**HOLISTIC ENERGY MANAGEMENT AND THERMAL WASTE INTEGRATED SYSTEM FOR ENERGY OPTIMIZATION**

HEATWISE

# Renewable Energy Integration Guidelines

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## Table of contents

# Executive Summary

This deliverable evaluates the potential of integrating on-site PV and PVT systems across selected HEATWISE demo sites: AAU (Denmark), EMPA (Switzerland), RISE (Sweden), and TOFAS (Turkey). The objective was to quantify their electrical and thermal production under realistic climatic conditions and to assess their contribution to emission reduction. The PSNC site (Poland) is additionally considered as a reference case to illustrate the limitations of on-site integration in high energy-demand environments.

The simulations show that PV systems achieve annual specific yields between 209 and 342 kWh/m²·year, depending on location and installation configuration. However, the results demonstrate that the overall impact of PV systems is primarily driven by the available installation surface and the local electricity demand. While AAU and EMPA reach only around 12% electricity self-coverage due to limited roof area, larger-scale configurations such as RISE and TOFAS enable significantly higher utilisation of PV generation, with RISE achieving surplus electricity production during several months of the year.

The integration of PVT systems increases the total energy yield per unit area due to the additional thermal contribution, with thermal yields typically 2–3 times higher than electrical output. Annual solar fractions reach approximately 22% at AAU, 20% at EMPA, and 51% at RISE without seasonal storage. However, at larger scale, high storage temperatures during summer, caused by low heat demand, reduce useful heat extraction.

To address this limitation, seasonal pit thermal energy storage (PTES) was analysed for the RISE case. The integration of PTES increases the annual solar fraction to 97% and raises avoided emissions from natural gas displacement from 138 to 264 $tCO_2$ per year.

In terms of decarbonisation, the results show that the overall impact depends on the combined effect of system scale and local energy context. Large-scale systems maximise total emission reductions, while specific $CO_2$ mitigation is strongly influenced by the local grid emission factor. The PSNC case highlights that, in high energy-demand facilities such as data centres, limited available surface prevents significant on-site impact, making off-site renewable generation and storage essential.

Overall, the findings confirm that installation scale, demand profiles, climatic conditions, and storage integration are decisive factors for both energy performance and decarbonisation potential in tertiary buildings, and provide practical guidance for selecting suitable renewable integration strategies.

# List of abbreviations

| Acronym | Meaning |
|---|---|
| **BIPV** | Building-Integrated Photovoltaics |
| **DHW** | Domestic Hot Water |
| **EED** | Energy Efficiency Directive |
| **EPBD** | Energy Performance of Buildings Directive |
| **ESPR** | Eco-design for Sustainable Products Regulation |
| **HVAC** | Heating, ventilation, and air conditioning |
| **ICT** | Information and Communications Technology |
| **NEST** | Next Evolution in Sustainable Building Technologies |
| **NZEB** | Nearly Zero-Energy Building |
| **PTES** | Pit Thermal Energy Storage |
| **PV** | Photovoltaic |
| **PVT** | Photovoltaic-Thermal |
| **ZEB** | Zero-Emission Building |

# 1. Introduction

The decarbonisation of the European building stock is a cornerstone of the European Union's climate and energy strategy. Nevertheless, while residential buildings have traditionally received most of the attention, non-residential or tertiary buildings represent a substantial and still underexploited opportunity for accelerating the energy transition. These buildings are characterised by high and diversified energy demands, complex operational patterns, and specific technical constraints, but also by a significant potential for integrating on-site renewable energy solutions.

In parallel, recent policy developments at both the European and national levels have strengthened regulatory requirements for energy efficiency, renewable energy deployment, and greenhouse gas emissions reduction in non-residential buildings. The combination of increasingly ambitious climate targets, rising energy prices, and the maturation of renewable energy technologies is reshaping the role of the tertiary sector, turning it into a key factor in achieving climate neutrality objectives.

In this evolving context, the HEATWISE project examines the role of advanced energy management concepts and renewable energy technologies in improving the energy performance and decarbonising tertiary buildings. This deliverable contributes to that objective by examining the potential role of on-site solar energy solutions, specifically photovoltaic (PV) and photovoltaic-thermal (PVT) systems, when applied to representative tertiary building contexts. The analysis seeks to support a better understanding of how such technologies can contribute to reducing conventional energy use and associated emissions, thereby informing future strategies for renewable energy integration in the tertiary sector.

## 1.1. Renewable Energy Context for Tertiary Buildings

### 1.1.1. Strategic Importance of Tertiary Buildings

The European tertiary building sector, which includes offices, hospitals, schools, data centres, public administration facilities, and commercial spaces, represents a key area for achieving climate neutrality by 2050. Despite accounting for around 34% of the EU's final energy demand for heating and hot water and 30% of its total floor area (Oeko-Institut, 2024), these buildings remain insufficiently addressed compared to residential ones. Tertiary buildings have distinct characteristics that enable the integration of renewable energies: they typically feature high daytime electricity demand coinciding with peak solar production, significant internal heat gains due to IT equipment and occupant density, continuous operational requirements, and often large areas of unshaded roof and facades suitable for solar installations (IEA, 2025), which would otherwise be underutilised. These characteristics create favourable conditions for on-site renewable energy generation, sector-coupling strategies, and advanced thermal management solutions, all of which are key aspects addressed by this project.

### 1.1.2.Regulatory Framework and Policy Drivers

In the context of the European Green Deal, the European Commission strengthened the 2030 targets for both final and primary energy consumption, aligning them with the objective of climate neutrality by 2050. The EU's long-term strategy aims to achieve climate neutrality by 2050. At the European level, policies in this area that focus on tertiary consumption include the Energy Efficiency Directive (EED), the Energy Performance of Buildings Directive (EPBD), and the Eco-design for Sustainable Products Regulation (ESPR).

The 2023 recast of the **Energy Efficiency Directive** (DIRECTIVE (EU) 2023/1791, 2023) sets targets of 763 million tonnes of oil equivalent (Mtoe) for final energy consumption and 992.5 Mtoe for primary energy consumption by 2030, including legislative instruments to meet the EU's target of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990. For the tertiary sector, Articles 5 and 6 of the EED set out specific obligations for non-residential public buildings:

- Article 5: Member States shall ensure that the total final energy consumption of all public bodies combined is reduced by at least 1.9% each year compared to 2021.
- Article 6: Member States shall ensure that at least 3% of the total floor area of heated and/or cooled buildings owned by public bodies is renovated each year to transform them into nearly zero-energy (NZEB) or zero-emission buildings (ZEB).

The 2024 recast of the **Energy Performance of Buildings Directive** (DIRECTIVE (EU) 2024/1275, 2024) is the EU's main policy for residential and non-residential buildings. Its most notable feature is the "solar mandate", which requires Member States to ensure that suitable solar systems are installed in eligible non-residential buildings, according to a phased timetable:

- By 31 December 2026: All new public and non-residential buildings with a useful floor area of over 250 m² must have solar installations.
- Progressively for existing public buildings: >2,000 m² (31 Dec 2027); >750 m² (31 Dec 2028); >250 m² (31 Dec 2030).
- By 31 December 2029: Extension to all new residential buildings; also applies to major renovations in non-residential buildings larger than 500 m² from 2027 onwards.

Member States retain flexibility in terms of technology selection (PV, solar thermal, or hybrid PVT systems) and implementation pathways, enabling context-specific solutions tailored to climate, existing infrastructure, and architectural constraints.

The EPBD recast replaces the NZEB standard with a stricter ZEB requirement, defined as buildings with very low energy demand, zero on-site fossil fuel emissions, and very low operational greenhouse gas emissions:

- New public buildings must achieve ZEB from 1 January 2028.
- All new buildings must meet the ZEB requirement from 1 January 2030.

Beyond building-focused directives, EU product policies directly reduce energy consumption in the tertiary sector. The **Eco-design for Sustainable Products Regulation** (REGULATION (EU) 2024/1781, 2024) establishes a comprehensive framework for improving environmental sustainability throughout the life cycle of products. For tertiary buildings, the ESPR focuses on critical components including construction materials (cement, steel, aluminium), Heating, ventilation, and air conditioning (HVAC) systems, information and communications technology (ICT) equipment, and energy-efficient building components, with requirements for enhanced durability, repairability, energy and resource efficiency, and increased recycled content.

At the national level, Member States have implemented specific measures targeting the tertiary sector, e.g., measures and funds for thermal rehabilitation, inspections of water boilers and air conditioning systems, mandatory renovation of public buildings, campaigns to promote NZEB, etc. (Economidou et al., 2020).

### 1.1.3.Renewable Energy Technology Trends in the Tertiary Sector

Impulsed by this policy and regulatory background, the integration of renewable energy technologies at building level has gained increasing relevance in the tertiary sector. Among the available options, solar-based technologies stand out due to their technical maturity, bankability, scalability, and compatibility with urban environments and existing building infrastructures.

There is a wide portfolio of technologies that allow to convert the bast solar resource into either thermal; photo-thermal or solar thermal, or electric power; photovoltaics. Moreover, in the last few decades hybrid solar technologies, namely PV and PVT collectors, have been developed and started gaining momentum in the market (mainly in Europe and Asia).

#### 1.1.3.1. Photovoltaic Technology

Solar PV technology is based on the photoelectric effect, whereby solar cells based in semiconductors convert solar radiation into direct current electricity that can be used to supply building loads or be fed into the grid. A typical PV panel consists of silicon cells encapsulated under glass. At the cell level, photons with energy above the semiconductor bandgap excite electrons across a p-n junction, generating electron-hole pairs that are separated by the internal field to produce a current. Silicon wafer-based technologies dominate the market, accounting for around 98% of global PV production in 2024, with n-type wafers representing about 70% of the share (Fraunhofer ISE, 2025).

In new buildings, orientation and available space can be optimised from the design stage to incorporate PV in an integrated manner. In existing building retrofits, PV can be added relatively easily on rooftops without major alterations, although structural strength (typically 15-25 kg/m² additional load (Leader Group, 2022)), shading from equipment such as HVAC units, and limited usable space must be considered. Beyond technical feasibility, PV in tertiary buildings often presents attractive economics, with investment costs for small rooftop systems (3-10 kWp) in Germany ranging from 900 to 1,300 €/kWp in 2024 (Fraunhofer ISE, 2025).

Real-world applications illustrate the integration of PV systems in tertiary buildings. Data centres, which are part of the tertiary sector and characterised by continuous high energy demand, are increasingly adopting PV to reduce operating costs and improve sustainability. For instance, the operator *nLighten* installed more than 1,000 panels (500 kW) on the roof of its data centre in Milton Keynes, UK (Data Centre Dynamics, 2025), covering 4,500 m² of surface, as shown in Figure 1. Thanks to this installation, there were periods during the day when the facility was fully powered by solar energy, although typically the plant only supplies a fraction of the total load.

*Figure 1. 500 kW PV installation on the roof of the Milton Keynes data centre, UK.*

Another example is Iron Mountain's NJE-1 data centre in New Jersey, USA, which in 2020 added 7.2 MW of rooftop PV. This large installation generates around 9 GWh annually and covers ~15% of the site's 30 MW electricity demand, demonstrating the significant contribution PV can make even in highly energy-intensive operations.

In a different sector, Poole Hospital in Dorset, UK (Centrica, 2024) stands a good example, where a rooftop PV system is being implemented. The system comprises 470 solar panels and is expected to generate approximately 200,000 kWh per year, avoiding approximately 50 tonnes of $CO_2$ emissions annually. Even though this PV installation is projected to meet only about 5 % of the hospital's total electricity demand, it illustrates how PV can deliver meaningful energy savings and emissions reductions in healthcare facilities.

Outside data centres and hospitals, PV is increasingly deployed in public and commercial buildings as part of net-zero and decarbonisation strategies. A representative case is Zaragoza City Hall in Spain, which plans to install 11.5 MWp of capacity on school rooftops and an additional 7.7 MWp on the rooftops of other municipal buildings (Pedrosa, 2025).

Overall, these examples illustrate how PV systems can provide a robust and widely applicable solution for increasing on-site renewable electricity generation in tertiary buildings, even when surface availability or load coverage remains limited.

#### 1.1.3.2. Photovoltaic-Thermal Technology

Photovoltaic-thermal (PVT) collectors enable simultaneous production of electricity and low-temperature heat in a single unit. Typically, the front side consists of a PV laminate, while the rear side integrates a hydraulic circuit where a working fluid circulates to extract residual heat from the cells. This configuration reduces cell temperature, improving electrical efficiency (Herrando & Markides, 2016), while the recovered heat can be used for domestic hot water (DHW), low-temperature space heating, or as a heat source (main or secondary) for water to water heat pumps. By delivering two energy streams from the same surface area, PVT acts as a compact solar cogeneration unit, increasing the overall solar conversion efficiency to values typically ranging between 60–70% when both thermal and electrical outputs are considered. In addition, it provides a higher specific energy yield, defined as the amount of energy per installed area, and higher decarbonisation potential than conventional solar technologies such as PV and solar thermal systems.

This configuration is particularly suitable for tertiary buildings characterised by simultaneous electricity and thermal demand and limited roof space (particularly in urban areas). Typical examples include hotels (with high consumption of heat for DHW and swimming pools heating, along with electricity), hospitals and clinics (continuous demand for DHW, space heating, and medical equipment sanitation), gyms and heated pools, commercial buildings, and similar facilities. In existing tertiary buildings, viability depends on having sufficient rooftop space and compatible thermal systems (e.g. hot water tanks or backup boilers that can be integrated). PVT systems are usually installed in parallel with conventional equipment: for example, a bank of hybrid panels connected to a thermal storage tank that preheats water before it is fed to an existing boiler or heat pump, or right before the consumption point. This reduces the consumption of fossil fuels or grid electricity by the primary equipment. PVT installations, however, require both electrical (inverters, cabling) and hydraulic ancillary equipment (piping, heat exchangers, pumps, and control system), making them relatively more complex to install and operate than pure PV. Nevertheless, they are particularly advantageous where rooftop area is limited, since each panel maximizes energy yield per square meter (Kang et al., 2021). In new buildings, PVT integration can be planned from the design stage, with appropriate sizing of storage tanks, exchangers, and control systems. For instance, in a newly built hotel, PVT could be deployed to cover most of the daily DHW demand and part of the pool heating, thereby reducing the required boiler capacity. A critical design criterion is to ensure that the building's thermal load can effectively use the recovered solar heat, avoiding summer overheating or surplus energy.

Similarly to PV, real-world applications of PVT in tertiary buildings showcase their potential around the world. As an example, a simulation for a 250-bed hotel in Madrid, Spain, analysed by Abora Solar (del Amo, 2023) illustrates the suitability for the tertiary sector: if equipped with 100 conventional PV panels (~35 kWp), the hotel would save about €10,171 annually in electricity costs and avoid 23,691 kg$CO_2$/year. Replacing them with 100 PVT panels would increase the savings to €31,532 per year by combining electricity and gas displacements, and cut emissions by 87,022 kg$CO_2$/year.

Another example is the Hotel Maritim Playa in Playa del Inglés, Spain, the first building in Las Palmas to integrate a hybrid PVT plant (La Provincia, 2025). The installation comprises 120 PVT panels, expected to supply around 30% of the hotel's electricity demand and 82% of its thermal demand, equivalent to producing 20,000 litres of hot water per day across six storage tanks. The system will reduce annual emissions by about 109 tonnes of $CO_2$, comparable to the footprint of 1,800 people, and the nearly €0.50 million investment is projected to be recovered within 3-4 years.

The impact of PVT systems will also be showcased by Mid-Kent College in the UK (Brimble, 2025), which is commissioning the largest PVT installation in the country. The project includes 600 Abora panels covering 1,200 m², installed as solar canopies over parking areas, as can be seen in Figure 2, and is expected to deliver about four times more total energy output and 3.5 times higher carbon savings than standard PV for the same surface. The installation is designed to work in combination with 800 kW of heat pumps, using the PVT field as a flexible and efficient heat source. Thanks to their fully glazed and insulated design (combined efficiency close to 89%), the panels can operate across a wide range of temperatures, directly matching thermal demand when solar energy is sufficient and reducing the operation hours of the heat pumps. The business model shifts the focus from electricity-only metrics (LCOE) to the total energy value per square meter, highlighting the potential advantages of hybrid solutions in applications with significant and simultaneous demand for electricity and heat.

*Figure 2. 1,200 m² hybrid PVT installation at Mid-Kent College, UK.*

### 1.1.3.3. Building-Integrated Photovoltaics

Building-Integrated Photovoltaics (BIPV) refers to the incorporation of solar modules as integral elements of a building's envelope (roofs, facades, curtain walls, skylights, railings, etc.), so that they fulfil a dual function: construction and electricity generation. Unlike conventional PV panels, which are mounted onto the structure (typically on rooftops), BIPV modules directly replace exterior components while maintaining their primary roles (weather protection, insulation, waterproofing, aesthetics). In essence, they become part of the building's design itself, enabling large surfaces that would otherwise remain passive to be converted into active, energy-generating areas without requiring additional space or altering the architectural appearance.

BIPV is particularly relevant in new constructions, where architects and engineers can integrate solar generation without compromising aesthetics. In tertiary buildings solutions include PV glazed facades, full solar-tile roofs , or shading elements equipped with solar modules (Vitro Solarvolt, n.d.). These elements not only generate electricity but can also improve building performance. For example, PV sunshades reduce indoor solar gains, lowering cooling demand. In existing buildings, BIPV retrofitting is also feasible, although more challenging. Typical rehabilitations include replacing curtain walls with PV glazing (while maintaining the substructure) or installing double-skin facades with integrated modules. A representative case is the Mercado de San Antón in Madrid, Spain (AVENSTON, 2021), a historic building renovated with a 168 m² semi-transparent PV glass roof (a-Si modules with 20% transparency), which now generates ~7.7 MWh/year while providing diffuse natural light. Nevertheless, retrofits are often limited to partial applications due to cost and complexity, and in many cases it is more practical to deploy conventional rooftop PV. The key is to evaluate whether each exterior surface receives adequate solar radiation and whether it can be replaced with a PV element while preserving its original functions. Finally, compliance with building codes is essential. BIPV modules are usually manufactured from laminated safety glass with added thickness and certifications for wind loads, fire safety, and waterproofing, ensuring they can serve as facade elements.

Across Europe and worldwide, several landmark projects illustrate the integration of BIPV in tertiary buildings. A reference case is the Copenhagen International School (Denmark), which features 12,000 PV panels across 6,000 m² of facades, as shown in Figure 3. This 700 kW installation generates ~500,000 kWh per year, covering nearly half of the school's electricity demand. Beyond energy production, the tinted facade creates a distinctive architectural effect while providing daylight control, thus combining aesthetics with sustainability.

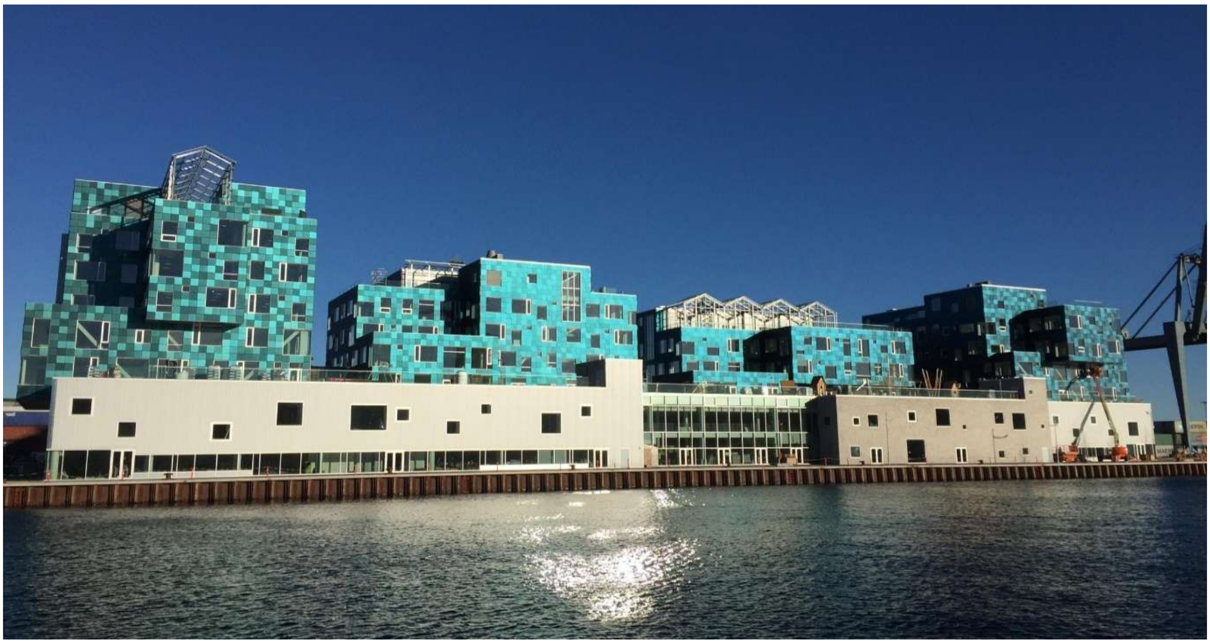

*Figure 3. 700 kW BIPV installation on the facade of the Copenhagen International School, Denmark.*

In Spain, the Iturralde winery and restaurant incorporated a 200 m² semi-transparent solar roof with amorphous silicon modules during its 2014 reconstruction. The system, with 21 kW installed capacity, generates ~16,400 kWh annually, partially covering the complex's energy demand. Similarly, the Treurenberg corporate headquarters in Brussels (Belgium), which integrated 667 m² of PV facades and roof (122 kW) into its construction, producing ~102 MWh per year. This office building demonstrates how even in dense urban contexts facades can be activated as energy-generating surfaces without compromising modern aesthetics.

From an energy system perspective, BIPV solutions allow tertiary buildings to activate facade and envelope surfaces that are otherwise unused, thereby complementing rooftop installations and expanding the overall on-site renewable generation potential.

## 1.2. Objectives and Scope of the Study

Once the solar technologies portfolio have been defined, focusing in applications in tertiary buldings, the objective of this deliverable is to assess the potential contribution of on-site solar energy systems to the energy performance and decarbonisation of tertiary buildings, using selected HEATWISE demo sites as representative case studies. The study aims to quantify the achievable electrical and thermal energy yields from PV and PVT technologies under realistic operating conditions, taking into account site-specific climate data, available installation surfaces, and measured building energy demand profiles. In addition to rooftop-mounted systems, BIPV solutions were considered in demo sites with sufficient available facade surface.

The analysis enables a comparative assessment of different solar integration options and their potential contribution to reducing the reliance on conventional energy sources. The resulting quantitative insights provide a technical basis to inform decision-making processes related to renewable energy integration strategies in tertiary buildings, support further techno-economic or system-level assessments, and can be further expanded and integrated once the heat recovery potential of HEATWISE technologies has been quantified.

In addition, the study evaluates the associated decarbonisation potential of the analysed systems through a displacement-based $CO_2$ assessment framework.

# 2. Methodology

The assessment of renewable energy integration presented in this report is based on dynamic energy simulations of PV and PVT systems deployed in selected demo sites. The simulations were not intended to focus on detailed system design or implementation, but rather to quantify potential energy yields, seasonal coverage of thermal and electrical demand, and the potential contribution to building-level decarbonisation targets. All simulations were carried out using the TRNSYS (Transient System Simulation Tool) software environment.

To efficiently manage the large number of input combinations across different buildings, technologies, configurations, and climate scenarios, a parametric Excel-based tool was developed. This utility served both to automate the generation of TRNSYS input files and to structure the visualisation of key simulation outputs. It handled the organisation of parameters such as available surface area, tilt, climate data, and monthly energy demand profiles, while also providing direct access to graphical representations of results. This workflow enabled a systematic, scalable, and transparent approach to scenario generation and evaluation, avoiding manual case-by-case configuration.

The detailed modelling setup, including system boundaries, assumptions, and component configuration, is described in Section 2.2. The simulation results provide the basis for the subsequent energy performance assessment and decarbonisation potential analysis presented in Section 2.3.

## 2.1. Data Sources and Demo Site Description

Detailed descriptions of each HEATWISE demo site are provided in previous project deliverables (D3.1, D3.2 and D3.5). Therefore, this section focuses on the specific buildings used for analysing the potential for on-site renewable energy integration, namely the sites at AAU (Denmark), EMPA (Switzerland), RISE (Sweden), and TOFAS (Turkey). For each site, operational energy data were collected and analysed to inform the simulations, including detailed measurements of electricity use and heating demand. Monthly aggregated energy demand (heating and electricity) was derived from raw data provided by site administrators and is presented in this section for context.

In addition, the PSNC site in Poland is presented as a reference case. Due to the limited availability of additional rooftop or facade area and the already saturated use of existing surfaces, its potential for further on-site renewable integration is highly constrained, and therefore it was not included in the simulation analysis. Nevertheless, it is included here as a representative illustrating the challenges associated with on-site renewable energy integration in high energy-demand data centre environment.

To support the simulations, climate data for each location, including ambient air temperature, solar irradiance, and mains (tap) water temperature, represented by typical meteorological year (TMY) files, were obtained using the Meteonorm climate database. Meteonorm is a widely used software that provides typical meteorological year data by interpolating measurements from weather stations and satellite observations. In practice, this allowed us to generate consistent weather profiles for each site. In the same way, key parameters such as hourly ambient temperature, global horizontal solar irradiance, and even estimates of cold-water supply temperature, were extracted from Meteonorm for the respective locations, ensuring that the renewable energy simulations for each demo site used realistic and site-specific climate conditions.

### 2.1.1. AAU (Denmark)

The AAU pilot is an educational building at the main campus of Aalborg University in Aalborg, Denmark. The building was constructed in 2016 and has a heated gross floor area of approximately 8,153 m². Figure 4 shows the south facade of the building. This building functions primarily as a university facility (lecture halls, offices, and laboratories), making it representative of a typical tertiary education building. High-resolution monitoring infrastructure is in place, providing detailed energy data for both electricity consumption and heating demand. In particular, the site is equipped with sub-meters that capture electricity usage and hot water usage for various purposes, including space heating, ventilation air heating, DHW, and other miscellaneous thermal loads. These measurements were recorded at fine time intervals (ranging from 1-minute to 5-minute resolution) throughout 2023, offering a detailed view of the building's energy demand patterns.


*Figure 4. The AAU demo site building in Aalborg, Denmark. Picture: Thomas Pedersen*

Using the high-resolution 2023 data, the electricity and heat consumption are aggregated into monthly totals to analyse broader trends. Figure 5 illustrates the resulting monthly profile of energy demand (in MWh) alongside the site available solar energy and average temperatures, exhibiting the expected seasonal pattern in its energy use. As shown, heating demand is higher during the winter months, reflecting Denmark's seasonal heating needs, whereas it drops to minimal levels in summer. Electricity demand, in contrast, is more evenly distributed across the year, driven by lighting, equipment, and HVAC systems associated with the building's academic and research activities. Both heating and electricity reach similar maximum monthly values (around 70 MWh).

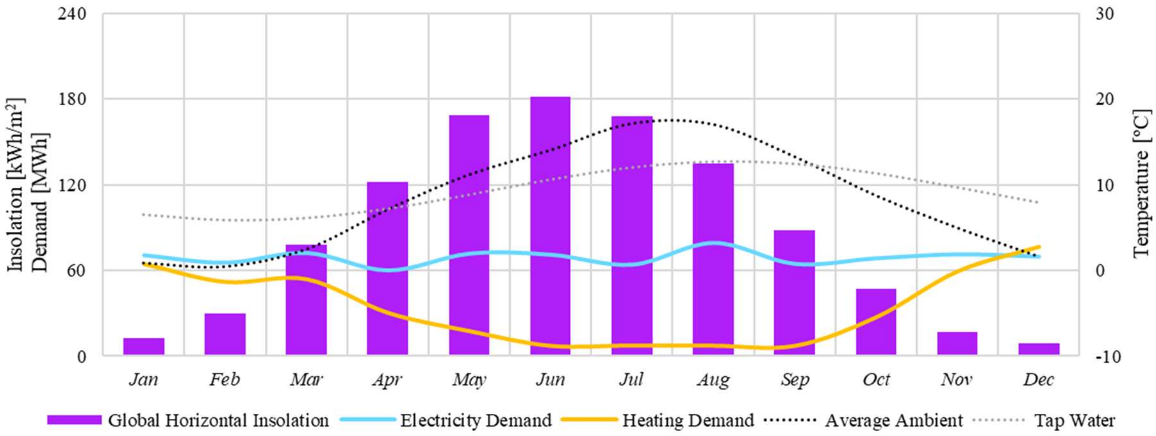


*Figure 5. Monthly data collected from the AAU demo site. Latitude: 57ºN*

The high latitude of the Denmark site (57°N) results in a noticeable seasonal contrast in solar irradiance. In the winter period from October through February, available solar energy is very limited due to short daylight hours and frequent overcast weather. Consequently, during these late autumn and winter months, on-site solar generation potential is minimal, and the building's heating requirements must be met almost entirely by other sources. This pronounced seasonal mismatch between solar availability and heating demand provides an early indication of the limitations of solar PV in contributing to the building's energy supply during periods of highest thermal demand, highlighting the challenges for winter solar integration at the AAU demo site. In contrast, spring and summer offer abundant solar resource, aligning with the period of lower heating demand. The annual average outdoor ambient temperature is about 8.2 °C. The average temperature of the incoming tap water (mains supply) is slightly higher, around 9.3 °C, reflecting the regional ground temperature.

The available roof and facade areas were estimated to assess the potential for on-site renewable systems integration. The following areas were identified as the theoretical maximum surfaces available without major alterations to the building's structure, based on the information given by site representatives. These areas form the basis for the simulations, allowing an evaluation of how much on-site solar generation could be achieved at the AAU site under typical conditions:

| Surface area | Category |
|---|---|
| 442 m² | Rooftop area: Building's flat roof, corresponding to the red-highlighted sections in Figure 6. |

| | |
|---|---|
| 205 m² | South-facing facade (1st floor): Also highlighted in red, in the lower level, in Figure 7. This facade area has good solar exposure and can host BIPV systems. |
| 114 m² | South-facing facade (3rd floor): An additional facade area was identified on the upper level. However, this area was excluded from the analysis due to its proximity to air intake vents for occupied zones, where mounting PV modules could lead to unwanted preheating of ventilation air and compromise indoor comfort. |

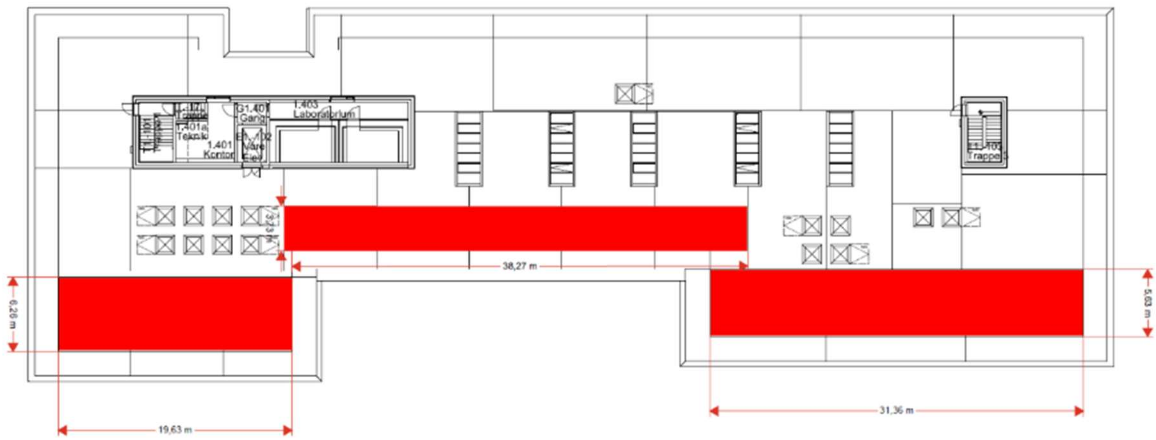


*Figure 6. Estimated available rooftop area at the AAU building. Source: AAU*

*Figure 7. South-facing facade surfaces identified for potential solar technology integration at the AAU building. First-floor areas were included in the simulations; third-floor areas were excluded. Source: AAU*

## 2.1.2. EMPA (Switzerland)

The EMPA demo site is the NEST (Next Evolution in Sustainable Building Technologies) building, an experimental modular research facility located in Dübendorf, Switzerland

(Figure 8). It was inaugurated in 2016 and it consists of a central core and three suspended floors, onto which individual research and innovation modules are installed as plug & play systems. In the sense of a "living lab," the installed units are not isolated laboratory environments, but real living and working environments. This unique configuration makes NEST a highly flexible experimental building, hosting various research projects simultaneously (e.g. sustainable construction materials, advanced HVAC systems, and IT infrastructure experiments).

*Figure 8. The EMPA demo site building in Dübendorf, Switzerland.*

Energy monitoring at NEST provides hourly measurements of both electricity consumption and heating demand for the entire year 2022. From this high-resolution dataset, a monthly energy profile has been derived for analysis, as shown in Figure 9. The profile exhibits seasonal variations similar to those observed at the AAU site, although NEST's total energy demands are significantly lower, which is consistent with the smaller scale of the building compared to the 8,153 m² heated area of the AAU facility. In 2022, electricity use at NEST peaked at approximately 14 MWh in May, while the maximum monthly heating demand was about 29 MWh in January.

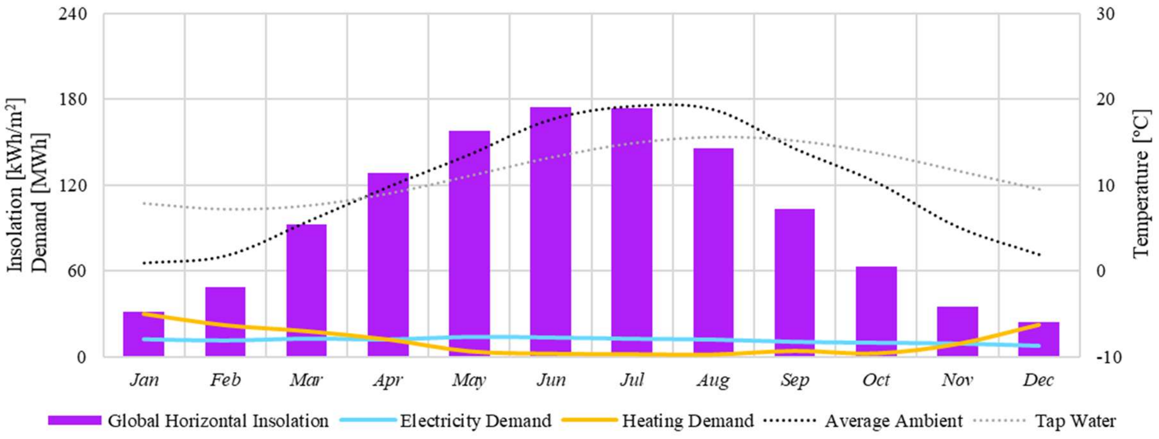


*Figure 9. Monthly data collected from the EMPA demo site. Latitude: 47ºN*

The average ambient air and mains water temperatures are comparable to those observed at AAU (9.9 ºC and 11.4 ºC, respectively). The local climate is temperate, with cold winters and mild summers comparable to northern Denmark. One minor difference is that winter solar radiation levels in Dübendorf are slightly higher than at AAU, offering marginally improved conditions for solar energy generation during the darkest months.

The available surface area for new on-site renewable energy installations at NEST is relatively limited. Due to the building's modular design and the presence of experimental modules and equipment on its facades and roof, only about 100 m² of additional rooftop area is considered suitable for deploying new technologies, according to information provided by site representatives. Notably, NEST already includes some integrated PV systems as part of its research units; the aforementioned ~100 m² figure refers only to potential space for additional capacity beyond the existing installations.

## 2.1.3. RISE (Sweden)

The RISE Infrastructure and Cloud Research & Test Environment (ICE) Data Centre is located in Luleå, in northern Sweden, and this facility is part of a larger commercial building owned by NP3, serving as a research and innovation hub for data center engineering. The building is substantial in size, with a footprint of approximately 95 m × 170 m (around 16,150 m² of floor area on the ground level), as can be seen in Figure 10. The usable building's flat roof (14,000 m² of area) offers ample space for potential solar installations, particularly in terms of electricity consumption, as the presence of energy-intensive equipment makes it a high-demand site. However, efficiently integrating on-site renewables here faces unique challenges due to the harsh seasonal variation.

*Figure 10. The RISE demo site building in Luleå, Sweden.*

Monthly energy use data for this site has been provided for a full year (2023), as presented in Figure 11, encompassing both electricity consumption and heating demand, which covers both space heating and hot water. Compared to the previous demo sites, high-frequency sub-metering is more challenging in this shared commercial building context, as detailed monitoring infrastructure is typically less extensive than in research-oriented facilities. Conversely, energy demands are substantially higher than at the other sites, while maintaining a pronounced seasonal variation in heating requirements. Electricity demand, however, remains relatively stable throughout the year.

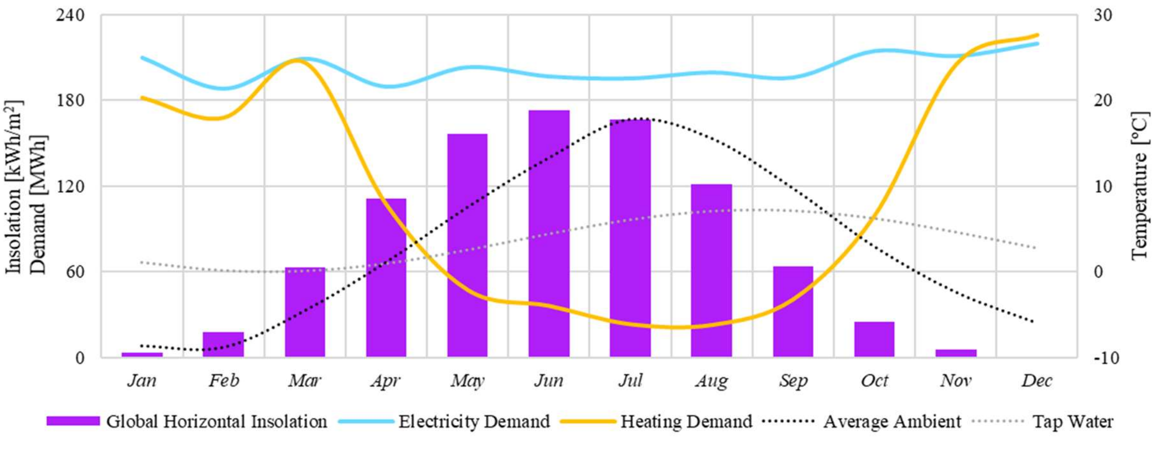


*Figure 11. Monthly data collected from the RISE demo site. Latitude: 66ºN*

Meteonorm data highlights an *Arctic* climate, with an annual mean of roughly 3.2 °C and 3.6 °C for the ambient and water supply temperatures, respectively. Moreover, solar irradiance at this latitude (66°N) is extremely limited in winter due to very short daylight hours (December's insolation is nearly zero).

## 2.1.4. TOFAS (Turkey)

The TOFAS demo site is the last site encompassed in this analysis. It is a large-scale automotive manufacturing facility located in Bursa, Turkey (Figure 12). The plant, originally established in 1968, occupies a total footprint of approximately 1 million m², of which around 350,000 m² correspond to enclosed buildings. It hosts multiple production units distributed across several buildings, including press, body, paint, assembly lines, as well as supporting facilities and administrative buildings.

Due to the scale of this automotive industrial site, it presents the highest electricity demand among the analysed sites. Energy is supplied through a combination of electricity and natural gas, the latter being primarily used for thermal applications such as steam generation and hot water production. In this work, the analysis focuses on electricity demand and on the thermal demand associated with hot water systems. The integration concept considered in this study is based on direct process integration rather than supply-level integration. Two main hot water circuits are in operation: the first provides heating for workshop spaces, while the second supplies process hot water for industrial processes, particularly in the paint shop (including pre-treatment and washing stages), as well as for office heating.

*Figure 12. The TOFAS  demo site facility in Bursa, Turkey.*

Operational energy data for the factory were provided monthly for 2025, including electricity consumption and thermal demand for the hot water systems. Due to the high magnitude of the energy demand at this site, the values shown in Figure 13 are scaled (divided by a factor of 40) to ensure consistency and readability when compared with the other demo sites. As observed, electricity demand remains relatively stable throughout the year, reflecting the continuous operation of industrial processes. In contrast, the thermal demand exhibits seasonal variation while maintaining a constant baseline attributable to process-related heat demand.

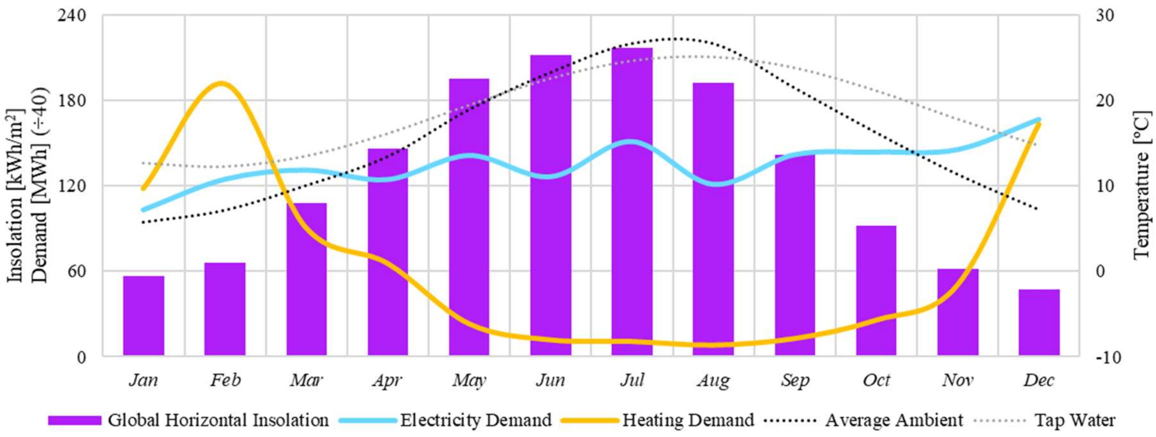


*Figure 13. Monthly data collected from the TOFAS demo site. Latitude: 40ºN*

The site is located at 40°N latitude, making it the southernmost location considered in this study. It therefore has higher solar irradiance levels than the other sites. The annual average ambient temperature is 15.7 °C, while the average mains (tap) water temperature is around 18.7 °C. Under these conditions, cooling demand is present at the site for comfort cooling and ventilation in the administrative buildings and the canteen, as well as for industrial processes. Cooling is not centrally monitored and is therefore not explicitly quantified in this analysis. Instead, it is accounted for in the overall electricity demand of the various buildings and production units, as it is primarily supplied by electrically driven systems, such as cooling towers and chillers.

An assessment of available surfaces for on-site deployment of renewable systems has been conducted based on information provided by site representatives. The following categories were identified:

| Surface area | Category |
|---|---|
| 52,500 m² | Existing installation: Rooftop area with PV capacity has already been deployed (completed in 2023), corresponding to the blue-highlighted sections in Figure 14. |
| 19,950 m² | Immediately available rooftop areas usable without major modifications, highlighted in green. |
| 227,800 m² | Largest portion of rooftop areas that would require refurbishment through structural or material upgrades, in yellow. |
| 220,000 m² | Parking areas are available for PV deployment through solar canopies, in grey. |

| | |
|---|---|
| 27,500 m² | Not available areas, in red. |

*Figure 14. Overview of available surfaces for on-site renewable energy deployment at the TOFAS site.*

For the purpose of this analysis, only rooftop areas are considered for on-site renewable system deployment, including both immediately available surfaces and those requiring refurbishment prior to implementation. In total, this corresponds to approximately 247,750 m² of rooftop area. The combination of high energy demand, favourable solar resource, and large available installation area indicates strong potential for on-site renewable integration, particularly in terms of self-consumption.

## 2.1.5. PSNC (Poland)

The Poznan Supercomputing and Networking Center (PSNC) is located in Poznan, in west-central Poland, where its main data centre and high-performance computing infrastructure are situated (Figure 15). The office building is equipped with two rooftop PV installations: 50 kWp operating on-grid and 20 kWp operating off-grid. The total building footprint is 3,830 m², of which approximately 550 m² of roof surface is occupied by PV systems.

*Figure 15. The PSNC demo site building in Poznan, Poland.*

The region is characterized by a moderate continental climate, with warm summers and relatively cold winters. This results in a clear seasonal variability in solar generation, with higher production during summer months and lower production in winter, further influenced by moderate cloud cover.

The annual IT load of the data centre reaches 14.9 GWh, while the total facility energy consumption amounts to approximately 16 GWh per year. In comparison, the total annual PV generation is around 910 MWh, which makes the solar fraction rather short. The majority of this production comes from external infrastructure, primarily the Kąkolewo campus (Figure 16), located approximately 70 km from the PSNC headquarters.

*Figure 16. Kąkolewo campus showing the 1 MWp PV installation and hangar facility.*

It serves as a living lab for testing and developing energy and infrastructure solutions. The site includes a 1 MWp PV farm supported by a 500-kWh energy storage system, as well as a hangar equipped with a 50 kWp PV micro installation, ventilation system, electric heating, and facilities for drone testing. A new building including research equipment and data centre infrastructure is currently under development.

The annual PV generation at the Kąkolewo site reaches approximately 815 MWh from the main installation and around 40 MWh from the hangar system. The functional concept is based on the direct coupling of PV generation with energy storage and local consumption, including potential data centre loads, enabling higher self-consumption of renewable energy and reduced transmission losses.

In parallel, PSNC is initiating the development of a new hybrid renewable energy system, starting in 2026. The planned system will consist of an off-grid 1 MWp PV installation, small wind turbines, battery energy storage, and a containerised data centre. The objective is to maximise the use of locally generated renewable energy, enable hybrid energy management combining multiple sources, and create a test environment for off-grid operation of high-performance computing infrastructure.

Only about 55 MWh is produced directly on the PSNC rooftop, including 40 MWh from the 50 kWp installation and 15 MWh from the 20 kWp off-grid system. Figure 17 clearly illustrate that the energy demand of high-performance computing systems significantly exceeds the available on-site PV generation capacity.

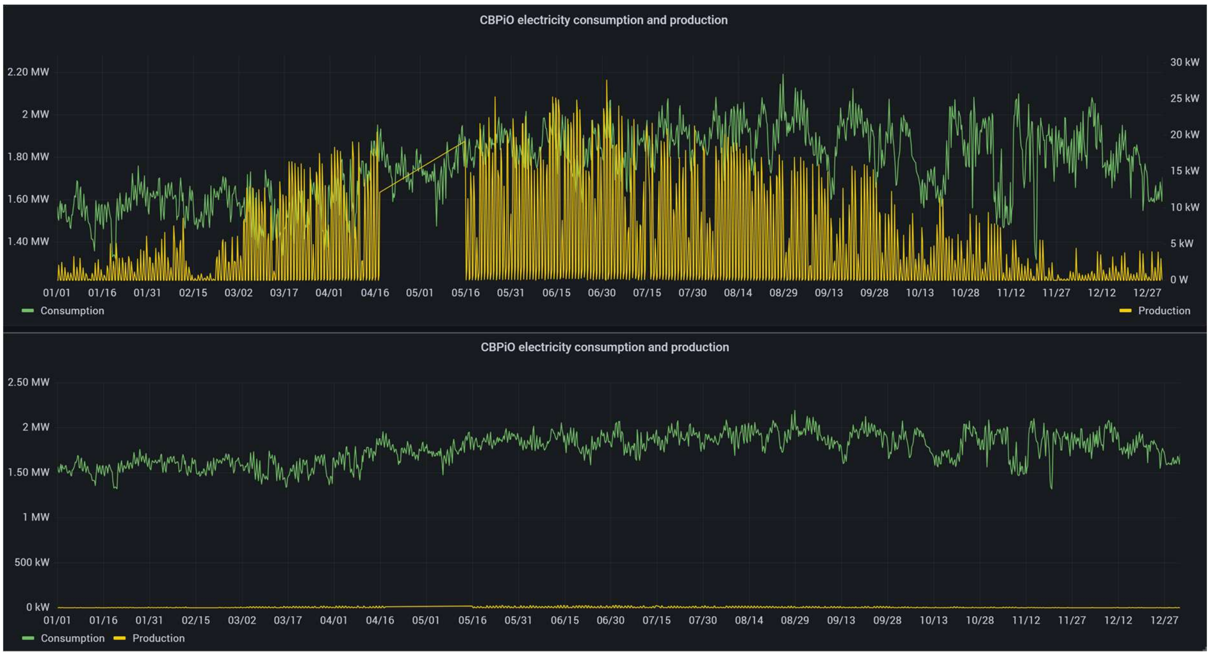


*Figure 17. Annual electricity consumption and PV generation at the PSNC demo site: (top) separate scale and (bottom) single scale. The data gap corresponds to a PV system reconfiguration period.*

The available rooftop area is already fully utilised, leaving no space for additional installations. Moreover, in a potential transition from conventional air cooling to high-density liquid cooling systems for IT equipment, additional rooftop space may be required for auxiliary components such as dry coolers, further limiting or even reducing the available area for on-site installations.

From an energy perspective, the gap between demand and local generation is substantial, with total consumption of approximately 16 GWh per year compared to only about 55 MWh of on-site PV production. This makes any meaningful scaling of local renewable generation infeasible within the existing infrastructure.

The use of PVT systems at PSNC is not justified, as the data centre cannot effectively utilize all available thermal energy. Furthermore, the planned connection to the campus district heating network would not enable full utilisation of the PVT system potential, due to the limited heating demand during summer months, when solar thermal production is highest. As a consequence, a significant portion of the generated thermal energy would remain unused, reducing both the efficiency and economic viability of such systems.

## 2.2. Modelling and Simulation Framework

### 2.2.1. PV System Design

The PV systems analysed in this study are designed within an Excel-based environment, presented in Figure 18, using a rule-based methodology that combines physical constraints of PV modules with inverter operational limits. The aim is to ensure that all simulated configurations are technically feasible, scalable, and consistent with standard engineering practice.

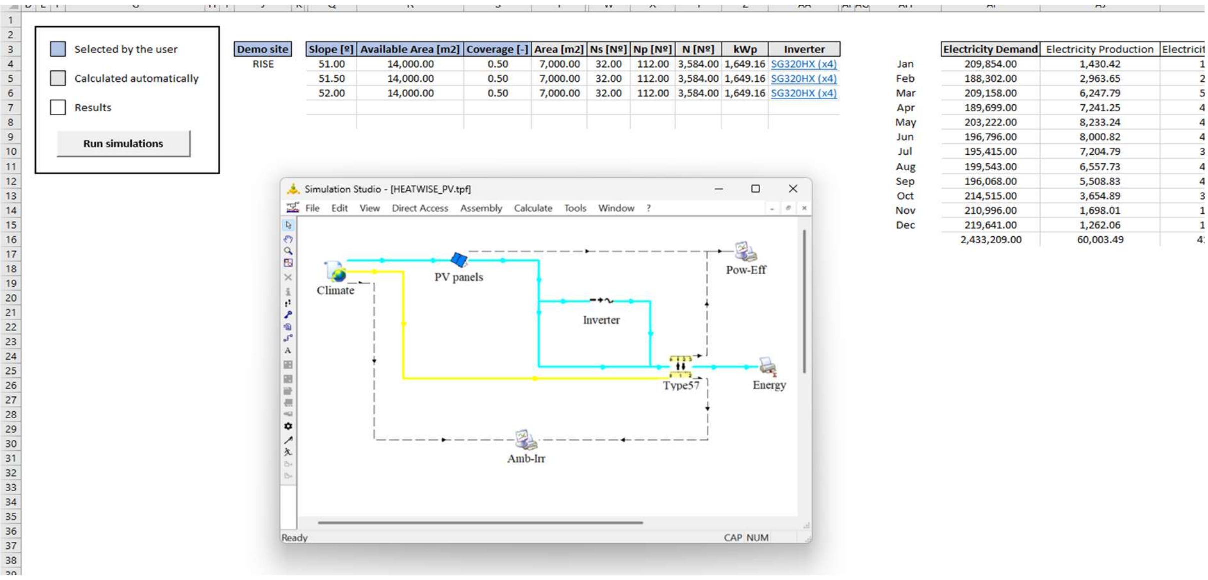


*Figure 18. TRNSYS simulation layout of the PV system model implemented within the Excel–TRNSYS framework.*

By selecting the demo site from a dropdown menu, the tool automatically loads the corresponding climate data and monthly electricity demand profile. The array tilt (slope) can be specified by the user.

Different tilt angles were tested for each site, and the final configurations were selected using inclination angles that maximise annual electricity production at each location. The resulting tilt angles were 33º for TOFAS (40ºN), 37° for EMPA (47°N), 43° for the AAU rooftop installation (57°N), and 52° for RISE (65°N). For the AAU facade-integrated BIPV system, a vertical installation (90°) was considered. As expected, higher-latitude sites require steeper tilt angles to better align the module surface with the lower solar path, whereas lower latitudes allow for more moderate inclinations.

For each case, the available installation surface can also be selected. Since not all of the available rooftop surface can be effectively covered by PV modules (due to spacing requirements, shading avoidance, and maintenance access) a coverage factor is applied to represent the fraction of usable area occupied by active module surface. Coverage ratios for fixed-tilt systems typically range between 0.15 and 0.68 depending on latitude and installation geometry (Tonita et al., 2023). In this study, a coverage factor of 0.60 was adopted for TOFAS (40ºN) and EMPA (47°N), while a slightly lower value of 0.50 was applied for AAU (57°N) and RISE (65°N) to account for increased spacing requirements associated with steeper tilt angles at higher latitudes.

The electrical design is based on the characteristics of the selected PV module, including open-circuit voltage (Voc), short-circuit current (Isc), and maximum power point parameters (Vmp, Imp, Pmp). All simulations use the Black Tiger RCM-460-7RCG module (RECOM, 2023), a high-efficiency PV panel recommended for tertiary building installations (Clean Energy Reviews, 2025) which delivers a nominal power output of approximately 460 W with an efficiency of 23.6% and a module area of 1.95 m². In TRNSYS, the PV array is modelled using Type 103, electrical output based on incident solar radiation, cell temperature, and module performance parameters.

Inverter selection is performed using discrete capacity ranges, each corresponding to a commercially available inverter class. For a given PV capacity, an inverter type is selected and the number of modules connected in series is chosen so that the string voltage at maximum power remains between the inverter's minimum and maximum MPPT voltages. Once a valid series configuration is identified, parallel strings are progressively added until the inverter's capacity is approached. The sizing algorithm aims to maximise the number of connected PV modules while respecting all electrical and operational constraints. When the required PV capacity exceeds the maximum capacity of the largest inverter class, the system is scaled by deploying multiple identical inverters in parallel. In this case, the total number of strings increases proportionally, while the electrical characteristics of each inverter remain unchanged. This modular approach allows the model to represent PV systems ranging from small installations to multi-megawatt plants.

Once the PV system configuration is defined, the user initiates the simulation directly from the Excel interface. The model then automatically calls the TRNSYS simulation engine. Simulation outputs are written back to the Excel model, where PV electricity production results are stored on a monthly basis in kilowatt-hours (kWh).

The resulting PV system configurations are summarised in Table 1, including the number of modules, installed capacity, tilt angle, and total active module area

*Table 1. Summary of PV system configurations at the HEATWISE demo sites.*

| Site | Type | N° modules | Installed Area [m²] | Installed Capacity [kWp] | Tilt [°] |
|---|---|---|---|---|---|
| **AAU** | Rooftop | 110 | 215 | 51 | 43 |
| **AAU** | Facade | 102 | 199 | 47 | 90 |
| **EMPA** | Rooftop | 30 | 59 | 14 | 37 |
| **RISE** | Rooftop | 3,584 | 6,999 | 1,649 | 52 |
| **TOFAS** | Rooftop | 76,104 | 148,612 | 35,019 | 33 |

## 2.2.2.PVT System Design

Building on the PV system design framework described in Section 2.2.1, the modelling of PVT systems is implemented within the same Excel–TRNSYS environment, presented in Figure 19, extending the scope to include simultaneous thermal and electrical energy production.

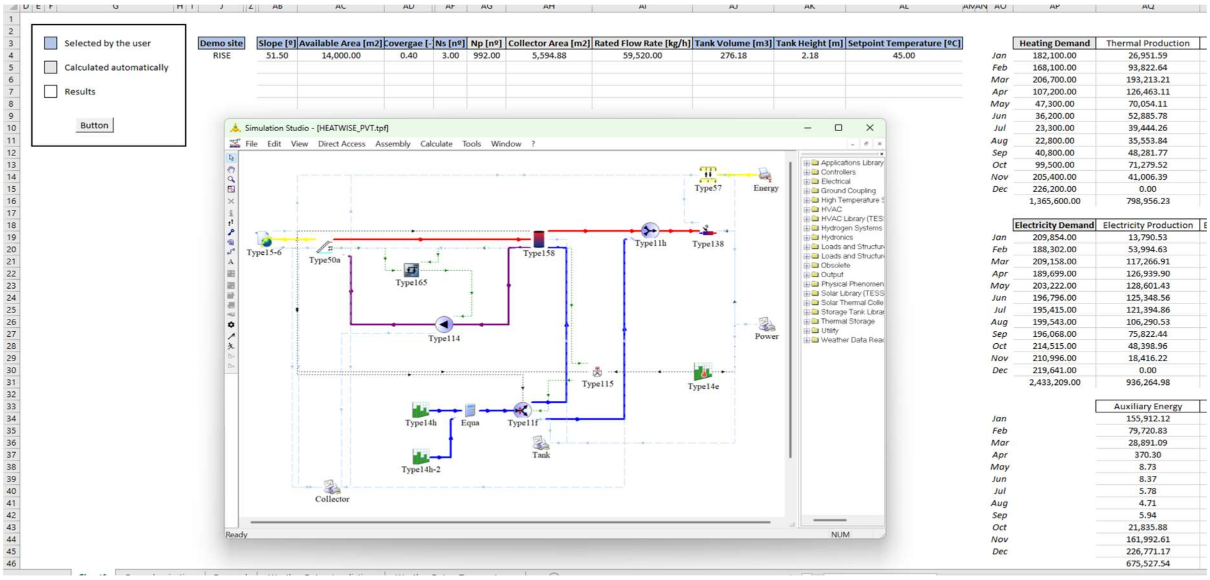


*Figure 19. TRNSYS simulation layout of the PVT system model implemented within the Excel–TRNSYS framework.*

Within the Excel model, the main PVT-specific operating assumptions are defined, while site selection and climatic data handling remain consistent with the PV simulations. The PVT systems are primarily designed to supply hot water at 45 °C. Hot water demand is assumed to steadily occur over a 12-hour daily period, from 08:00 to 20:00, reflecting typical occupancy and usage patterns in tertiary buildings.

As with the PV systems, a coverage factor is applied to represent the fraction of rooftop area effectively occupied by collectors. Due to additional spatial requirements associated with hydraulic piping, maintenance access, and integration of the storage system, slightly lower coverage factors are adopted for PVT installations: a value of 0.50 is considered for the EMPA site, while 0.40 is applied for both AAU and RISE.

The simulations are based on a commercially available PVT collector manufactured by Abora (Abora Energy, 2026). The selected collector operates at a nominal mass flow rate of 60 L/h and delivers approximately 350 W of electrical output and 700 W of thermal output under standard operating conditions. In TRNSYS, the PVT collector is modelled using Type 50, which represents hybrid PVT collectors by coupling electrical and thermal behaviour within a single component. Electrical and thermal outputs are simulated simultaneously, allowing the interaction between collector temperature, electrical efficiency, and thermal recovery to be captured consistently.

The PVT solar field is configured by connecting collectors in series–parallel arrangements, with three modules in series to increase outlet temperature, while additional collectors are arranged in parallel to maximise the use of the available installation surface and increase overall system capacity. The thermal subsystem is modelled as a primary hydraulic loop connected to a thermal energy storage tank. A storage capacity of approximately 50 L per m² of collector area is adopted, following balanced design conditions. Fluid circulation is controlled by a differential temperature controller, which activates the circulation pump when the temperature difference between the collector outlet and the bottom of the storage tank exceeds 10 °C. If the delivered water temperature does not meet the hot water setpoint, an auxiliary heating system supplies the remaining thermal demand.

Once the PVT system configuration is defined, the simulation is initiated from the Excel interface, which automatically calls the TRNSYS simulation engine. Monthly electrical and thermal energy production values are written back to the Excel model and used for subsequent performance assessment.

The resulting PVT system configurations for each demo site are summarised in Table 2, including the number of modules, installed capacity, tilt angle, and total active module area. In this study, PVT integration was limited to rooftop installations, as façade-integrated PVT systems were not considered.

*Table 2. Summary of PVT system configurations at the HEATWISE demo sites*

| Site | Nº collectors | Installed Area [m$^2$] | Storage Volume [m$^3$] | Tilt [º] |
|---|---|---|---|---|
| **AAU** | 93 | 175 | 10 | 43 |
| **EMPA** | 24 | 45 | 2.5 | 37 |
| **RISE** | 2,976 | 5,595 | 276 | 52 |
| **TOFAS** | 5,304 | 9,972 | 500 | 33 |

## 2.3. Assessments

To enable a consistent comparison across installations of different sizes and climatic conditions, system performance was evaluated using specific energy yield indicators expressed per unit of active solar area ($kWh/m^2$·year). This normalisation allows the intrinsic productivity of each configuration to be assessed independently of installed capacity.

The $CO_2$ reduction potential of the analysed PV and PVT systems was assessed using a displacement-based methodology, following an approach consistent with previous hybrid solar system studies (Acosta-Pazmiño et al., 2020). The displacement method assumes that renewable thermal and electrical production directly offsets energy that would otherwise be supplied by conventional systems. Avoided emissions were therefore calculated separately for the thermal and electrical components.

Emission factors for thermal energy were derived from the International Energy Agency (IEA) Emissions Factors 2025 data (IEA, 2025a). Natural gas was selected as the reference fuel for thermal energy displacement for heat generation in European tertiary buildings. This value falls within the typical European emission factor range reported by the IEA:

- Natural gas: 0.20 $kgCO_2$/kWhth

Grid electricity emission factors were obtained from the European Environment Agency (EEA) greenhouse gas emission intensity indicator (EEA, 2025), with the Swiss value sourced from (Romano et al., 2024), and the value for TOFAS provided directly by the site.

- Denmark (AAU): 0.076 $kgCO_2$/kWhel
- Switzerland (EMPA): 0.033 $kgCO_2$/kWhel
- Sweden (RISE): 0.007 $kgCO_2$/kWhel
- Turkey (TOFAS): 0.428 $kgCO_2$/kWhel

These factors reflect the markedly different decarbonisation levels of national electricity mixes, which influence the relative $CO_2$ mitigation potential of on-site electricity generation.

Annual avoided $CO_2$ emissions were calculated by multiplying displaced energy by the corresponding emission factor. Only the portion of renewable production directly offsetting on-site demand was considered, ensuring a conservative estimation of avoided emissions. To enable comparison across systems of different sizes, annual avoided emissions were normalised by the total active solar field area, yielding a specific decarbonisation indicator expressed in $kgCO_2/m^2$.

# 3. Analysis and Discussion

## 3.1. Specific Energy Yield Assessment

This section presents the performance analysis of the simulated on-site PV and PVT installations at the selected HEATWISE demo sites. Monthly production profiles are examined in relation to building demand, and subsequently results are compared using specific energy yield indicators (kWh/m²·year) to enable a consistent evaluation across sites with different scales and climatic conditions.

### 3.1.1. PV Systems

As shown in Figure 20, the simulated PV installations at AAU, both rooftop and facade-integrated, cover only a limited share of the building's total electricity demand (~12% annually). This outcome should not be interpreted as a limitation of the technology itself, but rather as a direct consequence of the installed PV capacity (limited by available area) relative to the building's total consumption. The objective of the study is to evaluate the renewable generation potential within the available installation surface, rather than to achieve energy self-sufficiency. Electricity production follows the expected seasonal pattern, with higher output during spring and summer months and reduced contribution during winter months, primarily due to variations in solar irradiance and daylight duration throughout the year.

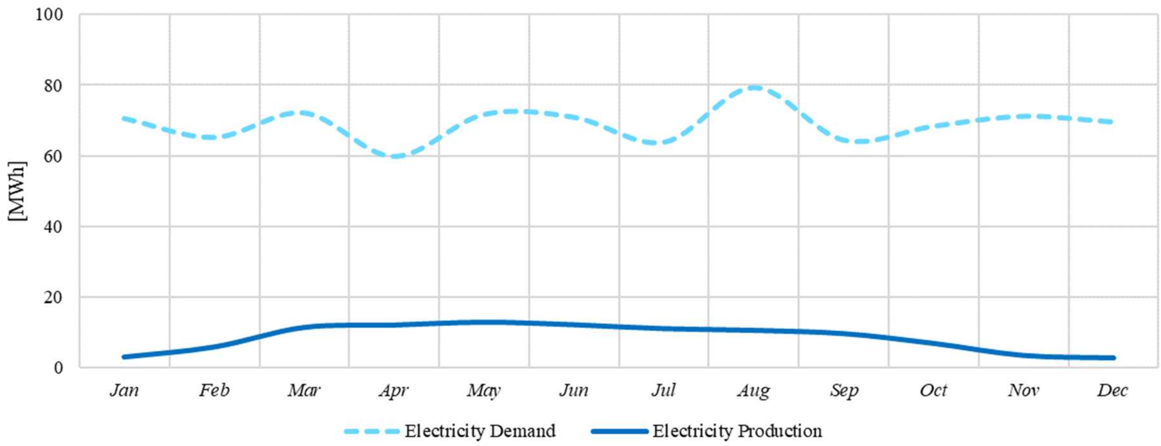


*Figure 20. Monthly electricity demand and PV electricity production at the AAU demo site (110 rooftop modules, 51 kWp; 102 facade-integrated modules, 47 kWp installed capacity).*

A similar behaviour is observed at EMPA, as presented in Figure 21. Electricity production remains below monthly demand (annual self-coverage is also ~12%) primarily due to the limited available installation area (59 m$^2$).

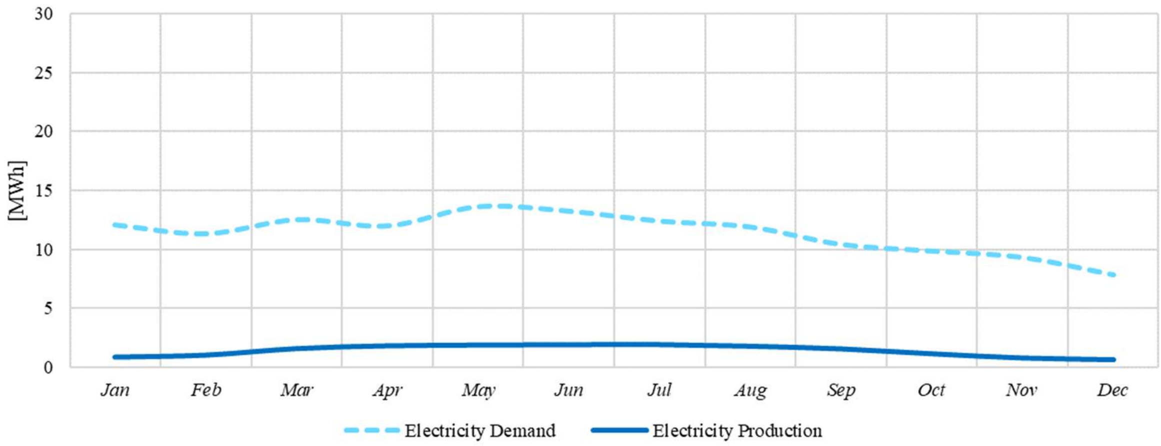


*Figure 21. Monthly electricity demand and PV electricity production at the EMPA demo site (30 modules, 14 kWp installed capacity).*

In contrast to the previous demo sites, the RISE facility presents a markedly different performance profile. As depicted in Figure 22, the large available rooftop area enables a high installed PV capacity (1,649 kWp), resulting in electricity production that exceeds on-site demand during six months of the year (March-August). This leads to sustained periods of surplus generation, which would need to be exported to the grid.

In winter, solar availability is extremely limited due to the high latitude of the site (66ºN), resulting in negligible electricity production during these months.

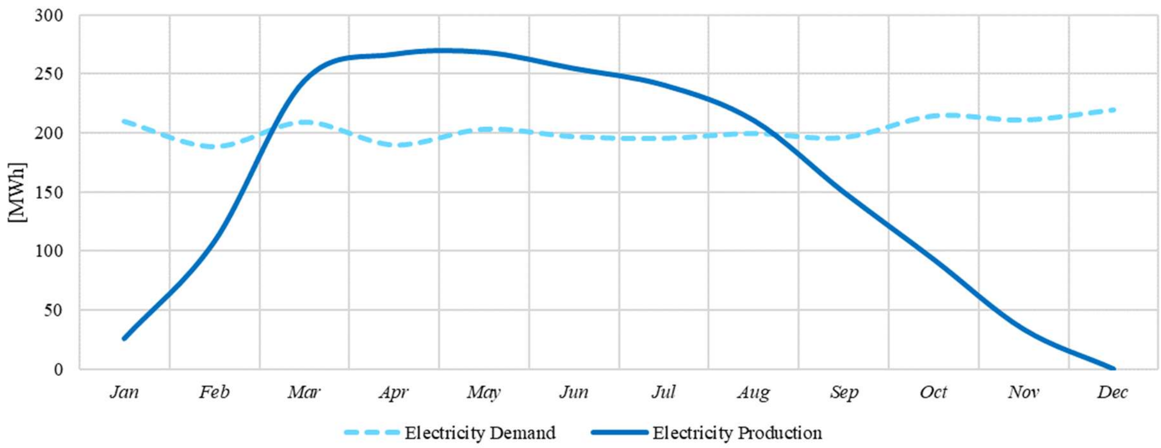


*Figure 22. Monthly electricity demand and PV electricity production at the RISE demo site (3,584 modules, 1,649 kWp installed capacity).*

The TOFAS facility, as shown in Figure 23, benefits from the highest installed PV capacity (35,019 kWp) among the analysed sites, as it considers both immediately available rooftop areas in the factory and those requiring refurbishment, resulting in a total installed area of 148,612 m². At the same time, the high and continuous electricity demand results in a load profile capable of absorbing a large share of the PV generation, 78% of the building's total electricity demand.

During warm periods, when both solar generation and cooling demand increase, a portion of electricity demand is attributable to cooling systems, including electrically driven cooling towers and chiller units used in both industrial processes and building services. PV electricity production can therefore contribute to covering cooling-related consumption.

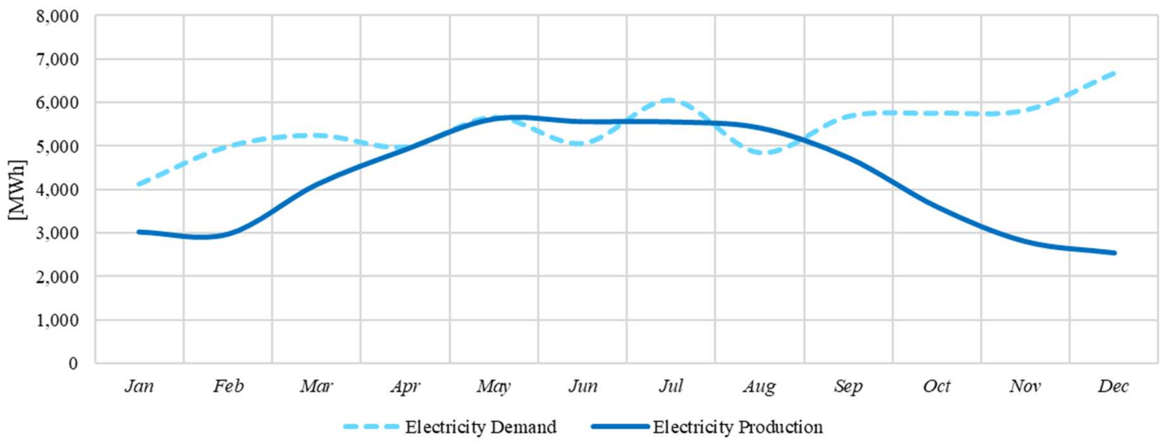


*Figure 23. Monthly electricity demand and PV electricity production at the TOFAS demo site (76,104 modules, 35,019 kWp installed capacity).*

Figure 24 compares the monthly and annual specific electricity production across the three demo sites and installation types. At the AAU site, the rooftop PV systems achieves an annual specific yield of 279 kWh/m$^2$·year, compared to 209 kWh/m$^2$·year for the facade-integrated BIPV installation. This difference is primarily related to the vertical orientation of the facade system, which limits the annual irradiance captured on the module surface. In fact, the BIPV system presents the lowest annual specific yield among all analysed cases. However, at AAU, during winter months, the BIPV system shows slightly higher specific yields than the rooftop installation, reflecting the improved incidence of low-altitude solar radiation on vertical surfaces.

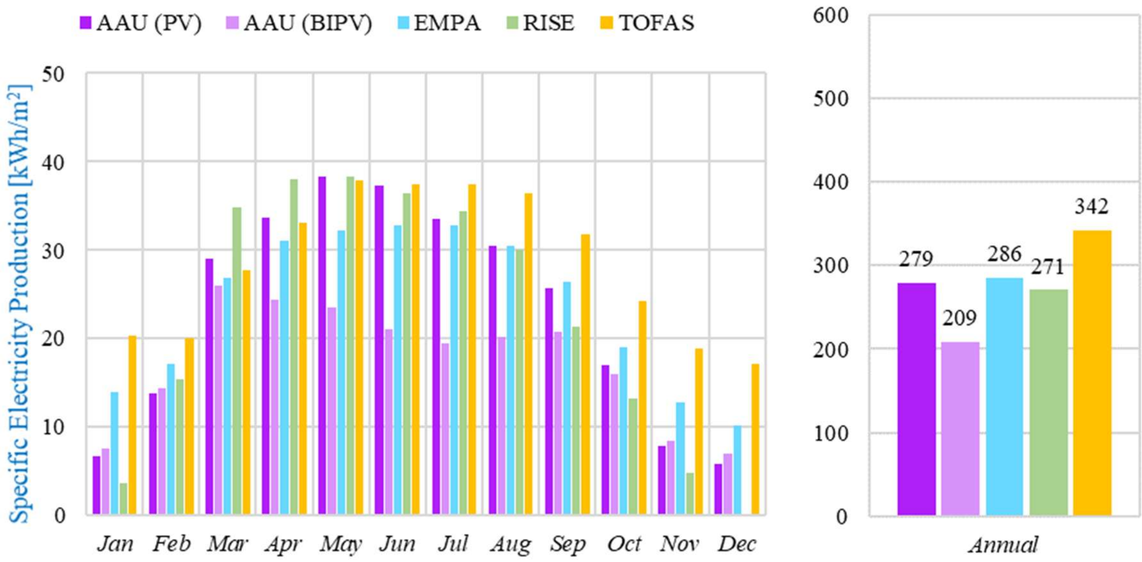


*Figure 24. Monthly profiles and annual specific electricity yield of the analysed PV systems.*

When comparing the rooftop installations across sites, TOFAS achieves the highest annual specific electricity yield among all analysed configurations, 342 kWh/m²·year, followed by EMPA, AAU (PV), RISE, and AAU (BIPV). This indicates that, on a yearly basis, the combination of more favourable solar conditions at lower latitudes, their seasonal distribution, and the selected installation geometry leads to higher electricity production.

However, the monthly results show that from March to July, the specific production of the AAU rooftop system and the RISE installation is higher than that of EMPA, and from March to May, it is also higher than that of TOFAS. This behaviour is mainly related to the irradiance effectively received by the modules. While global horizontal irradiation provides a general indication of solar availability, electricity generation depends on the irradiance on the inclined surface. During these months, the irradiance on the plane of array is comparatively higher at AAU and RISE, which explains their superior monthly yields in spring and early summer.

## 3.1.2.PVT systems

Figure 25 shows the monthly heating demand, useful thermal production from the PVT system, auxiliary energy contribution, and the corresponding electricity demand and production at the AAU site. On an annual basis, the solar contribution accounts for approximately 22% of the total thermal demand. The seasonal pattern is clearly visible: during winter and early spring, solar production remains limited, leading to a strong reliance on auxiliary heating to cover high heating demand. From May to September, however, the PVT system is able to cover the full monthly thermal demand, and auxiliary energy is close to zero.

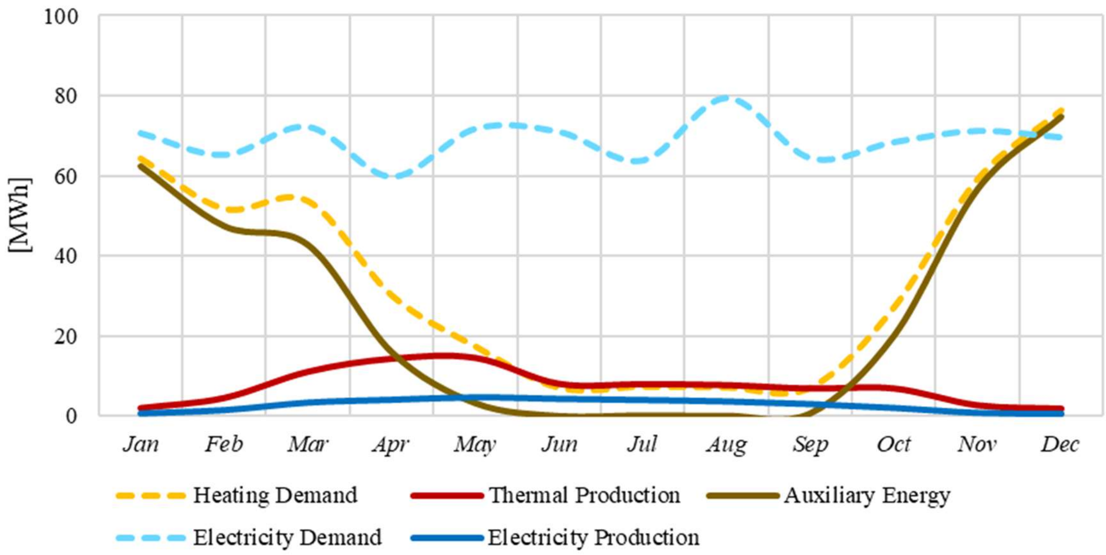


*Figure 25. Monthly thermal and electrical performance of PVT system at AAU (Solar field: 175 $m^2$)*

Despite favourable solar conditions in summer, an interesting behaviour can be observed, with a reduction in useful thermal production in June, July, and August. This effect is not driven by reduced irradiance, but by the operating temperature conditions during summer, when the building's thermal demand is low and the storage tank remains at elevated temperatures. As a result, the collectors operate at higher mean temperatures, which reduces their thermal efficiency and limits useful heat recovery. In addition, as the temperature difference between the collector outlet and the bottom of the tank decreases, the potential for effective heat transfer is reduced. When this differential falls below the controller threshold, circulation is reduced or stopped, leading to stagnation periods during which the collectors do not deliver useful thermal energy even though solar resource is available.

Figure 26 presents the corresponding PVT performance at the EMPA site, where solar production is lower than at AAU, reflecting the more limited available installation area. On an annual basis, the PVT system covers approximately 20% of the total thermal demand. In absolute terms, peak monthly thermal production reaches around 4 MWh, compared to approximately 15 MWh at AAU.

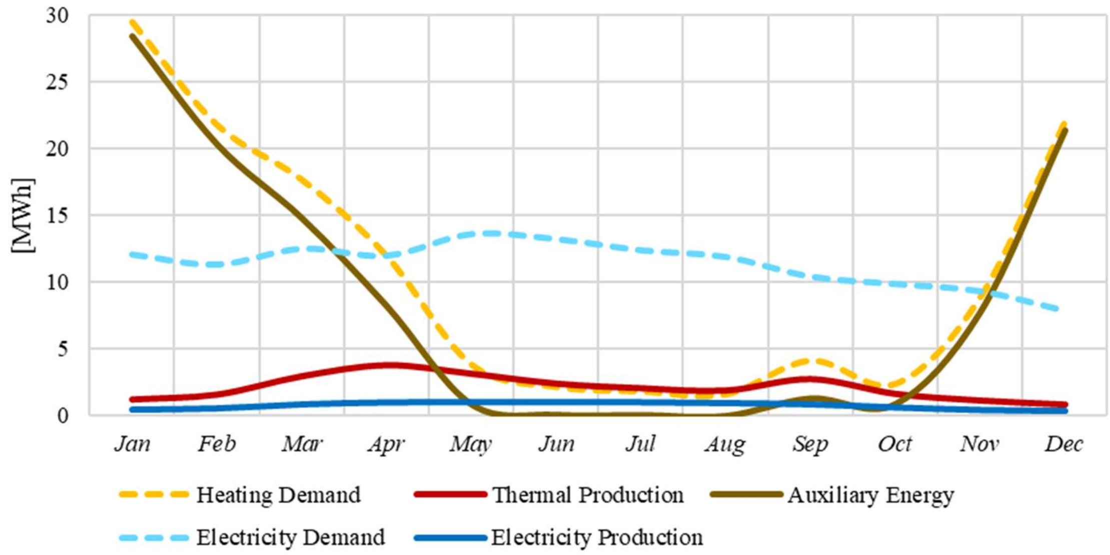


*Figure 26. Monthly thermal and electrical performance of PVT system at EMPA (Solar field: 45 m²)*

Figure 27 presents the PVT system performance at the RISE site. In this case, the installed solar field is 5,595 m² of collector aperture area, taking advantage of the extensive available rooftop surface. As a result, the solar contribution reaches approximately 51% of the annual thermal demand.

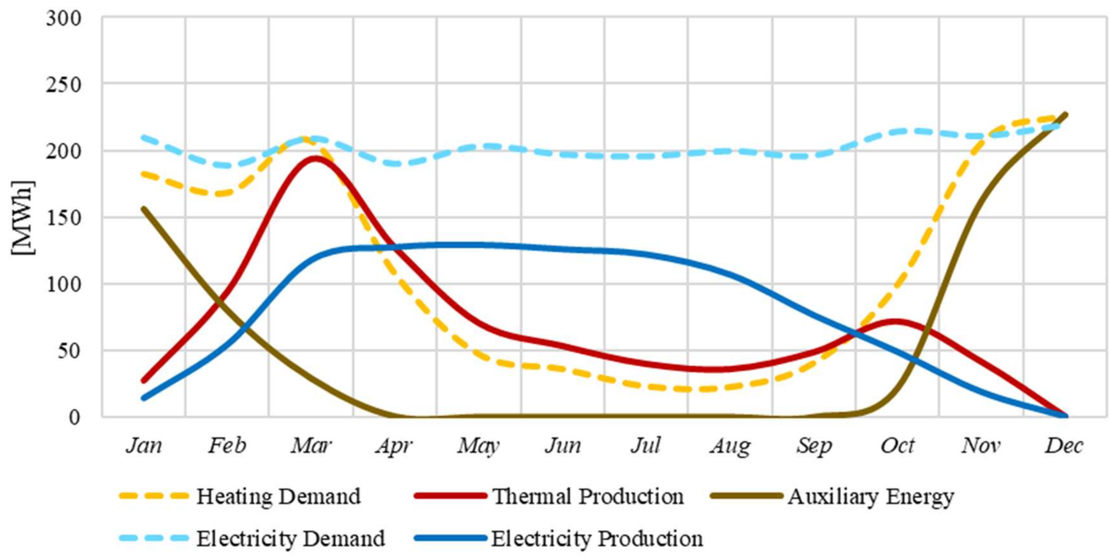


*Figure 27. Monthly thermal and electrical performance of PVT system at RISE (Solar field: 5,595 m²)*

The seasonal pattern remains consistent with the previous cases, with auxiliary support required primarily during the coldest months. Furthermore, as previously discussed, elevated storage temperatures during periods of low demand limit useful heat extraction, leading to extended intervals (from April to August) in which the available solar resource is not fully utilised.

Given the scale of the solar field, the investigation of seasonal thermal energy storage was considered a relevant added value within this study. At this capacity level, the system is able to produce sustained thermal surpluses over extended summer periods, making inter-seasonal shifting a technically viable strategy to reduce auxiliary energy consumption.

To evaluate this potential, a pit thermal energy storage (PTES) system was incorporated into the RISE configuration. A storage volume corresponding to approximately 1.8 m³ per m² of collector area was considered (Dahash et al., 2023), resulting in a total storage capacity of 10,000 m³. In TRNSYS, as shown in Figure Figure 28, the PTES was modelled using Type 1535 to represent the large-scale stratified water storage volume, coupled with Type 1301 to simulate heat transfer to the surrounding soil and associated ground thermal losses.

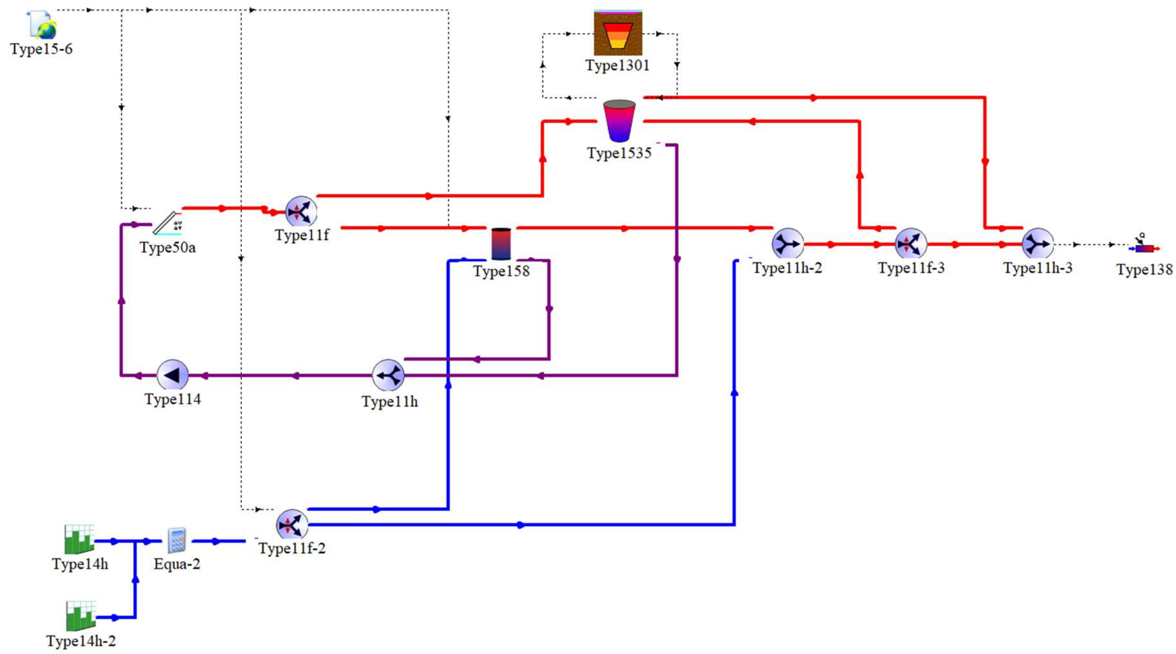


*Figure 28. TRNSYS schematic of the PVT system with integrated PTES*

The configuration was simulated over a two-year period, as shown in Figure 29, in order to evaluate the dynamic behaviour of the seasonal storage. As can be seen, the integration of the PTES effectively removes the summer limitation previously observed in the system without seasonal storage. When the primary storage tank reaches elevated temperatures (60 °C in the present simulation), excess thermal energy is redirected to the PTES. This enables the PVT collectors to continue operating under favourable temperature differentials, increasing useful thermal production during high-irradiance periods.

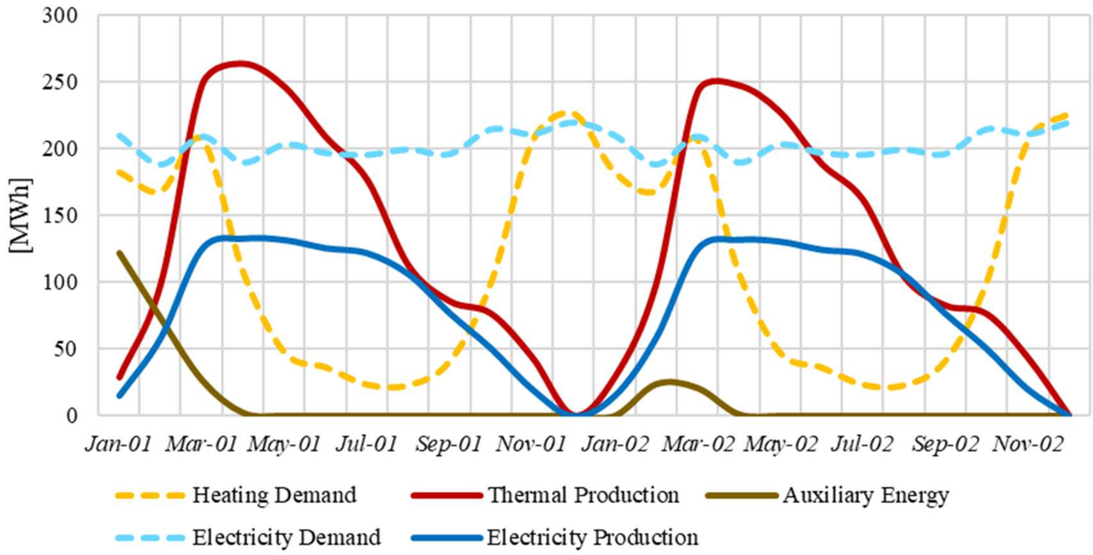


*Figure 29. Two-year operational performance of the PVT system with integrated PTES at RISE (Solar field: 5,595 m²; PTES: 10,000 m³)*

During the first simulation year, the PTES is assumed to start at 15ºC. As a result, auxiliary energy is still required during the initial winter months. However, as the system accumulates surplus thermal energy over the summer period, the storage becomes progressively charged. Consequently, auxiliary heating demand decreases towards the end of the first year.

In the second year, the PTES begins the heating season with a significant stored energy level carried over from the previous cycle. This substantially reduces auxiliary energy requirements during the winter months, as the stored summer surplus can now be utilised. As a result, the annual solar fraction increases from approximately 84% in the first year to around 97% in the second year.

On the other hand, a lower thermal production is observed in the second year compared to the first. For instance, in April, the useful thermal output decreases from 264 to 247 kWh/m² (−6%), which is related to the higher initial storage temperature of the PTES. As the storage remains at elevated temperatures for longer periods, the average operating temperature of the collectors increases, slightly reducing thermal efficiency compared to the initial charging phase of year one.

In the case of TOFAS (Figure 30), the solar field has been designed to primarily cover the thermal demand during summer periods. As a result, only the immediately available rooftop area has been considered for the installation.

Given the warm climate conditions at the site, an additional scenario was considered in which part of the cooling demand is supplied using thermally driven technologies, such as absorption chillers.

In this case, the analysis does not modify the system operation but rather considers an alternative utilisation pathway for the available thermal energy. The resulting thermal production, accounting for the utilisation of excess heat during summer, is represented by the dashed red line.

Under this assumption, the excess thermal energy available during summer can be effectively utilised, leading to improved system utilisation and higher annual heat recovery. In quantitative terms, the annual useful thermal production increases from 6,508 MWh to 10,314 MWh, a 58% increase.

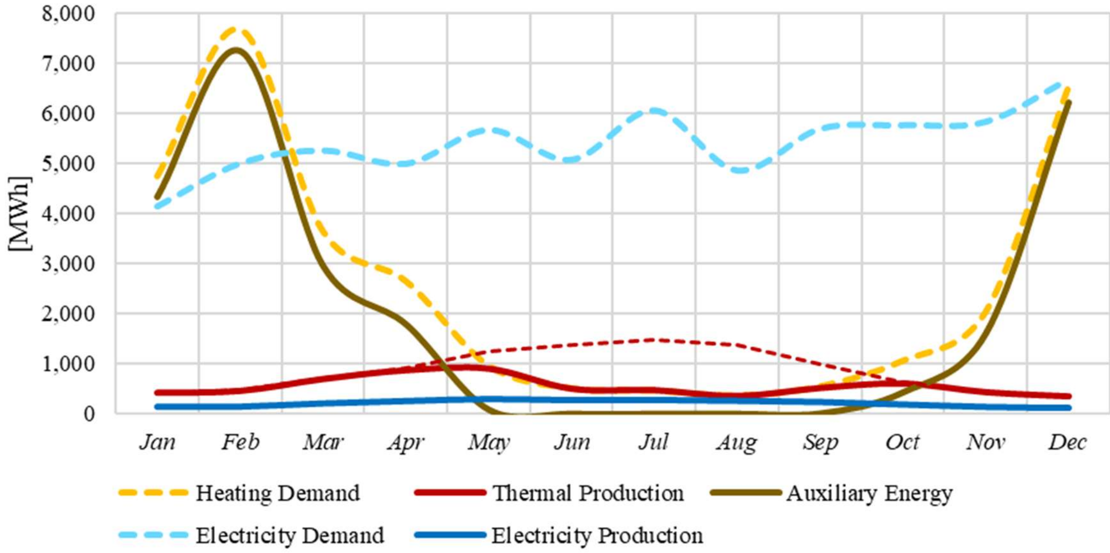


*Figure 30. Monthly thermal and electrical performance of PVT system at TOFAS (Solar field: 9,972 m²)*

Figure 31 presents the annual specific thermal and electrical production of the analysed PVT systems. AAU, EMPA, and TOFAS exhibit higher (approximately 2.5 times greater) specific yields compared to their electrical output. At the RISE site without seasonal storage, the specific thermal yield is noticeably lower than in AAU and EMPA. This is primarily linked to the prolonged summer limitation previously discussed, where high storage temperatures and low demand reduce effective heat extraction.

Moreover, when thermal energy is used to cover cooling demand during summer in TOFAS, the collectors operate under more favourable conditions, resulting in higher efficiencies and sustained peak production levels. This leads to an increase in the useful thermal output and, consequently, the specific thermal production of 1,034 kWh/m$^2$·year.

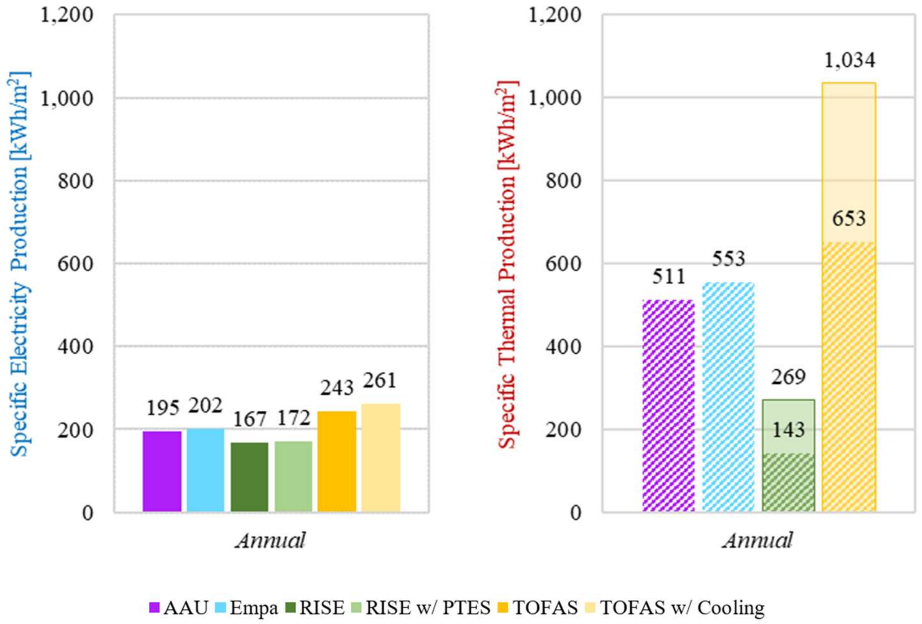


*Figure 31. Annual specific electricity and thermal yield of the analysed PVT systems*

The integration of PTES increases the specific thermal yield at RISE from 143 to 269 kWh/m$^2$·year (+88%). By enabling the utilisation of sustained summer surpluses, the seasonal storage effectively removes the operational limitation associated with high primary storage temperatures. As a result, the specific thermal production nearly doubles compared to the configuration without PTES. However, it does not reach the same level as AAU and EMPA, partly due to the harsher climatic conditions at higher latitudes, including extended periods of very low winter irradiance.

Regarding electricity generation, the specific yields follow the same relative trend previously observed in the PV-only systems, albeit at lower magnitudes. This reduction is consistent with the lower electrical efficiency of hybrid PVT collectors compared to standalone high-efficiency PV modules. Nevertheless, while the electrical yield per square metre is reduced, the PVT technology compensates by simultaneously delivering useful thermal energy, resulting in a higher overall energy output per unit area.

## 3.2. Decarbonisation Assessment

### 3.2.1.PV Systems

Table 3 and Figure 32 present the annual avoided $CO_2$ emissions for the analysed PV installations, expressed both in absolute terms ($tCO_2$/year) and normalised by installed area (kg $CO_2$/m$^2$·year).

In absolute terms, the TOFAS installation achieves the highest emission reduction. This is primarily due to the combination of its larger installed capacity, leading to higher total electricity generation, and the comparatively high grid emission factor at the site. It is followed by RISE, despite the low grid emission factor. AAU shows moderate annual savings, while EMPA exhibits the lowest absolute $CO_2$ reduction due to its comparatively small installed capacity.

*Table 3. Annual avoided $CO_2$ emissions ($tCO_2$/year) for the analysed PV installations.*

| Site | AAU (PV) | AAU (BIPV) | EMPA | RISE | TOFAS |
|---|---|---|---|---|---|
| **$CO_2$ emissions avoided [ton] from Electricity** | 4.56 | 3.16 | 0.55 | 11.2 | 21,309 |

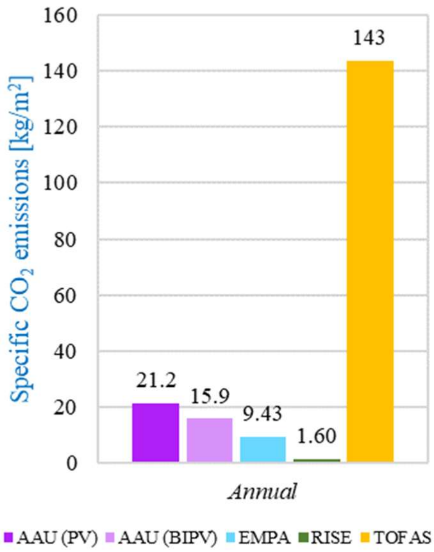


*Figure 32. Annual specific $CO_2$ emissions avoided from PV electricity generation.*

When results are normalised by installed area, the highest specific decarbonisation potential is observed at TOFAS, followed by AAU, the facade-integrated BIPV configuration, and EMPA, while RISE shows by far the lowest specific reduction per square metre. This outcome is directly linked to national grid carbon intensity. Sites with higher grid emission factors, such as TOFAS and AAU (Denmark) amplifies the $CO_2$ mitigation impact of each kWh generated, whereas Sweden's highly decarbonised electricity mix substantially limits the marginal benefit of additional on-site PV generation.

These results highlight the importance of distinguishing between absolute and specific indicators. While large-scale installations maximise total avoided emissions, the carbon intensity of the displaced energy system Is the dominant factor determining the decarbonisation effectiveness per unit of installed area.

## 3.2.2.PVT Systems

Table 4 and Figure 33 present the annual avoided $CO_2$ emissions for the PVT systems, distinguishing between electricity-related emissions and natural gas displacement.

*Table 4. Annual avoided $CO_2$ emissions ($tCO_2$/year) for the analysed PVT installations.*

| Site | AAU | EMPA | RISE | RISE (PTES) | TOFAS | TOFAS (Cooling) |
|---|---|---|---|---|---|---|
| $CO_2$ emissions avoided [ton] from Electricity | 2.59 | 0.30 | 6.55 | 6.73 | 1,036 | 1,115 |
| $CO_2$ emissions avoided [ton] from Natural Gas | 17 | 4.67 | 138 | 263 | 1,293 | 1,328 |

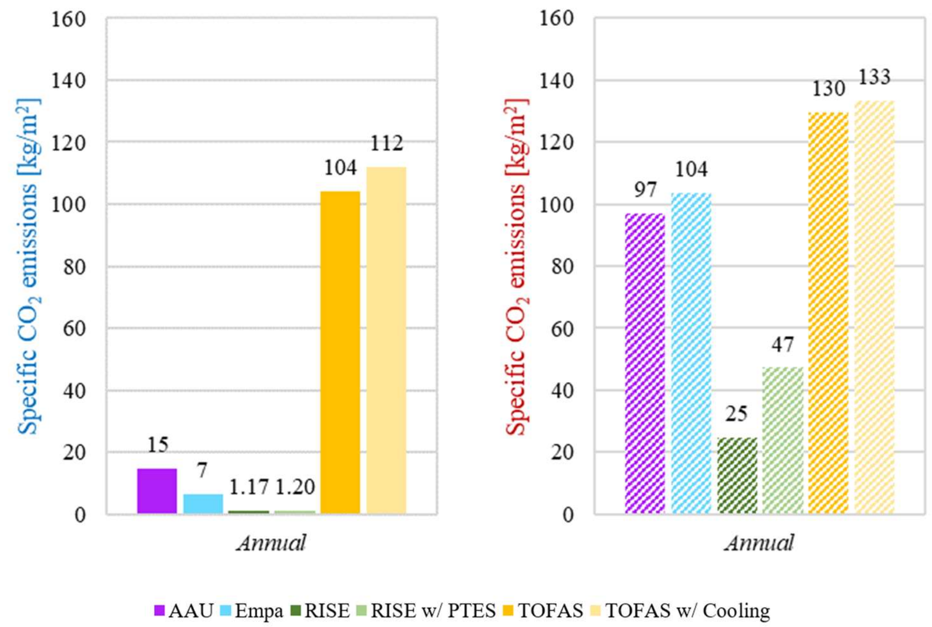


*Figure 33. Annual specific $CO_2$ emissions avoided from PVT electricity (blue) and thermal (red) generation.*

The electricity-related emission reductions follow the same relative trend observed in the PV-only analysis, where absolute savings are primarily driven by system size, while specific savings depend strongly on national grid carbon intensity.

In contrast, the thermal component represents the dominant factor of emission reduction in all PVT configurations, as avoided emissions associated with natural gas displacement are substantially higher than those linked to electricity generation, both in absolute and specific terms.

In absolute terms, the TOFAS configuration achieves by far the highest $CO_2$ emissions reduction associated with natural gas displacement, reaching 1,293 $tCO_2$, increasing slightly to 1,328 $tCO_2$ when cooling demand is also considered. Without seasonal storage, the avoided emissions reach 138 $tCO_2$ annually. At RISE, with the integration of PTES, this value increases dramatically from 138 to 264 $tCO_2$ per year, representing a near doubling of the mitigation impact, and unlocking the full decarbonisation potential of large-scale solar thermal systems.

When results are normalised by installed area, AAU and EMPA exhibit higher specific decarbonisation values than RISE with PTES. Specific avoided emissions reach approximately 104 $kgCO_2/m^2$·year at EMPA and 97 $kgCO_2/m^2$·year at AAU, compared to 47 $kgCO_2/m^2$·year at RISE with PTES. This reflects the higher annual heat extraction per unit area at these sites, while the larger RISE installation primarily maximises total emission reduction rather than specific performance.

## 3.3. Guidelines for Renewable Energy Integration

Based on the results obtained across the analysed scenarios, this section provides general guidelines for the integration of PV and PVT systems in tertiary and industrial buildings. The findings confirm that installation scale, demand profiles, climatic conditions, and storage integration are decisive factors for both energy performance and decarbonisation potential. The following recommendations in Table 5 synthesise these aspects into practical considerations for future implementations.

*Table 5. Typical integration scenarios*

| Scenario Description | Typical Building Types | PV Suitability | PVT Suitability | Key Recommendations |
|---|---|---|---|---|
| **Stable electricity demand, low thermal demand, and limited area** | Data centres, university and research sites (AAU, EMPA) | High | Low | Prioritise PV systems, as thermal energy from PVT is unlikely to be effectively utilised |
| **Stable electricity demand, stable thermal demand, and limited area** | Hospitals, hotels, sports facilities, mixed-use buildings | High | Very high | PVT preferred to maximise total energy yield per unit area, especially when thermal demand is continuous |
| **High energy demand, and large area** | Large industrial sites (TOFAS) | High | High | Combine PV and PVT systems; overall system design should be driven by energy demand and decarbonisation targets |
| **High electricity demand, high-temperature thermal demand, and large area** | Industrial processes | High | Conditional | Collector selection must be aligned with required temperature levels and integration point |
| **High energy demand, and large area**<br>**(Seasonal solar-thermal mismatch)** | High-latitude buildings (RISE) | High | Conditional | Integration of seasonal thermal storage are recommended to address supply-demand mismatch, and ensure effective heat utilisation |

| | | | | |
|---|---|---|---|---|
| **High electricity demand, low thermal demand, and limited area** | Data centres (PSNC) | Limited | Low | On-site solar contribution is constrained; alternative strategies such as off-site generation should be considered |

PV systems are generally easier to integrate, as their performance mainly depends on available installation area and the presence of sufficient on-site electricity demand. In contrast, PVT and solar thermal systems require a more careful design approach, since their performance strongly depends on thermal demand profiles, operating temperatures, and the effective utilisation of the generated heat. Direct integration at process level is generally preferred, as it enables lower operating temperatures and therefore higher collector efficiencies. Similarly, the selection of collector type (e.g., unglazed, glazed, or concentrating) must be aligned with the required temperature levels and the specific application, and it should also take into consideration local technology availability, since this will allow faster and more cost-effective system deployment.

This is particularly relevant in cases such as RISE, where strong seasonal variations limit heat utilisation during summer and make seasonal thermal storage an important design element. In warm-climate sites such as TOFAS, excess thermal production during summer can instead be advantageously used to support cooling demand, improving overall system utilisation and collector performance. Therefore, the deployment of solar technologies necessitates a comprehensive system-level integration approach. This involves optimising the design to ensure seamless compatibility with auxiliary technologies such as thermal energy storage systems and heat pumps, as well as harmonious integration within the building's environmental context.

Ultimately, the optimal system design should balance efficient energy use with the overall decarbonisation potential, taking into account both collector performance and the characteristics of the local energy demand.

# 4. Conclusions

This deliverable assessed the potential contribution of on-site PV and PVT systems to the energy performance and decarbonisation of selected HEATWISE demo sites under realistic climatic and operational conditions.

From an electricity perspective, PV systems achieved annual specific electricity yields ranging from 209 to 342 kWh/m²·year, depending on installation geometry and location. However, specific yield alone is not a sufficient indicator of system impact. Instead, the availability of installation surface and the magnitude of the electricity demand are the dominant factors determining the overall contribution of PV systems.

In this regard, sites with limited available surfaces, such as AAU and EMPA, achieved relatively low levels of electricity self-coverage (around 12%). In contrast, configurations such as those implemented at RISE and TOFAS enabled a significantly higher utilisation of PV generation, with the RISE case even reaching periods of surplus electricity production. These results highlight the decisive role of available surface in determining energy impact in tertiary buildings.

The PSNC case further reinforces this conclusion, as despite existing PV installations, the available surface is insufficient to significantly offset the energy demand, making alternative strategies such as off-site renewable generation and energy storage essential.

PVT systems increased the overall energy productivity per unit area, with specific thermal yields typically 2–3 times higher than electrical yields. These results confirm that hybrid systems are particularly advantageous where simultaneous electricity and heat demand exist, maximising energy extraction from constrained roof areas.

However, operational limitations became evident at large scale. At RISE, high storage temperatures during summer, caused by low heat demand, reduced useful thermal output despite high solar availability. The integration of seasonal PTES effectively removed this limitation, increasing specific thermal yield from 143 to 269 kWh/m²·year (+88%) and raising the annual solar fraction from 51% to 97%. This demonstrates the strategic importance of seasonal storage in high-latitude contexts with strong seasonal mismatch between solar availability and heating demand.

Regarding decarbonisation, at RISE, the integration of PTES increased avoided emissions associated with natural gas displacement to 264 $tCO_2$/year, reflecting the effect of large system scale. However, when normalised by collector area, the specific mitigation remained lower (47 $kgCO_2/m^2$·year) than at EMPA (104 $kgCO_2/m^2$·year) and AAU (97 $kgCO_2/m^2$·year). This indicates that while large-scale systems maximise total emission reduction, climatic conditions and annual heat extraction per unit area strongly influence specific decarbonisation performance.

In contrast, for electricity generation, the specific $CO_2$ mitigation per unit area is strongly influenced by both the local grid emission factor and the scale of the installation. In the case of TOFAS, the combination of large available surface and a higher grid emission factor results in a significant decarbonisation potential. Conversely, although the RISE site benefits from large-scale deployment, the relatively low carbon intensity of the Swedish electricity mix reduces the specific $CO_2$ mitigation achieved. At AAU, despite the limited available installation area, the specific $CO_2$ mitigation remains higher than at RISE due to the higher grid emission factor in Denmark.

In all PVT cases, thermal displacement of natural gas was the dominant contributor to emission reductions, substantially exceeding the impact of electricity generation, despite natural gas's comparatively low emission factor.

This deliverable provides the technical basis for the development of feasible system configurations and business case assessments in deliverables 9.3 and 9.4. The simulation results and analysis define the performance ranges, applicability conditions, and limitations of PV and PVT technologies across the analysed tertiary and industrial buildings, including aspects such as energy production, solar fractions, storage requirements, and decarbonisation potential.

These findings will be used in D9.3 to define feasible and scalable system configurations, and in D9.4 to assess their economic viability and replication potential.

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# List of figures

# List of tables