Evaluation of positive energy districts with district heating and heat pumps

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Abstract

The transformation of districts into Positive Energy Districts (PEDs) is one of the major EU goals on the path to a sustainable building stock. When connecting PEDs to district heating systems, which typically rely on non-renewable sources, the energy balance requires careful consideration. Methods for calculating the necessary photovoltaic energy to achieve a positive balance are not yet available. To consider different energy carriers, the energy demands have to be converted to primary energy or CO_2 emissions. In addition to the annual energy balance typically used in PED calculations, time-depending methods, i.e. monthly conversion factors, address the impact of seasonal variations on energy demand and supply. These methods are applied to a case study of a realized residential district in Austria. Alternative system concepts district heating (DH) and heat pumps (HP) and different combinations of DH and HP are investigated by applying different balancing methods. Insights into the challenges and feasibility of achieving PED for multi-family buildings in urban areas with DH are derived.

Keywords: Positive energy district, district heating, heat pump, CO_2 emissions, monthly conversion factors

1. Introduction and aim of the study

Numerous studies have extensively explored the concept of Positive Energy Districts (PEDs), providing a range of definitions and methodologies (Lindholm, et al., 2021), (Albert-Seifried, et al., 2021), (Guarino, et al., 2023), (Moreno, et al., 2021), (Walker, et al., 2018), (Shnapp, et al., 2020). Key performance indicators (KPIs), including primary energy (PE) (Guarino, et al., 2023), non-renewable (non-RE) PE (Moreno, et al., 2021), and carbon footprint (Guarino, et al., 2023), have been used in these investigations. The primary focus of these studies is on assessing the annual balance between energy demand and supply. However, annual methodologies overlook grid-related challenges arising from energy imbalances (i.e. energy demand peaks in winter and supply peaks in summer, the so-called winter gap).

The transformation of districts with multi-apartment buildings connected to a non-RE district heating (DH) system requires careful consideration of the balancing method, i.e. annual vs. monthly, PE vs. CO_2. Furthermore, it is important to address whether it is acceptable and if so, how to overcompensate the use of gas in the DH with an additional supply of photovoltaic (PV) energy. As shown in (Ochs, et al., 2022) for the DH in Vienna and Innsbruck, the gas demand in DH is particularly high during the winter months due to space heating (SH) needs. Hence, the future development of the DH system has to be considered, too.

This study aims to develop and compare methods for assessing the performance of PEDs connected to DH systems. The goal is to determine the necessary PV energy (i.e. PV area) to achieve a PED. The required PV area depends on the method employed for the calculation of the PE or CO_2 balance. Various methods will be developed and tested by means of a comprehensive case study of an existing residential district in Innsbruck, Austria. The study will use the design data of the existing system and expand the methods to explore alternative system concepts involving DH and heat pumps (HP). This approach aims to draw more general conclusions about the requirements for achieving PED with DH and HP. The alternative system concepts that will be investigated, include: 1) HP for space heating (SH), and DH for domestic hot water (DHW) (i.e., as built), 2) HP only (for both SH and DHW), 3) DH only (for both SH and DHW), and 4) DH for SH, and HP for DHW (i.e., opposite of as-built).

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2. Case Study

The "Campagne-Areal" Smart City Quarter is a project involving 16 new buildings subdivided into four blocks (Figure 1, left). Predominantly residential, some buildings also accommodate non-residential facilities (e.g. supermarket and kindergarten). The first four buildings (i.e. the first block) have already been built and tenants have been moving in in late 2022, which is also the start of a three-year monitoring campaign. The total living area amounts to 22277 m^2. A common technical room accommodates the main components of the central heating system (Figure 1, right) for the entire quarter. The goal of the Smart City Quarter is the creation of a "Zero Emission Urban Region" and to contribute to the Energy Strategy Tyrol 2050, thus it can serve as an example of achieving PED in an urban environment with DH.

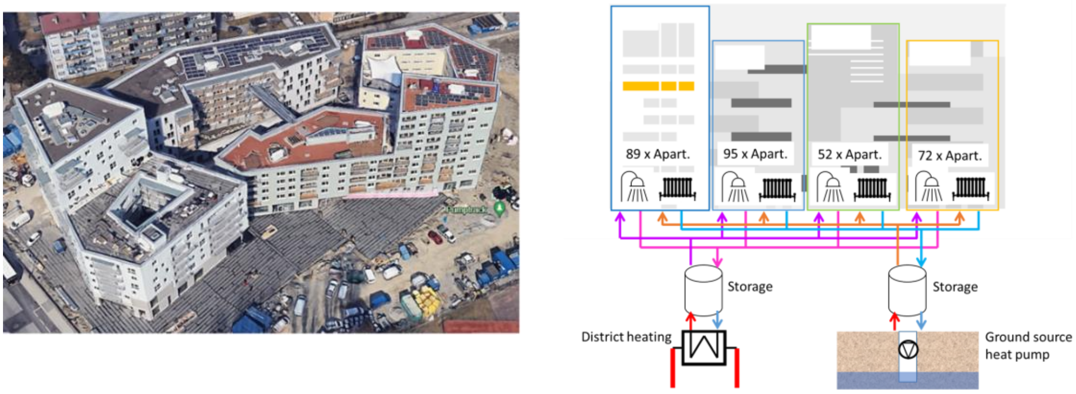

Figure 1: Left: Campagne Areal district (source: Google Earth). Right: Scheme of the energy system

The buildings were designed to meet the Passive House standard, with space heating demands ranging from 15 kWh/(m²a) to 21 kWh/(m²a). A mechanical ventilation system with heat recovery (MVHR) is installed. SH is provided by a ground source HP, while DHW is provided by the city DH. Storages for SH and DHW are integrated into the hydronic circuit. The Passive House Planning Package (PHPP) (Feist, et al., 2007) was used during the planning phase to design the four buildings. Energy demands for space heating, domestic hot water, auxiliaries and appliances are calculated on a monthly basis using PHPP. The monthly SH and DHW demands are calculated including distribution and storage losses. Monitoring data for the first two years of the districts are available on district-, building-, and apartment-level. A comparison between design results and monitoring data is carried out in (Venturi, et al., 2024). The annual electricity demand for the HP for SH amounts to 77 MWh$_{el}$, while the electricity demand for appliances is 392 MWh$_{el}$, and for auxiliaries (including the MVHR) is 153 MWh$_{el}$. The thermal demand from the DH system for DHW is 582 MWh$_{th}$. The monthly electric and thermal energy demands are shown in Figure 2.

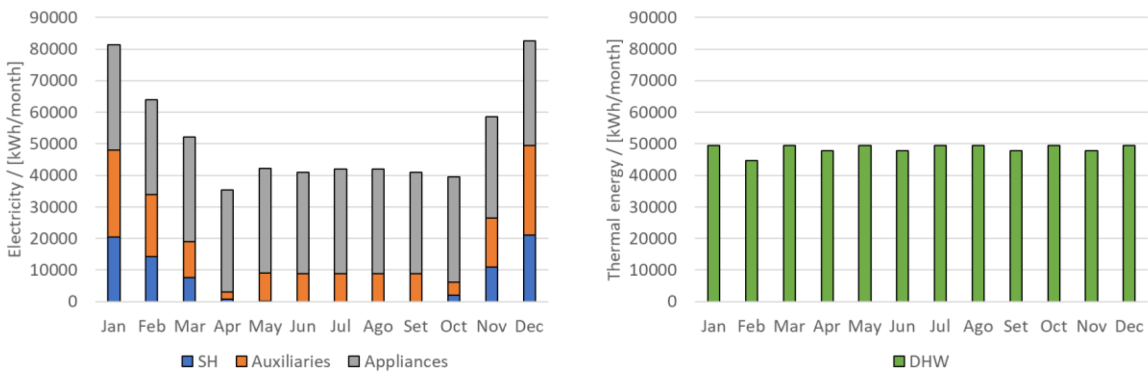

Figure 2: Left: Monthly electric energy required by HP (for SH), auxiliaries and appliances. Right: thermal energy required by DH (for DHW)

3. Methods

Several conversion factors and CO_2 balances are proposed in order to explore the necessary PV energy (i.e. PV area) to reach a positive energy balance. The conversion factors vary based on the balanced quantity (CO_2 or non-RE PE) and the type of conversion factor (annual or time-dependent). The CO_2 balances differ in the type of storage considered (grid as an ideal storage or hydrogen storage with losses). The methods are tested on the case study to assess the performance of PEDs connected to DH and HP. Additionally, different variants of heat generation are introduced, and the methods are applied to these variants accordingly.

3.1 Conversion factors

3.1.1 Balanced quantity

Primary energy (PE), non-renewable primary (non-RE PE) energy and CO_2 emissions are commonly used in the PED assessment. Since the goal of this study is to calculate the necessary PV area to offset the energy from non-renewable sources, the CO_2 and the non-RE PE conversion factors are relevant. The renewable part of PE is excluded, as it does not require offsetting with PV energy (as it already comes from renewable sources). In the case of absence of nuclear energy, CO_2 and non-RE PE conversion factors are the same. Therefore, for sake of simplicity, only the CO_2 conversion factor is considered in the current study, however, the method is valid with non-RE PE, too.

The quantity of equivalent CO_2 (in kg) produced by the energy (electric and thermal) demand is calculated according to eq. 1:

$$CO_2 = W_{el} \cdot f_{CO2eq,el} + Q_{DH} \cdot f_{CO2eq,DH} \quad \text{(eq. 1)}$$

Where:

- W_{el} is the electric energy demand from the electric grid [kWh_{el}]
- Q_{DH} is the thermal energy demand from the city district heating [kWh_{th}]
- $f_{CO2eq,el}$ is the CO_2 conversion factor for electricity [kg_{CO2}/kWh_{el}]
- $f_{CO2eq,DH}$ is the CO_2 conversion factor for DH [kg_{CO2}/kWh_{th}]

Since the energy mix for DH is highly dependent on the specific city or region, this study uses the energy mix specific to the DH of Innsbruck, rather than the Austrian national values. In contrast, the conversion factors for electricity are based on the Austrian national energy mix.

3.1.2 Type of conversion factor (annual and time-dependent)

In the current study both annual and time-dependent (i.e., monthly) conversion factors are used. The annual conversion factors represent the energy mix (electricity or DH) over the course of a year, providing a generalized average of the energy sources used in each month. In contrast, the monthly conversion factors, which vary throughout the year, reflect the energy mix for each individual month. These monthly variations occur due to the fluctuating availability of renewable sources throughout the year.

The annual values of the CO_2 conversion factor for electricity are country-specific and are documented in the literature, often provided in standards and norms. For example, the Austrian norm OIB 2023 (OIB, 2023) specifies the CO_2 conversion factor for electricity as $f_{CO2eq,el}$ = 156 g/kWh. The annual values used in the current paper for the DH of Innsbruck is $f_{CO2eq,DH}$ = 127 g/kWh (Ochs, et al., 2022), based on (Streicher, 2018). Although the data from (Streicher, 2018) refers to the year 2017, the annual values for 2023 from (TIGAS, 2024) confirm similar shares with only minor changes.

To account for the timing of energy demand and supply, it is necessary to assess the CO_2 conversion factor based on the time of the year (at least on monthly basis). In the current study, monthly conversion factors are considered. This approach, initially proposed by (Ochs & Dermentzis, 2018) and then applied by (Dermentzis, et al., 2021), allows for consideration of the so-called winter gap. Monthly conversion factors for the Austrian electricity mix are available in (OIB, 2023), while those related to the Innsbruck DH system are derived by (Ochs, et al., 2022). It is important to note that the availability of monthly conversion factors depends on the country, or in case of DH on the specific city/region. Finding accurate monthly conversion factors for DH can be challenging and the assumptions used in their calculation can have a significant impact on the results.

The monthly and annual CO_2 conversion for electricity and DH are illustrated in Figure 3.

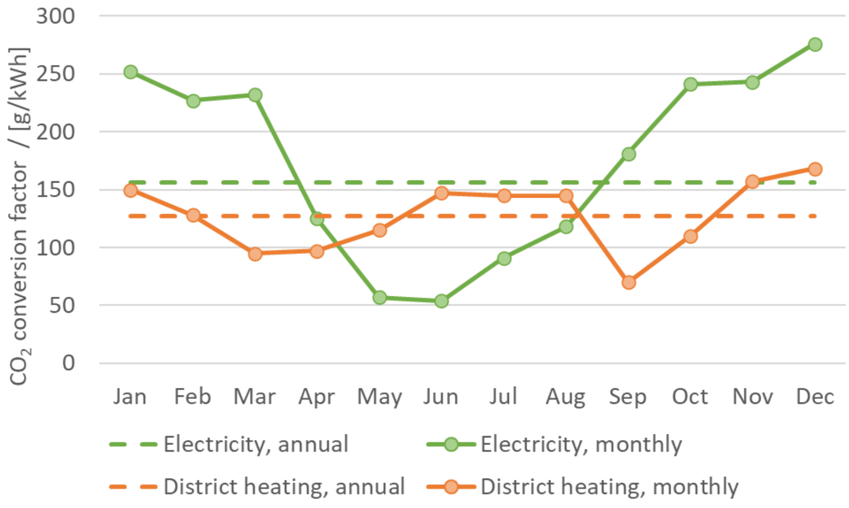

Figure 3: Annual (dotted line) and monthly (continuous line) CO_2 conversion factor for electricity (in green) and DH (in orange). Source for electricity: (OIB, 2023). Source for DH: (Ochs, et al., 2022)

The monthly conversion factor for electricity shows peaks during the winter months. In contrast, the monthly conversion factors for the DH system in Innsbruck have peaks in both winter and summer (June to August) when fewer renewable sources are utilized (Ochs, et al., 2022).

3.2 CO_2 balance

A CO_2 balance between the required energy and the produced energy by the PV system is necessary, regardless of the conversion factor used. The CO_2 balance means that the annual CO_2 emissions due to the energy demand must be offset by the annual CO_2 savings due to the PV production (see eq. 3).

$$\sum_{i=1}^{12} CO_{2,demand,i} = \sum_{i=1}^{12} CO_{2,supply,i} \qquad \text{(eq. 3)}$$

Where:

- $CO_{2,demand,i}$ is the CO_2 emissions due to the energy demand in every month (i)
- $CO_{2,supply,i}$ is the CO_2 savings (or negative emissions) due to the PV production in every month (i)

Knowing the annual required CO_2 negative emissions, the necessary PV energy (i.e., PV area) to achieve a PED can be calculated. In the current study, two CO_2 balance approaches are used: one considers the grid as an "ideal storage" (i.e., no losses), and the other involves a seasonal storage system with losses (i.e., a more realistic approach), such as using hydrogen (H_2) technologies. These two possible balances are called: "Grid as ideal storage" and "Seasonal storage (H_2)" and are detailed in the following sections.

3.2.1 CO_2 balance: "Grid as ideal storage"

The most common balance used in the literature is the annual balance with the grid (here called "Grid as ideal storage"). In this scenario, the required PV energy to achieve PED can be produced during the summer months (when the PV production is high and the energy consumption is low) and used in winter. Since no losses are accounted for, the grid is considered as an ideal storage system. The required PV area for the case "Grid as ideal storage" is calculated to have CO_2 balance according to eq. 4:

$$Area_{PV} = \frac{\sum_{i=1}^{12}\left(\frac{CO_{2,supply,i}}{f_{CO2,eq,i}}\right)}{\sum_{i=1}^{12} I_{sol,i} \cdot \eta_{PV}} \quad \text{(eq. 4)}$$

Where:

- $Area_{PV}$ is the required PV area
- $I_{sol,i}$ is the solar radiation in each month (i)
- η_{PV} is the efficiency of the PV panel
- Monthly CO_2 negative emissions ($CO_{2,supply,i}$) and monthly conversion factors ($f_{CO2,eq,i}$) are as described in section 3.2 and 3.1.1

The efficiency of the PV panels (η_{PV}) is assumed to be 22%. The monthly solar radiation is obtained from the standard weather data of Innsbruck provided in Passive House Planning Package (PHPP), see Table 1.

Table 1: Solar radiation in kWh/(m^2 month) for Innsbruck according to PHPP

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
58.5	70.9	106.2	134.6	139.2	125.8	137.3	129.0	113.9	96.7	50.5	49.8

It has to be noted that when the current method is applied using annual conversion factors, the balance is known as the so-called "net balance".

3.2.2 CO_2 balance: "Seasonal storage (H_2)"

Hydrogen can serve as an alternative method for storing electric energy produced during the summer months for later use in the winter months. This CO_2 balance accounts for the losses in the hydrogen storage process. The process includes: electrolyzer (efficiency $\eta = 70\%$ (Tosatto & Ochs, 2024)), H_2 storage (charging efficiency $\eta_{charge} = 89\%$ and discharging efficiency $\eta_{discharge} = 100\%$ (Tosatto & Ochs, 2024)), and fuel cells (efficiency $\eta = 50\%$). Consequently, the total roundtrip efficiency (η_{H2}) of the process is 31%, which affects the PV overproduction in the summer months (i.e., the electricity that can be stored).

The calculation of the required PV area must consider the energy self-consumption in each month (unlike in the "Grid as ideal storage" calculation where the process efficiency was assumed to be 100%). The required PV area is determined by solving the eq. 5, which is based on eq. 6, and further derived from eq. 7. The calculation necessitates an iterative process.

$$\sum_{i=1}^{12} W_{PVover,i} = 0 \quad \text{(eq. 5)}$$

$$\begin{cases} W_{PVover,i} = \left(W_{prod_{PV},i} - \frac{CO_{2,supply,i}}{f_{CO2,eq,i}}\right) \cdot \eta_{H_2} & when \left(W_{prod_{PV},i} - \frac{CO_{2,supply,i}}{f_{CO2,eq,i}}\right) > 0 \\ W_{PVover,i} = \left(W_{prod_{PV},i} - \frac{CO_{2,supply,i}}{f_{CO2,eq,i}}\right) & when \left(W_{prod_{PV},i} - \frac{CO_{2,supply,i}}{f_{CO2,eq,i}}\right) < 0 \end{cases} \quad \text{(eq. 6)}$$

$$W_{prod_{PV},i} = I_{sol.i} \cdot \eta_{PV} \cdot Area_{PV} \quad \text{(eq. 7)}$$

Where:

- $W_{PVover,i}$ is the PV overproduction in each month (i). $W_{PVover,i}$ is negative in months when the PV production is less than the required energy
- $W_{prod_{PV},i}$ is the produced energy by PV panels in each month (i)
- η_{H_2} is the roundtrip efficiency of the total H_2 process (electrolyzer, H_2 storage and fuel cells), which is 31%
- Monthly CO_2 negative emissions ($CO_{2,supply,i}$) and monthly conversion factors ($f_{CO2,eq,i}$) are as described in section 3.2 and 3.1.1. Monthly solar radiation ($I_{sol.i}$) and PV efficiency (η_{PV}) are as described in section 3.2.1

3.3 Methods for assessing the performance of PEDs

Four methods are derived from the combination of the type of conversion factors (section 3.1.2) and the CO_2 balance (section 3.2). These methods are illustrated by the white cells in Figure 4. The methods become eight when also the balanced quantity of the conversion factor (section 3.1.1) is changed (CO_2 and non-RE PE, in case of presence of nuclear energy in the grid). The comparisons of the possible methods are indicated by the colored arrows in Figure 4 and include:

- Comparison of the type of the conversion factor (green arrow), it will be presented in section 4.1.1 (i.e. annual vs. monthly conversion factor)
- Comparison of the CO_2 balance (orange arrow), it will be presented in section 4.1.2. (i.e. “Grid as ideal storage” vs. “Seasonal storage (H_2)”)

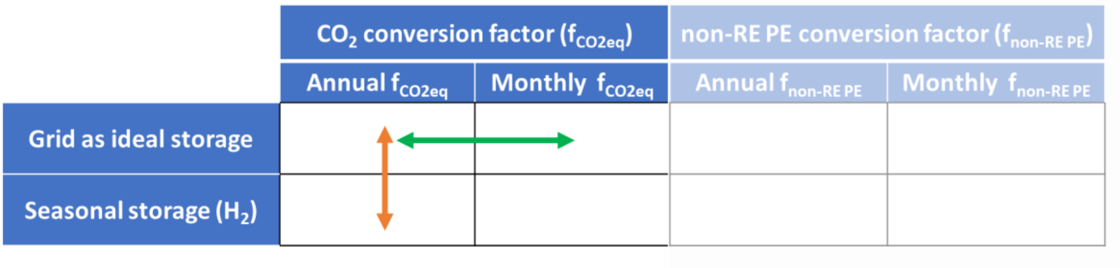

Figure 4: Schematic representation of the 4 methods (illustrated by the white cells) resulting from different combinations of conversion factors and CO_2 balances. The number of methods increases to 8 when the non-RE PE conversion factors are also considered

3.4 Variants of the heat generation

To draw more general conclusions on the requirements to achieve PEDs using DH and HP, several alternative system concepts are investigated. These variants combine different heat generations and are as follows:

1) HP for SH, and DH for DHW (i.e., as built),

2) HP only (for both SH and DHW),

3) DH only (for both SH and DHW),

4) DH for SH, and HP for DHW (i.e. opposite of as-built).

The electric and thermal energy demands for these four systems are calculated using PHPP. Electricity for auxiliaries and appliances is included. The energy demands are available on monthly basis.

4. Results

The methods are compared in section 4.1. Section 4.2 focuses on comparing the different heat generation's variants. The different methods are applied to the four heat generation's variants of the Campagne district, but for simplicity, results are presented using only the monthly CO_2 conversion factor.

4.1 Comparison of the methods

4.1.1 Comparison of the type of conversion factors

The influence of using the annual or the monthly conversion factor (green arrow of Figure 4) is discussed in the current section.

The monthly CO_2 emissions (due to the energy demand) are presented in Figure 5 with calculations using annual and monthly CO_2 conversion factors.

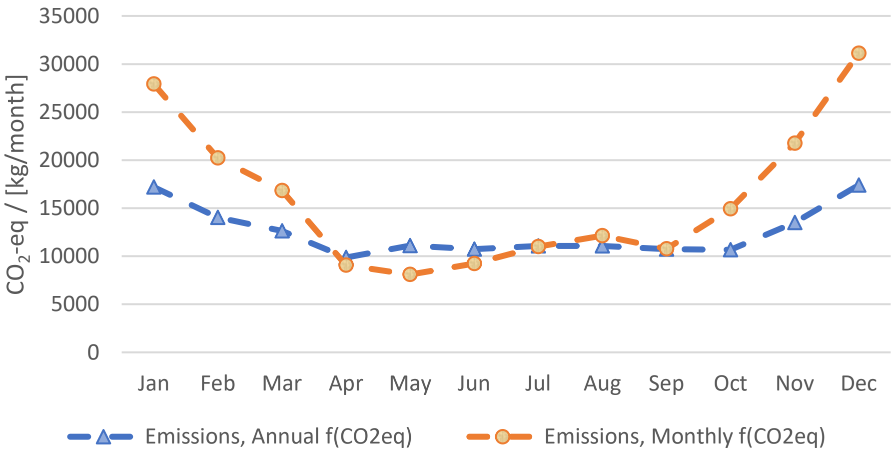

Figure 5: Equivalent CO_2 emissions calculated using the annual (blue line) and monthly (orange line) CO_2 conversion factors (based on the same energy demand)

The use of monthly conversion factors leads to higher CO_2 emissions during the winter months, reflecting the increased reliance on non-renewable sources during these months. In contrast, the annual conversion factor tends to underestimate these emissions. This discrepancy impacts the calculation of the required PV area: 3604 m^2 using the annual CO_2 conversion factor and 4518 m^2 using the monthly CO_2 conversion factor, according to the "Grid as ideal storage" CO_2 balance, which is commonly used in the literature. The PV production corresponding to these PV areas results in negative CO_2 emissions, shown in Figure 6 alongside the positive CO_2 emissions due to the energy demand (as depicted in Figure 5).

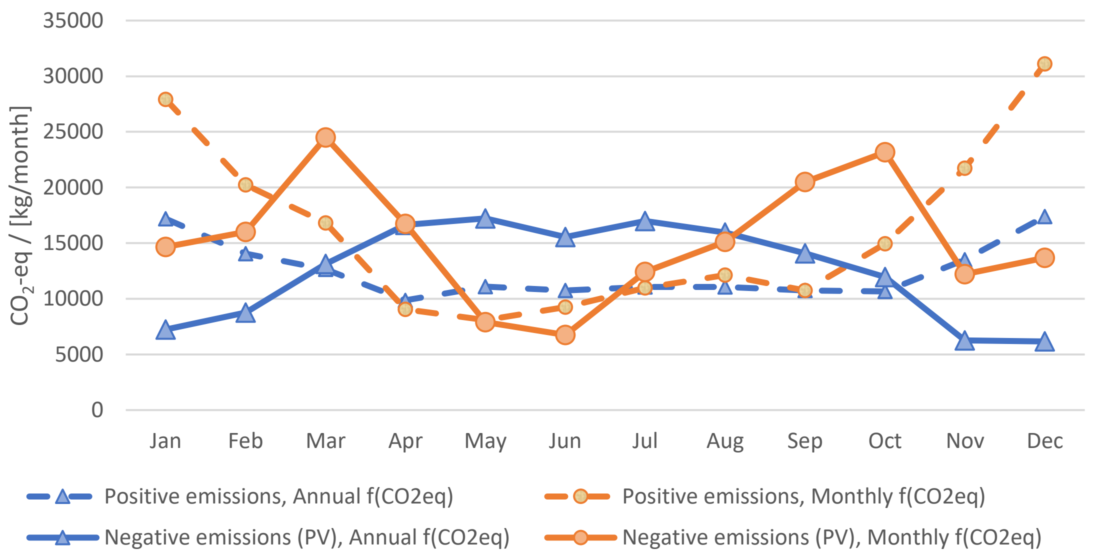

Figure 6: Positive CO_2-equivalent emissions (dotted lines) due to the energy demand and negative CO_2-equivalent emission (continuous lines) due to the PV production. Monthly emissions are presented using annual f_{CO2eq} (blue) and monthly f_{CO2eq} (orange)

As observed in Figure 5, the monthly conversion factors affect also the negative emissions associated with the PV production. The peaks in negative CO_2 emissions calculated using the monthly CO_2 conversion factor during the intermediate months (e.g., March and October) result from the combination of relatively high conversion factors (higher than the annual value, see Figure 3) and the relatively high PV production compared to the winter months (due to the higher solar radiation, see Table 1).

4.1.2 Comparison of the CO_2 balance

The impact of the ideal or seasonal storage in CO_2 balance (orange arrow of Figure 4) is discussed in the current section. The two CO_2 balances (i.e. “Grid as ideal storage” and “Seasonal storage (H_2)”, as described in section 3.2) are calculated using monthly conversion factors.

Due to the losses associated with the “Seasonal storage (H_2)”, the required PV area is 5623 m^2, which is 24% larger than the area calculated using the “Grid as ideal storage” (4518 m^2). The resulting monthly PV production is illustrated in Figure 7.

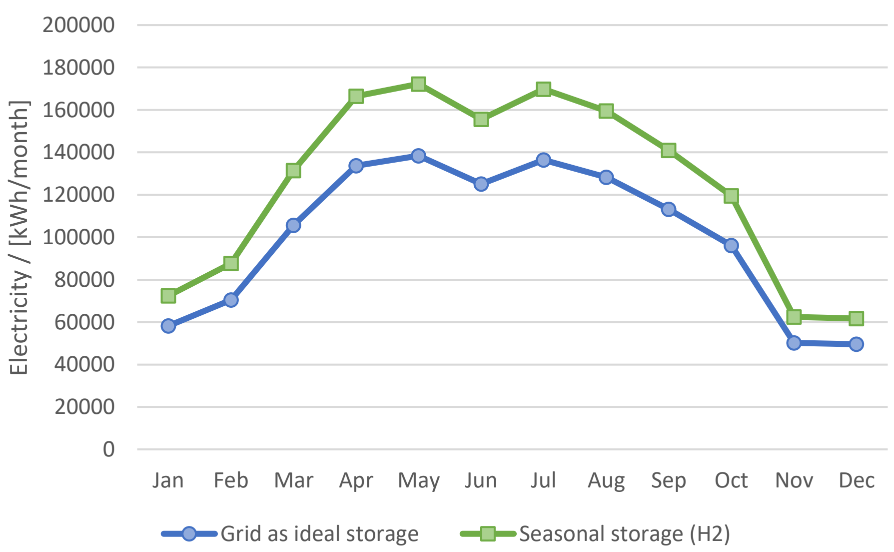

Figure 7: Electricity produced by the PV areas calculated according the two CO_2 balances. Calculations with monthly f_{CO2eq}

Figure 8 shows the equivalent CO_2 emissions, highlighting the positive emissions due to the energy demand (black line) and the negative emissions due to the PV production.

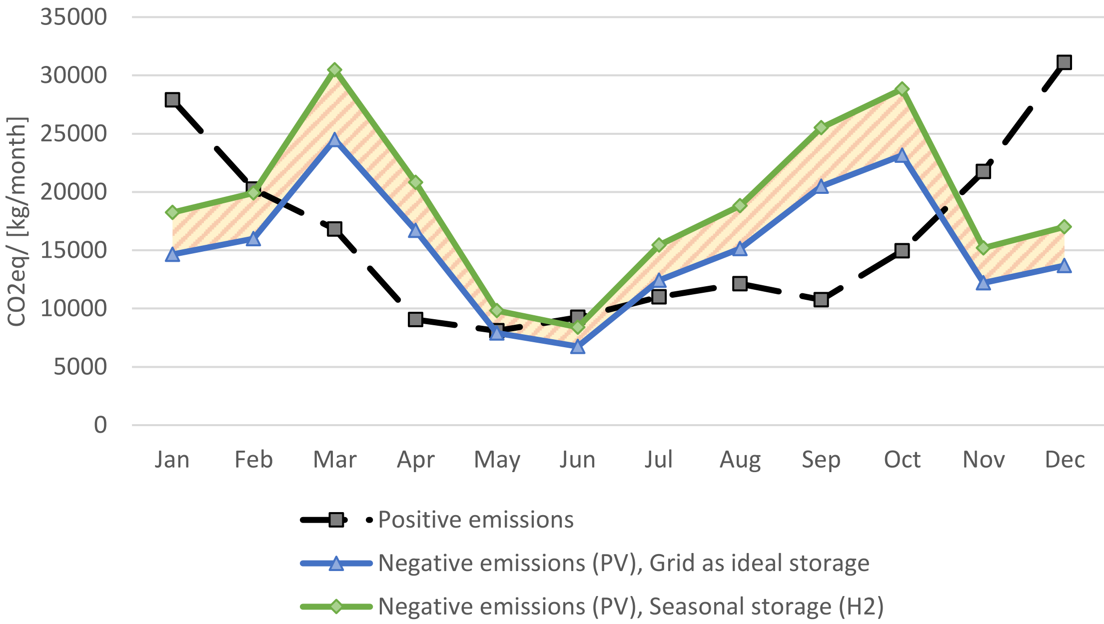

Figure 8: Monthly equivalent CO_2 emissions calculated with the monthly f_{CO2eq}. Positive emissions (black) are due to the energy demand, negative emissions are due to the PV production, based on the PV area calculated using the two CO_2 balances. The area between the two lines of negative emission represents the conversion losses associated with the H_2 storage process.

The areas under the black line (representing the CO_2 emissions) and the blue line (representing the CO_2 savings, calculated using the “Grid as ideal storage” balance) are identical. This indicates that the total annual CO_2 emissions and CO_2 savings due to the PV installation are equal, as defined by the “Grid as ideal storage” CO_2 balance. This implies that the overproduction of electricity during summer (characterized by high solar radiation and low energy demand) is shifted to the winter months without accounting for any associated losses. In contrast, the “Seasonal storage (H_2)” CO_2 balance exhibits a similar trend, but with increased required CO_2 negative emissions (i.e., increased PV production) because a part of these will be lost due to the H_2 storage process. The yellow area between the two lines of negative emissions represents the conversion losses associated with the H_2 storage process (roundtrip efficiency η_{H2} = 31%).

4.1.3 Comparison of the methods based on the required PV area

To summarize the comparison of methods discussed in the previous sections, the required PV area calculated using each method is presented in Table 2.

Table 2: Required PV area (in m^2) to achieve PED calculated according to the four different methods

	CO_2 conversion factor (f_{CO2eq})	
	Annual f_{CO2eq}	**Monthly f_{CO2eq}**
Grid as ideal storage	3604	4518
Seasonal storage (H_2)	4866	5623

The net balance (i.e. the combination of annual f_{CO2eq} and “Grid as ideal storage” balance) results in the smallest required PV area (3604 m^2). Conversely, using monthly conversion factor combined with the “Seasonal storage

(H_2)" balance yields the largest required PV area (5623 m^2), which is 56% more than the area determined by the net balance. The other combinations produce results that fall between these two cases.

4.2 Comparison of the heat generation variants

The four variants of the heat generation are compared using the monthly CO_2 conversion factors. The required PV area to reach PED is calculated using both CO_2 balances.

The required PV areas are presented in Figure 9, and Table 3 shows the increase in PV area relative to the "as built" case.

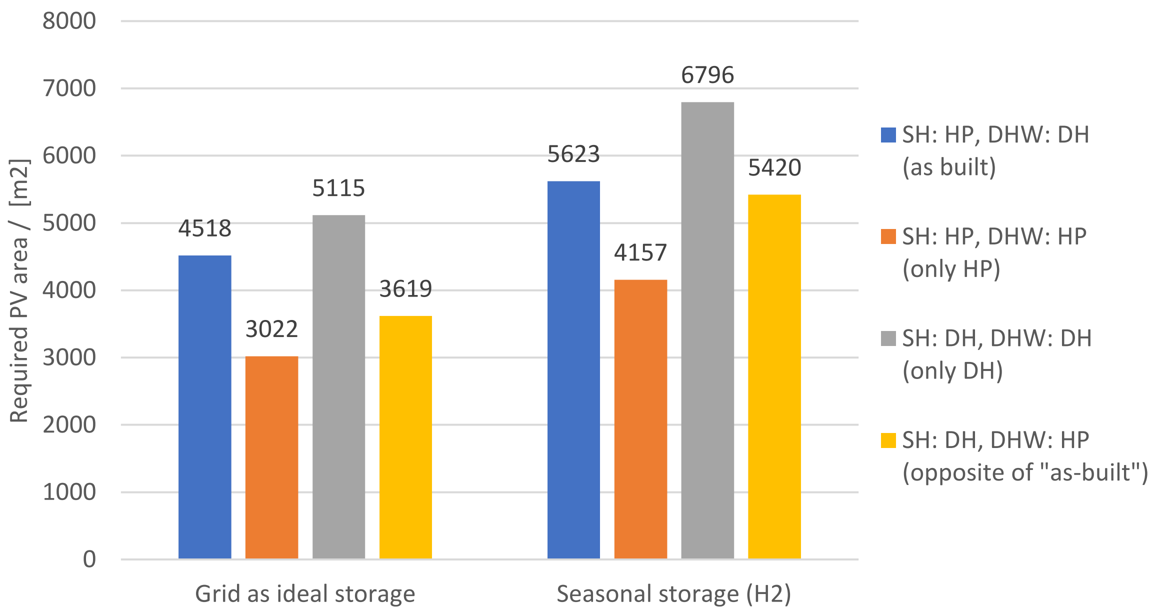

Figure 9: Required PV area (in m^2) to achieve PED for different heat generation variants and the two CO_2 balances. Calculation with monthly f_{CO2eq}

Table 3: Increase in the required PV area compared to the "as-built" case. Calculation with monthly f_{CO2eq}

	SH: HP DHW: DH (as-built)	**SH: HP DHW: HP (only HP)**	**SH: DH DHW: DH (only DH)**	**SH: DH DHW: HP (opposite of as-built)**
Grid as ideal storage	0%	-33%	13%	-20%
Seasonal storage (H_2)	0%	-26%	21%	-4%

Regardless of the CO_2 balance, the solution involving only the HP results in a reduced required PV area to reach PED, while the solution using only DH increases the required PV area. The "Grid as ideal storage" balance significantly reduces the required PV area for the "opposite of as-built" variant (-20%), while the "Seasonal Storage (H_2)" balance narrows the reduction to just -4%, making the two system concepts comparable in terms of PV area. Therefore, the choice of CO_2 balance can significantly impact the results and influence the evaluation of systems that implement different energy sources.

5. Discussion and conclusions

Various methods for calculating the necessary photovoltaic energy (i.e., required PV area) to achieve a positive CO_2 balance in PEDs with combinations of heat pump (HP) and district heating (DH) are investigated and compared. The methods differ for the type of conversion factors (annual or time-dependent, i.e., monthly), and the CO_2 balance, i.e., the use of “Grid as an ideal storage” or “Seasonal storage (H_2)”. The methods are tested using an existing residential district in Innsbruck. To draw more general conclusions on the requirements to achieve PED with DH and HP, four system concepts are investigated, varying the heat generation: 1) HP for space heating (SH), and DH for domestic hot water (DHW) (i.e., as built), 2) HP only (for both SH and DHW), 3) DH only (for both SH and DHW), and 4) DH for SH, and HP for DHW.

As in case of absence of nuclear energy in the electric grid (as in the case of Austria), using CO_2 or non-RE PE conversion factors leads to the same conclusions, the analysis is carried out only by implementing the CO_2 conversion factors (f_{CO2eq}). Using monthly conversion factors results in higher CO_2 emissions during the winter months compared to annual conversion factors and provides a more accurate or “fair” representation of the available renewable sources throughout the year (which contrasts with the significantly higher demand in winter). In contrast, the use of annual conversion factors tends to underestimate this mismatch. However, obtaining monthly conversion factors could be challenging, especially for DH systems, which depend on the city/region and where often there is a lack of information about the time depending operation of the DH.

The net balance (i.e., the combination of annual f_{CO2eq} and “Grid as ideal storage” balance) leads to the smallest required PV area. Considering the grid as an ideal storage underestimated the required PV area because it assumes that the surplus of PV energy produced in summer can be used in the winter months without any loss. In contrast, implementing the seasonal storage (H_2 with roundtrip efficiency of 31%) in the CO_2 balance leads to a 23% increase of the required PV area (using monthly CO_2 conversion factor). The adoption of monthly CO_2 conversion factor and “Seasonal storage (H_2)” results in a 56% increase of the required PV area (5623 m^2) compared to the net balance.

Different heat generation variants are compared in terms of the required PV area against the “as-built” case. The choice of CO_2 balance method can significantly impact the results and even change the ranking of the systems implementing different energy sources. For the system with DH for SH and HP for DHW (opposite of “as-built”), the required PV has different trends (compared to the “as-built” case) depending on the CO_2 balance used. When using the “Grid as ideal storage”, the required PV area significantly decreases (-20%), whereas with the “Seasonal storage (H_2)” balance, it slightly decreases (-4%), making the two variants comparable. Contrarily, the system concept with only HPs achieves the greatest savings in PV area independently of the use of storage in CO_2 balance (e.g. -26% with the “Seasonal storage (H_2)”) and the case with only DH shows the largest increase in the required PV area (e.g. +21% with the “Seasonal storage (H_2)”).

The results of the current study are influenced by the choice of the conversion factors, which are subject to change as the electric grid and the DH systems are supposed to undergo future decarbonization. The use of adapted conversion factors could significantly affect the results. Future studies should consider future scenarios of energy sources and the development of the load in particular in the building stock, such as e.g. in case of the electricity conversion factors suggested by (Ochs & Dermentzis, 2018). Challenging is the decarbonization of the DH, which will rely on high-temperature HPs and seasonal energy storage. To achieve a comprehensive assessment, it is also essential to consider the industry and mobility sectors, in particular electric vehicle charging. An open question that remains is, whether it is appropriate or justified at all to compensate non-renewable sources (e.g., natural gas in the DH) with renewable sources (e.g., PV), or whether a district relying on non-renewable energy sources can be considered a PED at all.

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