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Sizing tool for collective heat pump systems in Near-Zero and Energy-Positive Apartment Buildings

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Abstract

A first version of a decision-support tool was developed to analyze integrated building energy systems by combining insulation measures, ventilation strategies, PV generation, heat pump capacity, and storage options. The tool was applied to a positive energy building (PEB) case in the Overvecht district in the city of Utrecht, evaluating pre- and post-renovation conditions. Validation against measured annual consumptions shows that the model predicts energy demand and electricity production with sufficient accuracy, with the main uncertainties arising from ventilation rates and domestic hot water usage.
The tool generates both visual and numerical outputs, including costs, capacities and energy usages, grid congestion, energy positivity, autarky, and CO_2 emissions, making it suitable for use by various stakeholders. It provides insight into building performance and energy systems supporting discussions about collective versus individual measures, particularly regarding grid connection limits. The results demonstrate that achieving an energy-positive building with heat pump technology and solar panels is not guaranteed without addressing measures concerning grid congestion, which requires building related measures, properly sizing heat pumps and thermal or electrochemical buffers. While thermal storage can be highly effective within a certain range and may in some cases offer cost advantages, it is not inherently superior to electrochemical battery storage. Its suitability should be assessed case by case, taking into account not only costs but also the required storage volume and associated spatial footprint, which can become a limiting factor at larger scales. Overall, the tool offers a practical framework for decision-making toward energy-positive apartment buildings with collective heat pump and buffering strategies.

Keywords: Positive Energy District, Positive Energy Building, collective heat pump system, thermal buffer, design tool

1. Introduction

Energy-positive districts have gained a prominent position on the European innovation agenda [1]. Within the built environment, particularly the existing housing stock, substantial technological and organizational innovations are required to meet the Dutch 2050 ambitions. This ranges from gas-free and nearly zero-energy buildings to fully energy-positive ones [2]. In the Netherlands, roughly five million dwellings constructed before the 1990s hold an energy label of B or lower. Residential buildings account for approximately 14% of national energy consumption, with high-rise buildings representing an estimated 7% of this share [3]. Addressing the resulting large-scale decarbonization challenge in a scalable and affordable manner requires a more industrialized and standardized renovation approach, which is not yet common practice.

Technological measures, such as improved insulation, CO_2-controlled ventilation, and heat-recovery systems, already substantially reduce heating and cooling demand. However, it also requires the integration of local renewable energy sources. Herein the heat pump technology play a central role alongside photovoltaic (PV) systems, which harvest both ambient heat and solar energy. According to the Dutch *Klimaatakkoord* (2019), more than 70% of residential heating will rely on electrified heat pump systems by 2050 [4].

However, this electrification trajectory is increasingly constrained by severe grid congestion in the Netherlands due capacity shortages in the electrical infrastructure on several levels [5–7]. This underscores the need for strategies of smart control and integrating electrical and thermal buffering to ensure continuation in future-proof energy systems.

In 2020, Inside-Out Technologies introduced a novel industrial concept under a national subsidy program, resulting in the first residential Positive Energy Building (PEB) in Europe, see Fig.1. The project achieved its performance targets through the integration of standardized roof- and façade-mounted PV modules with a collective air-to-water heat pump system serving 58 apartments in the Overvecht district of Utrecht, originally built in the 1960s and 1970s. To maximize solar yield, the available roof area was expanded through the addition of an extra storey frame incorporating vertical panels and a zigzag profile on top. Importantly, the system utilized the under-loaded three-phase electrical connection originally reserved for elevators and shared lighting [8,9]. Although residents and the housing association reported high satisfaction, the concept as total has not yet been replicated.

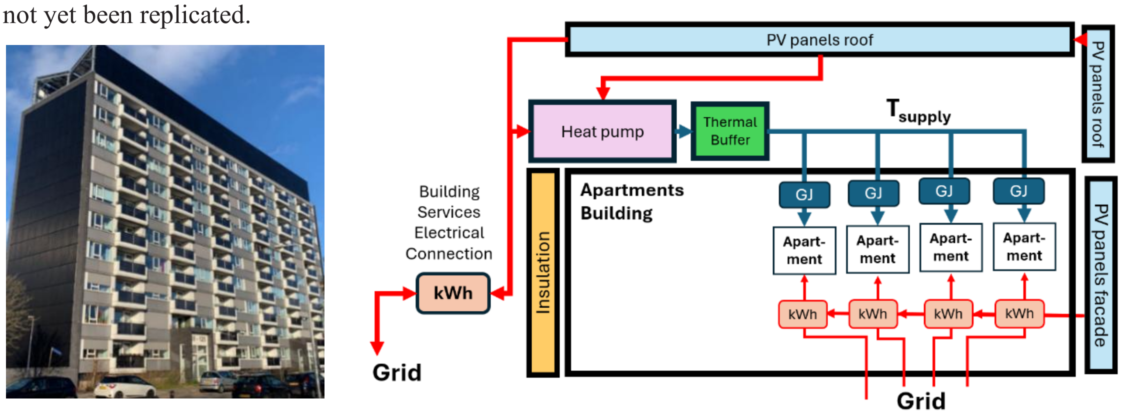

Figure 1. Realized energy-positive apartment building by Inside-Out Technologies, featuring a collective air-to-water heat pump and extensive PV integration on both façades and roof surfaces. The right-hand panel shows a simplified schematic of the system configuration applied in this project.

One of the barriers include limited insight into the system's complexity, uncertainties regarding life-cycle costs and maintenance, and evolving PV feed-in compensation schemes expected to change after 2027. Current tools and approaches often focus on a limited set of aspects, without integrating the full spectrum of relevant components around the collective heat pump systems, such as PV façades, thermal buffers and grid issues [10, 11]. With the increasing adoption of large-scale thermal water buffers (10–10,000 m³) and electrochemical batteries in residential areas, understanding the interactions between system components has become even more critical. [12, 13]. The objective of this work is to develop a first-step tool that enables stakeholders to identify promising renovation strategies capable of delivering affordable, grid-sensitive, energy-positive apartment buildings in which the collective heat pump forms the basis. Thereby the Inside-Out Technologies renovation approach has matured to a stage where also a stepwise retrofit is feasible, supported by their refined portfolio of solutions. This portfolio includes roof-integrated PV systems (Alpha and Echo), collective air-to-water heat pump systems (Bravo), energy-efficient mechanical ventilation with CO_2-based control (Charlie), façade retrofit modules with building-integrated PV (Delta), and a system-control strategy with optional auxiliary heating (Foxtrot) [14]. These products are illustrated in Fig. 2.

Figure 2. Modular subdivision of the Inside-Out Technologies renovation concept. The portfolio consists of six components (Alpha, Bravo, Charlie, Delta, Echo, and Foxtrot) covering roof-integrated PV systems, collective heat pump modules with buffers, high-efficiency ventilation, prefabricated insulated façade elements with BIPV, balcony-mounted PV, and the centralized automation and control unit [14].

2. Methods and Approach

In this section, we outline the methodology of the dimensioning tool, including its modelling structure, data inputs, key design parameters, and performance outputs. We describe how building physics, PV generation, the heat pump system, grid specifications, thermal buffers, batteries, and control strategies interact to understand renovation scenarios.

2.1 Simulation Framework

Fig. 3 provides a schematic overview of the system that forms the conceptual foundation of the model. It illustrates a central air-to-water heat pump with thermal buffer. This buffer supplies at least 50 °C to the apartment-level heat-interface units, each equipped with local hygienic legionella-prevention boosters. The figure also shows the roof- and façade-integrated PV systems, and optionally a scalable thermal buffer and collective battery. In the current model, all PV is connected to the building's central electrical supply point, normally reserved for general building services. Hybrid operation is included by allowing gas for residual heat demand when heat pump power or electrical capacity is insufficient.

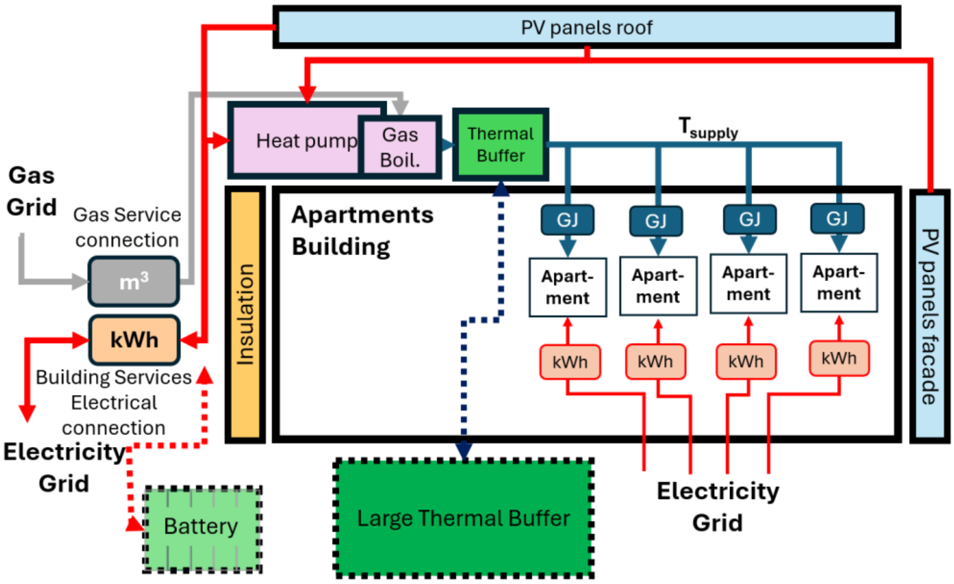

Figure 3. Schematic representation of the system concept for energy-positive apartment buildings. All elements are considered to be connected to the Building Services electrical connection, which serves as the core interface between local generation, storage components, heat pump and the electrical grid.

2.2 Core Model Structure

The internal model structure is illustrated schematically in Fig. 4 and implemented in an Excel-environment. The upper block depict the input parameters that determine the thermal and electrical behavior of the building, ultimately defining the hourly heat demand at the left of the simplified Sankey diagram. This diagram provides a schematic overview of how the model processes the energy flows to meet this heat demand based on the defined energy system parameters.

Heat is supplied first from the thermal buffer; if the buffer is insufficient, the heat pump delivers the remaining load, and auxiliary gas heating is used as a final fallback option. Electricity for the heat pump is sourced in a fixed order, prioritizing PV, followed by the collective battery, and finally the grid.

When thermal-buffer charging via the grid is enabled, the model uses remaining import capacity to pre-heat the buffer. It gives control of two variants. The first focuses strictly on local self-consumption by charging the thermal buffer only from PV. The second allows grid-assisted pre-heating of the buffer during periods with available import capacity via the grid. More advanced control strategies, such as weather-based predictive charging, are planned for future development. The current implementation is therefore primarily intended for comparative scenario exploration rather than detailed operational optimization.

The simulation operates on an hourly timestep and is being expanded toward higher temporal resolution to accommodate near-future dynamic electricity pricing and grid-capacity constraints in Python.

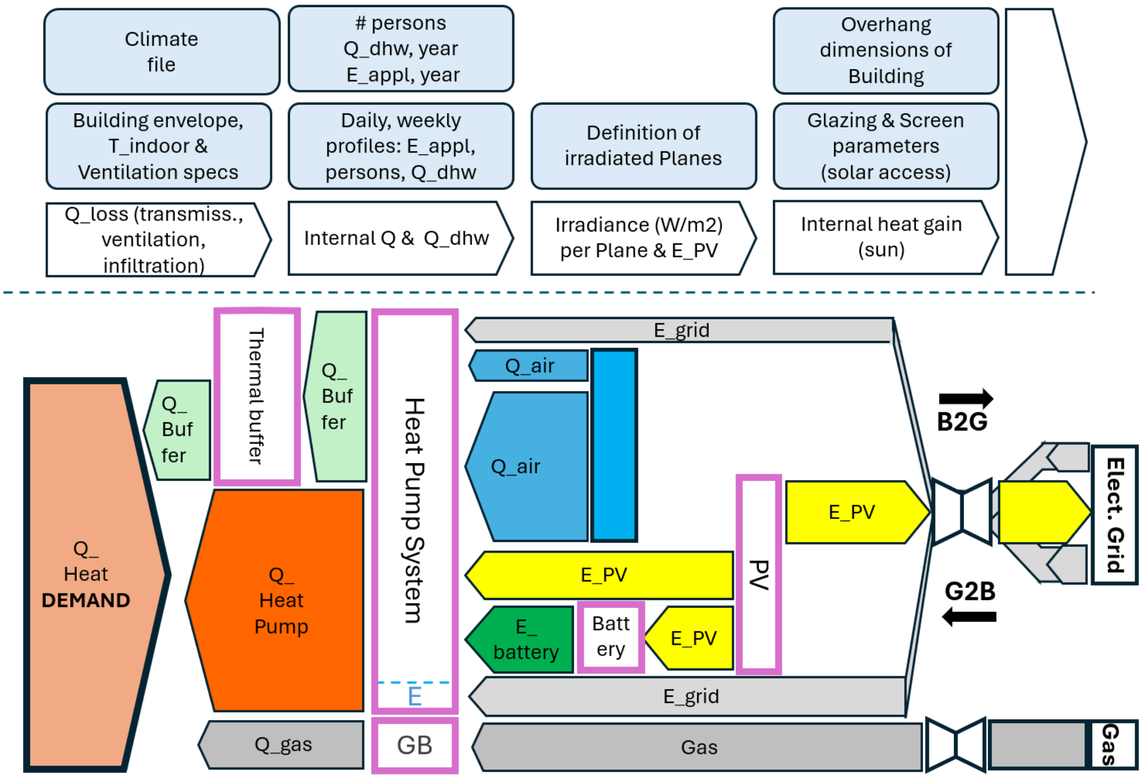

Figure 4. Conceptual overview of the energy model. Input parameters (upper light-blue boxes) determine hourly energy flows within the building and thereby determining the total heating demand per hour at the left of the lower 'Sankey' diagram. The diagram illustrates how this demand will be supplied via the thermal buffer (light green), direct heat pump operation (red) and possibly via the gas boiler (GB) (dark grey). The heat pump is supplied by battery support(dark green), local PV (yellow) and ambient air (blue), supplemented by the electrical grid (grey) through the electrical connection.

2.3 Inputs, Parameters, and Outputs

Figure 5 presents the overall structure of the model, distinguishing between fixed input data, variable design parameters, and key performance indicators as outputs. Although the full model incorporates nearly one hundred inputs it remains accessible through a set of generalized, high-level design controls that enable rapid exploration of renovation scenarios. These slider-based parameters allow users to adjust insulation levels ($R;U$), ventilation efficiency η_{vent}, PV coverage on roofs and façades (A_{PV}), heat pump configuration (monovalent or hybrid via β), and the capacities of thermal and electrical buffers (V_{th} and C_{batt}). Two additional switches represent the choice for auxiliary gas or electricity in case of hybrid operation and whether the thermal buffer may be charged using grid electricity when grid-capacity is available.

A central aspect of the model concerns the heat pump performance and thermal buffer operation. The capacities of the heat pump and auxiliary heating unit are determined automatically based on the design outdoor temperature (typically $T_{out} = -10$ °C) and building physics parameters, yielding the total required heating power P_{total}. The heat pump capacity is then set as $P_{HP} = \beta \cdot P_{\text{total}}$, where the β-factor is 1.0 for monovalent systems and typically between 0.6 and 0.7 for hybrid systems. The β-factor defines the share of the load carried by the heat pump.

The coefficient of performance (COP) is modeled using the empirical Carnot efficiency factor η_C, which can be estimated using a rule of thumb (0.3-0.5) or, preferably, through a fit to manufacturer data (EN 14511). After determining this factor the COP can be calculated on the heat pump supply and outdoor air temperatures (°C)

$$COP = \eta_C \cdot \frac{T_{HP-buff.}+273}{T_{HP-buff.}-T_{air}} \qquad (1)$$

The thermal buffer operates within a temperature window between T_{min} = 50 °C and T_{max} = 70 °C as dictated by the heat pump supply temperature (R290 refrigerant), which is modeled to be 5 K above the buffer temperature. This temperature range corresponds to a maximum storage capacity of roughly 23 kWh_{th} /m^3. The state of charge (SoC) of the buffer is defined as

$$SoC_{buff.} \ = \frac{T_{buff.} - T_{min}}{T_{max} - T_{min}} \, SoC_{buff,max} \qquad (2)$$

Using these two inputs, along with the broader set of model parameters, the tool generates a comprehensive suite of indicators. These include annual demands and productions (including maximum powers), the contribution of renewable and fossil sources, CO_2 emissions , indicative investment and operational costs, and the number of hours per year during which the central grid connection experiences overload.

Two composite performance metrics are calculated: the Energy Positivity Index (EPI), expressing the balance between annual exports and imports relative to the building's total energy demand, and the Energetic Autarky Index (EAI), which quantifies the share of demand covered by local renewable resources. Both indicators are normalized to the annual (y) thermal demand on space heating (sh), domestic hot water (dhw), $Q_{sh\&dhw,y}$, and electricity use for appliances $E_{appl,ap.,y}$ for the N_{ap} apartments (ap). They are defined as

$$EPI \ = \ \frac{\sum_i MIN(E_{B2G,i}, P_{grid\ conn.}) \ - \sum_i MIN(E_{G2B,i}, P_{grid\ conn.})}{Q_{sh\&dhw,y} + N \cdot E_{appl,ap.,y}} \qquad (3)$$

$$EAI \ = \ \frac{E_{PV,y} - E_{B2G,y} + Q_{air,y}}{Q_{sh\&dhw,y} + N \cdot E_{appl,ap.,y}} \qquad (4)$$

In the upper equation, the summation runs over the hourly computed electricity flows. The MIN-function limits exports and imports to the connection-capacity constraint $P_{grid\ conn}$ ensuring that Building-to-Grid (B2G) and Grid-to-Building (G2B) flows reflect realistic electric infrastructure limitations.

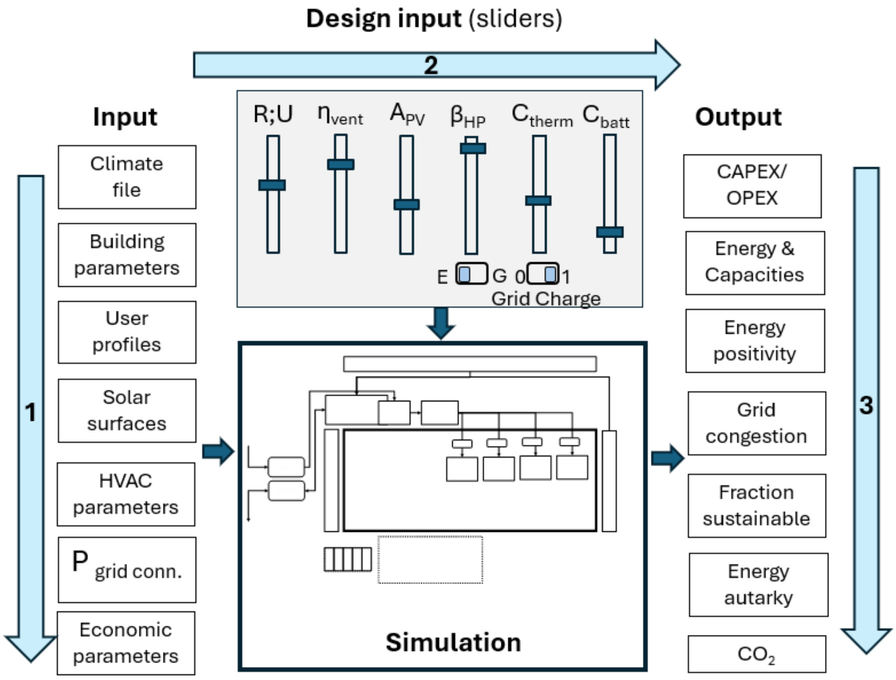

Figure 5. Structure of the design tool and its calculation process. Fixed inputs (1) feed the system model, which generates performance outputs (3), including grid-load indicators. Adjustable design parameters are controlled via sliders and include insulation level, ventilation efficiency, PV surface areas, heat pump configuration, and thermal and electrical storage capacities. Two switches determine a) the use of gas or electric auxiliary heating and b) whether the thermal buffer may be recharged using electricity from the grid when possible.

3. Results and Discussion

To assess the applicability of the developed simulation tool, the deep renovation of the above mentioned apartment block of 58 apartments in the Overvecht district, completed in 2021, was used as a validation case. Although the project relied on a highly industrialized renovation method, with complete façade elements removed and replaced by prefabricated modules that already contained HVAC units, the underlying methodology can be translated to more common stepwise renovation strategies used by housing associations. The case therefore provides an appropriate benchmark for evaluating both the modelling framework and its ability to support phased retrofit planning.

Since most Dutch apartment buildings follow a "non-regret," incremental retrofit pathway [16], the modular product portfolio used in this study was designed to allow for such phased improvement while remaining compatible with long-term decarbonization targets. A suite of scenarios was constructed to emulate a realistic retrofit-advice sequence, starting with low-investment thermal improvements, continuing with electrification measures, and culminating in deep renovation and large storage systems.

In Table 1 these scenarios are displayed. Each scenario was evaluated using key indicators such as grid overload hours, the Energy Positivity Index, the Autarky Index, annual CO_2 emissions, indicative Capital Expenditures (CapEx) and Operational Expenditures (OpEx). Additional sensitivity analyses within the scenarios examined how variations in thermal-buffer volume and electrical-battery capacity influence system performance. Fig. 6 shows how the scenarios are linked.

Reference Case: Gas-Fired System (1)

Although the Overvecht building was historically connected to district heating rather than gas, a gas-fired system was included as the reference baseline to reflect the dominant configuration in the Dutch multifamily stock. With limited envelope quality (Rc ≈ 1.0 m²K/W, double glazing U = 3.0 W/m²K, air exchange 0.3 h^{-1}), the simulated heating demand of roughly 122 kWh/m²·yr (see Fig. 6C) aligns well with national reference datasets [15] for apartment buildings from the '60s and '70s, but deviates somewhat from the measured values of 83 kWh/m^2 yr before retrofitting [18]. This may be caused by additional window retrofitting, reduced ventilation rates (manual airtightness 'improvements'), and domestic hot water consumption below standard assumptions; however, the results remain within the accepted bandwidth. Because thermal energy in this configuration is produced without electricity, no grid congestion occurs, providing a clear contrast with subsequent electrified scenarios.

Table 1. Scenarios and sub scenarios

Retrofit scenario	Subscenario id-numbers	R;U [m^{2}K/W; W/m^{2}K]	η_{vent} [0-1]	β [0-1]; aux	f_{fac};f_{roof}; f_{sides} [0-1]	Therm. buffer charge via grid [Y/N]	V_{th} [m^3]	C_{batt} [kWh/ap.]
Reference situation (gas-fired)	1	1.0; 3.0	0	0; gas	0;0;0	-	1	0
Monovalent heat pump, no building optimization.	2-6	1.0; 3.0	0	1.0	0;0;0	N;Y;Y;Y ;Y	1;1;10;20;30	0
Bivalent heat pump, gas hybrid	7	1.0; 3.0	0	0.6;gas	0;0;0	Y	1	0
Improved ventilation and insulation (step 1)	8-9	2.0;1.5	0.8	1.0	0;0;0	Y	1	0
Application of solar panels / BIPV	10-11	2.0;1.5	0.8	1.0	0;1;1 / 0.5;1;1	Y	1	0
Sensitivity analysis V_{th}., no charge via grid	12-16	2.0;1.5	0.8	1.0	0.5;1;1	N	1;10;100; 1000;10000	0
Sensitivity analysis C_{batt} with V_{th} = 1 m^3	17-19	2.0;1.5	0.8	1.0	0.5;1;1	N	1	5;10;20
Improved insulation (deep renovation) with C_{batt} = 5 kWh/ap.	20-21	4.0;1.5 /8.0;1.5	0.8	1.0	0.5;1;1	N	1	5

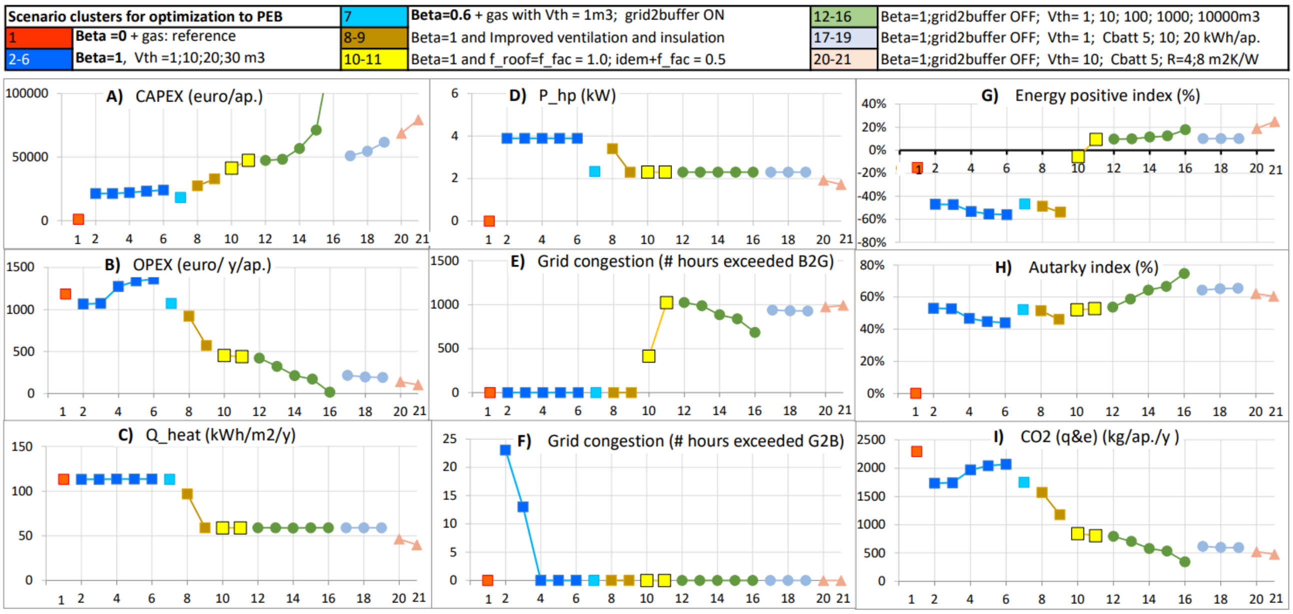

Figure 6. Key performance indicators as output, which are relevant for the development of positive-energy buildings (PEBs) under grid-constrained conditions. Left: indicative CapEx and OpEx based on commercial material prices and energy price rates. Center: annual number of hours in which the building exceeds the allowable power at the grid connection, illustrating that summer curtailment remains necessary. Right: Energy Positivity Index (EPI), Energetic Autarky Index (EAI) and annual CO_2 emissions.

Full Heat Pump Replacement without Envelope or Ventilation Upgrades (2-6)

Replacing the fossil-based system with a monovalent heat pump, while leaving the envelope and ventilation system untouched, results in grid overload during winter, see Fig. 7 (left graph). Heat pump demand regularly exceeds the 95 kW electric capacity, confirming that full electrification is infeasible without preparatory measures. Thermal storage was explored as a mitigation option, yet results show that modest buffer volumes provide only partial relief. A 1 m³ buffer (temp. range 50 – 70 ºC), pre-charged before cold spells, halves the number of overload hours, but even 10–20 m³ volumes leave significant peaks unresolved. Only at around 30 m³ the longest cold period can be bridged, but such large volumes come at the cost of increased OpEx (Fig 6B.) because high-temperature charging reduces the heat pump's COP. Thereby the CapEx (Fig. 6A) does not increase as rapidly [13]. These findings indicate that sensible heat storage can be energetically attractive when primarily applied to buffer peak electrical loads, even if the associated energy costs are somewhat higher.

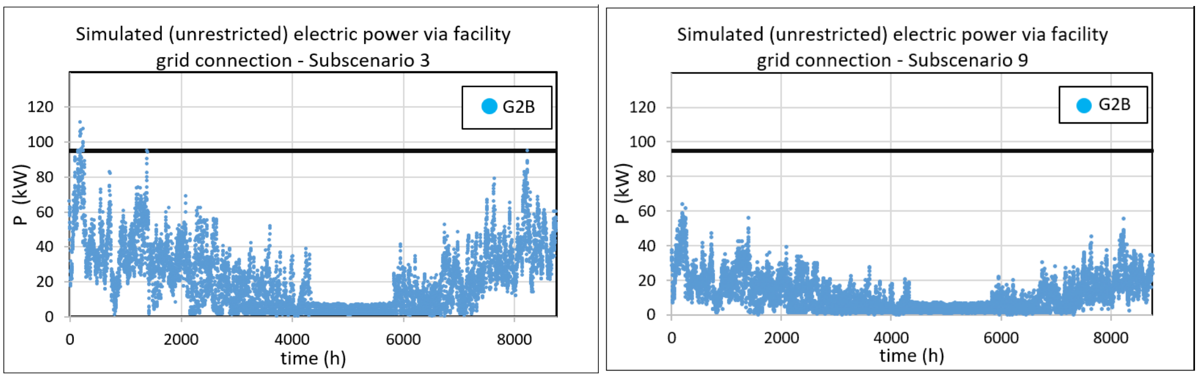

Figure 7. Left: electricity demand of the Bravo heat pump system when no envelope or ventilation improvements are implemented (sub scenario 3). The black line indicates the maximum available electrical capacity (2 × 47 kW via facility connection). Right: significant reduction in heat pump electricity demand when CO_2-controlled ventilation, heat recovery, and upgraded glazing (U = 1.5 W/m²K) are applied (sub scenario 9).

Hybrid Heat Pump Configuration (7)

Introducing a hybrid system, where a gas boiler supplies peak loads and the heat pump covers the base load, eliminates directly the grid congestion even with minimal thermal storage (see Fig. 6F light blue square-marker). While technically effective, the hybrid configuration conflicts with full-electrification objectives and is incompatible with buildings that have transitioned away from gas or district heating. For such cases, a reduction in heating demand becomes a prerequisite before electrification.

Initial Heat-Demand Reduction Measures (8-9)

A set of mid-level retrofit measures was explored next, consisting of CO_2-controlled or heat recuperation-based ventilation, upgraded double or even triple glazing (in existing frames), and moderate façade (cavity) insulation improvements. These interventions substantially reduce peak heating loads and almost eliminate grid congestion (see Fig 6F, brown square markers and Fig 7, right graph). Because these measures are financially quite accessible and technically feasible they represent a realistic first step in many Dutch renovation trajectories.

Integration of Photovoltaics (10-11)

PV systems were introduced to evaluate the potential for net-positive energy operation [17]. For high-rise buildings, roof-PV alone is insufficient; vertical façade PV is indispensable for achieving energy-positive performance. The simulations confirm that only when both front and side façades are used for PV, the building achieves an annual positive balance. Peak PV output does, however, exceed the available grid capacity, requiring curtailment. However, even under curtailment, the building remains energy-positive. See Fig. 6G yellow markers and Fig. 8.

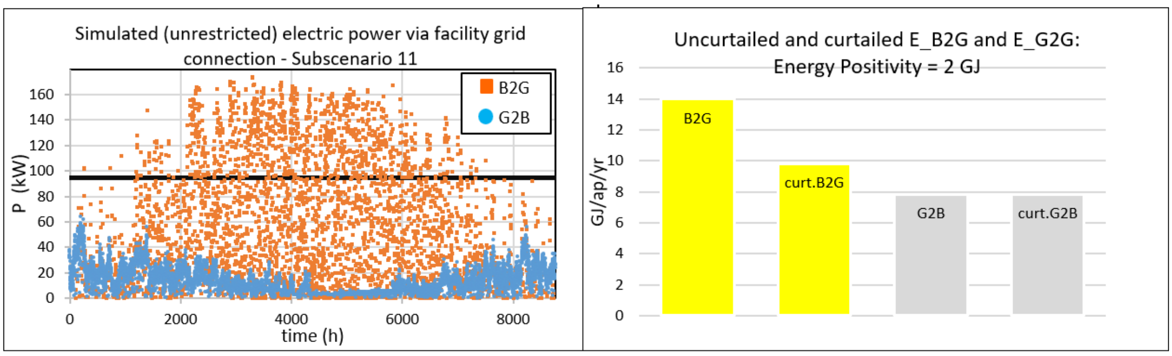

Figure 8. Due to limited grid connection capacity, a considerable share of potential building-to-grid (B2G) electricity cannot be exported for sub scenario 11. This results in an overall energy positivity of only 2.00 GJ/year per apartment (see 2nd yellow and 4th grey bars at the right graph). At the left an illustration of grid-to-building (G2B, blue) and building-to-grid (B2G, orange) electricity flows. In summer time capacities exceed the connection with the grid.

Seasonal Thermal Buffers (12-16)

Large thermal buffers in the 1 m³ to 10,000 m³ range were examined to assess their impact on the design, with each buffer being ten times larger than the previous one. While such buffers increase energy autarky and reduce grid export peaks, the associated investment costs dominate the overall financial profile (see fig. 6A, green dots) [12]. State-of-charge analyses reveal that smaller systems (< 10 m³) are depleted daily during extended cold periods, whereas volumes beyond 100 m³ can sustain heat delivery for a few days, see Fig. 9-10. Despite their technical advantages, the substantial CapEx spatial requirements make large seasonal buffers challenging to justify for renovation projects.

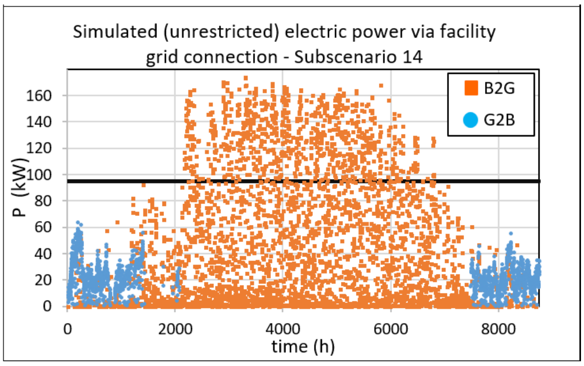

Figure 9. Example of power exchange with the grid and building in case of V_{th} = 100 m^3 (sub scenario 14). Large-scale thermal buffers suppress G2B electricity import throughout the year, with the exception of winter, as evidenced by the absence of blue data points in the non-winter periods. However, B2G curtailment still occurs in summer time when the buffer becomes fully charged, forcing excess PV generation to be exported to the grid.

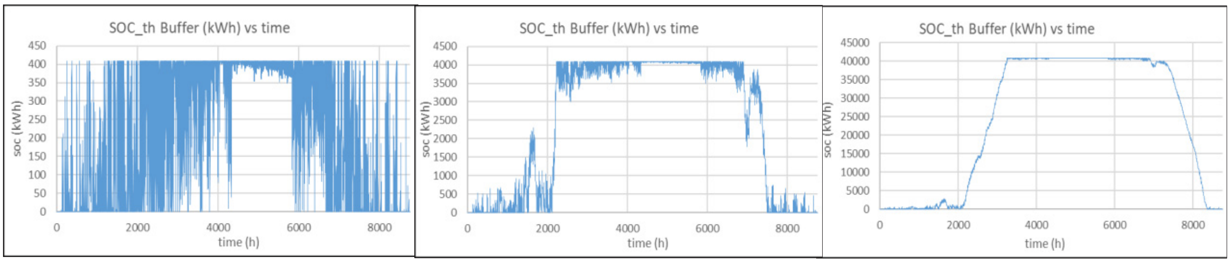

Figure 10. From left to right the SoC of the thermal buffers of 10, 100, and 1000 m^3 (sub scenarios 13, 14,15). It demonstrates that PV creates progressively stronger seasonal-scale storage effects, visible as the charging shifts further to the left and right with increasing full buffer usage to cover the heat demand.

Battery Storage (17-19)

Also electrochemical storage (batteries) is introduced and evaluated for home battery ranges between 5 and 20 kWh per apartment in combination with a 1 m^3 thermal buffer, represented by scenarios from 17 through 19. The most significant improvements in autarky and operating costs occur when moving the capacity from zero (scenario 12) to approximately 5 kWh (scenario 17). To more clearly illustrate the impact of battery capacity on sustainability (i.e., reduced CO_2 emissions), an additional analysis was conducted. In this analysis, both the CO_2 emission reduction and the investment cost per avoided kilogram of CO_2 are plotted as a function of battery capacity (0–20 kWh per apartment) and thermal storage volume (1–60 m^3), with grid-recharging disabled to optimize autarky. Fig. 11 at the left-hand side reveals that for a thermal storage volume of 1 m^3, CO_2 reductions are noticeable up to a battery capacity of approximately 10 kWh per apartment. For 10 m^3 thermal buffers, noticeable reductions occur only up to 5 kWh per apartment, and for 20 m^3 only up to 2 kWh per apartment. From 40 m^3 onwards, increasing battery capacity has only a minor effect. The adjacent graph shows the cost per avoided kilogram of CO_2 for the different combinations of thermal buffer volume and domestic battery capacity. Here, we see that a 5 kWh battery results in CO_2 reductions comparable to those of a collective 40 m^3 buffer at the same cost. The results highlight the potential relevance of batteries, particularly in cases where large thermal storage volumes become impractical or undesirable.

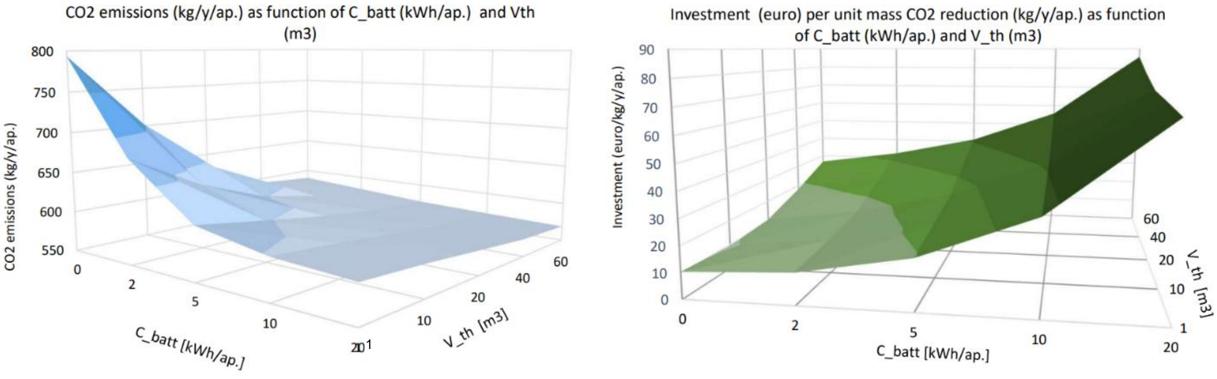

Figure 11. The CO_2 emissions per year (kg/yr/apartment) and the CapEx per avoided annual CO_2 emission (kg/y/apartment) as a function of thermal buffer volume (V_{th}) and battery capacity (C_{batt}).

Deep Renovation (20-21)

Advanced façade systems, such as the prefab façade-modules *Delta*, were finally assessed to investigate the effect of deep renovation with insulation levels up to 8 m^{2}K/W on energy performance. These measures sharply reduce heating demand and improve the Energy Positivity Index (see Fig. 6G), yet they also shift the building's energy balance toward electricity appliances. As a result, the normalized Autarky Index decreases slightly to 61%, even though overall energy use declines. Thereby, the V_{th} = 1 m^3 has been dedicated for PV charging only, i.e. no thermal charging via the grid.

This final sub scenario with an increased insulation level closely approximates the as-built thermal performance realized in the Overvecht-district project in 2021. Although in reality no central electrical battery capacity was installed to support heat pump operation, and the thermal buffer tank was continuously charged from the grid (i.e., not exclusively via PV generation), this sub scenario can be adjusted to compare it with the measured data from 2022 as reported in reference [18].

The adjusted sub scenario 21 (without battery capacity and with grid-to-thermal-buffer charging) results in a simulated total space-heating demand of 48 kWh/m^2·yr. Based on the 2022 measurements, an indicative value of approximately 42 kWh/m^2·yr was derived. For this comparison, the measured seasonal coefficient of performance (SCOP) was applied to translate the total measured electricity consumption (heat pump and household electrical appliances), corrected for pre-renovation household electricity use, into an estimated heat demand. The results are broadly consistent; however, sensitivities related to ventilation rates and domestic hot water consumption may account for deviations of up to approximately ±10 kWh/m^2·yr.

The measured PV yield reported in reference [18] also corresponds well with the simulations when normalized per dwelling, with measured values of 57 kWh/m^2·yr compared to a simulated yield of 55 kWh/m^2·yr.

Overall, the simulations do not exhibit significant deviations from measured data at this aggregate level. It should be noted, however, that the primary purpose of the simulation tool is to identify trends and relative impacts on energy autarky, energy positivity and peak shaving by integrating allocated thermal and electrical storage, rather than to predict absolute values with high precision. A robust assessment of the actual added value of different buffer configurations, system typologies, and control strategies for improving this aspects requires further dedicated, case-specific analyses and measurement protocols. These capabilities are available within the project and will be addressed in future research.

4. Conclusions

This study presented a first-order simulation tool to support the design and evaluation of energy-positive apartment buildings within the context of strict electrical capacity constraints. The Overvecht demonstration project provided a first case for evaluating the methodological validity and practical applicability.

The results show that the tool effectively supports stepwise retrofit planning. Its scenario-based structure enables technical partners and, once embedded in a user interface, also e.g. housing corporations and associations to explore combinations of envelope measures, heat pump configurations, PV integration, and storage technologies while ensuring alignment with long-term decarbonization objectives.

The tool effectively captures the influence of grid constraints, revealing that full electrification with heat pump technology without preparatory measures leads to unacceptable overload, thereby underlining the necessity of mid-level insulation and efficient ventilation as early, “no-regret” steps, dealing with the grid congestion.

A relevant insight of the study concerns the interaction between thermal and electrical storage. Modest thermal buffers help shave peak heating loads, but large seasonal buffers become financially challenging for now. In contrast, electrochemical batteries offer extra gains in operational flexibility, particularly in the 5–10 kWh range per apartment.

Deep renovation remains the most effective strategy for reducing heating demand and improving building-level energy performance.

While the current version relies on simplified representations of the building’s energy balance, domestic hot-water use, and control behavior, its modular and simplified structure provides a solid foundation for exploring system trends. Future extensions could incorporate pricing schedules, standby and transport losses, predictive charging strategies, and more detailed occupant-behavior modelling (in particular domestic hot water). For now, the next step will be migrating the tool to a web-based beta version to test its applicability, accessibility, and performance in practice, while gradually integrating datasets from newly completed retrofits to support validation and further refinement.

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