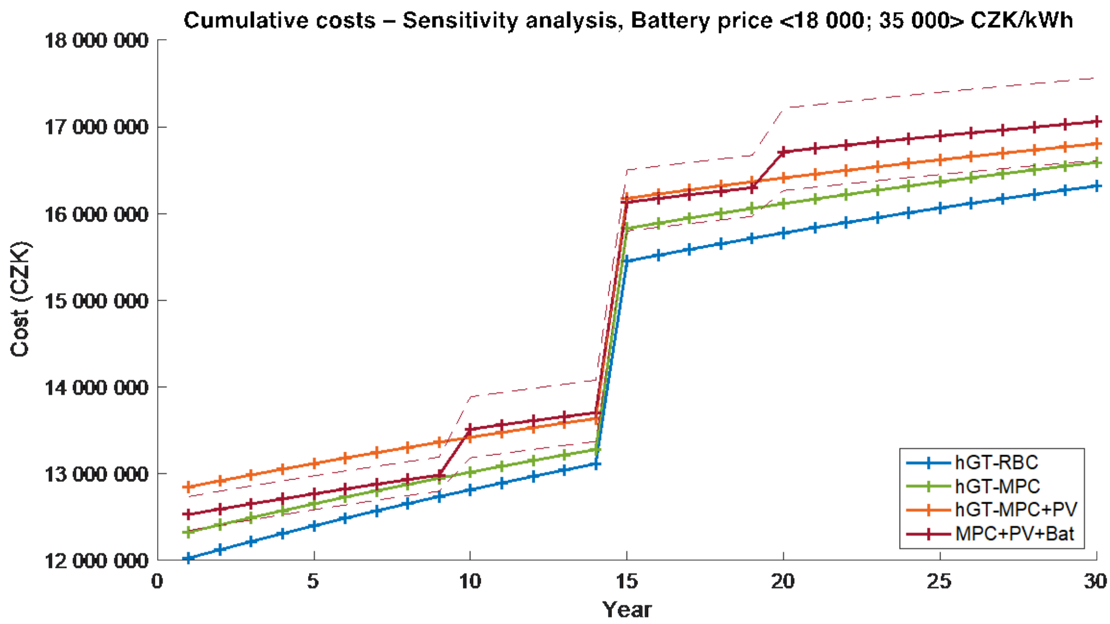



*Figure 11 – Líbeznice: Sensitivity analysis, battery price*

For the Líbeznice school, we have also performed a sensitivity analysis for the battery price, in the range from 18 000 CZK/kWh (€ 700 per kWh), which may be the target price for batteries, to the unlikely price of 35 000 CZK/kWh (€ 1300 per kWh). With the low battery prices, the battery variant becomes the most economical.

## 3.9. Conclusions

For Líbeznice, the RBC case is the cheapest one in the sense of global financial value. However, the other three variants are very similar, with the hybridGEOTABS variant with MPC and photovoltaics being slightly more expensive (less than 1 %), and is also not sensitive to the change of parameters.

For better decision-making process, Table 10 presents the summary of the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. The preferred variant (hybridGEOTABS, MPC and PV) is highlighted. It can be seen that it is about 0.96 % more expensive than the baseline variant, but that is out of our choice because of the environmental impact. Its environmental impact is about 60.1 % of the baseline.

An interesting point is the non-geo variant, with air source heat pump, MPC, photovoltaics and batteries. This variant is 0.5 % more expensive than the hybridGETOABS + MPC + PV variant, but has only 74.0 % of its environmental impact in the sense of $CO_2$. Of course, the environmental impact of the batteries is questionable. The variant with the batteries is sensitive to the input prices in the sense that if the battery price will decrease, it will become very advantageous. So this variant may be the choice of the investor as well.

**The recommendation is the hybridGEOTABS + MPC + PV variant, but the non-geothermal variant with batteries should be considered as well.**

*Table 10 – Líbeznice: Summary of the CBA results.*

**Líbeznice**

**Global financial value (NPV) – comparison**

| | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC,PV,Bat. |
|---|---|---|---|---|
| hGT-RBC | 0,00% | -0,54% | -0,97% | -1,47% |
| hGT-MPC | 0,54% | 0,00% | -0,43% | -0,93% |
| hGT-MPC, PV | 0,96% | 0,42% | 0,00% | -0,50% |
| MPC, PV, Bat. | 1,45% | 0,92% | 0,50% | 0,00% |

**CO2 footprint – comparison**

| | hGT-RBC | hGT-MPC | hGT-MPC,PV | MPC,PV,Bat. |
|---|---|---|---|---|
| hGT-RBC | 100,0% | 120,1% | 166,5% | 224,9% |
| hGT-MPC | 83,2% | 100,0% | 138,6% | 187,3% |
| hGT-MPC, PV | 60,1% | 72,2% | 100,0% | 135,1% |
| MPC, PV, Bat. | 44,5% | 53,4% | 74,0% | 100,0% |

# 4. Infrax/Fluvius

## 4.1. Project identification

*Figure 4: Infrax/Fluvius office building*

| | |
|---|---|
| Number of spaces | 21 spaces: offices, kitchen, cafeteria, server cooling rooms & parking |
| Number of occupants (design) | +/- 90 |
| Net floor area | 2,232 $m^2$ + parking |
| Conditioned floor area | 2,232 $m^2$ (area that is heated and/or cooled) |
| Type of ground source | Vertical Borehole Thermal Energy Storage (BTES) |
| Total annual thermal energy use | 28.23 (heating) + 36.94 (cooling) = 65.17 kWh/($m^2$·annum) |
| Heating | Small electric boiler (domestic hot water) & heat pump (space heating) |
| Ventilation | Central |
| Ventilation characteristics | mechanical supply, mechanical exhaust, heat recovery |
| Net volume | 7,520$m^3$ (without basement) |
| Building envelope:floor area ratio | 1.067 (conditioned), 0.68 (conditioned and non-conditioned) |

## 4.2. Presentation of the context – social, environmental, economic

The Infrax building is a 2232 $m^2$ conditioned space four-story office building located in Brussels, Belgium. The building envelope model is composed of 27 zones, of which 21 are conditioned for heating and cooling. The 1$^{st}$, 2$^{nd}$ and 3$^{rd}$ floors are mainly open offices and separate zones exist for the north and south spaces, the individual meeting rooms and the bathrooms (which are not conditioned). The ground floor includes individual conference rooms and several facilities (first aid room, canteen, storage and server rooms). The U-values for the outer walls and roof are between 0.18-0.25 and 0.14-0.15 W/($m^2$.K) respectively. The air-tightness of the building is measured with a $n_{50}$ value of 1.3 ACH. The AHU is a centralized double flux mechanical ventilation with heat recovery provided by a thermal wheel which is located after the heating coil in the ventilation system.

## 4.3. Definition of objectives

The objective of the CBA is to compare for variants and present their financial value, with sensitivity analysis of important parameters. The IEQ will also be described.

## 4.4. Technical feasibility

For the analysis, we will compare four variants of the building:

| Variant | nonGEOTABS-RBC | hybridGEOTABS-RBC | hybridGEOTABS-MPC | hybridGEOTABS-MPC with PVs |
|---|---|---|---|---|
| Weather | Brussels | | | |
| Ventilation | Mechanical extraction variable flow rate + $CO_2$ control | | | |
| Primary heating | AHU, FCU + Gas Boiler | GSHP – TABS (ceiling) + AHU + re-heating coils | | |
| Primary cooling | AHU, FCU + Chiller | TABS (ceiling) – ground heat exchanger TABS | | |
| Secondary cooling | NO | NO | | |
| Control | RBC | | MPC | |
| Renewables | NO | GSHP | | GSHP + PV |

## 4.5. Financial and environmental analysis

For the four variants of the building, we will use the following numerical values of the parameters specified in part 1.13 Main parameters used in the CBA.

| Name | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV | Units used |
|---|---|---|---|---|---|
| Area | 2 232 | 2 232 | 2 232 | 2 232 | m2 |
| Nominal energy consumption | 41,3 | 42,4 | 26,4 | 26,4 | kWh/m2/year |
| Construction cost | 6 026 400 | 6 026 400 | 6 026 400 | 6 026 400 | EUR |
| Constrol system cost | 83 850 | 111 809 | 142 337 | 142 337 | EUR |
| Borefield cost total | - | 135 061 | 135 061 | 135 061 | EUR |
| Gas boiler cost | 18 600 | - | - | - | EUR |
| Heat pumpt cost | 94 586 | 122 137 | 122 137 | 122 137 | EUR |
| End energy consumption | 92 182 | 94 637 | 58 925 | 31 025 | kWh/year |
| End energy price | 10 755 | 11 041 | 6 875 | 3 620 | EUR/year |
| PV cost | - | - | - | 36 000 | EUR |
| Installed kWp | - | - | - | 30 | kWp |
| Energy produced | - | - | - | 27 900 | kWh/year |
| Energy in-house | - | - | - | 27 900 | kWh/year |
| CO2 emissions nominal | 4,42 | 1,04 | 0,65 | 0,65 | kg/m2/year |
| CO2 emissions | 9,87 | 2,32 | 1,45 | 0,76 | ton/year |
| CO2 price | 493,27 | 116,06 | 72,54 | 38,19 | EUR |
| Technology extras | 516 192 | 592 981 | 592 981 | 592 981 | EUR |
| Design fee | 53 492 | 72 149 | 74 439 | 74 439 | EUR |
| Maintenance | 9 000 | 7 000 | 8 000 | 8 000 | EUR |

The energy values are based on simulations performed on the virtual test bed, Deliverable 4.9. In the CBA, we will also assume the following constants and boundary conditions:

| Name | Basic value | Units used |
|---|---|---|
| Consumption_decrease_for_MPC | 1,00 | - |
| Electricity price per kWh | 0,28 | EUR/kWh |
| Residual value | 0,25 | - |
| Calculation period | 30 | years |
| Discount rate | 1,50% | - |
| PV cost | 1 200 | EUR/kWh |
| Overall efficiency | 930 | kWh/kWp/year |
| In-house use ratio | 1,00 | - |
| CO2 price | 50,00 | EUR/ton |

Local energy factors for Belgium were used in the calculations, as described in Deliverable 4.9.

## 4.6. Financial net present value

When calculating the global net present value according to the above parameters, we get the results as shown in Figure 12. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

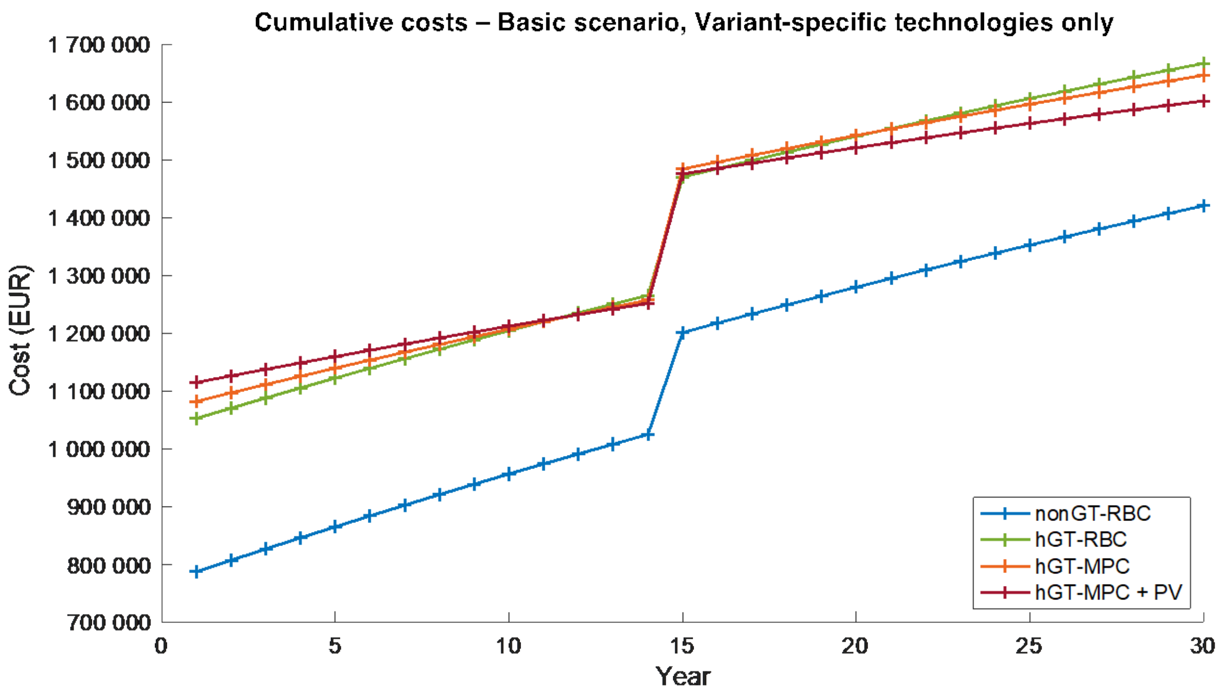



*Figure 12 – Infrax/Fluvius, Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

It is clear from the figure that the benchmark, i.e. non-GEOTABS, RBC version of the building is the most financially viable. However, this version is the least environmentally friendly and is not of our concern, we only use it as a benchmark. The step in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced. The final cost performance overview in the form required by the EC Regulation No. 244/2012 is shown in Table 11 – Final cost performance overview of Infrax/Fluvius.

*Table 11 – Final cost performance overview of Infrax/Fluvius.*

| | Variant | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|---|
| | Initial investment cost | € 6 793 120 | € 7 060 537 | € 7 093 355 | € 7 129 355 |
| Annual running cost | Maintenance cost | € 7 313 | € 5 688 | € 6 500 | € 6 500 |
| | Operational cost (reinvestments) | € 5 332 | € 6 331 | € 7 157 | € 7 157 |
| | Energy cost by fuel with the medium energy price scenario | € 8 738 | € 8 971 | € 5 586 | € 2 941 |
| | Calculation period | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | € 12 024 | € 2 829 | € 1 768 | € 931 |
| | Residual value | € 978 324 | € 978 324 | € 978 324 | € 978 324 |
| | Discount rate | 1,50% | 1,50% | 1,50% | 1,50% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | € 7 038 005 | € 7 379 869 | € 7 361 516 | € 7 317 334 |

The baseline scenario has lowest global cost calculated, but it is out of our concern because of its high environmental impact. The other three variants are very similar, the results are within 1 % of the global cost and thus within an error of estimation.

*Table 12 – Minimum annual income from Infrax/Fluvius needed to achieve positive financial NPV.*

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| Annual income needed to achieve positive financial NPV | € 234 600 | € 245 996 | € 245 384 | € 243 911 |

Table 12 shows the minimum income that the investor or owner needs to achieve from Infrax/Fluvius, should the building yield positive profit. Note that the residual value is not included in this calculation.

## 4.7. Economic value

### 4.7.1. Financial value

Comparing the four variants, the financial value (in the sense of net present value) is shown in Table 13. Without the benchmark variant (non GEOTABS, RBC), the financial value of the other three variants is very similar. The difference between the hybridGEOTABS, MPC and hybridGEOTABS, MPC + PV variant is €44 181, which about 0.6 % of the full price. It is therefore clear that other than financial considerations will play role in the decision making process.

*Table 13 – Financial value of Infrax/Fluvius.*

| Variant | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| Global cost (Net Present Value) | € 7 038 005 | € 7 379 869 | € 7 361 516 | € 7 317 334 |
| Difference between the variant and baseline (nonGT-RBC) | € - | € 341 864 | € 323 510 | € 279 329 |
| The varinat being more expensive than baseline in % | 0,00% | 4,63% | 4,39% | 3,82% |

### 4.7.2. Energies and Environmental impact

As already mentioned, the energy values are based Deliverable 4.9 – Concept and impact validation for the case-study buildings based on the virtual test bed. Here, in Table 14, we show the summary of the energies and environmental impact of Infrax/Fluvius.

*Table 14 – Infrax/Fluvius: Environmental impact and energy requirements.*

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV | |
|---|---|---|---|---|---|
| **Nominal energy requirements** | 41,3 | 42,4 | 26,4 | 26,4 | kWh/m2/year |
| **End energy consumption** | 92 182 | 94 637 | 58 925 | 31 025 | kWh/year |
| **End energy price** | 10 755 | 11 041 | 6 875 | 3 620 | CHF/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 0 | 27 900 | kWh/year |
| **Total CO2 emissions** | 9,87 | 2,32 | 1,45 | 0,76 | ton/year |
| ***Nominal prices, not adjusted for inflation.*** | | | | | |

As the investor has the intention to build Infrax/Fluvius according to sustainability principles, the benchmark variant (nonGEOTABS, RBC) is not recommended because of significantly high $CO_2$ emissions. As can be seen, the carbon footprint of the other three variants is at least 5 times lower. The best environmental performance is for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 4.7.3. Indoor environment quality

The TABS system provides in general a very good comfort associated with radiant heating and cooling. The advantage of the radiant heating and cooling is the better human temperature sensing, and the inhabitants of the building with TABS system may feel comfortable with ambient temperature lower by ca. 1 °C compared to traditional heating and cooling systems, such as radiators or FCUs. This can result of additional energy savings of 5–10 %. In addition, MPC control can slightly improve the indoor environment quality by better maintaining the desired indoor temperatures.

The mechanical ventilation system is controlled by CO2 levels measured in the rooms, which provides excellent air quality and is in line with EU standards.

In general, the advantages and disadvantages of the TABS system concerning the indoor environment quality are as follows:

- Advantages
  - Better space utilization – minimum of heating, cooling or ventilation equipment is present or visible inside the building occupation spaces, which allows the inhabitants to use the space more freely
  - Radiant heating and cooling – better perceived by some people
  - Lower ventilation rates in comparison with air-conditioned buildings, which results in less draught and infection spreading
  - High stability – indoor air quality is quickly restored e.g. after a window is opened and closed
- Disadvantages
  - Sensitivity to additional installations – one has to be careful to not pierce through the pipes
  - Worse acoustics
  - High thermal inertia, inability to change temperature quickly – this is partially compensated by the secondary system

## 4.8. Sensitivity analysis and risk assessment

The sensitivity analysis shows the variation of the global financial value in the sense of NPV due to ± 1 % variation of the analysed variable and a criticality judgement – if the change of global financial value is more than 1 %, the variable is considered critical.

*Table 15 – Infrax/Fluvius: Sensitivity analysis*

| Variable | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC+PV | |
|---|---|---|---|---|---|---|---|---|
| | Variation | Criticality | Variation | Criticality | Variation | Criticality | Variation | Criticality |
| **Discount rate** | 0.018 % | No | 0.017 % | No | 0.016 % | No | 0.014 % | No |
| **Energy tariff** | 0.037 % | No | 0.037 % | No | 0.023 % | No | 0.012 % | No |
| **$CO_2$ price** | 0.017 % | No | 0.0004 % | No | 0.0002 % | No | 0.0001 % | No |
| **PV price** | - | - | - | - | - | - | 0.0049 % | No |
| **Heat pump price** | 0.024 % | No | 0.030 % | No | 0.030 % | No | 0.030 % | No |
| **Borefield price** | - | - | 0.018 % | No | 0.018 % | No | 0.018 % | No |
| **MPC savings** | - | - | - | - | 0.45 % | No | 0.46 % | No |

We can see that there is no critical variable for Infrax/Fluvius. However, given very small differences in global financial values for the variants, energy tariff and MPC savings ratio can be considered as important parameters. We will also have a more detailed look on the variations of the discount rate.

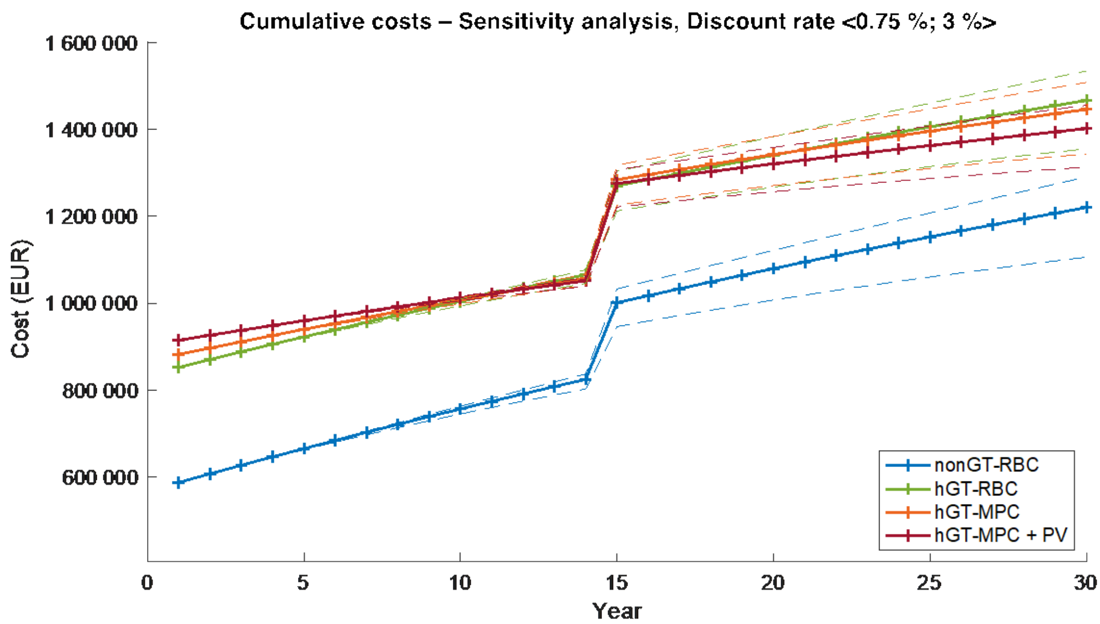



*Figure 13 – Infrax/Fluvius: Sensitivity analysis, discount rate.*

The global financial value is not very sensitive to variations of the discount rate for Infrax/Fluvius, but it is clear that it may have some effect, especially in the comparison of the three hybridGEOTABS variants. The nominal value for discount rate is 1.5 %, we have performed the sensitivity analysis for half and double the value, i.e. for

0.75 % and 3 %. The three hybridGEOTABS solutions are still well separated from the benchmark case and are similarly influenced by the change in the discount rate.

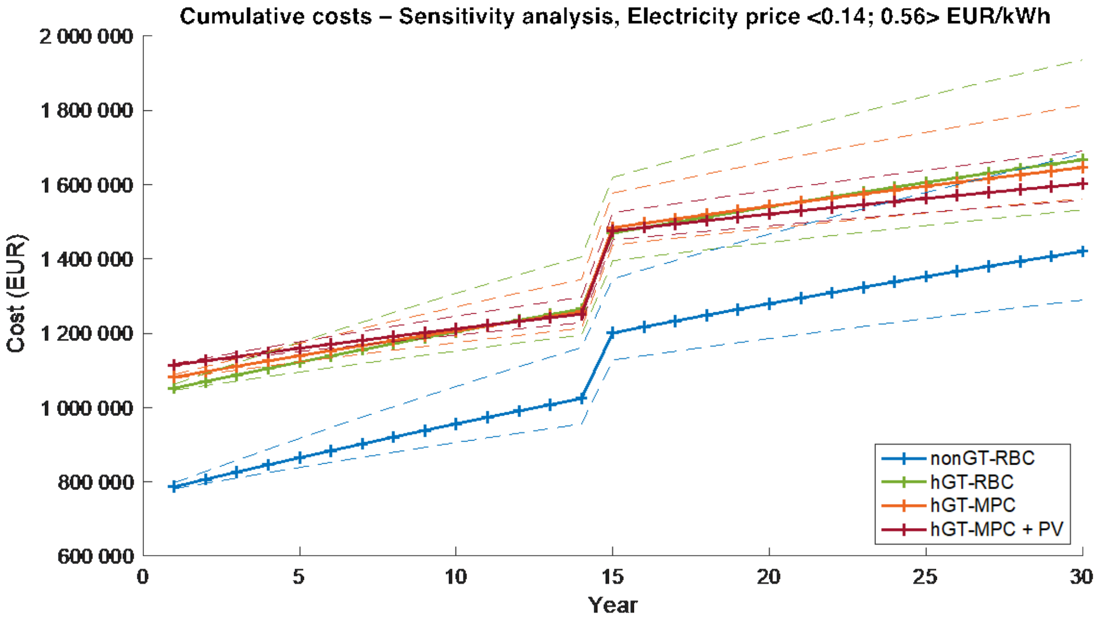



*Figure 14 – Infrax/Fluvius: Sensitivity analysis, electricity price.*

The electricity price has a more significant effect. Again, we took the half and the double of the nominal value. It can be seen that the benchmark case (nonTABS, RBC) is very sensitive to energy prices and can actually become more expensive than the hybridGEOTABS variants if electricity price increases by the factor of ca. 1.5 and more. The least sensitive variant is the hybridGEOTABS with MPC and photovoltaics, which becomes significantly cheaper for high electricity prices.

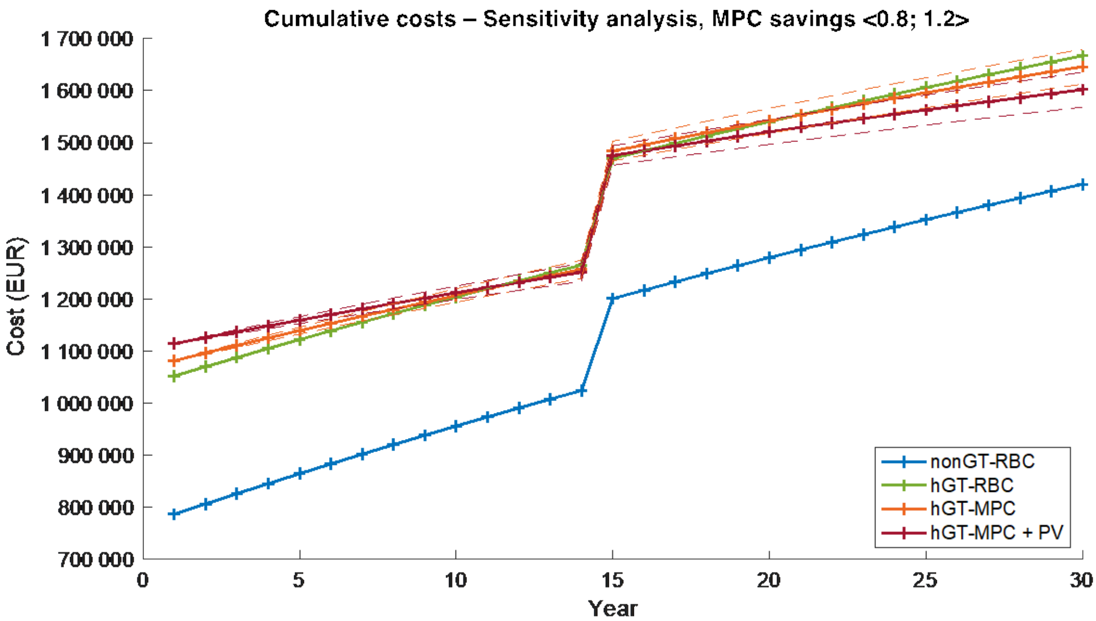



*Figure 15 – Infrax/Fluvius: Sensitivity analysis, MPC savings.*

The MPC savings have a very small effect on the last two variants, but it can be seen that for lower MPC effects, the variant without PV can become more expensive than the RBC variant. The PV variant remains on the safe side.

## 4.9. Conclusions

For Infrax/Fluvius, the benchmark case is the cheapest one in the sense of global financial value. However, due to the demand of the investor to have a small environmental impact, it is not recommended. The other three variants are very similar, with the hybridGEOTABS variant with MPC and photovoltaics being slightly least expensive. What is also important, the MPC+PV variant is also least sensitive to variations of parameters and provides the best environmental performance.

For better decision-making process, Table 16 presents the summary of the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. The preferred variant (hybridGEOTABS, MPC and PV) is highlighted. It can be seen that it is about 3.82 % more expensive than the baseline variant, but that is out of our choice because of the environmental impact. It is 0.85 % and 0.60 % cheaper than the hybridGEOTABS + RBC, and hybridGEOTABS + MPC variant, respectively. Its environmental impact is only about 7.7 % of the baseline, and 32.9 % and 52.7 % of the other two variants.

The yearly revenue of the Infrax/Fluvius building, needed to pay-off the initial investment, is around €250 000, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 16 – Infrax/Fluvius: Summary of the CBA results.*

**Infrax/Fluvius**

**Global financial value (NPV) – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 0,00% | -4,86% | -4,60% | -3,97% |
| **hGT-RBC** | 4,63% | 0,00% | 0,25% | 0,85% |
| **hGT-MPC** | 4,39% | -0,25% | 0,00% | 0,60% |
| **hGT-MPC,PV** | 3,82% | -0,85% | -0,60% | 0,00% |

**CO2 footprint – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 100,0% | 425,0% | 680,0% | 1291,5% |
| **hGT-RBC** | 23,5% | 100,0% | 160,0% | 303,9% |
| **hGT-MPC** | 14,7% | 62,5% | 100,0% | 189,9% |
| **hGT-MPC,PV** | 7,7% | 32,9% | 52,7% | 100,0% |

# 5. Ter Potterie

## 5.1. Project identification

*Figure 5: Ter Potterie building*

| | |
|---|---|
| Number of spaces | 121 rooms, 5 shared bathrooms, 1 bathroom ground flr, 1 nursing station per living group, living room/lounge areas and central storage. |
| Number of occupants (design) | 121 residents |
| Gross floor area | 16,103 m² |
| Conditioned floor area | 10,048 m² ( area that is heated and/or cooled ) |
| Type of ground source | BTES (Borehole Thermal Energy Storage) |
| Total annual thermal energy use | kWh/(m²·annum) not yet available |
| Heating | Gas (Condensing) boiler |
| Ventilation | Central |
| Ventilation characteristics | mechanical supply, mechanical exhaust, heat recovery |
| Net volume | 41,316 m³ |
| Building envelope:floor area ratio | 2.83 |

## 5.2. Presentation of the context – social, environmental, economic

The Ter Potterie building is a 10 048 m² conditioned space (16 103 m² gross floor area) elderly care home building located in Bruges, Belgium. This building mostly contains single bedrooms but also common living rooms, offices, a kitchen, a cafeteria, and some rooms for staff. To reduce the size of the model, rooms of similar type, located at the same level and adjacent to each other, and of identical orientation were lumped together if they are connected to a same air handling unit. The resulting model is composed by 27 conditioned and 13 unconditioned zones.

All conditioned rooms have floor heating and/or TABS, except the kitchen and the polyvalent room. Additionally, all rooms are equipped with radiators sized such that they can cover approximately 30 % of the heat losses at nominal conditions.

## 5.3. Definition of objectives

The objective of the CBA is to compare four variants and present their financial value, with sensitivity analysis of important parameters. The IEQ will also be described.

## 5.4. Technical feasibility

For the analysis, we will compare four variants of the building:

| Variant | nonGEOTABS-RBC | hybridGEOTABS-RBC | hybridGEOTABS-MPC | hybridGEOTABS-MPC with PVs |
|---|---|---|---|---|
| Weather | Brussels | | | |
| Ventilation | Mechanical extraction fixed flow rate | | | |
| Primary heating | AHU, FCU + Gas Boiler | GSHP – TABS (ceiling) + floor heating<br>Natural Gas Boiler – AHU + Radiators | | |
| Primary cooling | AHU, FCU + Chiller | TABS (ceiling) + Floor cooling + AHU – ground heat exchanger TABS | | |
| Secondary cooling | NO | NO | | |
| Control | RBC | | MPC | |
| Renewables | NO | GSHP | | GSHP + PV |

## 5.5. Financial and environmental analysis

For the four variants of the building, we will use the following numerical values of the parameters specified in part 1.13 Main parameters used in the CBA.

| Name | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV | Units used |
|---|---|---|---|---|---|
| Area | 10 048 | 10 048 | 10 048 | 10 048 | m2 |
| Nominal energy consumption | 80,3 | 74,8 | 73,3 | 73,3 | kWh/m2/year |
| Construction cost | 27 129 600 | 27 129 600 | 27 129 600 | 27 129 600 | EUR |
| Constrol system cost | 193 955 | 192 215 | 242 215 | 257 722 | EUR |
| Borefield cost total | - | 354 434 | 354 434 | 354 434 | EUR |
| Gas boiler cost | 54 500 | 37 120 | 37 120 | 37 120 | EUR |
| Heat pumpt cost | 268 035 | 283 030 | 283 030 | 283 030 | EUR |
| End energy consumption | 806 854 | 751 992 | 736 619 | 504 119 | kWh/year |
| End energy price | 94 133 | 87 732 | 85 939 | 58 814 | EUR/year |
| PV cost | - | - | - | 300 000 | EUR |
| Installed kWp | - | - | - | 250 | kWp |
| Energy produced | - | - | - | 232 500 | kWh/year |
| Energy in-house | - | - | - | 232 500 | kWh/year |
| CO2 emissions nominal | 8,14 | 5,96 | 5,35 | 5,35 | kg/m2/year |
| CO2 emissions | 81,79 | 59,89 | 53,76 | 36,79 | ton/year |
| CO2 price | 4 089,54 | 2 994,30 | 2 687,84 | 1 839,47 | EUR |
| Technology extras | 1 815 311 | 1 837 368 | 1 837 368 | 1 837 368 | EUR |
| Design fee | 139 908 | 162 250 | 170 170 | 170 170 | EUR |
| Maintenance | 21 000 | 18 000 | 19 000 | 19 000 | EUR |

The energy values are based on simulations performed on the virtual test bed, Deliverable 4.9. In the CBA, we will also assume the following constants and boundary conditions:

| Name | Basic value | Units used |
|---|---|---|
| Consumption_decrease_for_MPC | 1,00 | - |
| Electricity price per kWh | 0,28 | EUR/kWh |
| Residual value | 0,25 | - |
| Calculation period | 30 | years |
| Discount rate | 1,50% | - |
| PV cost | 1 200 | EUR/kWh |
| Overall efficiency | 930 | kWh/kWp/year |
| In-house use ratio | 1,00 | - |
| CO2 price | 50,00 | EUR/ton |

Local energy factors for Belgium were used in the calculations, as described in Deliverable 4.9.

## 5.6. Financial net present value

When calculating the global net present value according to the above parameters, we get the results as shown in Figure 16 – Ter Potterie, Global NPV. Only cumulative costs of the variant-specific technologies are shown.. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

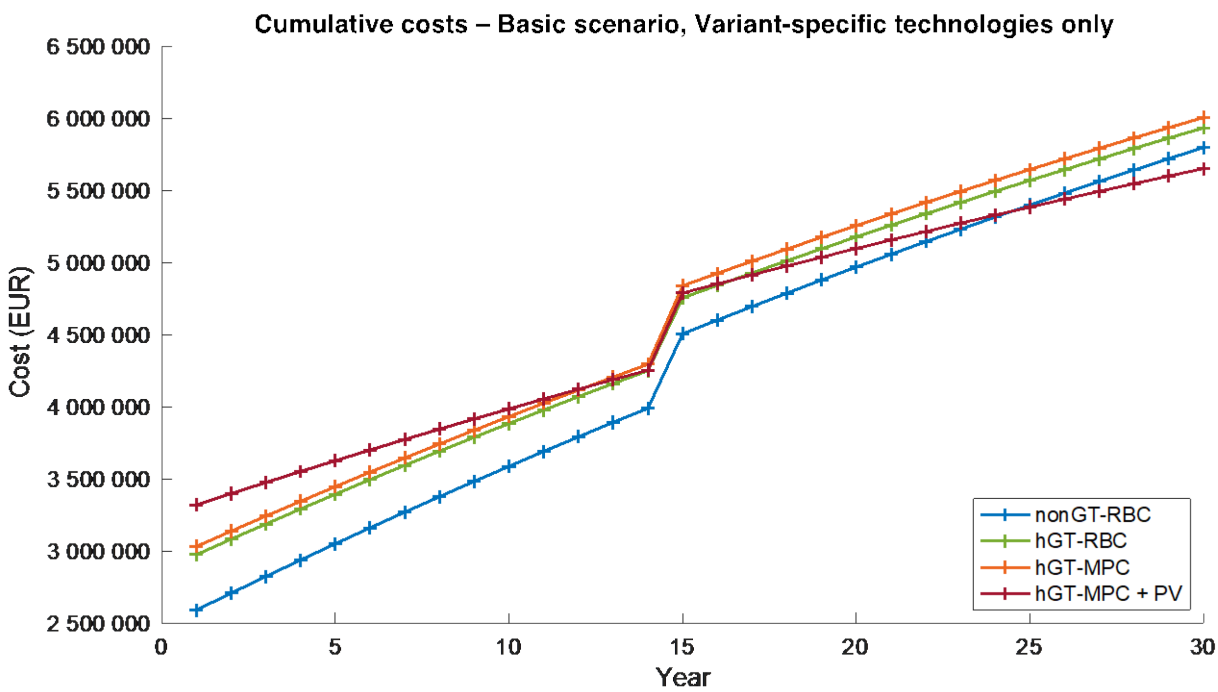



*Figure 16 – Ter Potterie, Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

Ter Potterie is an elderly home and has therefore high energy demands, regardless on the energy supply system. Its nominal energy consumption (73–81 kWh/m²/year) is fairly high, and thus the savings potential from the use of efficient energy sources is high as well. From the comparison of the cumulative costs for the four variants, we can see that all four are close to each other, with the hybridGEOTABS MPC + PV variant performing the best. The step in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced. The final cost performance overview in the form required by the EC Regulation No. 244/2012 is shown in Table 17 – Final cost performance overview of Ter Potterie.

*Table 17 – Final cost performance overview of Ter Potterie.*

| | | | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC,PV |
|---|---|---|---|---|---|---|---|---|---|
| | Variant | | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC,PV |
| | Initial investment cost | € | 29 601 309 | € | 29 996 017 | € | 30 053 937 | € | 30 369 444 |
| Annual running cost | Maintenance cost | € | 17 063 | € | 14 626 | € | 15 438 | € | 15 438 |
| | Operational cost (reinvestments) | € | 13 977 | € | 13 865 | € | 15 219 | € | 15 638 |
| | Energy cost by fuel with the medium energy price scenario | € | 76 486 | € | 71 286 | € | 69 828 | € | 47 788 |
| | Calculation period | | 30 | | 30 | | 30 | | 30 |
| | Cost of greenhouse gas emissions | € | 99 687 | € | 72 989 | € | 65 519 | € | 44 839 |
| | Residual value | € | 4 404 212 | € | 4 404 212 | € | 4 404 212 | € | 4 404 212 |
| | Discount rate | | 1,50% | | 1,50% | | 1,50% | | 1,50% |
| | Estimated economic lifetime | | 30 | | 30 | | 30 | | 30 |
| | Disposal cost | | N/A | | N/A | | N/A | | N/A |
| | Global cost calculated (NPV) | € | 30 477 806 | € | 30 657 718 | € | 30 737 336 | € | 30 383 551 |

The hybridGETOABS MPC + PV has lowest global cost calculated, outperforming even the baseline scenario. However, the global costs are very close to each other, within 1.2 % difference.

*Table 18 – Minimum annual income from Ter Potterie needed to achieve positive financial NPV.*

| | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC,PV | |
|---|---|---|---|---|---|---|---|---|
| Annual income needed to achieve positive financial NPV | € | 1 015 927 | € | 1 021 924 | € | 1 024 578 | € | 1 012 785 |

Table 18 shows the minimum income that the investor or owner needs to achieve from Ter Potterie, should the building yield positive profit. Note that the residual value is not included in this calculation.

## 5.7. Economic value

### 5.7.1. Financial value

Comparing the four variants, the financial value (in the sense of net present value) is shown in Table 19. Net present financial value of the four variants is very similar – this can be attributed to high energy demand of the building, as discussed earlier. The difference between the hybridGEOTABS, MPC and hybridGEOTABS, MPC + PV variant is €353 785, which about 1.2 % of the full price. It is therefore clear that the baseline variant, without a significant amount of renewables, is not competitive with the more advanced hybridGEOTABS variants.

*Table 19 – Financial value of Ter Potterie.*

| Variant | | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC,PV |
|---|---|---|---|---|---|---|---|---|
| Global cost (Net Present Value) | € | 30 477 806 | € | 30 657 718 | € | 30 737 336 | € | 30 383 551 |
| Difference between the variant and baseline (nonGT-RBC) | € | - | € | 179 912 | € | 259 530 | -€ | 94 256 |
| The variant being more expensive than baseline in % | | 0,00% | | 0,59% | | 0,84% | | -0,31% |

### 5.7.2. Energies and Environmental impact

As already mentioned, the energy values are based Deliverable 4.9 – Concept and impact validation for the case-study buildings based on the virtual test bed. Here, in Table 14, we show the summary of the energies and environmental impact of Ter Potterie.

*Table 20 – Ter Potterie: Environmental impact and energy requirements.*

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV | |
|---|---|---|---|---|---|
| **Nominal energy requirements** | 80,3 | 74,8 | 73,3 | 73,3 | kWh/m2/year |
| **End energy consumption** | 806 854 | 751 992 | 736 619 | 504 119 | kWh/year |
| **End energy price** | 94 133 | 87 732 | 85 939 | 58 814 | EUR/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 0 | 232 500 | kWh/year |
| **Total CO2 emissions** | 81,79 | 59,89 | 53,76 | 36,79 | ton/year |
| ***Nominal prices, not adjusted for inflation.*** | | | | | |

All three variants are quite close to each other also in the sense of environmental impact. The best environmental performance is for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building. Because of the high energy demand of the building, the installation of photovoltaic panels would provide a significant amount of energy, which the building is able to consume, and the environmental footprint is thus low.

### 5.7.3. Indoor environment quality

The TABS system provides in general a very good comfort associated with radiant heating and cooling. The advantage of the radiant heating and cooling is the better human temperature sensing, and the inhabitants of the building with TABS system may feel comfortable with ambient temperature lower by ca. 1 °C compared to traditional heating and cooling systems, such as radiators or FCUs. This can result of additional energy savings of 5–10 %. In addition, MPC control can slightly improve the indoor environment quality by better maintaining the desired indoor temperatures.

The mechanical ventilation system is controlled by $CO_2$ levels measured in the rooms, which provides excellent air quality and is in line with EU standards.

In general, the advantages and disadvantages of the TABS system concerning the indoor environment quality are as follows:

- Advantages
    - Better space utilization – minimum of heating, cooling or ventilation equipment is present or visible inside the building occupation spaces, which allows the inhabitants to use the space more freely
    - Radiant heating and cooling – better perceived by some people
    - Lower ventilation rates in comparison with air-conditioned buildings, which results in less draught and infection spreading
    - High stability – indoor air quality is quickly restored e.g. after a window is opened and closed
- Disadvantages
    - Sensitivity to additional installations – one has to be careful to not pierce through the pipes
    - Worse acoustics
    - High thermal inertia, inability to change temperature quickly – this is partially compensated by the secondary system

## 5.8. Sensitivity analysis and risk assessment

The sensitivity analysis shows the variation of the global financial value in the sense of NPV due to ± 1 % variation of the analysed variable and a criticality judgement – if the change of global financial value is more than 1 %, the variable is considered critical.

*Table 21 – Ter Potterie: Sensitivity analysis*

| | nonGT-RBC | | hGT-RBC | | hGT-MPC | | hGT-MPC+PV | |
|---|---|---|---|---|---|---|---|---|
| Variable | Variation | Criticality | Variation | Criticality | Variation | Criticality | Variation | Criticality |
| Discount rate | 0.022 % | No | 0.020 % | No | 0.020 % | No | 0.016 % | No |
| Energy tariff | 0.075 % | No | 0.070 % | No | 0.068 % | No | 0.047 % | No |
| $CO_2$ price | 0.0033 % | No | 0.0024 % | No | 0.0021 % | No | 0.0015 % | No |
| PV price | - | - | - | - | - | - | 0.0099 % | No |
| Heat pump price | 0.016 % | No | 0.017 % | No | 0.017 % | No | 0.017 % | No |
| Borefield price | - | - | 0.012 % | No | 0.011 % | No | 0.012 % | No |
| MPC savings | - | - | - | - | 1.4 % | No | 1.4 % | No |

We can see that the only critical variable for Ter Potterie is the MPC savings assumed ratio. Fiven very small differences in global financial values for the variants, energy tariff and discount rate can be considered as important parameters as well.

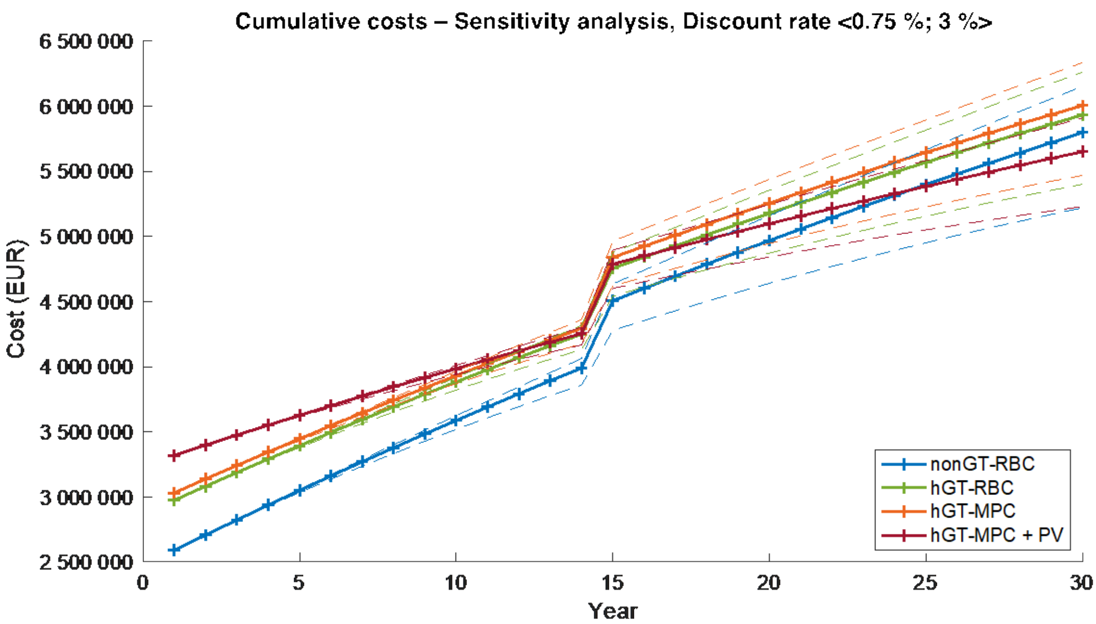



*Figure 17 – Ter Potterie: Sensitivity analysis, discount rate.*

The global financial value is indeed sensitive to variations of the discount rate for Ter Potterie. The nominal value for discount rate is 1.5 %, we have performed the sensitivity analysis for half and double the value, i.e. for 0.75 % and 3 %. All four variants are close to each other at the global financial value, and the variation of the discount rate can mix all variants up. The figure also shows that the hybridGEOTABS with MPC and PV is best influenced by high discount rate, while not sensitive to low discount rates.

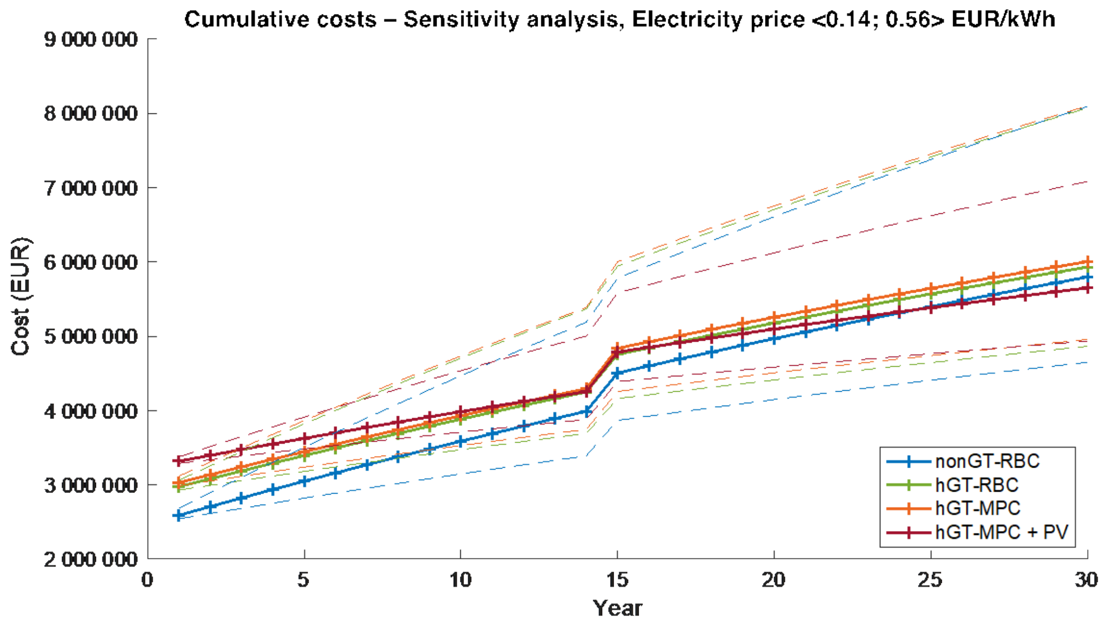



*Figure 18 – Ter Potterie: Sensitivity analysis, electricity price.*

The electricity price has an even more significant effect. Again, we took the half and the double of the nominal value. It can be seen that the benchmark case (nonTABS, RBC) is very sensitive to energy prices and can actually become more expensive than the hybridGEOTABS variants if electricity price increases by the factor of 2 and more. The least sensitive variant is the hybridGEOTABS with MPC and photovoltaics, which becomes significantly cheaper for high electricity prices.

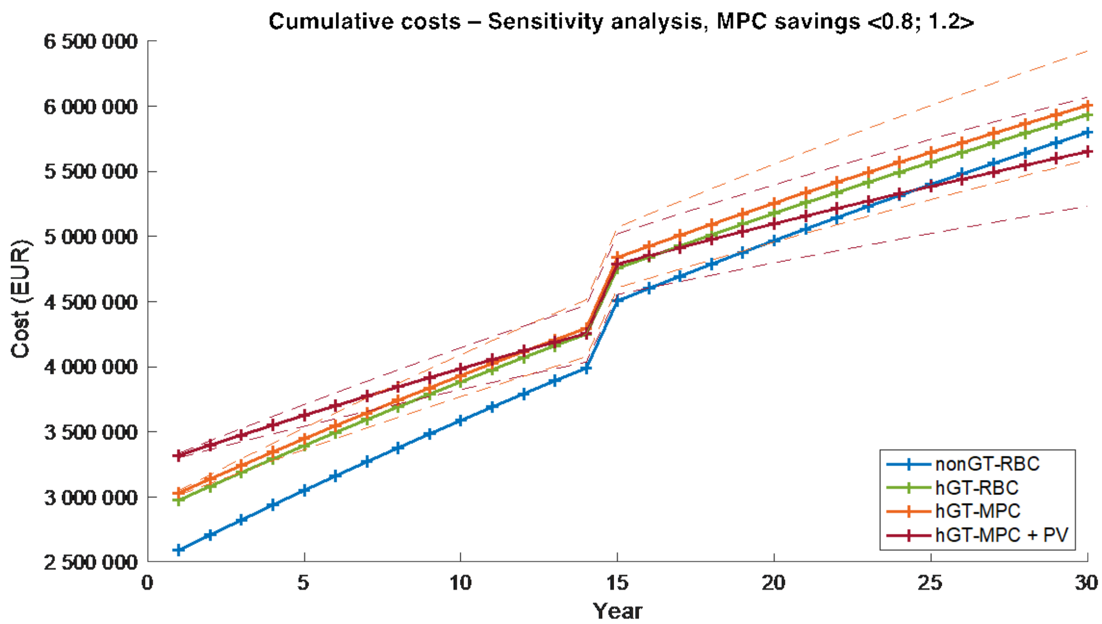



*Figure 19 – Ter Potterie: Sensitivity analysis, MPC savings.*

The MPC savings ratio is a critical variable, and we can see that it has a big effect on the last two variants, but it can be seen that for lower MPC effects, the variant without PV can become more expensive than the RBC variant. The PV variant remains on the safe side and can become much cheaper for even better MPC savings.

## 5.9. Conclusions

For Ter Potterie, the hybridGEOTABS variant with MPC and photovoltaics is the cheapest one in the sense of global financial value. It is also least sensitive to pessimistic scenarios, and performs significantly better even for small improvements of the MPC efficiency. The other three variants are very similar. The hybridGEOTABS with MPC and PV provides also the best environmental performance.

For better decision-making process, Table 22 presents the summary of the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. The preferred variant (hybridGEOTABS, MPC and PV) is highlighted. It can be seen that it is about 0.31 % cheaper than the baseline variant, and 0.90 % and 1.16 % cheaper than the hybridGEOTABS + RBC, and hybridGEOTABS + MPC variant, respectively. Its environmental impact is only about 45.0 % of the baseline, and 61.4 % and 68.4 % of the other two variants.

The yearly revenue of the Ter Potterie building, needed to pay-off the initial investment, is around €1 020 000, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 22 – Ter Potterie: Summary of the CBA results.*

**Ter Potterie**

**Global financial value (NPV) – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 0,00% | -0,59% | -0,85% | 0,31% |
| **hGT-RBC** | 0,59% | 0,00% | -0,26% | 0,89% |
| **hGT-MPC** | 0,84% | 0,26% | 0,00% | 1,15% |
| **hGT-MPC,PV** | -0,31% | -0,90% | -1,16% | 0,00% |

**CO2 footprint – comparison**

| | nonGT-RBC | hGT-RBC | hGT-MPC | hGT-MPC,PV |
|---|---|---|---|---|
| **nonGT-RBC** | 100,0% | 136,6% | 152,1% | 222,3% |
| **hGT-RBC** | 73,2% | 100,0% | 111,4% | 162,8% |
| **hGT-MPC** | 65,7% | 89,8% | 100,0% | 146,1% |
| **hGT-MPC,PV** | 45,0% | 61,4% | 68,4% | 100,0% |

# 6. Analysis of cases for various climatic zones

## 6.1. Objectives

In the previous chapters, we have shown a detailed CBA for the four case study buildings used in the hybridGEOTABS project. However, these study buildings are quite different from each other – it was the purpose of the project to show the hybridGEOTABS system on various types of buildings, but it also makes it difficult to draw general conclusions. We have developed a large set of building models in Deliverable 2.2 – A set of parametric geometries for the (sub)typologies studied, which are situated into the following three climatic zones:

- Warsaw / transitional temperate/transitional cold
- (Uccle) Brussels / Maritime temperate warm
- Madrid / continental intermediate subtropical

This set of building comprises various building types (offices, residential buildings, elderly homes), and we have chosen the office type for the comparison study.

As described in Deliverable 2.2, we are considering three types of buildings based upon the envelope properties (Table 23).

*Table 23 – Building envelope properties for the comparison study used in this chapter.*

| | U-Value opaque [W/m². K] | U-Value non-opaque [W/m². K] | Airtightness at n50 value 1/h | G-value glazing |
|---|---|---|---|---|
| Group(A) | 0.15 | 0.80 | 0.6 | 0.40 |
| Group(B) | 0.27 | 1.5 | 2.0 | 0.56 |
| Group(C) | 0.50 | 2.5 | 5 | 0.6 |

For a heavy mass building, we assume concrete structure, and timber structure for light mass. We have also two types of occupancies, as shown in Table 24.

*Table 24 – Office zones internal heat gains from appliances, occupancy and lighting.*

| Type | High density office (1p/10 m²) | Low density office (1p/20 m²) |
|---|---|---|
| Occupancy | 10.0 W/m² | 5.0 W/m² |
| Lighting | 8.0 W/m² | 8.0 W/m² |
| Appliances | 15.0 W/m² | 5.5 W/m² |
| Total | 33.0 W/m² | 18.5 W/m² |

The specific cases were chosen from the database collected within Deliverable 2.2, along with the energy consumption parameters. We have tried to choose the typical examples, with various types of envelope, mass and occupancy, always in the same climatic zone. The groups of chosen examples are shown in Table 25.

*Table 25 – Case sets for comparison study*

Set 01

| PHYS_ID | Climate | Envelope | Mass | Occupancy | Shading | Orientation |
|---|---|---|---|---|---|---|
| P021 | Brussels | GroupB | Heavy | Lowdense | YeSH | N |
| P069 | Warsaw | GroupB | Heavy | Lowdense | YeSH | N |
| P117 | Madrid | GroupB | Heavy | Lowdense | YeSH | N |

Set 02

| PHYS_ID | Climate | Envelope | Mass | Occupancy | Shading | Orientation |
|---|---|---|---|---|---|---|
| P003 | Brussels | GroupA | Heavy | Highdense | YeSH | W |
| P053 | Warsaw | GroupA | Heavy | Lowdense | YeSH | N |
| P133 | Madrid | GroupC | Heavy | Lowdense | YeSH | N |

Set 03

| PHYS_ID | Climate | Envelope | Mass | Occupancy | Shading | Orientation |
|---|---|---|---|---|---|---|
| P041 | Brussels | GroupC | Light | Highdense | YeSH | N |
| P089 | Warsaw | GroupC | Light | Highdense | YeSH | N |
| P137 | Madrid | GroupC | Light | Highdense | YeSH | N |

Set 04

| PHYS_ID | Climate | Envelope | Mass | Occupancy | Shading | Orientation |
|---|---|---|---|---|---|---|
| P027 | Brussels | GroupB | Light | Highdense | YeSH | W |
| P080 | Warsaw | GroupB | Light | Lowdense | NoSH | W |
| P141 | Madrid | GroupC | Light | Lowdense | YeSH | N |

## 6.2. Method

In order to be able to compare the buildings, we have not used national parameters for the CBA, but the EU average for the economic parameters (Table 26).

*Table 26 – General parameters for the comparison study.*

| Parameter | Value | Source |
|---|---|---|
| Primary energy factor – electricity | 2.0 | Eurostat |
| Primary energy factor – natural gas | 1.1 | Eurostat |
| CO2 emission factor – electricity | 0.260 kg/kWh | Eurostat |
| CO2 emission factor – natural gas | 0.220 kg/kWh | Eurostat |
| Monetary unit | EUR | – |
| Discount rate | 1.5 % | Eurostat |
| Electricity price | 0.21 EUR/kWh | Eurostat |
| Natural gas price | 0.066 EUR/kWh | Eurostat |
| $CO_2$ price (Emission Trading System) | 50 EUR/ton | ETS estimate as of 01/2021 |
| Gas boiler price – full installation | 130 EUR/kW | ENER[2] |
| Electric chiller – full installation | 280 EUR/kW | ENER |
| Ground source heat pump price – full installation | 480 EUR/kW | ENER |
| PV price | 1100 EUR/kWp | *Estimate* |
| Borefield cost | 60 EUR/m | *Estimate* |
| Basic construction cost | 2400 EUR/m² | FIAC |
| Basic design cost | 190 EUR/m² | *Estimate* |
| hybridGEOTABS specific construction cost | 45 EUR/m² | *Estimate* |
| hybridGEOTABS specific design cost | 19 EUR/m² | *Estimate* |
| MPC cost – flat | EUR 30 000 | *Estimate* |
| PV efficiency | Brussels: 930 kWh/kWp/year<br>Warsaw: 980 kWh/kWp/year<br>Madrid: 1580 kWh/kWp/year | |

The estimates were made as follows:

- PV Price, borefield cost – our own estimate based on the internal pricings of the consortium members
- Basic design cost, hybridGEOTABS specific costs (construction, design) – rounded average of the four case study buildings
- MPC cost – based on experience of Energoklastr from similar installations – the MPC has roughly the same price for the buildings, regardless on the size of the building

We will not consider maintenance costs for this comparison study.

[2] https://ec.europa.eu/energy/sites/ener/files/documents/mapping-hc-final_report-wp2.pdf

For the basic construction cost, we assume that for the B class of the EU energy level, which also corresponds to our class B. The difference to A or C will be calculated as 7 % (3).

## 6.3. Heavy building, medium insulated, low density occupancy

### 6.3.1. CBA Parameters

For the first set of building examples, we assume the following parameters, as specified in Table 27.

*Table 27 – Parameters for the first dataset (Heavy building, medium insulated, low density occupancy).*

| Name | Nominal value | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | Units used |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | - | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | m2 |
| Energy demand primary system heating | - | - | 23,5 | 23,5 | - | 22,0 | 22,0 | - | 13,3 | 13,3 | kWh/m2/year |
| Energy demand primary system Cooling | - | - | 12,4 | 12,4 | - | 11,6 | 11,6 | - | 13,3 | 13,3 | kWh/m2/year |
| Energy demand secondary system heating | - | 29,1 | 6,0 | 6,0 | 40,9 | 19,8 | 19,8 | 14,5 | 1,6 | 1,6 | kWh/m2/year |
| Energy demand secondary system Cooling | - | 13,6 | 1,5 | 1,5 | 14,0 | 3,2 | 3,2 | 29,2 | 16,3 | 16,3 | kWh/m2/year |
| Heat pump power | - | - | 18,3 | 18,3 | - | 19,2 | 19,2 | - | 17,1 | 17,1 | kW |
| Gas boiler power | - | 89,3 | 29,4 | 29,4 | 106,6 | 45,8 | 45,8 | 77,6 | 17,6 | 17,6 | kW |
| Chiller Power | - | 83,9 | 23,9 | 23,9 | 14,0 | 40,6 | 40,6 | 94,4 | 51,6 | 51,6 | kW |
| Borefield power | - | - | 20,4 | 20,4 | - | 22,0 | 22,0 | - | 17,1 | 17,1 | kw |
| Borefield lenght | - | - | 611,2 | 611,2 | - | 660,2 | 660,2 | - | 513,9 | 513,9 | m |
| Gas consumption | - | 83 452 | 14 282 | 14 282 | 117 356 | 47 260 | 47 260 | 41 694 | 3 808 | 3 808 | kWh/year |
| Electricity consumption heating | - | - | 11 242 | 11 242 | - | 10 498 | 10 498 | - | 6 383 | 6 383 | kWh/year |
| Electricity consumption cooling | - | 11 126 | 3 522 | 3 522 | 11 485 | 4 463 | 4 463 | 23 915 | 13 765 | 13 765 | kWh/year |
| Electricity production | - | - | - | 7 440 | - | - | 6 860 | - | - | 7 900 | kWh/year |
| Electricity total | - | 11 126 | 14 763 | 7 323 | 11 485 | 14 961 | 8 101 | 23 915 | 20 149 | 12 249 | kWh/year |
| SPF heat pump heating | 5,0 | | | | | | | | | | - |
| SPF heat pump cooling | 12,0 | | | | | | | | | | - |
| SPF chiller cooling | 3,5 | | | | | | | | | | - |
| Electricity Primary | 2,0 | 22 253 | 29 527 | 14 647 | 22 970 | 29 922 | 16 202 | 47 830 | 40 297 | 24 497 | kWh/year |
| Gas Primary | 1,1 | 91 797 | 15 710 | 15 710 | 129 092 | 51 986 | 51 986 | 45 863 | 4 189 | 4 189 | kWh/year |
| Electricity CO2 | 0,26 | 5,79 | 7,68 | 3,81 | 5,97 | 7,78 | 4,21 | 12,44 | 10,48 | 6,37 | ton/year |
| Gas CO2 | 0,22 | 20,20 | 3,46 | 3,46 | 28,40 | 11,44 | 11,44 | 10,09 | 0,92 | 0,92 | ton/year |
| CO2 emissions | - | 25,98 | 11,13 | 7,26 | 34,37 | 19,22 | 15,65 | 22,53 | 11,40 | 7,29 | ton/year |
| CO2 price | 50 | 1 299 | 557 | 363 | 1 719 | 961 | 782 | 1 126 | 570 | 365 | EUR |
| Gas Price - Total | 0,066 | 5 508 | 943 | 943 | 7 746 | 3 119 | 3 119 | 2 752 | 251 | 251 | EUR |
| Electricity Price - Total | 0,210 | 2 337 | 3 100 | 1 538 | 2 412 | 3 142 | 1 701 | 5 022 | 4 231 | 2 572 | EUR |
| Energy demand - total | - | 51,2 | 43,4 | 43,4 | 65,9 | 56,5 | 56,5 | 52,4 | 44,5 | 44,5 | kWh/m2/year |
| Construction_costs | 2 590 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | 6 192 690 | EUR |
| MPC_cost | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | EUR |
| Borefield_cost_total | 60 | - | 36 670 | 36 670 | - | 39 609 | 39 609 | - | 30 832 | 30 832 | EUR |
| Gas_boiler_cost | 130 | 11 605 | 3 818 | 3 818 | 13 861 | 5 955 | 5 955 | 10 089 | 2 294 | 2 294 | EUR |
| Heat_pump_cost | 480 | - | 8 801 | 8 801 | - | 9 200 | 9 200 | - | 8 222 | 8 222 | EUR |
| Chiller Cost | 280 | 23 502 | 6 698 | 6 698 | 3 923 | 11 365 | 11 365 | 26 439 | 14 460 | 14 460 | EUR |
| Consumption factor for MPC/RBC | 0,80 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | - |
| Electricity price per kWh | 0,210 | | | | | | | | | | EUR/kWh |
| Gas price per kWh | 0,066 | | | | | | | | | | EUR/kWh |
| End energy consumption | - | 114 050 | 45 237 | 30 357 | 152 062 | 81 908 | 68 188 | 93 693 | 44 486 | 28 686 | kWh/year |
| End energy price | - | 7 844 | 4 043 | 2 481 | 10 157 | 6 261 | 4 820 | 7 774 | 4 483 | 2 824 | EUR/year |
| Residual value | 0,25 | | | | | | | | | | - |
| Calculation period | 30 | | | | | | | | | | years |
| Discount rate | 1,5% | | | | | | | | | | - |
| PV cost | 1 100 | 0 | 0 | 8800 | 0 | 0 | 7700 | 0 | 0 | 5500 | EUR |
| Overall efficiency | 930 | 930 | 930 | 930 | 980 | 980 | 980 | 1580 | 1580 | 1580 | kWh/kWp/year |
| Installed kWp | - | 0 | 0 | 8 | 0 | 0 | 7 | 0 | 0 | 5 | kWp |
| Energy produced | - | 0 | 0 | 7440 | 0 | 0 | 6860 | 0 | 0 | 7900 | kWh/year |
| Technology extras | 45 | 0 | 107595 | 107595 | 0 | 107595 | 107595 | 0 | 107595 | 107595 | EUR |
| Design fee | 19 | 0 | 45429 | 45429 | 0 | 45429 | 45429 | 0 | 45429 | 45429 | EUR |

### 6.3.1. Global financial value

When calculating the global financial value according to the above parameters, we get the results as shown in Figure 20. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

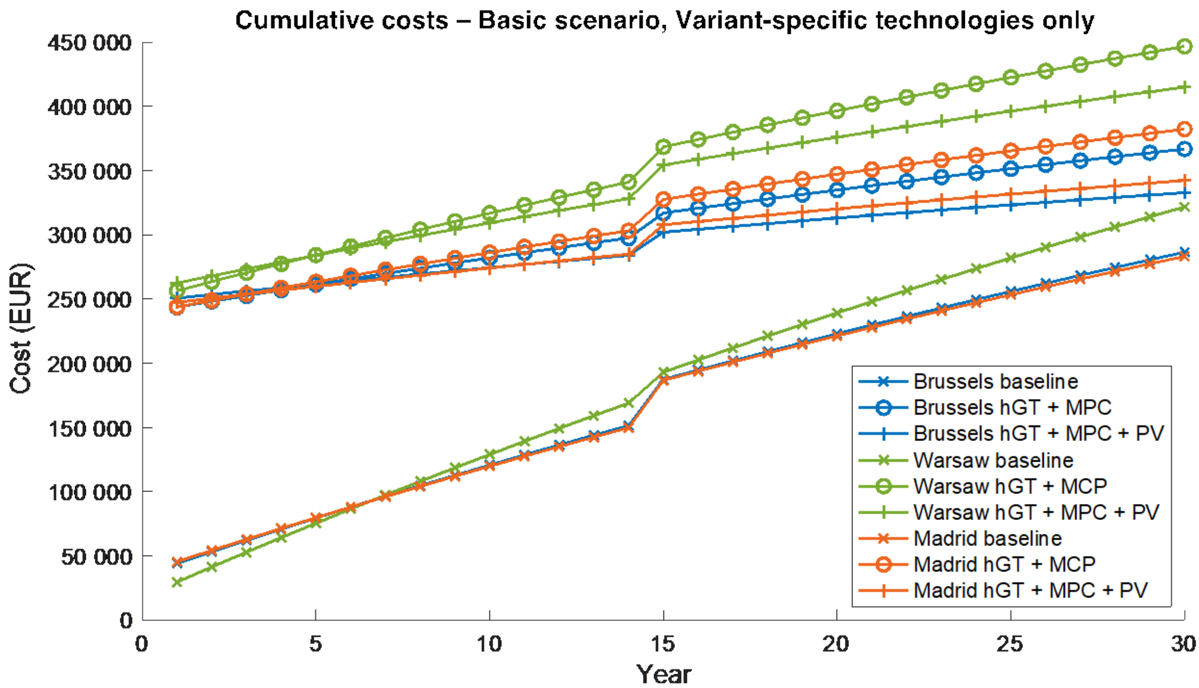



*Figure 20 – First data set (heavy building, medium insulated, low density occupancy), Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

We can see that the baseline scenario is always the cheapest one, despite its significantly higher energy and $CO_2$ costs. For all three climatic zones, the use of photovoltaics brings additional value to the hybridGEOTABS building. The step in Figure 20 in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced.

The final cost performance overview in the form required by the EC Regulation No. 244/2012 for all three climatic zones is shown in Table 28. The baseline variant has the lowest global cost calculated, but the hybridGEOTABS variant with MPC and PV is only less than 1 % more expensive for all three climatic zones.

*Table 28 – First data set (heavy building, medium insulated, low density occupancy) – Final cost performance overview.*

| | Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial investment cost | € 6 227 797 | € 6 431 701 | € 6 440 501 | € 6 210 474 | € 6 441 843 | € 6 449 543 | € 6 229 218 | € 6 431 523 | € 6 437 023 |
| Annual running cost | Maintenance cost | € - | € - | € - | € - | € - | € - | € - | € - | € - |
| | Operational cost (reinvestments) | € 950 | € 523 | € 523 | € 481 | € 718 | € 718 | € 989 | € 676 | € 676 |
| | Energy cost by fuel with the medium energy price scenario | € 6 374 | € 3 285 | € 2 016 | € 8 253 | € 5 087 | € 3 917 | € 6 317 | € 3 642 | € 2 294 |
| | Calculation period | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | € 31 666 | € 13 569 | € 8 854 | € 41 893 | € 23 421 | € 19 073 | € 27 454 | € 13 893 | € 8 886 |
| | Residual value | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 | € 1 005 320 |
| | Discount rate | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | € 5 473 860 | € 5 554 184 | € 5 520 183 | € 5 509 084 | € 5 634 091 | € 5 602 328 | € 5 470 507 | € 5 569 640 | € 5 529 693 |

Table 29 shows the minimum income that the investor or owner needs to achieve from the building, should the building yield positive profit. Note that the residual value is not included in this calculation.

*Table 29 – First data set (heavy building, medium insulated, low density occupancy) – Minimum annual income needed to achieve positive financial NPV.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| **Annual income needed to achieve positive financial NPV** | € 182 462 | € 185 139 | € 184 006 | € 183 636 | € 187 803 | € 186 744 | € 182 350 | € 185 655 | € 184 323 |

## 6.3.2. Economic value

Comparing all the variants, the financial value (in the sense of net present value) is shown in Table 30. Net present financial value of all the variants is very similar. The difference between the baseline and hybridGEOTABS with MPC is only about 1.5–1.8 % of the full price. It is therefore clear that the baseline variant, without a significant amount of renewables, is not competitive with the more advanced hybridGEOTABS variants.

*Table 30 – First data set (heavy building, medium insulated, low density occupancy) – Financial value.*

| **Variant** | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| **Global cost (Net Present Value)** | € 5 473 860 | € 5 554 184 | € 5 520 183 | € 5 509 084 | € 5 634 091 | € 5 602 328 | € 5 470 507 | € 5 569 640 | € 5 529 693 |
| **Difference between the variant and baseline (nonGT-RBC)** | € - | € 80 324 | € 46 324 | € - | € 125 008 | € 93 244 | € - | € 99 133 | € 59 186 |
| **The varinat being more expensive than baseline in %** | 0,00% | 1,45% | 0,84% | 0,00% | 2,22% | 1,66% | 0,00% | 1,78% | 1,07% |

Table 31 shows the summary of the energies and environmental impact of all the variants. We can see that the total $CO_2$ emissions are about three times lower for the hybridGEOTABS + MPC + PV variant than for the baseline.

*Table 31 – First data set (heavy building, medium insulated, low density occupancy) – Environmental impact and energy requirements.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal energy requirements** | 51,2 | 43,4 | 43,4 | 65,9 | 56,5 | 56,5 | 52,4 | 44,5 | 44,5 | kWh/m2/year |
| **Primary energy consumption** | 114 050 | 45 237 | 30 357 | 152 062 | 81 908 | 68 188 | 93 693 | 44 486 | 28 686 | kWh/year |
| **End energy price** | 7 844 | 4 043 | 2 481 | 10 157 | 6 261 | 4 820 | 7 774 | 4 483 | 2 824 | EUR/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 7440 | 0 | 0 | 6 860 | 0 | 0 | 7 900 | kWh/year |
| **Total CO2 emissions** | 25,98 | 11,13 | 7,26 | 34,37 | 19,22 | 15,65 | 22,53 | 11,40 | 7,29 | ton/year |

*Nominal prices, not adjusted for inflation.*

The best environmental performance is always for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 6.3.1. Conclusions

For the first data set (heavy building, medium insulated, low density occupancy), the baseline variant is the cheapest one in the sense of global financial value. However, the other two variants are very similar. The hybridGEOTABS with MPC and PV provides the best environmental performance.

As a summary, Table 32 presents the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. It can be seen that the preferred variant, hybridGEOTABS with MPC and PV it is 0.84–1.66 % more expensive than the baseline variant, and 0.57–0.72 % cheaper than the hybridGEOTABS with MPC variant. Its environmental impact is only 28.0–45.5 % of the baseline, and 64.0–81.4 % of the hybridGEOTABS with MPC variant.

The yearly revenue of the building, needed to pay-off the initial investment, stays around €185 000 for all variants, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 32 – First data set (heavy building, medium insulated, low density occupancy) – CBA Summary*

**Heavy building, medium insulated, low density occupancy**

**Global financial value (MPV) – comparison**

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Brussels - benchmark | 0,00% | -1,47% | -0,85% | -0,64% | -2,93% | -2,35% | 0,06% | -1,75% | -1,02% |
| Brussels - hGT | 1,45% | 0,00% | 0,61% | 0,81% | -1,44% | -0,87% | 1,51% | -0,28% | 0,44% |
| Brussels - hGT + PV | 0,84% | -0,62% | 0,00% | 0,20% | -2,06% | -1,49% | 0,90% | -0,90% | -0,17% |
| Warsaw - benchmark | 0,64% | -0,82% | -0,20% | 0,00% | -2,27% | -1,69% | 0,70% | -1,10% | -0,37% |
| Warsaw - hGT | 2,84% | 1,42% | 2,02% | 2,22% | 0,00% | 0,56% | 2,90% | 1,14% | 1,85% |
| Warsaw - hGT + PV | 2,29% | 0,86% | 1,47% | 1,66% | -0,57% | 0,00% | 2,35% | 0,58% | 1,30% |
| Madrid - benchmark | -0,06% | -1,53% | -0,91% | -0,71% | -2,99% | -2,41% | 0,00% | -1,81% | -1,08% |
| Madrid - hGT | 1,72% | 0,28% | 0,89% | 1,09% | -1,16% | -0,59% | 1,78% | 0,00% | 0,72% |
| Madrid - hGT + PV | 1,01% | -0,44% | 0,17% | 0,37% | -1,89% | -1,31% | 1,07% | -0,72% | 0,00% |

**CO2 footprint – comparison**

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Brussels - benchmark | 100,0% | 233,4% | 357,6% | 75,6% | 135,2% | 166,0% | 115,3% | 227,9% | 356,4% |
| Brussels - hGT | 42,9% | 100,0% | 153,3% | 32,4% | 57,9% | 71,1% | 49,4% | 97,7% | 152,7% |
| Brussels - hGT + PV | 28,0% | 65,2% | 100,0% | 21,1% | 37,8% | 46,4% | 32,2% | 63,7% | 99,6% |
| Warsaw - benchmark | 132,3% | 308,7% | 473,2% | 100,0% | 178,9% | 219,6% | 152,6% | 301,5% | 471,4% |
| Warsaw - hGT | 74,0% | 172,6% | 264,5% | 55,9% | 100,0% | 122,8% | 85,3% | 168,6% | 263,6% |
| Warsaw - hGT + PV | 60,2% | 140,6% | 215,4% | 45,5% | 81,4% | 100,0% | 69,5% | 137,3% | 214,6% |
| Madrid - benchmark | 86,7% | 202,3% | 310,1% | 65,5% | 117,2% | 143,9% | 100,0% | 197,6% | 309,0% |
| Madrid - hGT | 43,9% | 102,4% | 156,9% | 33,2% | 59,3% | 72,8% | 50,6% | 100,0% | 156,3% |
| Madrid - hGT + PV | 28,1% | 65,5% | 100,4% | 21,2% | 37,9% | 46,6% | 32,4% | 64,0% | 100,0% |

# 6.4. Heavy building, well insulated, low density occupancy

## 6.4.1. CBA Parameters

For the second set of building examples, we assume the following parameters, as specified in Table 27. The basic construction cost has been increased by 7 %, which corresponds to the increase in one energy level in the energy labelling scheme, as proposed by the research conducted for the energy plus houses in Germany (3).

*Table 33 – Parameters for the second dataset (Heavy building, well insulated, low density occupancy).*

| Name | Nominal value | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | Units used |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| Area | - | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | m2 |
| Energy demand primary system heating | - | - | 3,7 | 3,7 | - | 14,2 | 14,2 | - | 45,9 | 45,9 | kWh/m2/year |
| Energy demand primary system Cooling | - | - | 4,4 | 4,4 | - | 10,9 | 10,9 | - | 24,3 | 24,3 | kWh/m2/year |
| Energy demand secondary system heating | - | 4,1 | 1,0 | 1,0 | 15,8 | 2,2 | 2,2 | 14,5 | 4,1 | 4,1 | kWh/m2/year |
| Energy demand secondary system Cooling | - | 28,6 | 24,9 | 24,9 | 12,0 | 1,6 | 1,6 | 29,2 | 2,5 | 2,5 | kWh/m2/year |
| Heat pump power | - | - | 10,9 | 10,9 | - | 14,3 | 14,3 | - | 46,2 | 46,2 | kW |
| Gas boiler power | - | 56,5 | 12,8 | 12,8 | 66,1 | 14,9 | 14,9 | 120,8 | 25,6 | 25,6 | kW |
| Chiller Power | - | 105,7 | 40,6 | 40,6 | 12,0 | 26,0 | 26,0 | 107,0 | 37,7 | 37,7 | kW |
| Borefield power | - | - | 12,1 | 12,1 | - | 18,8 | 18,8 | - | 48,3 | 48,3 | kw |
| Borefield lenght | - | - | 363,6 | 363,6 | - | 562,8 | 562,8 | - | 1 448,6 | 1 448,6 | m |
| | | | | | | | | | | | |
| Gas consumption | - | 11 675 | 2 415 | 2 415 | 45 345 | 5 255 | 5 255 | 41 687 | 9 698 | 9 698 | kWh/year |
| Electricity consumption heating | - | - | 1 772 | 1 772 | - | 6 780 | 6 780 | - | 21 962 | 21 962 | kWh/year |
| Electricity consumption cooling | - | 23 444 | 17 889 | 17 889 | 9 817 | 3 281 | 3 281 | 23 911 | 6 536 | 6 536 | kWh/year |
| Electricity production | - | - | - | 9 300 | - | - | 5 880 | - | - | 14 220 | kWh/year |
| Electricity total | - | 23 444 | 19 661 | 10 361 | 9 817 | 10 061 | 4 181 | 23 911 | 28 498 | 14 278 | kWh/year |
| SPF heat pump heating | 5,0 | | | | | | | | | | - |
| SPF heat pump cooling | 12,0 | | | | | | | | | | - |
| SPF chiller cooling | 3,5 | | | | | | | | | | - |
| | | | | | | | | | | | |
| Electricity Primary | 2,0 | 46 888 | 39 322 | 20 722 | 19 634 | 20 122 | 8 362 | 47 822 | 56 997 | 28 557 | kWh/year |
| Gas Primary | 1,1 | 12 842 | 2 656 | 2 656 | 49 880 | 5 780 | 5 780 | 45 856 | 10 668 | 10 668 | kWh/year |
| | | | | | | | | | | | |
| Electricity CO2 | 0,26 | 12,19 | 10,22 | 5,39 | 5,10 | 5,23 | 2,17 | 12,43 | 14,82 | 7,42 | ton/year |
| Gas CO2 | 0,22 | 2,83 | 0,58 | 0,58 | 10,97 | 1,27 | 1,27 | 10,09 | 2,35 | 2,35 | ton/year |
| CO2 emissions | - | 15,02 | 10,81 | 5,97 | 16,08 | 6,50 | 3,45 | 22,52 | 17,17 | 9,77 | ton/year |
| CO2 price | 50 | 751 | 540 | 299 | 804 | 325 | 172 | 1 126 | 858 | 489 | EUR |
| | | | | | | | | | | | |
| Gas Price - Total | 0,066 | 771 | 159 | 159 | 2 993 | 347 | 347 | 2 751 | 640 | 640 | EUR |
| Electricity Price - Total | 0,210 | 4 923 | 4 129 | 2 176 | 2 062 | 2 113 | 878 | 5 021 | 5 985 | 2 998 | EUR |
| | | | | | | | | | | | |
| Energy demand - total | - | 39,2 | 34,0 | 34,0 | 33,3 | 28,9 | 28,9 | 52,4 | 76,8 | 76,8 | kWh/m2/year |
| | | | | | | | | | | | |
| Construction_costs | 2 771 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | 6 625 070 | EUR |
| MPC_cost | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | EUR |
| Borefield_cost_total | 60 | - | 21 817 | 21 817 | - | 33 768 | 33 768 | - | 86 918 | 86 918 | EUR |
| Gas_boiler_cost | 130 | 7 351 | 1 670 | 1 670 | 8 588 | 1 936 | 1 936 | 15 700 | 3 325 | 3 325 | EUR |
| Heat_pump_cost | 480 | - | 5 236 | 5 236 | - | 6 843 | 6 843 | - | 22 193 | 22 193 | EUR |
| Chiller Cost | 280 | 29 603 | 11 368 | 11 368 | 3 354 | 7 276 | 7 276 | 29 972 | 10 543 | 10 543 | EUR |
| | | | | | | | | | | | |
| Consumption factor for MPC/RBC | 0,80 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | - |
| Electricity price per kWh | 0,210 | | | | | | | | | | EUR/kWh |
| Gas price per kWh | 0,066 | | | | | | | | | | EUR/kWh |
| End energy consumption | - | 59 730 | 41 978 | 23 378 | 69 514 | 25 902 | 14 142 | 93 678 | 67 664 | 39 224 | kWh/year |
| End energy price | - | 5 694 | 4 288 | 2 335 | 5 054 | 2 460 | 1 225 | 7 773 | 6 625 | 3 639 | EUR/year |
| Residual value | 0,25 | | | | | | | | | | - |
| Calculation period | 30 | | | | | | | | | | years |
| Discount rate | 1,5% | | | | | | | | | | - |
| PV cost | 1 100 | 0 | 0 | 11000 | 0 | 0 | 6600 | 0 | 0 | 9900 | EUR |
| Overall efficiency | 930 | 930 | 930 | 930 | 980 | 980 | 980 | 1580 | 1580 | 1580 | kWh/kWp/year |
| | | | | | | | | | | | |
| Installed kWp | - | 0 | 0 | 10 | 0 | 0 | 6 | 0 | 0 | 9 | kWp |
| Energy produced | - | 0 | 0 | 9300 | 0 | 0 | 5880 | 0 | 0 | 14220 | kWh/year |
| | | | | | | | | | | | |
| Technology extras | 45 | 0 | 107577 | 107577 | 0 | 107577 | 107577 | 0 | 107577 | 107577 | EUR |
| Design fee | 19 | 0 | 45421,4 | 45421,4 | 0 | 45421,4 | 45421,4 | 0 | 45421,4 | 45421,4 | EUR |

## 6.4.2. Global financial value

When calculating the global financial value according to the above parameters, we get the results as shown in Figure 21. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

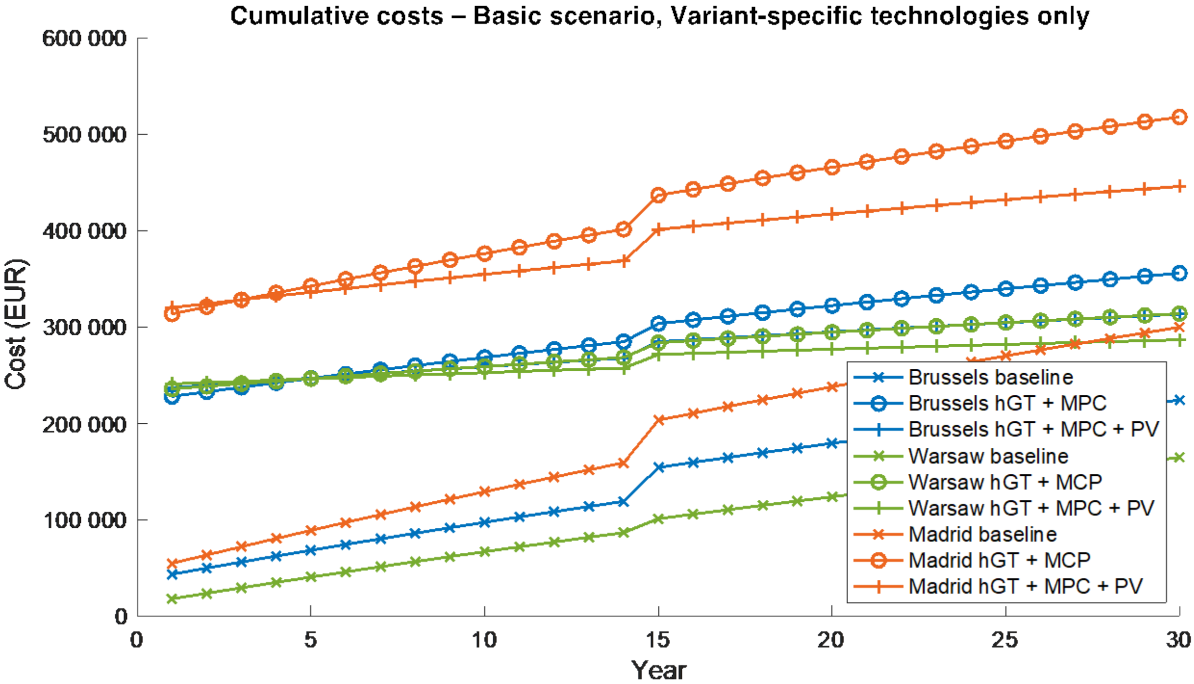



*Figure 21 – Second dataset (heavy building, well insulated, low density occupancy), Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

We can see that the baseline scenario is always the cheapest one again, despite its significantly higher energy and $CO_2$ costs. For all three climatic zones, the use of photovoltaics brings additional value to the hybridGEOTABS building, which is most significant for the Madrid building. The step in Figure 21 in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced.

The final cost performance overview in the form required by the EC Regulation No. 244/2012 for all three climatic zones is shown in Table 34. The baseline variant has the lowest global cost calculated, but the hybridGEOTABS variant with MPC and PV is about 1.5–2.5 % more expensive for all three climatic zones.

*Table 34 – Second dataset (heavy building, well insulated, low density occupancy) – Final cost performance overview.*

| | Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial investment cost | € 6 662 024 | € 6 848 160 | € 6 859 160 | € 6 637 012 | € 6 857 891 | € 6 864 491 | € 6 670 741 | € 6 931 047 | € 6 940 947 |
| Annual running cost | Maintenance cost | € - | € - | € - | € - | € - | € - | € - | € - | € - |
| | Operational cost (reinvestments) | € 1 000 | € 495 | € 495 | € 323 | € 434 | € 434 | € 1 236 | € 976 | € 976 |
| | Energy cost by fuel with the medium energy price scenario | € 4 626 | € 3 484 | € 1 897 | € 4 107 | € 1 998 | € 995 | € 6 316 | € 5 383 | € 2 956 |
| | Calculation period | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | € 18 302 | € 13 173 | € 7 279 | € 19 596 | € 7 926 | € 4 200 | € 27 450 | € 20 922 | € 11 910 |
| | Residual value | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 | € 1 075 512 |
| | Discount rate | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | € 5 773 607 | € 5 905 187 | € 5 862 687 | € 5 713 997 | € 5 863 295 | € 5 836 069 | € 5 849 224 | € 6 067 217 | € 5 995 313 |

Table 35 shows the minimum income that the investor or owner needs to achieve from the building, should the building yield positive profit. Note that the residual value is not included in this calculation.

*Table 35 – Second dataset (heavy building, well insulated, low density occupancy) – Minimum annual income needed to achieve positive financial NPV.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Annual income needed to achieve positive financial NPV | € 192 454 | € 196 840 | € 195 423 | € 190 467 | € 195 443 | € 194 536 | € 194 974 | € 202 241 | € 199 844 |

## 6.4.3. Economic value

Comparing all the variants, the financial value (in the sense of net present value) is shown in Table 36. Net present financial value of all the variants is similar, but larger than the previous case – this may be caused by higher, but different demands for the better insulation in various climates. The difference between the baseline and hybridGEOTABS with MPC is only about 2.5 % of the full price. It is again clear that the baseline variant, without a significant amount of renewables, is not competitive with the more advanced hybridGEOTABS variants.

*Table 36 – Second dataset (heavy building, well insulated, low density occupancy) – Financial value.*

| Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Global cost (Net Present Value) | € 5 773 607 | € 5 905 187 | € 5 862 687 | € 5 713 997 | € 5 863 295 | € 5 836 069 | € 5 849 224 | € 6 067 217 | € 5 995 313 |
| Difference between the variant and baseline (non GT-RBC) | € - | € 131 580 | € 89 080 | € - | € 149 298 | € 122 071 | € - | € 217 994 | € 146 090 |
| The varinat being more expensive than baseline in % | 0,00% | 2,23% | 1,52% | 0,00% | 2,55% | 2,09% | 0,00% | 3,59% | 2,44% |

Table 37 shows the summary of the energies and environmental impact of all the variants. We can see that the total $CO_2$ emissions are about three times lower for the hybridGEOTABS + MPC + PV variant than for the baseline for Brussels, about five times lower for Warsaw, and only about a half for Madrid.

*Table 37 – Second dataset (heavy building, well insulated, low density occupancy) – Environmental impact and energy requirements.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nominal energy requirements | 39,2 | 34,0 | 34,0 | 33,3 | 28,9 | 28,9 | 52,4 | 76,8 | 76,8 | kWh/m2/year |
| Primary energy consumption | 59 730 | 41 978 | 23 378 | 69 514 | 25 902 | 14 142 | 93 678 | 67 664 | 39 224 | kWh/year |
| End energy price | 5 694 | 4 288 | 2 335 | 5 054 | 2 460 | 1 225 | 7 773 | 6 625 | 3 639 | EUR/year |
| Renewable energy generation & self-consumption | 0 | 0 | 9300 | 0 | 0 | 5 880 | 0 | 0 | 14 220 | kWh/year |
| Total CO2 emissions | 15,02 | 10,81 | 5,97 | 16,08 | 6,50 | 3,45 | 22,52 | 17,17 | 9,77 | ton/year |

*Nominal prices, not adjusted for inflation.*

The best environmental performance is always for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 6.4.4. Conclusions

For the second data set (heavy building, well insulated, low density occupancy), the baseline variant is the cheapest one in the sense of global financial value. However, the other two variants are very similar, even though not as similar as in the first dataset. The hybridGEOTABS with MPC and PV provides the best environmental performance.

As a summary, Table 38 presents the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. It can be seen that the preferred variant, hybridGEOTABS with MPC and PV it is 1.52–2.44 % more expensive than the baseline variant, and 0.47–1.20 % cheaper than the hybridGEOTABS with MPC variant. Its environmental impact is only 21.4–43.4 % of the baseline, and 53.0–56.9 % of the hybridGEOTABS with MPC variant. It is to be noted that for the colder climate (Warsaw) the more environmentally friendly technologies give better global financial costs than for the two other climates.

The yearly revenue of the building, needed to pay-off the initial investment, stays around €190 000 – €200 000 for all variants, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 38 – Second dataset (heavy building, well insulated, low density occupancy) – CBA Summary*

| Heavy building, well insulated, low density occupancy | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Global financial value (MPV) – comparison | | | | | | | | | |
| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
| Brussels - benchmark | 0,00% | -2,28% | -1,54% | 1,03% | -1,55% | -1,08% | -1,31% | -5,09% | -3,84% |
| Brussels - hGT | 2,23% | 0,00% | 0,72% | 3,24% | 0,71% | 1,17% | 0,95% | -2,74% | -1,53% |
| Brussels - hGT + PV | 1,52% | -0,72% | 0,00% | 2,54% | -0,01% | 0,45% | 0,23% | -3,49% | -2,26% |
| Warsaw - benchmark | -1,04% | -3,35% | -2,60% | 0,00% | -2,61% | -2,14% | -2,37% | -6,18% | -4,92% |
| Warsaw - hGT | 1,53% | -0,71% | 0,01% | 2,55% | 0,00% | 0,46% | 0,24% | -3,48% | -2,25% |
| Warsaw - hGT + PV | 1,07% | -1,18% | -0,46% | 2,09% | -0,47% | 0,00% | -0,23% | -3,96% | -2,73% |
| Madrid - benchmark | 1,29% | -0,96% | -0,23% | 2,31% | -0,24% | 0,22% | 0,00% | -3,73% | -2,50% |
| Madrid - hGT | 4,84% | 2,67% | 3,37% | 5,82% | 3,36% | 3,81% | 3,59% | 0,00% | 1,19% |
| Madrid - hGT + PV | 3,70% | 1,50% | 2,21% | 4,69% | 2,20% | 2,66% | 2,44% | -1,20% | 0,00% |

| CO2 footprint – comparison | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
| Brussels - benchmark | 100,0% | 138,9% | 251,4% | 93,4% | 230,9% | 435,8% | 66,7% | 87,5% | 153,7% |
| Brussels - hGT | 72,0% | 100,0% | 181,0% | 67,2% | 166,2% | 313,7% | 48,0% | 63,0% | 110,6% |
| Brussels - hGT + PV | 39,8% | 55,3% | 100,0% | 37,1% | 91,8% | 173,3% | 26,5% | 34,8% | 61,1% |
| Warsaw - benchmark | 107,1% | 148,8% | 269,2% | 100,0% | 247,2% | 466,6% | 71,4% | 93,7% | 164,5% |
| Warsaw - hGT | 43,3% | 60,2% | 108,9% | 40,4% | 100,0% | 188,7% | 28,9% | 37,9% | 66,6% |
| Warsaw - hGT + PV | 22,9% | 31,9% | 57,7% | 21,4% | 53,0% | 100,0% | 15,3% | 20,1% | 35,3% |
| Madrid - benchmark | 150,0% | 208,4% | 377,1% | 140,1% | 346,3% | 653,6% | 100,0% | 131,2% | 230,5% |
| Madrid - hGT | 114,3% | 158,8% | 287,4% | 106,8% | 264,0% | 498,2% | 76,2% | 100,0% | 175,7% |
| Madrid - hGT + PV | 65,1% | 90,4% | 163,6% | 60,8% | 150,3% | 283,6% | 43,4% | 56,9% | 100,0% |

## 6.5. Light building, poorly insulated, high density occupancy

### 6.5.1. CBA Parameters

For the third set of building examples, we assume the following parameters, as specified in Table 39. The basic construction costs have been lowered by 7 % for the poorly insulated building, which corresponds to the difference in one energy class in the energy label (for explanation, see (3)).

*Table 39 – Parameters for the third dataset (Light building, poorly insulated, high density occupancy).*

| Name | Nominal value | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | Units used |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | - | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | m2 |
| Energy demand primary system heating | - | - | 21,3 | 21,3 | - | 12,0 | 12,0 | - | 36,0 | 36,0 | kWh/m2/year |
| Energy demand primary system Cooling | - | - | 11,3 | 11,3 | - | 6,0 | 6,0 | - | 32,9 | 32,9 | kWh/m2/year |
| Energy demand secondary system heating | - | 68,1 | 47,5 | 47,5 | 94,0 | 85,0 | 85,0 | 14,5 | 5,2 | 5,2 | kWh/m2/year |
| Energy demand secondary system Cooling | - | 14,0 | 3,4 | 3,4 | 12,0 | 8,0 | 8,0 | 29,2 | 5,3 | 5,3 | kWh/m2/year |
| Heat pump power | - | - | 27,4 | 27,4 | - | 22,0 | 22,0 | - | 56,1 | 56,1 | kW |
| Gas boiler power | - | 140,7 | 69,7 | 69,7 | 170,0 | 109,0 | 109,0 | 120,8 | 34,7 | 34,7 | kW |
| Chiller Power | - | 125,7 | 40,7 | 40,7 | 12,0 | 73,0 | 73,0 | 141,7 | 59,7 | 59,7 | kW |
| Borefield power | - | - | 32,5 | 32,5 | - | 25,0 | 25,0 | - | 56,6 | 56,6 | kw |
| Borefield lenght | - | - | 973,9 | 973,9 | - | 744,0 | 744,0 | - | 1 697,5 | 1 697,5 | m |
| | | | | | | | | | | | |
| Gas consumption | - | 195 287 | 113 459 | 113 459 | 269 705 | 203 235 | 203 235 | 41 687 | 12 375 | 12 375 | kWh/year |
| Electricity consumption heating | - | - | 10 202 | 10 202 | - | 5 738 | 5 738 | - | 17 215 | 17 215 | kWh/year |
| Electricity consumption cooling | - | 11 481 | 4 548 | 4 548 | 9 837 | 6 661 | 6 661 | 23 911 | 10 162 | 10 162 | kWh/year |
| Electricity production | - | - | - | 7 440 | - | - | 5 880 | - | - | 14 220 | kWh/year |
| Electricity total | - | 11 481 | 14 750 | 7 310 | 9 837 | 12 399 | 6 519 | 23 911 | 27 377 | 13 157 | kWh/year |
| SPF heat pump heating | 5,0 | | | | | | | | | | - |
| SPF heat pump cooling | 12,0 | | | | | | | | | | - |
| SPF chiller cooling | 3,5 | | | | | | | | | | - |
| | | | | | | | | | | | |
| Electricity Primary | 2,0 | 22 962 | 29 499 | 14 619 | 19 675 | 24 798 | 13 038 | 47 822 | 54 754 | 26 314 | kWh/year |
| Gas Primary | 1,1 | 214 816 | 124 804 | 124 804 | 296 675 | 223 559 | 223 559 | 45 856 | 13 612 | 13 612 | kWh/year |
| | | | | | | | | | | | |
| Electricity CO2 | 0,26 | 5,97 | 7,67 | 3,80 | 5,12 | 6,45 | 3,39 | 12,43 | 14,24 | 6,84 | ton/year |
| Gas CO2 | 0,22 | 47,26 | 27,46 | 27,46 | 65,27 | 49,18 | 49,18 | 10,09 | 2,99 | 2,99 | ton/year |
| CO2 emissions | - | 53,23 | 35,13 | 31,26 | 70,38 | 55,63 | 52,57 | 22,52 | 17,23 | 9,84 | ton/year |
| CO2 price | 50 | 2 661 | 1 756 | 1 563 | 3 519 | 2 782 | 2 629 | 1 126 | 862 | 492 | EUR |
| | | | | | | | | | | | |
| Gas Price - Total | 0,066 | 12 889 | 7 488 | 7 488 | 17 801 | 13 414 | 13 414 | 2 751 | 817 | 817 | EUR |
| Electricity Price - Total | 0,210 | 2 411 | 3 097 | 1 535 | 2 066 | 2 604 | 1 369 | 5 021 | 5 749 | 2 763 | EUR |
| | | | | | | | | | | | |
| Energy demand - total | - | 98,5 | 83,4 | 83,4 | 127,2 | 111,0 | 111,0 | 52,4 | 79,4 | 79,4 | kWh/m2/year |
| | | | | | | | | | | | |
| Construction_costs | 2 409 | 5 758 238 | 5 758 238 | 5 758 238 | 5 759 202 | 5 759 202 | 5 759 202 | 5 758 238 | 5 758 238 | 5 758 238 | EUR |
| MPC_cost | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | EUR |
| Borefield_cost_total | 60 | - | 58 432 | 58 432 | - | 44 640 | 44 640 | - | 101 848 | 101 848 | EUR |
| Gas_boiler_cost | 130 | 18 289 | 9 067 | 9 067 | 22 100 | 14 170 | 14 170 | 15 700 | 4 513 | 4 513 | EUR |
| Heat_pump_cost | 480 | - | 13 162 | 13 162 | - | 10 560 | 10 560 | - | 26 934 | 26 934 | EUR |
| Chiller Cost | 280 | 35 186 | 11 394 | 11 394 | 3 360 | 20 440 | 20 440 | 39 677 | 16 725 | 16 725 | EUR |
| | | | | | | | | | | | |
| Consumption factor for MPC/RBC | 0,80 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | - |
| Electricity price per kWh | 0,210 | | | | | | | | | | EUR/kWh |
| Gas price per kWh | 0,066 | | | | | | | | | | EUR/kWh |
| End energy consumption | - | 237 778 | 154 304 | 139 424 | 316 350 | 248 357 | 236 597 | 93 678 | 68 366 | 39 926 | kWh/year |
| End energy price | - | 15 300 | 10 586 | 9 023 | 19 866 | 16 017 | 14 783 | 7 773 | 6 566 | 3 580 | EUR/year |
| Residual value | 0,25 | | | | | | | | | | - |
| Calculation period | 30 | | | | | | | | | | years |
| Discount rate | 1,5% | | | | | | | | | | - |
| PV cost | 1 100 | 0 | 0 | 8800 | 0 | 0 | 6600 | 0 | 0 | 9900 | EUR |
| Overall efficiency | 930 | 930 | 930 | 930 | 980 | 980 | 980 | 1580 | 1580 | 1580 | kWh/kWp/year |
| | | | | | | | | | | | |
| Installed kWp | - | 0 | 0 | 8 | 0 | 0 | 6 | 0 | 0 | 9 | kWp |
| Energy produced | - | - | - | 7 440 | - | - | 5 880 | - | - | 14 220 | kWh/year |
| | | | | | | | | | | | |
| Technology extras | 45 | 0 | 107 577 | 107 577 | - | 107 595 | 107 595 | - | 107 577 | 107 577 | EUR |
| Design fee | 19 | 0 | 45 421 | 45 421 | - | 45 429 | 45 429 | - | 45 421 | 45 421 | EUR |

### 6.5.2. Global financial value

When calculating the global financial value according to the above parameters, we get the results as shown in Figure 22. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

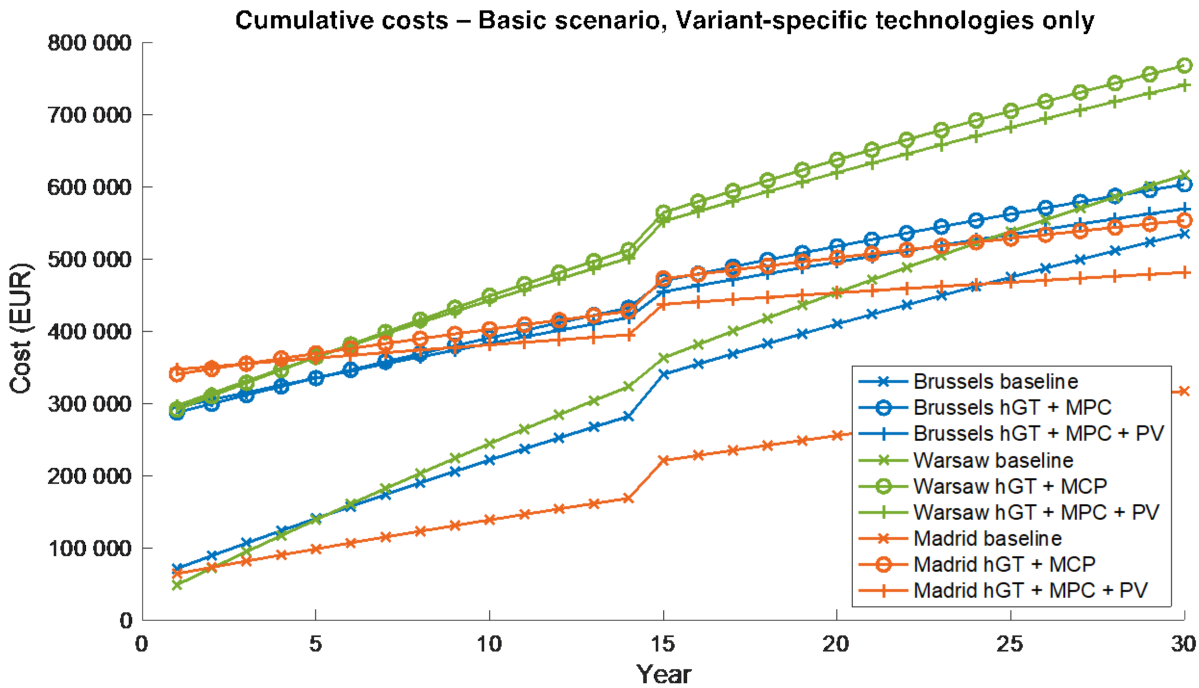



*Figure 22 – Third dataset (light building, poorly insulated, high density occupancy), Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

Again, we can see that the baseline scenario is always the cheapest one, despite its significantly higher energy and $CO_2$ costs. For all three climatic zones, the use of photovoltaics brings additional value to the hybridGEOTABS building, even though not significantly for Warsaw. On the other hand, for Brussels, even the baseline is very close to the hybridGEOTABS variants. The step in Figure 22 in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced.

The final cost performance overview in the form required by the EC Regulation No. 244/2012 for all three climatic zones is shown in Table 40. The baseline variant has the lowest global cost calculated, the hybridGEOTABS variant with MPC and PV is 0.6–3.1 % more expensive for all three climatic zones.

*Table 40 – Third dataset (light building, poorly insulated, high density occupancy) – Final cost performance overview.*

| | Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial investment cost | € 5 811 713 | € 6 033 292 | € 6 042 092 | € 5 784 662 | € 6 032 036 | € 6 038 636 | € 5 813 615 | € 6 091 258 | € 6 101 158 |
| Annual running cost | Maintenance cost | € - | € - | € - | € - | € - | € - | € - | € - | € - |
| | Operational cost (reinvestments) | € 1 447 | € 910 | € 910 | € 689 | € 1 222 | € 1 222 | € 1 499 | € 1 304 | € 1 304 |
| | Energy cost by fuel with the medium energy price scenario | € 12 432 | € 8 601 | € 7 332 | € 16 142 | € 13 015 | € 12 011 | € 6 316 | € 5 335 | € 2 909 |
| | Calculation period | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | € 64 876 | € 42 813 | € 38 097 | € 85 784 | € 67 803 | € 64 076 | € 27 450 | € 21 001 | € 11 988 |
| | Residual value | € 934 791 | € 934 791 | € 934 791 | € 934 947 | € 934 947 | € 934 947 | € 934 791 | € 934 791 | € 934 791 |
| | Discount rate | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | € 5 358 166 | € 5 426 649 | € 5 392 649 | € 5 440 432 | € 5 592 001 | € 5 564 775 | € 5 140 699 | € 5 376 627 | € 5 304 722 |

Table 41 shows the minimum income that the investor or owner needs to achieve from the building, should the building yield positive profit. Note that the residual value is not included in this calculation.

*Table 41 – Third dataset (light building, poorly insulated, high density occupancy) – Minimum annual income needed to achieve positive financial NPV.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Annual income needed to achieve positive financial NPV | € 178 606 | € 180 888 | € 179 755 | € 181 348 | € 186 400 | € 185 493 | € 171 357 | € 179 221 | € 176 824 |

### 6.5.3. Economic value

Comparing all the variants, the financial value (in the sense of net present value) is shown in Table 42. Net present financial value of all the variants is similar, but the difference may be up to 9 % for the third dataset, which is the largest difference in our comparison studies. The difference between the baseline and hybridGEOTABS with MPC is about 0.64–3.09 % of the full price. It is therefore clear that the baseline variant, without a significant amount of renewables, is not competitive with the more advanced hybridGEOTABS variants, maybe with the exception of Warsaw, as we will see in the following text. Even for Madrid, the hybridGEOTABS may be not considerable, as the difference between this variant and the baseline is already fairly high (4.39 %).

*Table 42 – Third dataset (light building, poorly insulated, high density occupancy) – Financial value.*

| Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| Global cost (Net Present Value) | € 5 358 166 | € 5 426 649 | € 5 392 649 | € 5 440 432 | € 5 592 001 | € 5 564 775 | € 5 140 699 | € 5 376 627 | € 5 304 722 |
| Difference between the variant and baseline (nonGT-RBC) | € - | € 68 484 | € 34 483 | € - | € 151 570 | € 124 343 | € - | € 235 928 | € 164 024 |
| The varinat being more expensive than baseline in % | 0,00% | 1,26% | 0,64% | 0,00% | 2,71% | 2,23% | 0,00% | 4,39% | 3,09% |

Table 43 shows the summary of the energies and environmental impact of all the variants. We can see that the total $CO_2$ emissions are about one half for the hybridGEOTABS + MPC + PV variant than for the baseline. For the Warsaw variant here, the difference is even smaller, only about 25 %.

*Table 43 – Third dataset (light building, poorly insulated, high density occupancy) – Environmental impact and energy requirements.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal energy requirements** | 98,5 | 83,4 | 83,4 | 127,2 | 111,0 | 111,0 | 52,4 | 79,4 | 79,4 | kWh/m2/year |
| **Primary energy consumption** | 237 778 | 154 304 | 139 424 | 316 350 | 248 357 | 236 597 | 93 678 | 68 366 | 39 926 | kWh/year |
| **End energy price** | 15 300 | 10 586 | 9 023 | 19 866 | 16 017 | 14 783 | 7 773 | 6 566 | 3 580 | EUR/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 7440 | 0 | 0 | 5 880 | 0 | 0 | 14 220 | kWh/year |
| **Total CO2 emissions** | 53,23 | 35,13 | 31,26 | 70,38 | 55,63 | 52,57 | 22,52 | 17,23 | 9,84 | ton/year |

*Nominal prices, not adjusted for inflation.*

The best environmental performance is always for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 6.5.4. Conclusions

For the third data set (light building, poorly insulated, high density occupancy), the baseline variant is the cheapest one in the sense of global financial value. The other two variants are similar. The hybridGEOTABS with MPC and PV provides the best environmental performance.

As a summary, Table 44 presents the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. It can be seen that the preferred variant, hybridGEOTABS with MPC and PV it is 0.64–3.09 % more expensive than the baseline variant, and 0.49–1.36 % cheaper than the hybridGEOTABS with MPC variant. Its environmental impact is 43.7–74.7 % of the baseline, and 57.1–94.5 % of the hybridGEOTABS with MPC variant. As the environmental impact of the baseline variant in Warsaw is not significantly lower than the hybridGEOTABS variant, it is reasonable to aim for the baseline within the parameters given by the third dataset.

The yearly revenue of the building, needed to pay-off the initial investment, stays around €170 000 – €190 000 for all variants, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant for Brussels and Madrid, and the baseline variant should be considered for Warsaw.**

*Table 44 – Third dataset (light building, poorly insulated, high density occupancy) – CBA Summary*

| Light building, poorly insulated, high density occupancy | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Global financial value (MPV) – comparison | | | | | | | | | |
| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
| Brussels - benchmark | 0,00% | -1,28% | -0,64% | -1,54% | -4,36% | -3,86% | 4,06% | -0,34% | 1,00% |
| Brussels - hGT | 1,26% | 0,00% | 0,63% | -0,25% | -3,05% | -2,55% | 5,27% | 0,92% | 2,25% |
| Brussels - hGT + PV | 0,64% | -0,63% | 0,00% | -0,89% | -3,70% | -3,19% | 4,67% | 0,30% | 1,63% |
| Warsaw - benchmark | 1,51% | 0,25% | 0,88% | 0,00% | -2,79% | -2,29% | 5,51% | 1,17% | 2,49% |
| Warsaw - hGT | 4,18% | 2,96% | 3,56% | 2,71% | 0,00% | 0,49% | 8,07% | 3,85% | 5,14% |
| Warsaw - hGT + PV | 3,71% | 2,48% | 3,09% | 2,23% | -0,49% | 0,00% | 7,62% | 3,38% | 4,67% |
| Madrid - benchmark | -4,23% | -5,56% | -4,90% | -5,83% | -8,78% | -8,25% | 0,00% | -4,59% | -3,19% |
| Madrid - hGT | 0,34% | -0,93% | -0,30% | -1,19% | -4,01% | -3,50% | 4,39% | 0,00% | 1,34% |
| Madrid - hGT + PV | -1,01% | -2,30% | -1,66% | -2,56% | -5,42% | -4,90% | 3,09% | -1,36% | 0,00% |
| | | | | | | | | | |
| CO2 footprint – comparison | | | | | | | | | |
| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
| Brussels - benchmark | 100,0% | 151,5% | 170,3% | 75,6% | 95,7% | 101,2% | 236,3% | 308,9% | 541,2% |
| Brussels - hGT | 66,0% | 100,0% | 112,4% | 49,9% | 63,1% | 66,8% | 156,0% | 203,9% | 357,1% |
| Brussels - hGT + PV | 58,7% | 89,0% | 100,0% | 44,4% | 56,2% | 59,5% | 138,8% | 181,4% | 317,8% |
| Warsaw - benchmark | 132,2% | 200,4% | 225,2% | 100,0% | 126,5% | 133,9% | 312,5% | 408,5% | 715,6% |
| Warsaw - hGT | 104,5% | 158,4% | 178,0% | 79,0% | 100,0% | 105,8% | 247,0% | 322,9% | 565,6% |
| Warsaw - hGT + PV | 98,8% | 149,7% | 168,2% | 74,7% | 94,5% | 100,0% | 233,4% | 305,1% | 534,5% |
| Madrid - benchmark | 42,3% | 64,1% | 72,1% | 32,0% | 40,5% | 42,8% | 100,0% | 130,7% | 229,0% |
| Madrid - hGT | 32,4% | 49,1% | 55,1% | 24,5% | 31,0% | 32,8% | 76,5% | 100,0% | 175,2% |
| Madrid - hGT + PV | 18,5% | 28,0% | 31,5% | 14,0% | 17,7% | 18,7% | 43,7% | 57,1% | 100,0% |

## 6.6. Light building, moderately insulated, low density occupancy

### 6.6.1. CBA Parameters

For the fourth set of building examples, we assume the following parameters, as specified in Table 45.

*Table 45 – Parameters for the fourth dataset (Light building, medium insulated, low density occupancy).*

| Name | Nominal value | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | Units used |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | - | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | 2 391 | m2 |
| Energy demand primary system heating | - | - | 17,1 | 17,1 | - | 28,5 | 28,5 | - | 46,1 | 46,1 | kWh/m2/year |
| Energy demand primary system Cooling | - | - | 20,3 | 20,3 | - | 21,4 | 21,4 | - | 24,3 | 24,3 | kWh/m2/year |
| Energy demand secondary system heating | - | 20,6 | 3,8 | 3,8 | 35,2 | 7,8 | 7,8 | 14,5 | 4,1 | 4,1 | kWh/m2/year |
| Energy demand secondary system Cooling | - | 26,9 | 7,0 | 7,0 | 28,9 | 8,7 | 8,7 | 29,2 | 2,6 | 2,6 | kWh/m2/year |
| Heat pump power | - | - | 24,9 | 24,9 | - | 36,7 | 36,7 | - | 46,5 | 46,5 | kW |
| Gas boiler power | - | 89,3 | 21,2 | 21,2 | 106,6 | 29,5 | 29,5 | 120,8 | 25,9 | 25,9 | kW |
| Chiller Power | - | 118,6 | 46,7 | 46,7 | 28,9 | 66,7 | 66,7 | 107,0 | 39,3 | 39,3 | kW |
| Borefield power | - | - | 27,7 | 27,7 | - | 47,9 | 47,9 | - | 53,5 | 53,5 | kw |
| Borefield lenght | - | - | 829,8 | 829,8 | - | 1 436,7 | 1 436,7 | - | 1 604,8 | 1 604,8 | m |
| Gas consumption | - | 59 121 | 9 195 | 9 195 | 100 909 | 18 649 | 18 649 | 41 687 | 9 835 | 9 835 | kWh/year |
| Electricity consumption heating | - | - | 8 162 | 8 162 | - | 13 641 | 13 641 | - | 22 030 | 22 030 | kWh/year |
| Electricity consumption cooling | - | 22 072 | 8 822 | 8 822 | 23 685 | 10 175 | 10 175 | 23 911 | 6 595 | 6 595 | kWh/year |
| Electricity production | - | - | - | 8 370 | - | - | 11 760 | - | - | 14 220 | kWh/year |
| Electricity total | - | 22 072 | 16 984 | 8 614 | 23 685 | 23 816 | 12 056 | 23 911 | 28 625 | 14 405 | kWh/year |
| SPF heat pump heating | 5,0 | | | | | | | | | | - |
| SPF heat pump cooling | 12,0 | | | | | | | | | | - |
| SPF chiller cooling | 3,5 | | | | | | | | | | - |
| Electricity Primary | 2,0 | 44 144 | 33 968 | 17 228 | 47 369 | 47 632 | 24 112 | 47 822 | 57 250 | 28 810 | kWh/year |
| Gas Primary | 1,1 | 65 033 | 10 115 | 10 115 | 110 999 | 20 514 | 20 514 | 45 856 | 10 819 | 10 819 | kWh/year |
| Electricity CO2 | 0,26 | 11,48 | 8,83 | 4,48 | 12,32 | 12,38 | 6,27 | 12,43 | 14,88 | 7,49 | ton/year |
| Gas CO2 | 0,22 | 14,31 | 2,23 | 2,23 | 24,42 | 4,51 | 4,51 | 10,09 | 2,38 | 2,38 | ton/year |
| CO2 emissions | - | 25,78 | 11,06 | 6,70 | 36,74 | 16,90 | 10,78 | 22,52 | 17,27 | 9,87 | ton/year |
| CO2 price | 50 | 1 289 | 553 | 335 | 1 837 | 845 | 539 | 1 126 | 863 | 494 | EUR |
| Gas Price - Total | 0,066 | 3 902 | 607 | 607 | 6 660 | 1 231 | 1 231 | 2 751 | 649 | 649 | EUR |
| Electricity Price - Total | 0,210 | 4 635 | 3 567 | 1 809 | 4 974 | 5 001 | 2 532 | 5 021 | 6 011 | 3 025 | EUR |
| Energy demand - total | - | 57,0 | 48,2 | 48,2 | 76,9 | 66,4 | 66,4 | 52,4 | 77,0 | 77,0 | kWh/m2/year |
| Construction_costs | 2 590 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | 6 191 654 | EUR |
| MPC_cost | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | - | 30 000 | 30 000 | EUR |
| Borefield_cost_total | 60 | - | 49 787 | 49 787 | - | 86 201 | 86 201 | - | 96 286 | 96 286 | EUR |
| Gas_boiler_cost | 130 | 11 605 | 2 754 | 2 754 | 13 861 | 3 832 | 3 832 | 15 700 | 3 367 | 3 367 | EUR |
| Heat_pump_cost | 480 | - | 11 949 | 11 949 | - | 17 629 | 17 629 | - | 22 305 | 22 305 | EUR |
| Chiller Cost | 280 | 33 208 | 13 069 | 13 069 | 8 091 | 18 677 | 18 677 | 29 972 | 11 013 | 11 013 | EUR |
| Consumption factor for MPC/RBC | 0,80 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | 1,2 | 1 | 1 | - |
| Electricity price per kWh | 0,210 | | | | | | | | | | EUR/kWh |
| Gas price per kWh | 0,066 | | | | | | | | | | EUR/kWh |
| End energy consumption | - | 109 177 | 44 083 | 27 343 | 158 369 | 68 146 | 44 626 | 93 678 | 68 069 | 39 629 | kWh/year |
| End energy price | - | 8 537 | 4 174 | 2 416 | 11 634 | 6 232 | 3 763 | 7 773 | 6 660 | 3 674 | EUR/year |
| Residual value | 0,25 | | | | | | | | | | - |
| Calculation period | 30 | | | | | | | | | | years |
| Discount rate | 1,5% | | | | | | | | | | - |
| PV cost | 1 100 | 0 | 0 | 9900 | 0 | 0 | 13200 | 0 | 0 | 9900 | EUR |
| Overall efficiency | 930 | 930 | 930 | 930 | 980 | 980 | 980 | 1580 | 1580 | 1580 | kWh/kWp/year |
| Installed kWp | - | 0 | 0 | 9 | 0 | 0 | 12 | 0 | 0 | 9 | kWp |
| Energy produced | - | - | - | 8 370 | - | - | 11 760 | - | - | 14 220 | kWh/year |
| Technology extras | 45 | 0 | 107 577 | 107 577 | - | 107 577 | 107 577 | - | 107 577 | 107 577 | EUR |
| Design fee | 19 | 0 | 45 421 | 45 421 | - | 45 421 | 45 421 | - | 45 421 | 45 421 | EUR |

### 6.6.2. Global financial value

When calculating the global financial value according to the above parameters, we get the results as shown in Figure 23. For better clarity, we plot here only the cumulative costs of the variant-specific technologies, i.e. NPV of all costs with the exception of the basic construction costs.

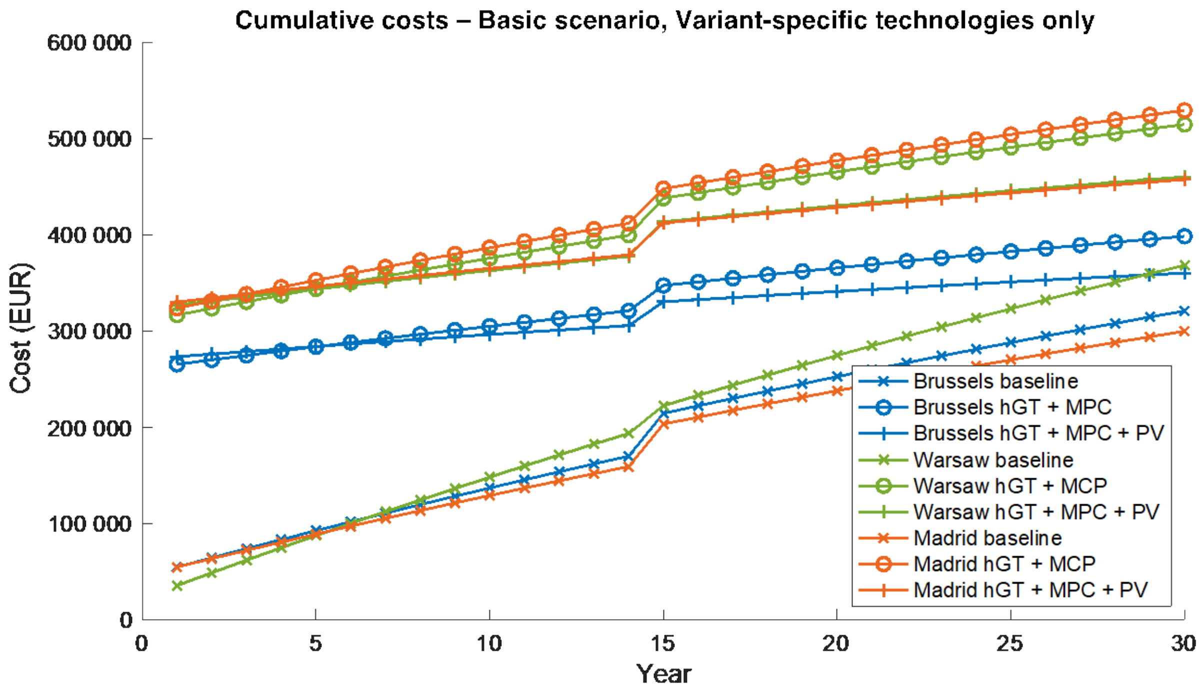



*Figure 23 – Fourth dataset (light building, medium insulated, low density occupancy), Global NPV. Only cumulative costs of the variant-specific technologies are shown.*

We can see that the baseline scenario is always the cheapest one, despite its significantly higher energy and $CO_2$ costs. For all three climatic zones, the use of photovoltaics brings additional value to the hybridGEOTABS building, the biggest for Madrid. The step in Figure 23 in the cost around year 15 is caused by the refurbishment costs of some of the technologies – heat pump, gas boiler and control system are replaced.

The final cost performance overview in the form required by the EC Regulation No. 244/2012 for all three climatic zones is shown in Table 46. The baseline variant has the lowest global cost calculated, but the hybridGEOTABS variant with MPC and PV is only less than 0.7–2.8 % more expensive for all three climatic zones.

*Table 46 – Fourth dataset (light building, medium insulated, low density occupancy) – Final cost performance overview.*

| | Variant | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial investment cost | € 6 236 467 | € 6 452 210 | € 6 462 110 | € 6 213 606 | € 6 500 991 | € 6 514 191 | € 6 237 325 | € 6 507 624 | € 6 517 524 |
| Annual running cost | Maintenance cost | € - | € - | € - | € - | € - | € - | € - | € - | € - |
| | Operational cost (reinvestments) | € 1 213 | € 752 | € 752 | € 594 | € 1 086 | € 1 086 | € 1 236 | € 993 | € 993 |
| | Energy cost by fuel with the medium energy price scenario | € 6 937 | € 3 391 | € 1 963 | € 9 453 | € 5 064 | € 3 057 | € 6 316 | € 5 412 | € 2 985 |
| | Calculation period | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Cost of greenhouse gas emissions | € 31 427 | € 13 476 | € 8 171 | € 44 774 | € 20 595 | € 13 141 | € 27 450 | € 21 043 | € 12 030 |
| | Residual value | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 | € 1 005 151 |
| | Discount rate | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% | 1,50% |
| | Estimated economic lifetime | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| | Disposal cost | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | Global cost calculated (NPV) | € 5 507 225 | € 5 584 815 | € 5 546 564 | € 5 554 636 | € 5 700 937 | € 5 646 484 | € 5 486 168 | € 5 715 651 | € 5 643 747 |

Table 47 shows the minimum income that the investor or owner needs to achieve from the building, should the building yield positive profit. Note that the residual value is not included in this calculation.

*Table 47 – Fourth dataset (light building, medium insulated, low density occupancy) – Minimum annual income needed to achieve positive financial NPV.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| **Annual income needed to achieve positive financial NPV** | € 183 574 | € 186 160 | € 184 885 | € 185 155 | € 190 031 | € 188 216 | € 182 872 | € 190 522 | € 188 125 |

## 6.6.3. Economic value

Comparing all the variants, the financial value (in the sense of net present value) is shown in Table 48. Net present financial value of all the variants is very similar. The difference between the baseline and hybridGEOTABS with MPC is only about 0.7–2.8 % of the full price. It is therefore clear that the baseline variant, without a significant amount of renewables, is not competitive with the more advanced hybridGEOTABS variants.

*Table 48 – Fourth dataset (light building, medium insulated, low density occupancy) – Financial value.*

| **Variant** | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV |
|---|---|---|---|---|---|---|---|---|---|
| **Global cost (Net Present Value)** | € 5 507 225 | € 5 584 815 | € 5 546 564 | € 5 554 636 | € 5 700 937 | € 5 646 484 | € 5 486 168 | € 5 715 651 | € 5 643 747 |
| **Difference between the variant and baseline (nonGT-RBC)** | € - | € 77 590 | € 39 339 | € - | € 146 300 | € 91 848 | € - | € 229 483 | € 157 579 |
| **The varinat being more expensive than baseline in %** | 0,00% | 1,39% | 0,71% | 0,00% | 2,57% | 1,63% | 0,00% | 4,01% | 2,79% |

Table 49 shows the summary of the energies and environmental impact of all the variants. We can see that the total $CO_2$ emissions are about three to four times lower for the hybridGEOTABS + MPC + PV variant than for the baseline.

*Table 49 – Fourth dataset (light building, medium insulated, low density occupancy) – Environmental impact and energy requirements.*

| | Brussels - benchmark | Brussels - hGT | Brussels - hGT + PV | Warsaw - benchmark | Warsaw - hGT | Warsaw - hGT + PV | Madrid - benchmark | Madrid - hGT | Madrid - hGT + PV | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal energy requirements** | 57,0 | 48,2 | 48,2 | 76,9 | 66,4 | 66,4 | 52,4 | 77,0 | 77,0 | kWh/m2/year |
| **Primary energy consumption** | 109 177 | 44 083 | 27 343 | 158 369 | 68 146 | 44 626 | 93 678 | 68 069 | 39 629 | kWh/year |
| **End energy price** | 8 537 | 4 174 | 2 416 | 11 634 | 6 232 | 3 763 | 7 773 | 6 660 | 3 674 | EUR/year |
| **Renewable energy generation & self-consumption** | 0 | 0 | 8370 | 0 | 0 | 11 760 | 0 | 0 | 14 220 | kWh/year |
| **Total CO2 emissions** | 25,78 | 11,06 | 6,70 | 36,74 | 16,90 | 10,78 | 22,52 | 17,27 | 9,87 | ton/year |
| ***Nominal prices, not adjusted for inflation.*** | | | | | | | | | | |

The best environmental performance is always for the last variant, i.e. hybridGEOTABS with MPC and photovoltaic panels. This variant was calculated such that no spill-over to the main grid happens for the energy produced within the building.

### 6.6.4. Conclusions

For the fourth data set (light building, medium insulated, low density occupancy), the baseline variant is the cheapest one in the sense of global financial value. However, the other two variants are very similar. The hybridGEOTABS with MPC and PV provides the best environmental performance.

As a summary, Table 50 presents the main outcomes of the CBA, the Global Financial Value (Net Present Value) and $CO_2$ footprint of the operation of the building. It can be seen that the preferred variant, hybridGEOTABS with MPC and PV it is 0.71–2.79 % more expensive than the baseline variant, and 0.96–1.27 % cheaper than the hybridGEOTABS with MPC variant. Its environmental impact is only 26.0–43.8 % of the baseline, and 57.2–43.8 % of the hybridGEOTABS with MPC variant.

The yearly revenue of the building, needed to pay-off the initial investment, stays around €185 000 for all variants, which corresponds to the ROI of 30 years.

**The recommendation is therefore for the hybridGEOTABS + MPC + PV variant.**

*Table 50 – Fourth dataset (light building, medium insulated, low density occupancy) – CBA Summary*

| **Light building, medium insulated, low density occupancy** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Global financial value (MPV) – comparison** | | | | | | | | | |
| | **Brussels - benchmark** | **Brussels - hGT** | **Brussels - hGT + PV** | **Warsaw - benchmark** | **Warsaw - hGT** | **Warsaw - hGT + PV** | **Madrid - benchmark** | **Madrid - hGT** | **Madrid - hGT + PV** |
| **Brussels - benchmark** | 0,00% | -1,41% | -0,71% | -0,86% | -3,52% | -2,53% | 0,38% | -3,78% | -2,48% |
| **Brussels - hGT** | 1,39% | 0,00% | 0,68% | 0,54% | -2,08% | -1,10% | 1,77% | -2,34% | -1,06% |
| **Brussels - hGT + PV** | 0,71% | -0,69% | 0,00% | -0,15% | -2,78% | -1,80% | 1,09% | -3,05% | -1,75% |
| **Warsaw - benchmark** | 0,85% | -0,54% | 0,15% | 0,00% | -2,63% | -1,65% | 1,23% | -2,90% | -1,60% |
| **Warsaw - hGT** | 3,40% | 2,04% | 2,71% | 2,57% | 0,00% | 0,96% | 3,77% | -0,26% | 1,00% |
| **Warsaw - hGT + PV** | 2,47% | 1,09% | 1,77% | 1,63% | -0,96% | 0,00% | 2,84% | -1,22% | 0,05% |
| **Madrid - benchmark** | -0,38% | -1,80% | -1,10% | -1,25% | -3,91% | -2,92% | 0,00% | -4,18% | -2,87% |
| **Madrid - hGT** | 3,65% | 2,29% | 2,96% | 2,82% | 0,26% | 1,21% | 4,01% | 0,00% | 1,26% |
| **Madrid - hGT + PV** | 2,42% | 1,04% | 1,72% | 1,58% | -1,01% | -0,05% | 2,79% | -1,27% | 0,00% |
| | | | | | | | | | |
| **CO2 footprint – comparison** | | | | | | | | | |
| | **Brussels - benchmark** | **Brussels - hGT** | **Brussels - hGT + PV** | **Warsaw - benchmark** | **Warsaw - hGT** | **Warsaw - hGT + PV** | **Madrid - benchmark** | **Madrid - hGT** | **Madrid - hGT + PV** |
| **Brussels - benchmark** | 100,0% | 233,2% | 384,6% | 70,2% | 152,6% | 239,1% | 114,5% | 149,3% | 261,2% |
| **Brussels - hGT** | 42,9% | 100,0% | 164,9% | 30,1% | 65,4% | 102,5% | 49,1% | 64,0% | 112,0% |
| **Brussels - hGT + PV** | 26,0% | 60,6% | 100,0% | 18,3% | 39,7% | 62,2% | 29,8% | 38,8% | 67,9% |
| **Warsaw - benchmark** | 142,5% | 332,2% | 547,9% | 100,0% | 217,4% | 340,7% | 163,1% | 212,8% | 372,2% |
| **Warsaw - hGT** | 65,5% | 152,8% | 252,0% | 46,0% | 100,0% | 156,7% | 75,0% | 97,9% | 171,2% |
| **Warsaw - hGT + PV** | 41,8% | 97,5% | 160,8% | 29,4% | 63,8% | 100,0% | 47,9% | 62,5% | 109,2% |
| **Madrid - benchmark** | 87,3% | 203,7% | 335,9% | 61,3% | 133,3% | 208,9% | 100,0% | 130,4% | 228,2% |
| **Madrid - hGT** | 67,0% | 156,1% | 257,5% | 47,0% | 102,2% | 160,1% | 76,7% | 100,0% | 174,9% |
| **Madrid - hGT + PV** | 38,3% | 89,3% | 147,2% | 26,9% | 58,4% | 91,5% | 43,8% | 57,2% | 100,0% |

# 7. Conclusions

As we have seen the four case studies of the hybridGEOTABS project are quite different from each other. While this was the intention of the choice, to show the suitability of the hybridGEOTABS system for a wide range of buildings, it makes it more difficult to make general conclusions for the whole EU market. The individual conclusions can be found in parts 2–5, which refer to the CBAs of Haus M, Líbeznice, Infrax/Fluvius and Ter Potterie.

To make general conclusions and to assess the effect of the hybridGEOTABS solution to the EU market, we have decided to use the mathematical models developed in Deliverable 2.2 – A set of parametric geometries for the (sub)typologies studied, to make a comparative analysis. The models cover three main climatic zones in Europe:

- Warsaw / transitional temperate/transitional cold
- (Uccle) Brussels / Maritime temperate warm
- Madrid / continental intermediate subtropical

For the comparison, we made many assumptions and simplifications, as declared in Part 1 and Section 6.2. The most important assumption is the economic one, where we assume that the whole EU can use Euro as a currency with the same discount rate. Furthermore, we used average economical and environmental values from Eurostat and the ENER project. We also used our own assumptions, which are based on cost analyses within this deliverable, D5.8 (Business model) and Work Package 2 in general (various parameters to allow optimal sizing in multiple deliverables of WP2).

We can see the most important results – global financial value and $CO_2$ emissions – are shown in Table 51 and in Figure 24. The results are shown with respect to the climatic zones.

*Table 51 – Results of the comparative CBA study, ordered by climatic zones.*

| Brussels | Moderate insul., Heavy const., Low dens. | | | Good insul., Heavy const., Low dens. | | | Poor insul., Light const., High dens. | | | Moderate insul., Light const., Low dens. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV |
| Global financial value | € 5 473 860 | € 5 554 184 | € 5 520 183 | € 5 773 607 | € 5 905 187 | € 5 862687 | € 5 358 166 | € 5 426 649 | € 5 392 649 | € 5 507 225 | € 5 584 815 | € 5 546 564 |
| CO2 Emissions | 25,98 | 11,13 | 7,26 | 15,02 | 10,81 | 5,97 | 53,23 | 35,13 | 31,26 | 25,78 | 11,06 | 6,70 |

| Warsaw | Moderate insul., Heavy const., Low dens. | | | Good insul., Heavy const., Low dens. | | | Poor insul., Light const., High dens. | | | Moderate insul., Light const., Low dens. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV |
| Global financial value | € 5 509 084 | € 5 634 091 | € 5 602 328 | € 5 713 997 | € 5 863 295 | € 5 836069 | € 5 440 432 | € 5 592 001 | € 5 564 775 | € 5 554 636 | € 5 700 937 | € 5 646 484 |
| CO2 Emissions | 34,37 | 19,22 | 15,65 | 16,08 | 6,50 | 3,45 | 70,38 | 55,63 | 52,57 | 36,74 | 16,90 | 10,78 |

| Madrid | Moderate insul., Heavy const., Low dens. | | | Good insul., Heavy const., Low dens. | | | Poor insul., Light const., High dens. | | | Moderate insul., Light const., Low dens. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV | Benchmark | hGT+MPC | hGT+MPC+PV |
| Global financial value | € 5 470 507 | € 5 569 640 | € 5 529 693 | € 5 849 224 | € 6067 217 | € 5 995 313 | € 5 140 699 | € 5 376 627 | € 5 304 722 | € 5 486 168 | € 5 715 651 | € 5 643 747 |
| CO2 Emissions | 22,53 | 11,40 | 7,29 | 22,52 | 17,17 | 9,77 | 22,52 | 17,23 | 9,84 | 22,52 | 17,27 | 9,87 |

The results are not surprising. It is clear that for better insulated, heavy buildings, the hybridGEOTABS solution is a competitive variant to the baseline variant. Our main findings, with respect to global financial value and total $CO_2$ emissions of the cases, are as follows:

- It is highly advantageous to use the hybridGEOTABS solution in combination with photovoltaics. In our study, this may decrease the global financial cost of the building by 0.4–1.5 % compared to the hybridGEOTABS solution without photovoltaics.
- For warm climates (Madrid), it can be strongly recommended to combine the hybridGEOTABS building with photovoltaics, as they decrease the final price significantly.
- The baseline variant is always cheaper than the hybridGEOTABS solution, but its environmental impact is higher. It is usually around 2 % cheaper than the hybridGEOTABS with photovoltaics, it tends to be more expensive in warmer climates – this may be caused by bigger cooling demands and thus larger borefield, which is an expensive part of the concept. For poorly insulated buildings in colder climates (Warsaw), the baseline may be a better choice because of small difference in environmental impact.

- Even for the worst case scenarios, the hybridGEOTABS solution is only 3 % more expensive than the baseline, and usually around 1 % more expensive, which makes the price difference negligible compared to the environmental impact.


*Figure 24 – Results of the comparative CBA study.*

Finally, Figure 25 shows the plot of the costs (in terms of global financial value, or net present value) versus environmental impact (in terms of $CO_2$ emissions). Our findings can be summarized into two points.

1. The more we invest into the building, the larger the environmental impact is. In terms of numbers, we have found in our study that for the increase in investments of about 7 %, we can decrease the $CO_2$ emissions from the operation of the building by more than 95 % (Warsaw scenario), 70 % (Brussels scenario) or 20 % (Madrid scenario).
2. It appears from our study that hybridGEOTABS buildings have increased effect on the performance of buildings (in terms of the cost X environment dilemma) for harsher climates.

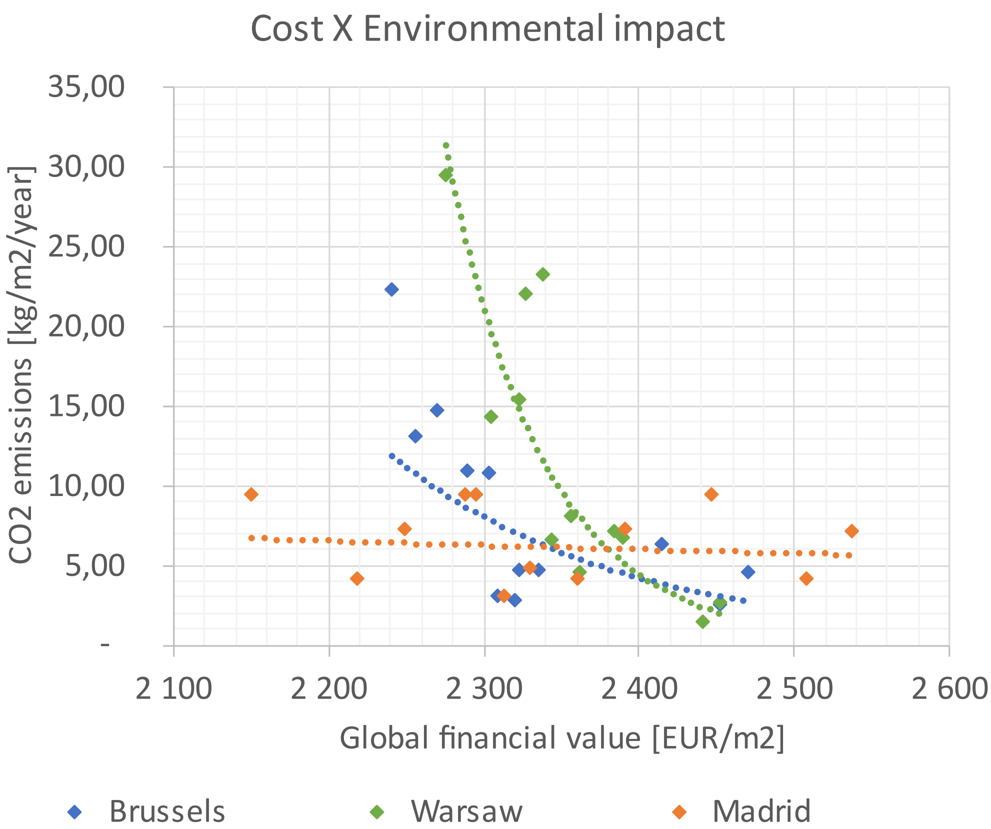



*Figure 25 – The relationship of cost and environmental impact of the CBA variants.*

## 8. Bibliography

1. **European Commission.** Commission Delegated Regulation (EU) No. 244/2012. 2012.
2. **Sartori, Davide et al.** *Guide to Cost-Benefit Analysis of Investment Projects.* Brussels : EC, DG Regio, 2015. ISBN 978-92-79-34796-2.
3. **Bundesministerium des Innern, für Bau und Heimat.** *Wege zum Effizienzhaus Plus.* Bonn/Berlin : Bundesamt für Bauwesen und Raumordnung, 2018.

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