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Multi-criteria feasibility assessment of cost-optimized alternatives to comply with heating demand of existing office buildings – A case study

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Abstract

In line with the EU’s goal to phase out the use of fossil fuel, the Dutch government is determined to have gas-free new buildings from 2018 onwards. However, with over 90% of the heating demand in both existing residential and commercial buildings currently accomplished with natural gas, transitioning to a gas-free system in existing buildings remains an enormous challenge. Though electric heat pumps are gaining large ground as a substitute, the increase in electricity consumption also introduces uncertainties and further complexities to an already constrained electricity grid.

This paper thus evaluates the impact of switching to a greener demand side with all-electric heating systems for existing characteristics of office buildings, with the current composition of the electricity production side in the Netherlands. Using multi-objective computational simulations with linear programming and feasibility assessment using the Kesselring method, the study reveals hybrid energy systems (utilizing electricity and gas) favors over all-electric energy systems for fulfilling the heating demand when the buildings are considered individually. This is because the switch to a greener heating system using electricity translates to a shift of demand for fossil energy from the building side to the central production side for the on-going situation in the Netherlands.

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1. Introduction

In the Netherlands, most energy consumption for heating is fulfilled with natural gas, and over 90% of the existing buildings are connected to the natural gas network [1]. Though the Dutch government has come up with legislation to ensure new buildings which are permitted after 1st of July 2018 must be built without natural gas connection [2], achieving the same in existing buildings present an enormous challenge. This is because the transition to a gas-free and greener energy infrastructure necessitates intense modifications of the existing energy systems inside and outside buildings [3]. With this in mind, it is thus essential to analyze different energy infrastructure development scenarios [4] for individual buildings and building neighborhoods [5] with uncertainties before initiating major changes.

At present, collective heating using low-temperature networks [6–8] at the neighborhood level and the integration of the heating sector with the electricity grid [9–11] at individual building level are two major possibilities for the fossil-fuel-free transition of the heating sector. In the Netherlands, the transition at the moment is more focused on the dwelling level [12] using individual all-electric energy systems. Since the existing projects inside the country are more focused on dwelling level [12], this paper aims to discuss the effect on commercial buildings, specifically, office buildings, using a similar individual building approach. (Please note that considering buildings at the neighborhood level is out of the scope of this study). With the notion of reducing fossil fuel utilization through electrifying the heating demand of individually considered buildings, heat pumps [10,13] are gaining large ground inside the country. The associated lower CO2 emissions [14] make electrical heat pumps an attractive choice [13]. Concerning the aspects of supply/demand management and operation, thermal energy storage (TES) [6,15,16] associated with heat pumps could also be a key additive to an optimized heating energy system of office buildings. TES temporarily holds the thermal energy in either hot or cold form for the utilization at a later period [17]. Since TES performs as
a buffer between demand and supply, it can help in load balancing and peak shaving [6] and improving energy flexibility [18]. The local utilization of non-dispatchable renewable energy sources such as PV could also be improved at the building level when TES systems are coupled with heat pumps [17]. In the Netherlands, aquifer thermal energy storage (ATES) is popular with building heating and cooling applications [19,20]. The typical operating temperature scale for space heating and domestic hot water is in the range 45–80 °C [17]. However, ATES is used with large-scale buildings [21], and due to the fact that aquifers are also limited by geographical locations, water tanks may provide an alternative option to assist the heating process of office buildings. Generally, literature found on water tank based applications are limited to residential uses [17,22,23] and most of the time, are connected with solar collectors [24] or gas-fired boilers as the charging source of the tank. If connected with a heat-pump as the charging mechanism of the water tank [25], it is possible to provide low-temperature space heating to the buildings adequately. All these alternatives discussed in the literature for fossil-free transition has always been solely focused on transitioning the demand side and making buildings greener. Most of these existing literature fails to give proper attention to the assessment of the feasibility of these alternatives (Table 1) and the impact it can create on the other systems/infrastructure. For example, utilizing heat pumps create additional electricity consumption. If all the buildings use these heat pumps simultaneously, it is at the moment not sure that the current electricity grid can cope with such a mass increment in peak loads [14]. Moreover, total replacement of natural gas consumption with electricity is also debatable.

One reason for the insufficient literature on feasibility analysis of gas-free alternatives could be the scarcity of coming across actual cases where gas consumption is completely discontinued. Other than that, the differences in legislation requirements and initiatives each country takes to realize a fossil-fuel-free energy system can also be a reason.

In order to analyze the alternatives or scenarios to fulfill the heating demand either with gas, hybrid (gas and electricity) or all-electric, a scenario-based assessment is required at early stages before taking any important decisions [32] to change the energy infrastructure. Nevertheless, in these scenario-based assessments, a large number of assumptions and uncertainties are associated in parameter selection [26]. Therefore, an information contradiction occurs where, almost no certain evidence is available, but, decisions have to be taken [32]. A qualitative feasibility assessment is meant to overcome this problem by providing an adequate explanation to the decision-makers by communicating the benefits and consequences [32].

Therefore, as an important step in the decision-making process that has been overlooked in most of the existing literature, this paper discusses the feasibility assessment of different scenarios to satisfy the heating demand of an existing office building in the Netherlands using a multi-criteria feasibility assessment technique named 'Kesselring method' [32–34]. The base case which discusses the existing situation of the building is compared with a hybrid (gas and electricity) scenario and all-electric options. The paper incorporates the Dutch governments’ legislation requirement for buildings in the analysis. The next sections of this paper are as follows. In section 2, it introduces the method and models exercised in this analysis. In section 3 and 4, the case study building, evaluation results, and the qualitative feasibility assessment are discussed. Finally, in Section 5, the conclusions of the study are revealed.

2. Method and models

The method exercised in the paper to compare the scenarios is summarized in Fig. 1. It consists of three steps, and each step is described below in detail. The focus of the methodology is on the

<table>
<thead>
<tr>
<th>Reference</th>
<th>Cost analysis</th>
<th>CO₂ emissions calculation</th>
<th>Feasibility assessment</th>
</tr>
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<tr>
<td>[26] Murray et al.</td>
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<td>[27] Ashfaq et al.</td>
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<td>[6] Flores et al.</td>
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<td>[28] Pinto et al.</td>
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<td>[29] Tromborg et al.</td>
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<tr>
<td>[10] Protopapadaki et al.</td>
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<tr>
<td>[24] Hsieh et al.</td>
<td>✓</td>
<td>x</td>
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<td>[30] Lund et al.</td>
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<tr>
<td>[31] Bartolozzi et al.</td>
<td>x</td>
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<tr>
<td>[15] Bozkaya et al.</td>
<td>x</td>
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</table>

Fig. 1. Illustration of the method.
existing buildings, and it is possible to use this framework for any individual building (houses or commercial buildings).

2.1. Step 1: Define building characteristics and scenarios

As illustrated in Fig. 1, it is necessary to understand in-depth the existing heating technology of the analyzed building and the associated technical parameters (Ex: supply and return temperature levels). Then, the energy consumption patterns of the buildings need to be obtained from the building energy management system (BEMS). If this is not available, the patterns should be estimated using a suitable modeling approach [33] and modeling tools (Ex: TRNSYS). The design characteristics of the heat pump and thermal storage system need to be defined based on the existing technical parameters, current and future regulations, and decision-maker preferences [36]. For example, if the existing heating system’s operating temperature levels are high (90/70 °C), it is not beneficial to introduce heat pumps directly. Proper improvement of building insulations and reduction of supply and return temperatures of the heating system inside the building is necessary before introducing heat pumps in such a situation. After understanding the building characteristics in-depth, the suitable alternative scenarios to comply with the heating for the building will be defined.

2.2. Step 2: Computational simulation and performance assessment of defined scenarios

The identification of characteristics and current energy demand of the building leads to the next step, which is the simulation and estimation of the building energy consumptions with the introduced new design characteristics and energy systems (scenarios). The energy performance of each scenario is then to be assessed concerning different energy carriers (gas, electricity, etc.) and compared with the current situation. At the same time, the modeling and identification of optimal design parameters of the introduced energy systems are allowed by the computational analysis.

This section discusses the main modeling concepts and the mathematical formulation of the scenarios. The model used for scenario simulation using different candidate energy technologies is based on the energy hub framework [37], which is represented by a linear programming model (LP) [38,39]. The different energy systems in each scenario are optimally used in a way that the total heating demand could be provided by this scheme. The multi-objective model minimizes the CO₂ emissions and total annual costs (including investment costs and maintenance costs) [27]. The described two objective functions formulate the model’s overall objective function. The design boundary parameters of the energy technologies are nested within technology constraints of the model. The mathematical formulation of the energy systems is presented in the next subsections 2.2.1-2.2.8. In the formulation of the conventions, an italic letter represents a scalar variable and bold letter represents a vector. A scalar and vector annotation are made to distinguish between design parameters of energy technologies (one single value) and optimal control of these devices (vector with a value per sample time). The models were programmed using MATLAB for YALMIP optimizer and were solved using Mosek solver. A full horizon of 8760 h was used with an hourly sample time (t) to assess the model accurately. The enthusiastic reader may refer to Refs. [26,40,41] for more details of the mathematical modeling of the energy systems.

2.2.1. Gas boiler modeling

The gas boiler was modelled with a constant nominal efficiency of 90% and contain a minimum and maximum capacity constraint as described in equation (1a). In this case, the minimum is considered as zero. Qₜ is a decision variable which is the outlet heating power capacity of the boiler. Qₜ(t) represents the output of the boiler in each time interval.

\[
Q_{B-h}^{min} \leq Q_{B-h}^{max} \quad (1a)
\]

\[
0 \leq Q_{B-h}(t) \leq Q_{B-h} \quad \forall t = 1, \ldots 8760 \quad (1b)
\]

2.2.2. Sensible heat storage system modeling

Despite the fact that heat can be stored in different forms, water-based thermal storage is omnipresent since it is one of the most robust and simplest ways to store heat [15,16]. In this simulation, charging and discharging energy flows of the water-based short-term storage tank is considered including heat losses as illustrated in Fig. 2. The model is described by (2a) – (2e).

\[
Q_{TES}^{min} \leq Q_{TES} \leq Q_{TES}^{max} \quad (2a)
\]

\[
0 \leq Q_{TES-in}(t) \leq Q_{TES-out}(t) \quad (2b)
\]

\[
0 \leq Q_{TES-out}(t) \leq Q_{TES-out}(t) - Q_{TES}(t) \quad (2c)
\]

\[
Q_{TES}(t) = Q_{TES}(t-1) \cdot (1 - \sigma_{TES}) + \frac{\eta_{Charge}}{\eta_{Discharge}} \frac{Q_{TES-in}(t)}{Q_{TES-out}(t)}; \forall t = 2, \ldots 8760 \quad (2e)
\]

Qₜₕ represents the decision variable of energy storage capacity. The notations Qₜₕ and Qₜₜₜ indicate the thermal power output of the heat pump and the space heating load of the building, respectively. Additionally, η_charge and η_discharge symbolize the charging and discharging efficiencies which is a representation of the charging, discharging losses of the tank. The stored energy decaying rate is presented by σ_TES. The charging, discharging efficiencies and decay rate are defined based on the work of Murray et al. [26].

2.2.3. Heat pump modeling

Ground source heat pump assumed to be favorable for the case study building over air source due to the low ambient temperature...
levels during the winter period. Charging of the tank is scheduled with the operation of the heat pump.

According to legislation, in order to prevent bacteria (legionella) conditions of hot tap water, at least a temperature of 60 °C is required. Therefore, the temperature distribution provided by the heat pump and thermal storage system is considered insufficient. Some can argue, it is possible to provide 60 °C with the heat pumps. However, the COP of the heat pump decreases significantly with increased supply temperatures. Therefore, in this study, it is taken that the heat pump supply temperature is designed to 50 °C. For scenarios where the gas boiler is not present, hot water demand is considered to be provided by an auxiliary electric heater. The capacity constraints used in the modeling of the heat pump is represented by equation (3). In this equation, the heat pump thermal output power capacity \(Q_{\text{HP}}\) is a decision variable. For the optimization, an average coefficient of performance (COP) over the full heating season or a seasonal performance factor (SPF) [42] value of 3.7 [43] is used throughout the whole time span.

\[
0 \leq Q_{\text{HP}}(t) \leq Q_{\text{HP}}; \forall t = 1, ..., 8760 \tag{3}
\]

2.2.4. Chiller modeling

Chiller was modelled similar to the boiler with a constant energy efficiency ratio (EER) of 3 and described in equation (4a). \(Q_{\text{C}}\) is a decision variable, which is the cooling power capacity of the chiller. \(Q_{\text{C}}(t)\) represents the output of the chiller in each time interval.

\[
Q_{\text{C}}^{\text{min}} \leq Q_{\text{C}} \leq Q_{\text{C}}^{\text{max}} \tag{4a}
\]

\[
0 \leq Q_{\text{C}}(t) \leq Q_{\text{C}}; \forall t = 1, ..., 8760 \tag{4b}
\]

2.2.5. Rooftop PV panels modeling

If the building already owns PV panels on rooftops and if a BEMS exists, it is possible to obtain the actual solar prediction data from the BEMS. Otherwise, for the case studies in the Netherlands, the hourly PV electricity production can be calculated using the global radiation values [26] obtained from KNMI (Koninklijk Nederlands Meteorologisch Instituut) [44] and the rooftop area available for solar installation. In this study, the PV production values were directly obtained from the BEMS. The case study building has 16.9 kWp installed capacity of PV panels, which counts for 65 PV-panels of 1.5 m² each.

2.2.6. Energy grid modeling

In the simulation model, electricity and natural gas grid are included. If the PV panels produce excess electricity, it is assumed that the excess production from PV is sent back to the grid without any restriction.

2.2.7. Energy balance

The three energy demand categories, electricity, heating, and cooling are simultaneously balanced including the constraints discussed above to ensure the supply meets demand at each time interval. The general balance equations used are presented in (5a) – (5c).

\[
\begin{align*}
Q_{\text{HL}}(t) &= Q_{\text{B}}(t) + Q_{\text{HP}}(t) + Q_{\text{TES out}}(t) - Q_{\text{TES in}}(t) \tag{5a} \\
Q_{\text{CL}}(t) &= Q_{\text{C}}(t) \tag{5b}
\end{align*}
\]

\[
P_{\text{EL}}(t) = P_{\text{grid}}(t) - P_{\text{HP}}(t) - P_{\text{C}}(t) + P_{\text{PV out}}(t) \tag{5c}
\]

The space heating, cooling, and electricity demand (including appliances and lighting) of the building is represented by \(Q_{\text{B}}, Q_{\text{C}},\) and \(P_{\text{grid}}\) respectively. The hot water demand \((Q_{\text{HW}})\) is known annually. Therefore, it is not included in the optimization. The calculations for hot water demand was done separately and added to the final result. The model itself prioritizes the scheduling of the energy systems at each time step based on the objective function.

2.2.8. Objective function

Equation (6a) – (6h) demonstrate the objective function of the scenarios which minimizes both the system costs and carbon emissions. The system costs \((C_{\text{Total}})\) comprises of \(C_{\text{Investment}}\) which is the sum of the annualized investment costs of each energy technology utilized, \(C_{\text{OMF}}\) which is the fixed operation and maintenance costs, and the variable costs \((C_{\text{V}})\) which are the costs for utilizing electricity and natural gas.

\[
C_{\text{Total}} = C_{\text{Investment}} + C_{\text{OMF}} + C_{\text{V}} \tag{6a}
\]

\[
C_{\text{Investment}} = \sum C_i = C_{\text{HP}} + C_{\text{PV}} + C_{\text{TES}} + C_{\text{B}} \tag{6b}
\]

\[
C_i = \text{Cost}_i \cdot \text{Cap}_i \cdot ACF_i \tag{6c}
\]

\[
ACF_i = \frac{r}{1 - \frac{1}{(1 + r)^{\text{Lifetime}_i}}} \tag{6d}
\]

\[
C_{\text{OMF}} = \sum OMF_i \cdot \text{Cap}_i \tag{6e}
\]

\[
C_{\text{V}} = \sum_{t=1}^{8760} Q_{\text{Grid}}^{\text{NG}}(t) \cdot \text{NGP} + \sum_{t=1}^{8760} P_{\text{Grid}}^{\text{E}}(t) \cdot \text{EP} \tag{6f}
\]

In equations (6b)–(6e), ‘r’ represent the set of energy conversion and storage technologies. \(ACF\) is the annualized cost factor calculated based on the lifetime of the energy technologies. In equation (6c), \(\text{Cost}_i\) represents the capital costs per unit of capacity installed, and \(\text{Cap}_i\) represents the capacity of each technology. \(\text{OMF}_i\) is the fixed operation and maintenance costs. The variable costs \((C_{\text{V}})\) were calculated as shown in equation (6f). For each energy carrier, the grid energy consumption in kWh is multiplied by the tariff accordingly. The computation model uses a constant tariff structure for grid electricity \((\text{EP} = 0.20 \text{ €/kWh})\) and natural gas \((\text{NGP} = 0.076 \text{ €/kWh})\). Apart from the total costs, minimization of the total annual CO₂ emissions is also an objective function. In equation (6g), the energy consumption of each energy carrier (electricity and gas) is multiplied by the carbon emission factors \((\text{CF} \text{ in kg-CO₂/kWh})\) of each energy carrier respectively.

\[
\text{CO}_2_{\text{Total}} = \sum_{t=1}^{8760} Q_{\text{Grid}}^{\text{NG}}(t) \cdot \text{CF}_\text{NG} + \sum_{t=1}^{8760} P_{\text{Grid}}^{\text{E}}(t) \cdot \text{CF}_\text{E} \tag{6g}
\]

Once both the objective functions are defined, the total optimization is performed as shown by equation (6h). In the equation, \(\alpha\) represents the weighting factor. When set to one, the objective focuses on the minimization of CO₂ emissions and when set to zero, the optimization only considers the cost objective. To solve the multi-objective case, \(\alpha\) is increased in 0.1 intervals from 0 (cost-optimal) to 1 (CO₂ optimal), thereby, calculating the Pareto optimal solutions.
Feasibility analysis methods are intended to help decision makers with three indicators namely, the energy requirement (kWh/m² year), primary fossil energy use (kWhprimary/m² year) and share of renewable energy (%). In order to benchmark the performance of the analyzed scenarios against the government requirements, in this study, the BENG indicators were calculated for each scenario (Equation (7a) – (7c)). Energy requirement, which is hereby named as BENG-1, presents the energy need for heating-cooling and lighting in the building per gross floor area (GFA). The primary fossil energy (PFE) use which is hereby named as BENG-2 counts the primary energy use for heating-cooling, hot tap water, lighting, ventilation, and humidification while subtracting the renewable energy (RE) component. RE presents the onsite energy production by renewable energy sources such as PV and the heat pump extracted heat from soil or air [46]. Please note that BENG criteria is under development and not definitive yet. The criteria which are currently in operation is used in this analysis and can be changed in the future.

\[
BENG - 1 = \left( \frac{\text{EnergyHeating} + \text{EnergyCooling} + \text{EnergyLighting}}{\text{GFA}} \right)
\]

\[
BENG - 2 = \left( \frac{\text{PFHEating} + \text{PFECooling} + \text{PFEHotwater} + \text{PFELighting} + \text{PFEVentilation} + \text{PFEHumidification} - \text{RE}}{\text{GFA}} \right)
\]

\[
BENG - 3 = \frac{\text{RE}}{\text{RE} + \text{PFE}}
\]

Table 2 presents all the model parameters, the government regulation (BENG) requirements need to be achieved for an office building (over 100 m² gross floor area) and the relevant reference sources used in this study.

### 2.3. Step 3: Performance assessment and feasibility analysis

In the Netherlands, for both residential and non-residential buildings, the government has imposed some indicators in the vision of realizing ‘almost energy neutral buildings’. This is a translation of the current energy performance building directive (EPBD-2010). These requirements are called the Bijna Energieneutrale Gebouwen (BENG) criteria [45]. The criteria is composed of three indicators namely, the energy requirement (kWh/m² year), primary fossil energy use (kWhprimary/m² year) and share of renewable energy (%). In order to benchmark the performance of the analyzed scenarios against the government requirements, in this study, the BENG indicators were calculated for each scenario (Equation (7a) – (7c)). Energy requirement, which is hereby named as BENG-1, presents the energy need for heating-cooling and lighting in the building per gross floor area (GFA). The primary fossil energy (PFE) use which is hereby named as BENG-2 counts the primary energy use for heating-cooling, hot tap water, lighting, ventilation, and humidification while subtracting the renewable energy (RE) component. RE presents the onsite energy production by renewable energy sources such as PV and the heat pump extracted heat from soil or air [46]. Please note that BENG criteria is under development and not definitive yet. The criteria which are currently in operation is used in this analysis and can be changed in the future.

\[
BENG - 1 = \left( \frac{\text{EnergyHeating} + \text{EnergyCooling} + \text{EnergyLighting}}{\text{GFA}} \right)
\]

\[
BENG - 2 = \left( \frac{\text{PFHEating} + \text{PFECooling} + \text{PFEHotwater} + \text{PFELighting} + \text{PFEVentilation} + \text{PFEHumidification} - \text{RE}}{\text{GFA}} \right)
\]

\[
BENG - 3 = \frac{\text{RE}}{\text{RE} + \text{PFE}}
\]

### 2.3.1. Multi-criteria feasibility assessment

After the performance analysis and benchmarking of the scenarios with BENG legislation, to investigate the barriers and bottlenecks in practical realization, a qualitative feasibility analysis is recommended. In this study, the feasibility assessment was conducted using the Kesselring method [34,51]. This is a simple but very effective support mechanism for the decision making process. This method forms the basis of the German Design standard VDI 2225 (1998) [52] and can be used for multi-criteria decision support for conceptual design of flexible energy infrastructure [53]. Feasibility analysis methods are intended to help decision makers and designers in making decisions [54]. This method formulates the analysis taking into account the objectives to be achieved, the available resources, and the prevailing boundaries.

The technique first defines key performance indicators in a way that it makes a possibility to visualize the valuation of a variant and splits the associated KPIs [55,56] under two different groups, namely functional and realizational. The functional KPIs are all aspects with regard to the operational stage of the scenarios. Realizational KPIs represent the requirements which are not directly related to the usage phase but, the pre-utilization phase of the energy systems. Certain criteria can be accommodated both in the realizing group and the functioning group. In that case, a choice must be made; however, the important thing is that the criteria are included in the total comparison. After indicating all the relevant KPIs, the method defines a scoring system which ranges from 1 to 4 (Table 3) to be allocated for each KPI. The method says the judgment scale range from 1 to 4 is sufficiently accurate as a larger differentiation could suggest an accuracy that cannot be met. Other than that, the even number of value possibilities make it impossible for the decision-maker to assign a neutral valuation, thereby, forcing to make a choice.

Consequently, the determined scores for each KPI are aggregated into an ‘overall’ value for each alternative or scenario. By doing this, the strong points can be seen and visualized in a so-called S-(Stärke) diagram [34]. The method is sometimes also called Economical-Technical evaluation method. From the diagram, a clear indication can be observed about the feasibility of the different scenarios and what improvements should be made either in realizational or functional point of view.

### 3. Case-study building description

This study uses an office building located in Princenhage, the Netherlands. Fig. 3 illustrates the selected building. Current office stock in the Netherlands can be categorized into five segments according to its size. The selected case study building belongs to the category representing 20% of the total office building stock in the Netherlands presented in Fig. 3.

In the current situation, the building uses conventional heating and cooling energy systems. Heating demand is satisfied with a central heating system using natural gas boilers and cooling demand by means of a central cooling system using compression chillers. The characteristics of the building are presented in Table 4. In Fig. 4, mean space-heating demand profiles through each season are presented.

### 3.1. Scenario description

Table 5 presents the scenario description exercised in this paper as an alternative to comply with the existing heating and hot water energy systems of the building. Scenario 2 to Scenario 5 symbolizes the alternative scenarios, and Scenario 1 presents the current situation.

- Scenario 1: This is the current situation of the building. If no energy systems are changed inside the building, this scenario...
evaluates the performance of the existing energy systems of the building. Even though the building has installed PV panels already, in Scenario 1, this was not taken into account.

- Scenario 2: This scenario evaluates the partial discontinuation of gas consumption using a ground-source heat pump in combination with the existing conventional energy system.
- Scenario 3: In the light of reducing the grid electricity consumption of the building after establishing the heat pump, in this scenario, PV panels are introduced.
- Scenario 4: This scenario evaluates the complete discontinuation of natural gas consumption of the building. To completely discontinue the natural gas consumption, a heat pump system together with water-based thermal storage is investigated. The building has already an energy label of "C". Therefore, further improvement of the building envelope to reduce heating

![Image](image_url)

**Table 2**

Model parameters used for the study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Requirement</th>
<th>Value-2018</th>
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<td></td>
<td>[45]</td>
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<td>BENG-3</td>
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<td><strong>Economic and other parameters</strong></td>
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<td>[46]</td>
</tr>
<tr>
<td>Primary energy factor – PV produced electricity</td>
<td>–</td>
<td>1.0</td>
<td></td>
<td>[40]</td>
</tr>
<tr>
<td>Carbon factor – grid electricity (Netherlands mix)</td>
<td>kgCO₂-eq/kWh</td>
<td>0.559</td>
<td></td>
<td>[47,48]</td>
</tr>
<tr>
<td>Carbon factor – Natural gas</td>
<td>kgCO₂-eq/kWh</td>
<td>0.231</td>
<td></td>
<td>[49]</td>
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<td>Carbon factor – PV</td>
<td>kgCO₂-eq/kWh</td>
<td>0.000</td>
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<td>[50]</td>
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<tr>
<td>Electricity price</td>
<td>€/kWhₘₜₐₜₐ</td>
<td>0.200</td>
<td></td>
<td>[23,26]</td>
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<td>Natural gas price</td>
<td>€/kWhₘₜₐₐ</td>
<td>0.076</td>
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<tr>
<td>Discount rate</td>
<td>%</td>
<td>6</td>
<td></td>
<td>[26]</td>
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<td><strong>Technology parameters</strong></td>
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<tr>
<td><strong>Thermal storage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Investment cost</td>
<td>€/m³</td>
<td>585</td>
<td></td>
<td>[26]</td>
</tr>
<tr>
<td>- Operation and Maintenance</td>
<td>€/m³</td>
<td>100</td>
<td></td>
<td>[26]</td>
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<tr>
<td>- Lifetime</td>
<td>years</td>
<td>25</td>
<td></td>
<td>[26]</td>
</tr>
<tr>
<td>- Overall efficiency</td>
<td>%</td>
<td>90</td>
<td></td>
<td>[26]</td>
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<tr>
<td><strong>Heat pump</strong></td>
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<td></td>
<td></td>
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<tr>
<td>- Investment cost</td>
<td>€/kW</td>
<td>1779</td>
<td></td>
<td>[26]</td>
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<td>- Operation and Maintenance</td>
<td>€/kW</td>
<td>5</td>
<td></td>
<td>[26]</td>
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<td>- SPF</td>
<td></td>
<td>3.7</td>
<td></td>
<td>[26]</td>
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<td>- Lifetime</td>
<td>years</td>
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<td></td>
<td>[26]</td>
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<tr>
<td><strong>PV</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>- Investment cost</td>
<td>€/m²</td>
<td>300</td>
<td></td>
<td>[26]</td>
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<td>- Operation and Maintenance</td>
<td>€/kWh</td>
<td>0.03</td>
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<td>[26]</td>
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<td>- Degradation factor</td>
<td>%</td>
<td>0.59</td>
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<tr>
<td>- Lifetime</td>
<td>years</td>
<td>20</td>
<td></td>
<td>[26]</td>
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<tr>
<td><strong>Gas boiler</strong></td>
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<td></td>
<td></td>
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<tr>
<td>- Investment cost</td>
<td>€/kW</td>
<td>234</td>
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<td>- Operation and Maintenance</td>
<td>€/kW</td>
<td>3.3</td>
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<td>[26]</td>
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<tr>
<td>- Efficiency</td>
<td>%</td>
<td>90</td>
<td></td>
<td>[26]</td>
</tr>
<tr>
<td>- Lifetime</td>
<td>years</td>
<td>15</td>
<td></td>
<td>[26]</td>
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**Table 3**

Scoring system.

<table>
<thead>
<tr>
<th>Value judgment</th>
<th>Sufficient</th>
<th>More than sufficient</th>
<th>Suitable</th>
<th>Most suitable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

![Image](image_url)

**Fig. 3.** The case study building (Left), Office building stock categorization (Right) in the Netherlands.
demand or further reduction of temperature levels of the distribution system were not considered. This scenario is illustrated in Fig. 5, A). An electric boiler is considered to fulfill the hot water demand.

**Scenario 5: Fig. 5, B) presents energy flows and the candidate technologies of this scenario, which is an adaptation of Scenario 4, including PV panels.**

### 4. Results and discussion

Based on the scenarios described in section 3.1, and using the case study building characteristics, a series of computational simulations were conducted and the results were benchmarked with BENG criteria.

#### 4.1. Scenario 1

Scenario 1 represents the current characteristics of the case study building. The buildings’ heating demand is fulfilled by conventional boilers (capacity - 90 kW) and the effect of the existing energy systems are counted for BENG criteria calculation shown in Table 6.
4.2. Scenario 2

This scenario evaluates a series of hybrid cases where the boiler and heat pump operates in parallel to fulfill the heating and hot water demand of the building. The heat pump capacities and the boiler capacities are decision variables from optimization according to the used weighting factor of the objective function. Fig. 6 shows the resulted values from simulation and the calculated BENG criteria accordingly.

The figure demonstrates that a significant improvement in CO₂ emission reduction can be obtained by introducing the electric heat pump. However, only the BENG–1 criteria can be realized with the combined heat pump and boiler scenario when the heat pump capacity is above 14 kW.

4.3. Scenario 3

In this scenario, PV panels were introduced to the flat rooftop of the building. Despite the fact that the renewable energy percentage increases and the primary fossil energy consumption decreases compared to scenario 2, the benchmark regulation cannot be met even after introducing PV panels (Fig. 7).

Another interesting fact was observed in the computational simulation of both scenario 2 and scenario 3. When the weighting factor increases from zero (cost-optimal) to one (CO₂ optimal), the energy system varies from an all-gas to an all-electric system while increasing the utilized heat pump capacity. However, beyond the 48 kW heat pump capacity point, the calculated values for BENG indicators almost stabilizes. Along with that, the CO₂ emission reduction also becomes unlikely to decline, yet, the annualized costs increase drastically. This observation indirectly indicates that an all-electric energy system does not provide the maximum benefits with the current energy mix in the Netherlands. A hybrid energy system with boiler and heat pump could be optimal for the existing situation. However, the Dutch government already decided to start disconnecting the gas connections to the buildings. Therefore, all buildings in the Netherlands are forced to move towards gas-free alternatives in the near future. Thus, in the next scenario, the thermal storage system is introduced along with the heat pump to fulfill the total heating demand of the building using electricity.

4.4. Scenario 4

Fig. 8 illustrates the computational simulation results obtained with varying thermal storage dimensions. In this case, the hot water demand was assumed to be fulfilled with an electric boiler. With higher thermal storage capacities, a slight increase in the CO₂ emissions is observed. This is due to the high frequency of charging and discharging and the associated losses which make slightly high consumption of electricity. Nonetheless, BENG–2 and BENG–3 criteria cannot be met in this case.

4.5. Scenario 5

Fig. 9 demonstrates the results obtained for scenario 5, which is a combination of thermal storage, heat pump, and rooftop mounted PV. A similar approach is followed as of scenario 4. However, none of the analyzed scenarios could meet the BENG–2 and BENG–3 criteria.

4.6. Selection of energy systems

The Pareto-frontiers obtained for each scenario with different combinations of energy systems is illustrated in Fig. 10. From these combinations, one set from each scenario (summarized in Table 7) was selected observing the CO₂ emission reduction and associated costs. This selection can be of the interest of the decision-makers such as policymakers, consultants, or building owners [40]. In this study, costs and CO₂ emissions were given similar priority.

![Scenario-2 computational simulation results.](image)
Therefore, the selection was made for $a$ equals 0.5 in the objective function (see 2.2.8). For all scenarios it can be seen, beyond the selected points, the observed CO2 emission reduction is not significant, but, the annualized costs are high.

4.7. Multi-criteria feasibility assessment

Next, the selection phase to decide on a timely and pragmatic scenario will be proceeded through the feasibility assessment using the Kesselring method. The KPIs used for the assessment under the categories functional and realizational are listed in Table 8, and the relevant score given for each alternative is demonstrated. Fig. 11 illustrates the calculated operational stage CO2 emissions and energy costs of the scenarios. It demonstrates a clear reduction in CO2 emissions for the PV introduced scenarios when compared with the current case. However, in the figure almost similar behavior of annualized costs and CO2 emissions were observed for the hybrid and all-electric cases. This is because, in all-electric scenarios, the fossil-fuel demand of the building side has shifted to the central electricity production side.

After applying the Kesselring evaluation, the resulted S-diagram is shown in Fig. 12. In this figure, the diagonal represents the most satisfying, balanced situation. The closer the scenarios are to this line and closer to the 100%, the better the satisfaction and feasibility of the scenarios are. This feasibility study resulted in a more contradictory result than expected as scenario 2 and 3, which led to the highest feasible energy systems. One may think all-electric systems are preferable than gas consumed energy systems. However, the computational simulation identified that all-electric situations using only electric heat pump could not give significantly better results when a gas boiler is present (section 4.2, 4.3). Other than that, the feasibility study discovered that scenario 2 and 3, which are hybrid scenarios with a combination of gas and electricity energy systems, are the most agreeable for the existing situation in the Netherlands.

5. Conclusion

This paper discussed five scenarios to comply with the heating demand of an office building in the Netherlands. First, the energy characteristics of the building have been identified using the data extracted from the BEMS. Second, multi-objective optimization has
been performed for each scenario and suitable capacities for each energy system have been identified. Then, the results have been benchmarked against government regulations (BENG criteria). Finally, using the results obtained from the computational analysis, a qualitative multi-criteria feasibility assessment has been performed by means of the Kesselring method for the five scenarios. The analysis discovered hybrid scenarios, which are a combination of natural gas and electricity is in favor of the existing characteristics of the building. Apart from this finding, when benchmarking the results with the government regulations, it is found out that the primary fossil energy requirement (BENG-2) is far from attainment.

The reasons for the higher feasibility of hybrid energy systems compared to the all-electric systems and the impossibility to reach BENG-2 is because higher demand for electricity translates to higher demand of fossil fuel as input for electricity generation. Currently, a higher percentage of the Netherlands’ electricity demand is fulfilled by coal and natural gas power plants. This reason has created the carbon emission factor for grid electricity to be 0.559 kg-CO2/kWh, which is a high number than most found in the other European countries (Ex: Austria- 0.151, Belgium- 0.224 kg-CO2/kWh, etc.). Apart from the carbon emission factor, another reason could be the primary energy factor (PEF) for grid electricity, which is a measure of the efficiencies of the power plants. At the moment, the primary energy factor for grid electricity counts 2.56 for the Netherlands. Nevertheless, this PEF value reduces with the number of renewable energy sources penetrate to the grid.

Considering these reasons, in order to reach the BENG criteria, it is first needed to reduce the existing energy demand of the commercial buildings. This would be a possibility by improving the

Table 7

<table>
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<tr>
<th>Unit</th>
<th>SI</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
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<tr>
<td>Boiler kW</td>
<td>90</td>
<td>50</td>
<td>50</td>
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<tr>
<td>Heat Pump kW</td>
<td></td>
<td>40</td>
<td>40</td>
<td>55</td>
<td>54</td>
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<td>Thermal Storage m³</td>
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<td></td>
<td>55</td>
<td></td>
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<td>PV kWp</td>
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<td></td>
<td>3.5</td>
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</table>

Fig. 9. Scenario-5 computational simulation results.

Fig. 10. Pareto-frontiers of each scenario (selected points for the feasibility analysis are marked in red).
building insulations. This requirement indicates the buildings should reach higher energy labels than label ‘C’. Another option would be fulfilling the heat demand requirement by using collective low-temperature heating strategies. Low-temperature heating also requires refurbishment of buildings to discard the potential mismatches between heat emitters inside the buildings and heating network. Future work of the authors will be regarding this aspect.

This kind of analysis can be instrumental in drawing the attention of the decision-makers such as policymakers, building owners, and other stakeholders because of the uncomplicated understandable strategies. However, the conceptual understanding from this study needs a follow up detailed analysis if the decision making parties agree upon the results. Such extended study includes a comprehensive exploration of energy systems, retrofitting of buildings, demand-side management strategies, and uncertainty assessment of the overall system. Conclusively, this study can be reflected as an efficient scientific and engineering approach.

**Conflict of interest and authorship confirmation form**

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a

<table>
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<tr>
<th>Table 8</th>
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<td>KPIs</td>
<td>Alternative</td>
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<tr>
<td>Functional requirements</td>
<td>Ease of operation and maintenance</td>
</tr>
<tr>
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<td>Annualized operation and maintenance costs</td>
</tr>
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<td>Energy costs – operational stage</td>
</tr>
<tr>
<td></td>
<td>Environmental impacts – operational stage CO₂ emissions</td>
</tr>
<tr>
<td></td>
<td>System reliability – susceptible to failure</td>
</tr>
<tr>
<td></td>
<td>Noise disturbance</td>
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<tr>
<td></td>
<td>Acceptance with energy transition</td>
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<td>Total score functioning</td>
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</tr>
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<td>Score as a percentage (%)</td>
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<td>Realizational requirements</td>
<td>Onsite execution time</td>
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<tr>
<td></td>
<td>Onsite execution space requirement</td>
</tr>
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<td>Resource feasibility</td>
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<td></td>
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<td>Investment cost</td>
</tr>
<tr>
<td></td>
<td>Adaptability of the system to the current situation</td>
</tr>
<tr>
<td></td>
<td>Adaptability of the system to future variations</td>
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<td>Technical maturity of energy technologies</td>
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<td>Score as a percentage (%)</td>
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**Fig. 11.** Operational stage energy costs and CO₂ emissions of the scenarios.
Acknowledgment

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