

Assessment of Integrated Solar-Based Residential Energy Systems with Seasonal Thermal Storage

Development and Evaluation of SOLSTICE V2 with a Focus on High-Temperature Aquifer Thermal Energy Storage

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Abstract

The transition to low-carbon energy systems requires the electrification of residential heating using renewable electricity. However, renewable electricity generation, of which solar electricity forms an important share, and residential heat demand are strongly mismatched across the seasons. This thesis critically evaluates and further develops the Solar Storage in Diverse Climates (SOLSTICE) modelling framework into SOLSTICE V2, an accessible and transparent hourly Excel-based model for the early-stage assessment of residential energy systems. The model is intended to enable users such as policymakers and planners to compare system configurations and explore energy-system behaviour without requiring advanced simulation software or specialised modelling expertise. SOLSTICE V2 combines photovoltaic or photovoltaic-thermal collectors, heat pumps, electrical battery storage, and high-temperature aquifer thermal energy storage. The existing component representations were assessed and adapted where necessary, with particular attention given to plane-of-array irradiance, duty-specific heat-pump operation, electrical battery losses, photovoltaic-thermal and heat-pump coupling, and the physical representation of useful heat stored in the aquifer. The resulting framework uses hourly weather, demand, and electricity-price data to simulate energy flows and compare system configurations under different climatic conditions. The results show that converting excess summer solar electricity into directly usable winter heat can achieve electrical self-sufficiency above 90%. For the Berlin reference case, adding high-temperature aquifer thermal energy storage to the photovoltaic and electrical battery configuration reduced annual grid import from 2024 kWh to 450 kWh per household. Replacing photovoltaic modules with photovoltaic-thermal collectors further improved system performance because the higher heat-source temperature significantly increased heat-pump performance. In Berlin, the investigated system used approximately 25 m² of solar collectors per household and a shared effective hot-well volume of 230,000 m³ for 1000 households. Under the higher solar irradiation and lower heating demand of Madrid, comparable performance was achieved with approximately 13 m² of solar collectors per household and an effective hot-well volume of 100,000 m³. The results demonstrate the complementary roles of short-term electrical storage and seasonal thermal storage, as well as the importance of climate-specific system sizing.

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Declaration on the Use of Generative AI

During the preparation of this thesis, the author used artificial intelligence tools, primarily ChatGPT by OpenAI, to assist with academic language editing, grammar correction, brainstorming, plotting, and Python code debugging and support during the development and review of the SOLSTICE V2 Excel model. All technical content, results, analysis, and conclusions were developed and verified by the author.

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List of Abbreviations

ATES	aquifer thermal energy storage
COP	coefficient of performance
DHI	diffuse horizontal irradiance
DHW	domestic hot water
DNI	direct normal irradiance
EB	electrical battery
GHI	global horizontal irradiance
HP	heat pump
HT-ATES	high-temperature aquifer thermal energy storage
POA	plane-of-array
PV	photovoltaic
PVT	photovoltaic-thermal
SH	space heating
SOLSTICE	Solar Storage in Diverse Climates
ST	solar thermal
UTES	underground thermal energy storage

List of Symbols

General notation and indices

Symbol	Description	Unit
i	Index denoting a heat-pump thermal duty	–
t	Hourly simulation timestep	–
$t - 1$	Preceding simulation timestep	–
$t + 1$	Subsequent simulation timestep	–
Δt	Simulation timestep duration	h
$\dot{Q}$	Thermal-power-rate notation	W _{th}

Solar irradiance and solar collectors

Symbol	Description	Unit
A_{PV}	Total photovoltaic module area	m ²
A_{PVT}	Total photovoltaic-thermal collector area	m ²
A_{ST}	Total solar-thermal collector area	m ²
$a_{1,ST}$	Linear heat-loss coefficient of the solar-thermal collector	W m ⁻² K ⁻¹
$E_{ST, supply}$	Hourly thermal energy supplied by the solar-thermal collector	kWh _{th}
G	Incident irradiance used in the solar-thermal collector relation	W m ⁻²
$G_{beam, POA}$	Direct-beam irradiance incident on the tilted collector plane	W m ⁻²
$G_{diffuse, POA}$	Diffuse irradiance incident on the tilted collector plane	W m ⁻²
$G_{ground, POA}$	Ground-reflected irradiance incident on the tilted collector plane	W m ⁻²
G_{POA}	Total plane-of-array irradiance	W m ⁻²
h_{int}	Effective internal heat-transfer coefficient between the photovoltaic-thermal module and working fluid	W m ⁻² K ⁻¹
P_{PV}	Instantaneous electrical power output of the photovoltaic array	W _e
P_{ST}	Instantaneous thermal power output of the solar-thermal collector	W _{th}
$P_{surplus}$	Surplus electrical power available to operate the heat pump	W _e
q_{cool}	Cooling heat flux extracted from the photovoltaic-thermal collector	W m ⁻²
$\dot{Q}_{src, PVT}$	Total source-side thermal power extracted from the photovoltaic-thermal collector	W _{th}
T_{amb}	Ambient-air temperature	°C
T_{house}	Indoor or house temperature used in the solar-thermal collector model	°C
T_m	Photovoltaic module temperature	°C
$T_{m, PVT}$	Photovoltaic-thermal module temperature	°C
T_{op}	Prescribed solar-thermal collector operating temperature	°C
$T_{source, PVT}$	Photovoltaic-thermal fluid temperature supplied to the heat-pump source side	°C
U_{PV}	Overall heat-loss coefficient of the photovoltaic module	W m ⁻² K ⁻¹
U_{PVT}	Overall heat-loss coefficient of the photovoltaic-thermal collector	W m ⁻² K ⁻¹

Symbol	Description	Unit
α	Effective solar absorption coefficient of the collector	—
β	Collector tilt angle	°
γ	Temperature coefficient of photovoltaic electrical efficiency	K ⁻¹
$\Delta T_{\text{inside,heating}}$	Temperature offset used to prescribe the solar-thermal operating temperature	K
ΔT_{PVT}	Prescribed photovoltaic-thermal module-to-fluid temperature difference in the original model	K
$\Delta T_{\text{PVT,max}}$	Maximum permitted photovoltaic-thermal module-to-fluid temperature difference	K
$\eta_{0,\text{ST}}$	Zero-loss optical efficiency of the solar-thermal collector	—
η_{PV}	Temperature-corrected photovoltaic electrical efficiency	—
η_{ref}	Reference photovoltaic electrical efficiency at 25 °C	—
ρ_g	Ground albedo	—
θ_i	Angle of incidence between the solar beam and collector-surface normal	°

Heat pump

Symbol	Description	Unit
COP_i	Coefficient of performance for thermal duty i	—
COP_{SH}	Coefficient of performance for space heating	—
COP_{DHW}	Coefficient of performance for domestic hot-water production	—
$\text{COP}_{\text{HTATES}}$	Coefficient of performance for high-temperature aquifer thermal energy storage charging	—
$P_{\text{el,heat}}$	Electrical power required to supply aggregated heating demand in the original model	W _e
$P_{\text{el,HP}}$	Total electrical power consumed by the adapted heat-pump model	W _e
$P_{\text{HP},i}$	Electrical power consumed by the heat pump for thermal duty i	W _e
T_{sink}	Nominal heat-pump sink temperature	°C
$T_{\text{sink},K}$	Heat-pump sink temperature expressed in Kelvin	K
$T_{\text{sink},i}$	Nominal sink temperature for thermal duty i	°C
$T_{\text{sink,eff},i}$	Effective condensation-side temperature for thermal duty i	°C
$T_{\text{sink,eff},K,i}$	Effective condensation-side temperature for thermal duty i , expressed in Kelvin	K
$T_{\text{sink,SH}}$	Nominal sink temperature for space heating	°C
$T_{\text{sink,DHW}}$	Nominal sink temperature for domestic hot-water production	°C
$T_{\text{sink,HTATES}}$	Nominal sink temperature for high-temperature aquifer thermal energy storage charging	°C
T_{source}	Heat-pump source temperature	°C
$T_{\text{source},i}$	Selected source temperature for thermal duty i	°C
$T_{\text{source,eff},i}$	Effective evaporator-side temperature for thermal duty i	°C
$T_{\text{source,air}}$	Ambient-air heat-source temperature	°C
$T_{\text{source,fallback}}$	Auxiliary cold-water heat-source temperature	°C
$T_{\text{source,PVT},t-1}$	Photovoltaic-thermal source temperature calculated during the preceding timestep	°C
$\dot{Q}_{\text{SH}}$	Thermal power supplied for space heating	W _{th}
$\dot{Q}_{\text{DHW}}$	Thermal power supplied for domestic hot-water production	W _{th}
$\dot{Q}_{\text{HTATES}}$	Thermal power supplied for high-temperature aquifer thermal energy storage charging	W _{th}
ΔT_{lift}	Effective heat-pump temperature lift in the original model	K
$\Delta T_{\text{lift},i}$	Effective heat-pump temperature lift for thermal duty i	K

Symbol	Description	Unit
$\Delta T_{\min}$	Minimum permitted temperature lift	K
ΔT_{sink}	Sink-side temperature offset	K
ΔT_{source}	Source-side temperature offset	K
$\Delta T_{\text{source,air}}$	Source-side temperature offset for air-source operation	K
$\Delta T_{\text{source,PVT}}$	Source-side temperature offset for photovoltaic-thermal water-source operation	K
η_{hp}	Heat-pump non-ideality factor relative to ideal Carnot performance	—

Electrical battery

Symbol	Description	Unit
$E_{\text{bat},t}$	Electrical energy stored in the battery at timestep t	kWh _e
$E_{\text{bat,max}}$	Nominal electrical battery energy capacity	kWh _e
$E_{\text{ch},t}$	Electrical energy supplied to the battery for charging during timestep t	kWh _e
$E_{\text{dis},t}$	Useful electrical energy delivered by the battery during timestep t	kWh _e
η_{rt}	Electrical battery round-trip efficiency	—

High-temperature aquifer thermal energy storage

Symbol	Description	Unit
c_{aq}	Volumetric heat capacity of the saturated aquifer	$\text{J m}^{-3} \text{K}^{-1}$
$c_{\text{aq,kWh}}$	Volumetric heat capacity of the saturated aquifer expressed in kilowatt-hours	$\text{kWh m}^{-3} \text{K}^{-1}$
$c_{p,w}$	Specific heat capacity of water	$\text{J kg}^{-1} \text{K}^{-1}$
c_r	Specific heat capacity of the aquifer matrix	$\text{J kg}^{-1} \text{K}^{-1}$
c_w	Volumetric heat capacity of water, equal to $\rho_w c_{p,w}$	$\text{J m}^{-3} \text{K}^{-1}$
E_{add}	Effective thermal energy added to storage in the original model	kWh _{th}
E_{extract}	Effective thermal energy extracted from storage in the original model	kWh _{th}
$E_{\text{heat,dem}}$	Total hourly thermal-energy demand in the original storage model	kWh _{th}
$E_{\text{HP,supply}}$	Thermal energy supplied by the heat pump during a storage-charging timestep in the original model	kWh _{th}
$E_{\text{store},t}$	Thermal energy stored in the original aquifer-storage representation at timestep t	kWh _{th}
$E_{\text{use},t}$	Useful hot-well thermal-energy inventory above the minimum useful temperature at timestep t	kWh _{th}
g	Gravitational acceleration	m s^{-2}
H_{aq}	Aquifer thickness	m
k_h	Horizontal aquifer permeability	m^2
k_v	Vertical aquifer permeability	m^2
$P_{\text{sur},t}$	Surplus electrical power available for storage charging at timestep t	kW _e
$Q_{\text{ch,pot},t}$	Potential thermal energy delivered to storage during timestep t	kWh _{th}
$Q_{\text{ch},t}$	Actual thermal energy charged to the hot well during timestep t	kWh _{th}

Symbol	Description	Unit
$Q_{\text{dis},t}$	Useful thermal energy discharged from the hot well during timestep t	kWh_{th}
Q_{DHW}	Hourly domestic hot-water thermal demand in the original storage model	kWh_{th}
Q_{SH}	Hourly space-heating thermal demand in the original storage model	kWh_{th}
R_{th}	Characteristic thermal radius of the annually injected water volume	m
Ra^*	Modified Rayleigh number used in the recovery-efficiency screening relation	–
T_{ch}	High-temperature aquifer thermal energy storage charging temperature	$^{\circ}\text{C}$
T_{cold}	Prescribed cold-well and heating-return temperature	$^{\circ}\text{C}$
T_g	Undisturbed ground temperature	$^{\circ}\text{C}$
$T_{\text{hot},0}$	Initial lumped hot-well temperature	$^{\circ}\text{C}$
$T_{\text{hot},t}$	Lumped hot-well temperature at timestep t	$^{\circ}\text{C}$
$T_{\text{min},\text{supply}}$	Minimum hot-well temperature for direct useful-heat supply	$^{\circ}\text{C}$
V_{cold}	Reference cold-well volume	m^3
V_{hot}	Effective hot-well volume	m^3
V_i	Annual injected water volume	$\text{m}^3 \text{yr}^{-1}$
α_f	Thermal expansion coefficient of water	K^{-1}
ΔT	Temperature difference between injection water and undisturbed ground	K
η_{heat}	Thermal-storage round-trip efficiency in the original model	–
η_r	Seasonal thermal recovery efficiency	–
λ_{aq}	Thermal conductivity of the saturated aquifer	$\text{W m}^{-1} \text{K}^{-1}$
μ	Dynamic viscosity of water at the average aquifer temperature	Pa s
ϕ	Aquifer porosity	–
ρ_r	Density of the solid aquifer matrix	kg m^{-3}
ρ_w	Representative water density	kg m^{-3}
$\text{COP}_{\text{ch},t}$	Heat-pump coefficient of performance during storage charging at timestep t	–

Building and thermal demand

Symbol	Description	Unit
A_{win}	Effective sun-facing window area	m^2
C_{th}	Effective thermal mass of the house	J K^{-1}
H	Building heat-loss coefficient	W K^{-1}
$Q_{\text{cool},t}$	Hourly cooling-energy demand at timestep t	kWh_{th}
$Q_{\text{SH},t}$	Hourly space-heating energy demand at timestep t	kWh_{th}
$T_{\text{end},t}$	Indoor temperature after the passive building response at timestep t	$^{\circ}\text{C}$
$T_{\text{max},\text{room}}$	Upper indoor comfort-temperature setpoint	$^{\circ}\text{C}$
$T_{\text{min},\text{room}}$	Lower indoor comfort-temperature setpoint	$^{\circ}\text{C}$
$T_{\text{out},t}$	Outdoor-air temperature at timestep t	$^{\circ}\text{C}$
$T_{\text{start},t}$	Indoor temperature at the start of timestep t	$^{\circ}\text{C}$

Introduction

1.1. Background

Residential buildings account for a substantial share of national energy use and carbon emissions. In the Netherlands, households are responsible for roughly 20% of final energy consumption across all sectors [1]. According to Eurostat data for the European Union, space heating (SH) and domestic hot water DHW together account for approximately 77.6% of final household energy consumption, followed by electricity use for appliances and lighting at around 14.5% [2].

In order to meet national and European climate targets, this sector must be decarbonised. In addition, recent geopolitical developments have highlighted the vulnerability associated with dependence on imported fossil fuels, motivating efforts to reduce reliance on external natural gas suppliers and to enhance energy security through increased deployment of renewable energy and electrification of residential energy systems [3]. As a result, many homes are transitioning from fossil fuel-based heating systems toward all-electric heating systems increasingly supplied by renewable electricity.

Solar energy plays a central role in this transition. In recent years, solar energy has grown extremely quickly and has become one of the main renewable energy sources worldwide. Global installed photovoltaic PV capacity has already surpassed 2 TW_p in late 2024, and annual reports predict that the world could be installing 1 TW_p of solar per year by the end of the decade [4].

In the Netherlands, 2.6 million households were equipped with solar panels by the end of 2023 [5]. Together, these installations represent an installed PV capacity of approximately 11.7 GW_p, corresponding to around 40 % of the country's total installed solar capacity [6]. However, the distribution of PV generation is misaligned with the residential load profile, as illustrated in Figure 1.1. The figure shows daily production curves for both a summer day and a winter day. Although short-duration storage (e.g., a home battery) can mitigate the mismatch within the day by shifting midday surplus into the evening demand window, it does not resolve the seasonal unevenness between supply and demand. As a result, only 30-40% of household PV production is used on-site. The remaining electricity is exported or curtailed.

While exported electricity can still be utilised elsewhere in the energy system, curtailment represents a direct loss of renewable energy. In the Netherlands, increasing solar penetration has led to frequent periods of electricity oversupply, during which market prices drop to zero or even negative values. By mid-2025, electricity prices had already been negative for 408 hours, nearly matching the total number of negative-price hours recorded in the whole of 2024 [7]. When excess electricity cannot be stored or exported, renewable generation is actively curtailed. On peak summer days, national electricity oversupply can reach up to 12 GW, of which approximately 4 GW must be curtailed even after export capacity is utilised [8]. Over a recent quarterly period, curtailment resulted in an estimated loss of 8.3 PJ of renewable energy, comparable to the annual electricity consumption of approximately 800,000 households [7]. These figures highlight the urgency of solutions that enable local utilisation and seasonal storage of excess renewable electricity.

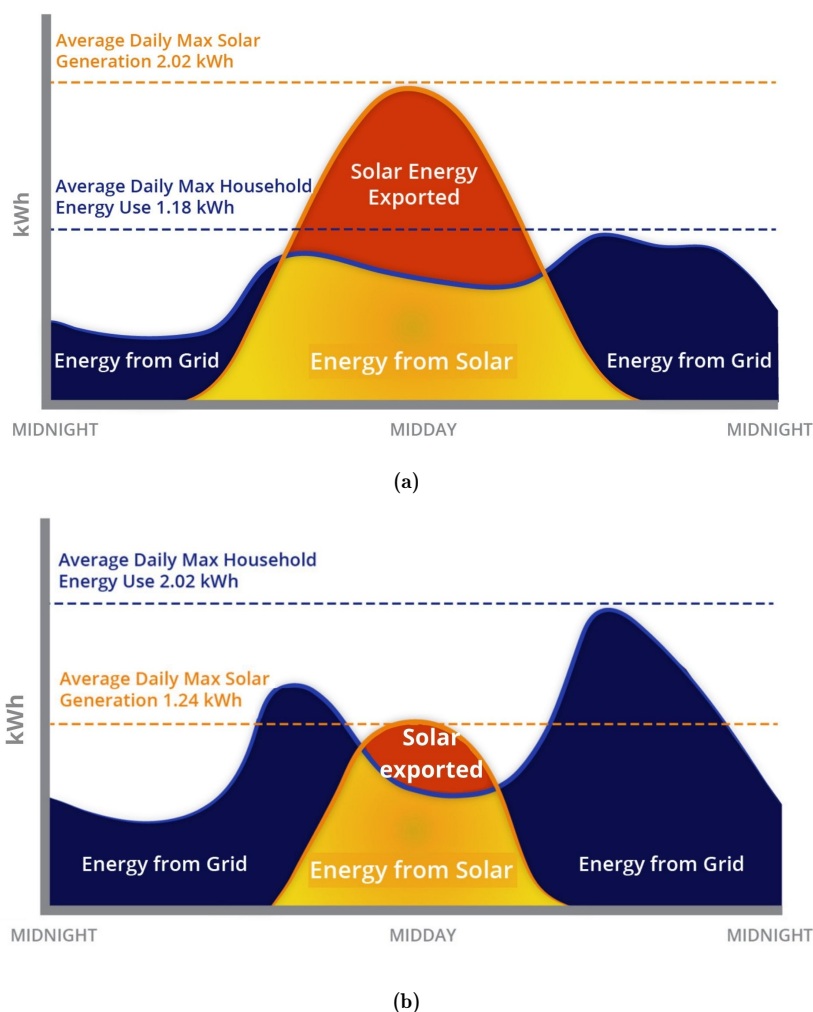


Figure 1.1: Data for a 3 kW_p solar energy installation where (a) solar production and electricity demand for a summer day and (b) solar production and electricity demand for a winter day [9].

This temporal mismatch has wider system implications beyond daily electricity balancing. In most temperate climates, the majority of PV electricity generation occurs during the summer months, while residential energy demand, driven largely by SH and DHW, peaks during winter [10]. As illustrated in Figure 1.2, this seasonal inversion results in substantial renewable energy surpluses in summer and high thermal energy demand in winter.

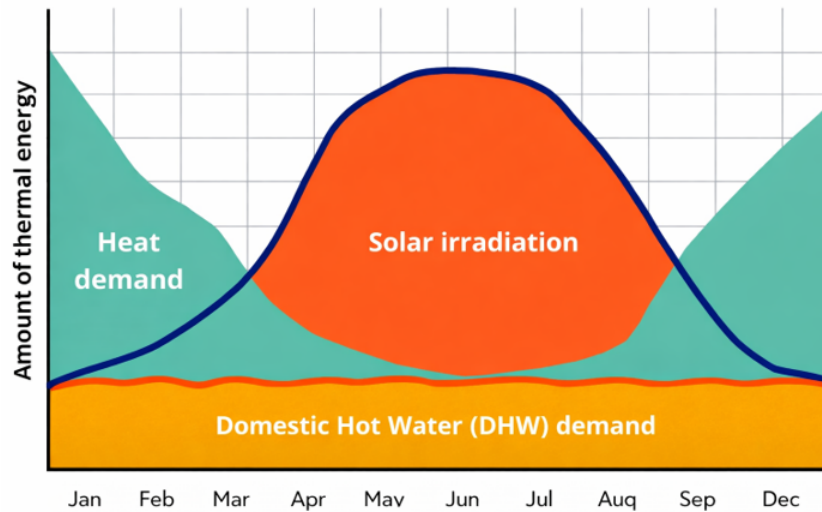


Figure 1.2: Relative solar output vs. heat demand [10]

Short-term storage technologies, such as household batteries, are insufficient to bridge this seasonal gap, as they are designed for intra-day balancing rather than long-term energy shifting. As a result, electrification of heating through heat pumps (HPs), while reducing direct fossil fuel use, can lead to high electricity demand peaks during winter periods when renewable generation is limited and the electricity mix is consequently more dependent on fossil-fuel generation. Addressing this challenge requires solutions that enable energy to be shifted from periods of renewable surplus to periods of high thermal demand, highlighting the importance of seasonal thermal energy storage.

These challenges underline that increasing renewable generation alone is not sufficient to achieve a resilient and efficient residential energy system. Instead, integrated solutions are required that address both the temporal mismatch between energy supply and demand and the limitations of existing electricity infrastructure.

1.1.1. Core Concept: Seasonal Electricity-to-Heat Conversion

One promising approach is the conversion of excess renewable electricity generated during summer into thermal energy that can be stored for use in winter. This concept is illustrated in Figure 1.3, which shows an integrated residential energy system combining solar energy generation, an HP, and seasonal thermal energy storage in the form of an aquifer thermal energy storage (ATES) system. During periods of high solar availability and low heat demand, electricity generated by PV or photovoltaic-thermal (PVT) collectors is used to operate an HP, which converts electrical energy into heat and stores it in the aquifer. During winter, the stored thermal energy can be recovered to supply SH and DHW demand, thereby reducing electricity consumption during peak periods.

Building upon this core configuration, additional solar technologies can further enhance system performance. Solar thermal (ST) collectors can provide direct thermal input to the storage system, while PVT collectors combine electricity generation with heat recovery, improving overall energy yield and supporting HP operation. These integrated system configurations and their interactions form the basis for the analysis conducted using the SOLSTICE model.

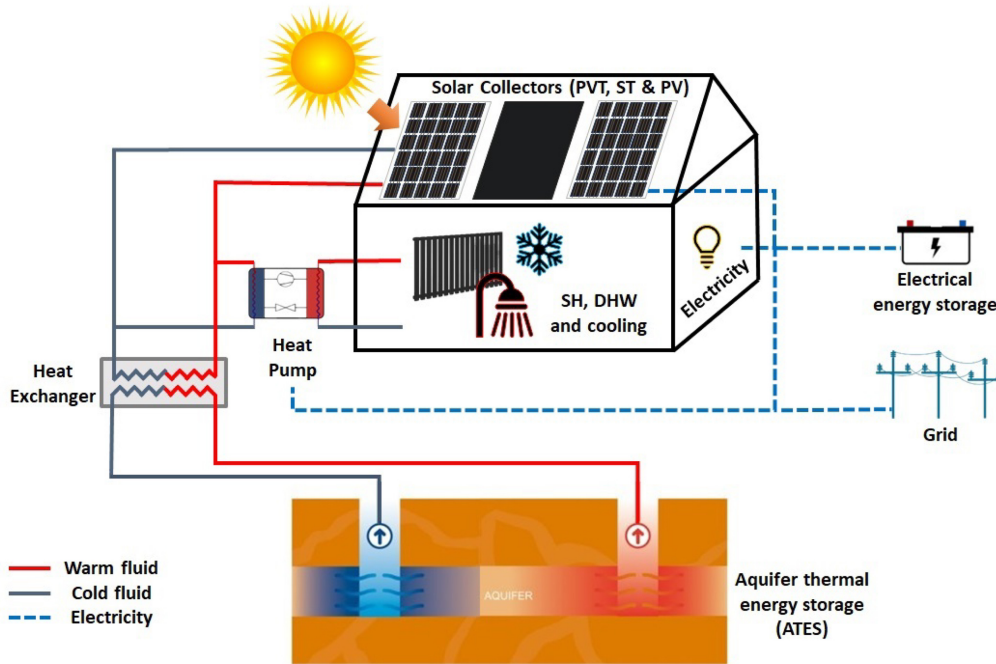


Figure 1.3: Schematic diagram of a solar system combined with solar collectors, a HP, an ATES, a heat exchanger and an electrical storage [11].

1.2. SOLSTICE

To analyse how combinations of renewable and storage technologies can improve the energy autonomy of households, the Solar Storage in Diverse Climates (SOLSTICE) model was developed by Pourbarghisofiyani [12] as a simplified, system-level decision-support tool. SOLSTICE is an Excel-based modelling framework designed for the early-stage evaluation of integrated residential energy systems across different climatic conditions. The model was intentionally developed with a focus on transparency, usability, and computational simplicity, making it accessible to users without specialised modelling expertise, such as policymakers and planners.

Within SOLSTICE, integrated residential energy systems are represented through a set of simplified component models that capture the dominant energy flows and interactions at system level. The model simulates hourly energy flows for a range of system configurations that may include PV modules, PVT collectors, ST collectors, HPs, household battery storage, and seasonal thermal energy storage in the form of ATES. By combining climate data, residential demand profiles, and simplified component representations, SOLSTICE provides insight into how electrical and thermal subsystems interact and how different technology combinations influence system performance and grid interaction. To clarify the structure of the SOLSTICE framework and the assumptions underlying its simulations, the following subsections briefly describe the main system components included in the model.

1.2.1. Photovoltaic Modules

PV modules convert incident solar irradiance directly into electrical energy through the photovoltaic (PV) effect in semiconductor solar cells. When photons with sufficient energy are absorbed by the solar cell, charge carriers are generated and separated by an internal electric field, resulting in a direct current (DC). This is converted to alternating current (AC) by an inverter before it can be used within the household or exported to the electricity grid. In residential energy systems, PV electricity can be consumed directly by household loads, used to operate an HP, stored in an electrical battery (EB), or fed back into the grid. A typical PV module consists of a series of interconnected solar cells encapsulated between protective layers of glass, encapsulant, and a backsheet, as illustrated in Figure 1.4.

Several PV cell technologies are commercially available, including monocrystalline silicon, polycrystalline silicon, and thin-film technologies. Among these, monocrystalline silicon (Mono-Si) modules dominate the residential market due to their high electrical efficiency, long operational lifetime, and steadily declining costs. Typical module-level electrical conversion efficiencies for modern Mono-Si PV modules range between 19% and 24% [13].

The electrical performance of PV modules is strongly influenced by operating temperature. As the cell temper-

ature increases, the open-circuit voltage decreases, leading to a reduction in electrical efficiency. For Mono-Si modules, this temperature dependence is commonly expressed by a temperature coefficient of approximately -0.35 to -0.45 $\%/^{\circ}\text{C}$ relative to standard test conditions [14]. During periods of high solar irradiance, PV modules can operate 20 – 40 $^{\circ}\text{C}$ above ambient temperature, resulting in a noticeable reduction in electrical output precisely when solar availability is highest.

Within the SOLSTICE model, PV modules are represented using a simplified performance model that accounts for solar irradiance and temperature-dependent efficiency. This approach captures the dominant effects of PV generation on household electricity supply and enables assessment of interactions with other system components, such as HPs, electrical storage, and seasonal thermal energy storage, without introducing unnecessary modelling complexity.

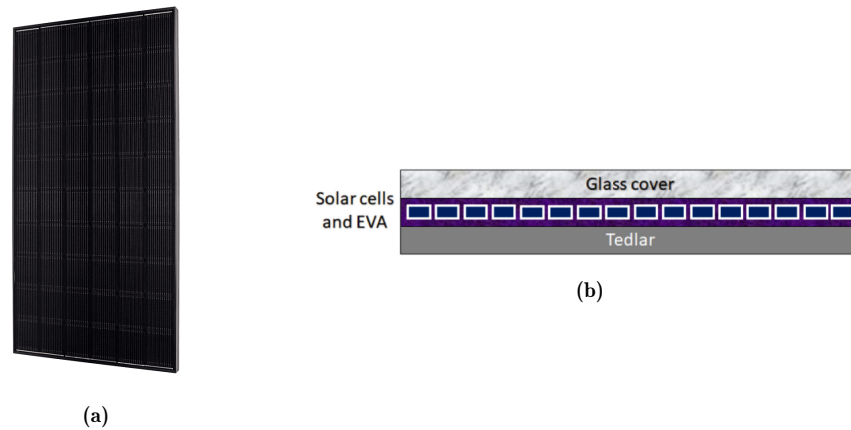


Figure 1.4: PV module examples: (a) photograph of a monocrystalline PV module [15] and (b) schematic overview of a PV module structure [11].

1.2.2. Solar Thermal Collectors

ST collectors convert incident solar radiation directly into thermal energy, which is transferred to a working fluid and can be used for DHW production, SH, or thermal storage [16]. In contrast to PV modules, which generate electricity, ST systems harvest solar energy in the form of heat and are therefore particularly relevant for residential applications where thermal demand represents a significant share of total energy use.

A typical ST collector is illustrated in Figure 1.5. It consists of an absorber that captures solar radiation, a heat transfer fluid that removes the generated heat, transparent glazing to reduce convective heat losses, and thermal insulation to limit heat transfer to the environment [17]. The absorber is often coated with a selective surface to maximise solar absorption while minimising thermal emission.

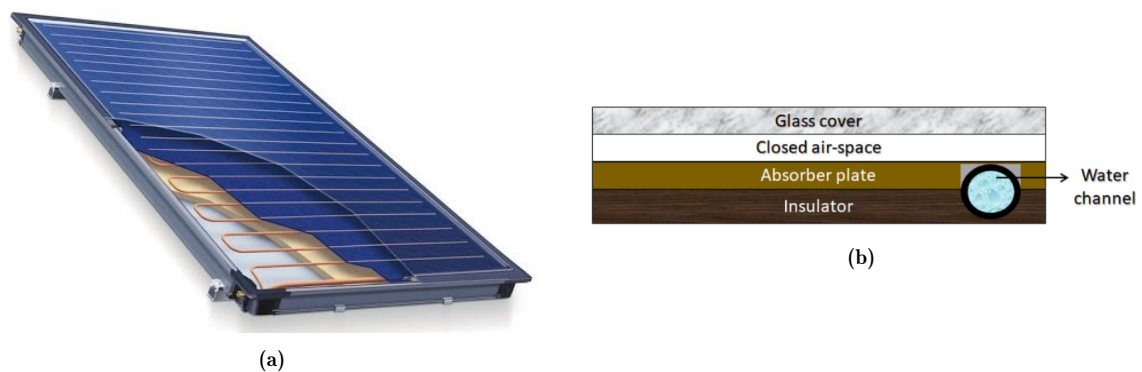


Figure 1.5: ST collectors: (a) example of flat-plate collector [18] and (b) schematic overview of an ST collector module [11].

Several types of ST collectors are commonly used in practice. Flat-plate collectors and evacuated tube collectors are non-concentrating designs that are well suited for low- to medium-temperature applications such as DHW

and SH [19]. Unglazed flat-plate collectors are typically applied in very low-temperature applications, such as swimming pool heating, while concentrating collectors can achieve much higher temperatures but are generally unsuitable for residential systems due to their complexity and tracking requirements.

The thermal performance of ST collectors is commonly described using an efficiency curve that relates collector efficiency to the reduced temperature difference, defined as $(T_m - T_a)/G$, where T_m is the mean fluid temperature, T_a the ambient air temperature, and G the incident solar irradiance. As the reduced temperature increases, thermal losses to the environment become more significant, resulting in a decrease in collector efficiency. Typical efficiency curves for different ST collector types are shown in Figure 1.6.

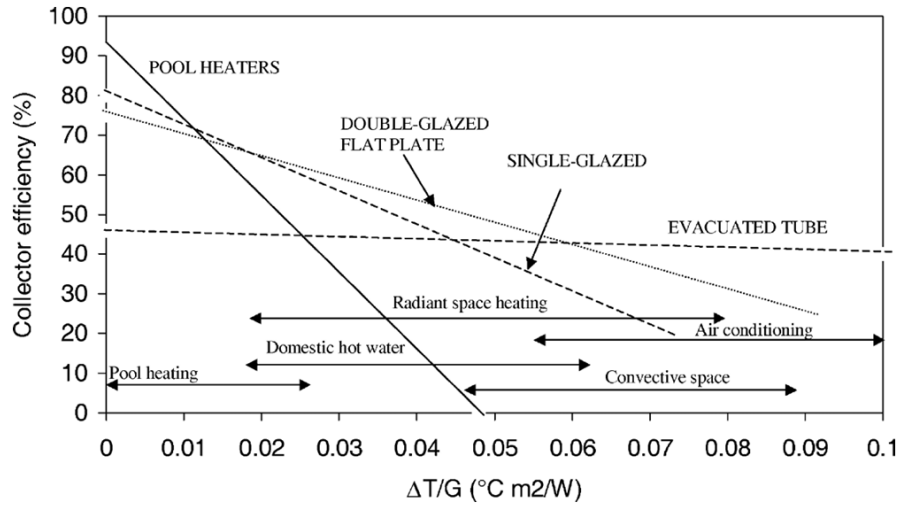


Figure 1.6: Typical thermal efficiency curves of different ST collector types as a function of reduced temperature difference $(T_m - T_a)/G$ [19].

Unglazed collectors exhibit high efficiency at very low reduced temperatures but suffer from large heat losses as operating temperature increases. Glazed flat-plate collectors maintain moderate efficiency over a wider temperature range, making them suitable for DHW and SH applications. Evacuated tube collectors benefit from reduced convective and conductive losses due to vacuum insulation and therefore retain higher efficiency at elevated reduced temperatures, enabling operation at higher fluid temperatures compared to flat-plate designs [17, 19].

1.2.3. Photovoltaic-thermal Collectors

A PVT collector combines a PV module and an ST module within a single device, as illustrated in Figure 1.7. In a PVT collector, the PV module is coupled to a thermal absorber located at the rear of the PV cells. While a conventional PV module converts only a fraction of the incident solar radiation into electricity, the remaining energy is largely dissipated as heat to the environment. PVT collectors recover this waste heat by transferring it to a working fluid, thereby producing electrical and thermal energy at the same time [20].

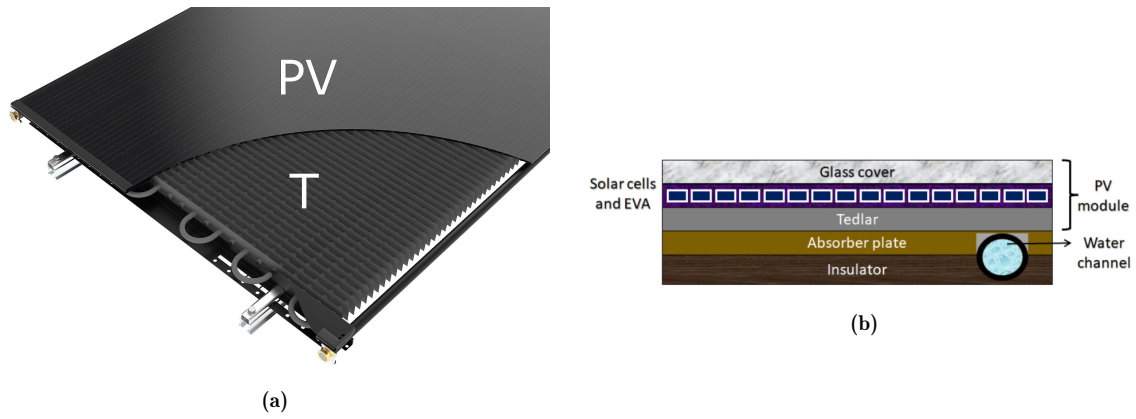


Figure 1.7: PVT modules: (a) example of a PVT module installation [21] and (b) schematic overview of a PVT module structure [11].

As discussed in Subsection 1.2.1, the electrical efficiency of PV modules decreases with high cell temperatures. By extracting heat from the rear of the PV module, PVT collectors can reduce the operating temperature of the cells under favourable conditions, leading to improved electrical performance [20, 22]. The extent of this cooling effect depends on factors such as irradiance level, fluid flow rate, inlet temperature, and system operation, and is therefore not constant over time. Nevertheless, the combined generation of electricity and useful heat results in a higher total energy yield per unit area compared to standalone PV or ST systems.

PVT collectors can be classified according to the type of working fluid used for heat extraction. Common configurations include air-based, liquid-based, and bi-fluid systems. Air-based PVT collectors are relatively simple and cost-effective, but generally exhibit lower thermal performance due to the low heat capacity and thermal conductivity of air, which limits heat transfer rates. Liquid-based PVT collectors, typically using water or water-glycol mixtures, provide higher and more stable thermal output, making them well suited for integration with HPs and thermal storage systems [23].

Most residential PVT systems employ flat-plate collector designs due to their structural simplicity and compatibility with rooftop installations. Flat-plate liquid PVT collectors typically operate at low to medium temperature levels, generally between 30 °C and 80 °C, depending on operating conditions and cooling strategy [22]. Compared to conventional ST collectors, PVT systems exhibit a reduced temperature rise per unit of absorbed solar energy, as part of the heat is continuously extracted to limit PV cell temperatures. Based on monitored data from twenty-eight PVT installations in France, Switzerland, and Portugal, the monthly average of the daily maximum collector outlet temperature exceeds 45 °C during approximately five months of the year, with an average maximum outlet temperature of around 65 °C [24]. These temperature levels are suitable for low-temperature SH systems and for use as a heat source for HPs.

In the context of integrated residential energy systems, PVT collectors are particularly attractive due to their high specific energy yield and efficient use of limited roof area. By delivering both electricity and heat from a single surface, PVT systems enable improved self-consumption of solar energy and facilitate seasonal energy storage when combined with technologies such as HPs and aquifer thermal energy storage. For these reasons, liquid-based flat-plate PVT collectors are considered the most suitable configuration for the system layouts investigated using the SOLSTICE model.

1.2.4. Heat Pump

HPs play a central role in the decarbonisation of residential energy systems by enabling the electrification of SH, DHW production, and space cooling. Instead of generating heat through combustion, a HP transfers thermal energy from a low-temperature heat source to a higher-temperature heat sink by consuming electrical energy. This process allows HPs to deliver several units of useful thermal energy per unit of electrical input, making them significantly more efficient than direct electric heating technologies [25].

A typical HP consists of four main components: an evaporator, a compressor, a condenser, and an expansion valve. In the evaporator, thermal energy is absorbed from the heat source, causing the refrigerant to evaporate. The compressor then raises the pressure and temperature of the refrigerant, after which heat is released to the heating system via the condenser. Finally, the expansion valve reduces the refrigerant pressure, completing the cycle [17]. An example of this process can be seen in Figure 1.8. HP performance is commonly expressed by the coefficient of performance (COP), defined as the ratio of useful heat output to electrical energy input.

Its theoretical maximum is described by the Carnot relation, which shows that performance increases as the temperature difference between source and sink decreases.

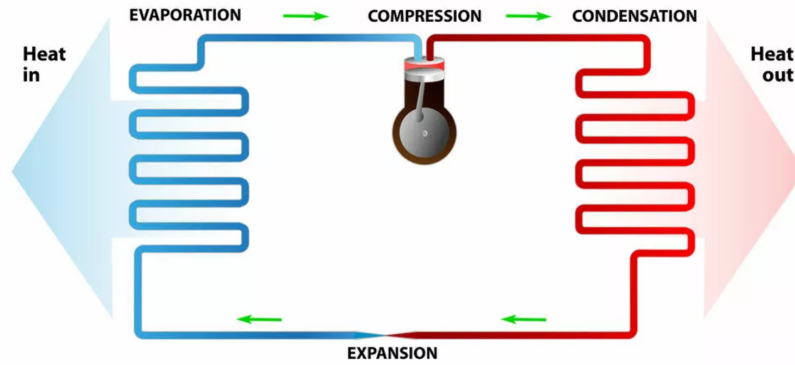


Figure 1.8: Diagram of the workings of a HP [26]

HPs can be classified according to their heat source. Air-source HPs extract heat from ambient air and are widely applied due to their low installation complexity. Ground-source HPs utilise subsurface temperatures, offering more stable operating conditions and higher seasonal efficiencies. Water-source HPs use groundwater or surface water as a heat source and can achieve particularly high performance when suitable resources are available [27]. The choice of heat source is therefore a key design parameter influencing system efficiency.

In integrated solar energy systems, HPs can be effectively combined with PV, ST, or PVT collectors. Electricity generated by PV or PVT modules can be used to operate the HP, increasing on-site consumption of renewable electricity. ST or PVT collectors can additionally serve as a low-temperature heat source, increasing the evaporator inlet temperature and thereby improving the HP COP [22]. This coupling is especially advantageous during summer, when solar electricity production is high and thermal demand is low, allowing excess energy to be converted into heat and stored in seasonal thermal energy storage systems for later use.

Within the SOLSTICE model, the HP functions as the primary interface between the electrical and thermal domains of the household energy system. It enables the conversion of surplus solar electricity into useful heat that can be supplied directly to the building or stored for later use in thermal storage systems such as aquifer thermal energy storage. By representing HP performance as a function of source and sink temperatures, SOLSTICE captures the influence of different heat sources, including ambient air, ST collectors, and PVT systems, while maintaining a level of model simplicity suitable for system-level analysis.

1.2.5. Home Battery

Home battery systems are commonly used in residential energy systems to store excess electricity generated by PV installations for short-term use. Their primary function is to increase on-site consumption of solar electricity by shifting surplus generation from midday to periods of higher household demand, such as the evening hours. In this way, batteries help reduce electricity export to the grid and improve household self-consumption rates.

Most residential battery systems are based on lithium-ion technology due to their high energy density, high round-trip efficiency, and declining costs. Typical home batteries have storage capacities in the range of a few kilowatt-hours, which makes them well suited for daily load shifting but insufficient for seasonal energy storage. A review by Luthander et al. [28] shows that residential battery capacities are commonly sized between 0.5 and 1 kWh per installed kilowatt of PV capacity, resulting in an increase in self-consumption of approximately 10-24%. As a result, batteries can mitigate short-term mismatches between electricity production and demand but cannot resolve the seasonal imbalance inherent to solar energy systems.

Within integrated solar energy systems, batteries complement other technologies such as HPs and thermal storage. While batteries address intra-day electricity balancing, thermal storage systems are required to manage longer-term energy shifts. This distinction is particularly important in residential systems aiming to maximise solar self-consumption without increasing grid congestion.

In the SOLSTICE model, the home battery is represented using a simplified energy balance approach. The battery charges when excess PV electricity is available and discharges when household demand exceeds local generation. This abstraction captures the primary system-level impact of battery storage on self-consumption and grid interaction, without introducing unnecessary modelling complexity.

1.2.6. Aquifer Thermal Energy Storage (ATES)

As discussed earlier in this chapter, the temporal mismatch between renewable energy supply and residential heat demand creates a strong need for seasonal thermal energy storage. Underground thermal energy storage (UTES) is widely considered a promising solution to this challenge, as it enables the storage of large amounts of thermal energy over extended periods with relatively low losses [29]. Compared to above-ground thermal storage tanks, UTES systems require significantly less surface space and are therefore particularly suitable for densely built urban environments.

ATES is a form of UTES that uses natural water-bearing geological formations to store thermal energy over long periods of time. An ATES system typically consists of a pair of wells: a warm well and a cold well. During periods of heat surplus, warm water is injected into the aquifer, while cold water is extracted and can be used directly for space cooling. Conversely, during periods of heat demand, stored thermal energy is extracted from the warm well and supplied to the energy system. An example of the basic working principle of ATES is shown in Figure 1.9. Due to the large storage volumes available underground and the relatively low thermal losses over seasonal timescales, ATES is particularly well suited for long-term seasonal heating and cooling applications [29].

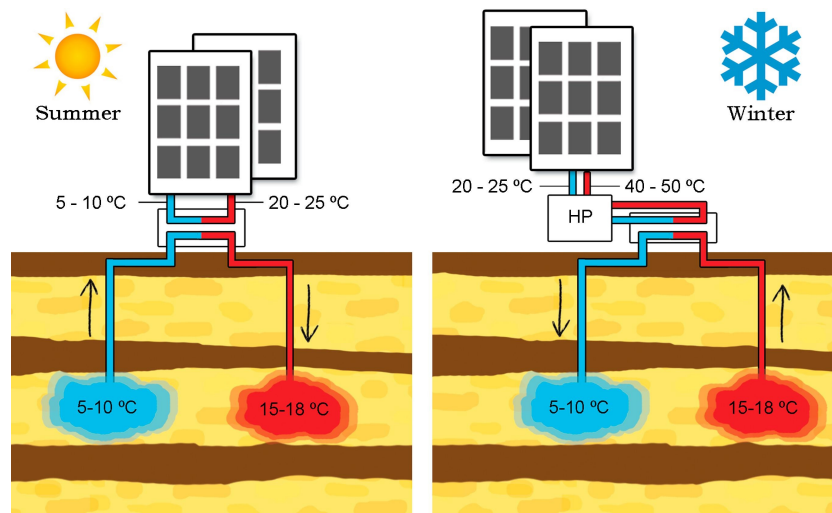


Figure 1.9: Working principle of ATES [30]

ATES systems are generally most effective when applied at a collective scale, serving multiple buildings or entire residential districts. Bloemendal et al. [31] show that ATES systems are often underutilised when deployed in isolation and argue that coordinated, district-scale operation leads to more efficient and sustainable use of the subsurface. This makes ATES especially attractive for neighbourhood-scale applications.

Depending on the operating temperature range, ATES systems can be classified as low-temperature (LT-ATES), medium-temperature (MT-ATES), or high-temperature (HT-ATES) systems. LT-ATES typically operates at temperatures below approximately 25 °C and is widely used for seasonal cooling and low-temperature heating applications, particularly in office buildings. MT-ATES operates in an intermediate temperature range, typically between 25 °C and 50 °C, although it is less commonly implemented in practice. HT-ATES systems operate at storage temperatures of approximately 50 °C or higher, with injection temperatures in the hot well typically ranging between 40 and 90 °C, and are capable of storing heat suitable for SH and DHW production [29, 32].

For residential energy systems with a high heat demand in winter, HT-ATES offers clear advantages over low- and medium-temperature storage concepts. While LT-ATES systems are well suited for seasonal cooling and low-temperature applications, their typical operating temperatures below 25 °C are insufficient to directly supply SH or DHW and therefore require a large temperature lift by HPs [31, 29]. As a result, the electricity demand of the HP remains high during winter operation. In contrast, HT-ATES can store heat at sufficiently high temperatures for direct use during the heating season, thereby avoiding HP operation whenever sufficient useful heat is available [29, 30]. This enables a shift from conventional demand-driven operation, in which the HP operates when heat is required, toward supply-driven operation, in which the HP operates primarily when surplus renewable electricity is available. When combined with PVT collectors and HPs, excess solar electricity generated during summer can therefore be converted into high-temperature thermal energy and stored in the aquifer for direct use during winter. This reduces winter electricity demand and alleviates stress

on the power grid, making HT-ATES a key enabling technology for seasonal energy balancing in solar-based residential systems.

Within the SOLSTICE model, HT-ATES is implemented as a seasonal thermal storage component that interacts with the HP and solar collectors. Excess thermal energy produced during summer operation is stored in the aquifer, while stored heat is extracted during winter to meet residential heat demand. The representation of HT-ATES in SOLSTICE is intentionally kept at a conceptual level, focusing on the main energy flows rather than detailed subsurface thermodynamics. This abstraction highlights the need for validation and further refinement before the model can be applied.

1.2.7. Energy System Configurations

Based on the components introduced in Section 1.2, several residential energy system configurations are analysed using the SOLSTICE model. These configurations represent different levels of system integration and are used to assess the impact of individual technologies and their combinations on residential energy performance.

- **HP:** A reference configuration in which a HP supplies residential heat demand without on-site electricity generation or storage.
- **HP + PV:** This configuration includes PV electricity generation, allowing part of the HP electricity demand to be supplied by on-site solar power.
- **HP + PV + EB:** An EB is added to increase self-consumption of PV electricity through short-term storage.
- **HP + PV + EB + HT-ATES:** HT-ATES is included to enable long-term shifting of thermal energy and to improve the temporal match between heat production and demand.
- **HP + PVT + EB + HT-ATES:** PVT collectors are used to provide both electricity and heat, strengthening the coupling between solar energy supply and HP operation.
- **PV + EB + ST + HT-ATES:** A configuration without an HP, in which PV electricity and ST collectors supply electrical and thermal demand supported by electrical and thermal storage.

Each configuration is modelled as a separate scenario within SOLSTICE. The detailed modelling approach, including energy flow assumptions and control strategies, is described in Chapter 3.

1.3. Research gap

Recent research has demonstrated the technical potential of integrated PV, PVT, HP, and ATES systems to address the seasonal mismatch between renewable energy supply and residential heat demand. While detailed simulation models provide valuable insights into component-level performance, their complexity often limits their use in early-stage system design and policy analysis.

To address this challenge, the SOLSTICE model was developed by Pourbarghisofiyani [12] as a simplified, system-level decision-support tool for analysing integrated residential energy systems. SOLSTICE was designed to enable transparent and user-friendly assessment of different technology combinations and climatic conditions, with a particular focus on accessibility for planners and policymakers rather than detailed component optimisation.

Although the SOLSTICE model provides a promising framework for early-stage system assessment, its simplified representation of complex system components has not yet been critically evaluated. In particular, the ability of the model to capture seasonal energy dynamics and to realistically represent HT-ATES remains uncertain. Given the strong influence of seasonal thermal storage on system performance, a systematic assessment of how such simplifications affect model outcomes is needed.

This thesis addresses these gaps by applying, improving, and critically evaluating the SOLSTICE model, with a particular focus on enhancing the realism of its representation of seasonal thermal energy storage. While maintaining the model's simplified and user-friendly structure, this work aims to refine key assumptions that influence system performance and decision-making outcomes. By analysing seasonal energy flows, system behaviour, and economic implications under different climatic conditions, the suitability of simplified system-level modelling for studying integrated solar-based residential energy systems is evaluated, and directions for further model refinement are identified.

1.4. Research Objectives

The main objective of this thesis is to **assess the performance of integrated residential energy systems combining photovoltaic or photovoltaic-thermal collectors, heat pump systems, electrical battery storage, and high temperature aquifer thermal energy storage across different climatic conditions using the SOLSTICE modelling framework**. The system configurations are evaluated in terms of annual and peak grid import and export, solar self-consumption, electrical self-sufficiency, HP electricity consumption and COP, operational electricity cost,

and HT-ATES cyclicity. Together, these indicators are used to assess how effectively each configuration utilises locally generated renewable energy and balances seasonal energy supply and demand.

In parallel, this thesis aims to critically evaluate and improve the SOLSTICE model itself while preserving its transparency and ease of use for non-technical stakeholders. To achieve these objectives, this work seeks to:

1. Assess the existing component models in SOLSTICE and adapt or develop them where necessary to improve their physical representation.
2. Integrate existing or newly developed component models into SOLSTICE V2 using hourly input data, defined system configurations, and rule-based operational modes.
3. Evaluate the integrated system under different climatic conditions and determine how selected design and operating parameters affect overall system performance.

1.5. Structure

This thesis is structured as follows. Chapter 2 presents the component modelling methodology used to assess the existing component models within SOLSTICE and introduces adapted or newly developed equations where necessary. Chapter 3 describes the system-level operation and simulation methodology of SOLSTICE V2, including the integrated system, hourly input data, system configurations, and rule-based operational modes. Chapter 4 presents and discusses the simulation results by evaluating the system configurations, component behaviour, integrated system operation, the influence of different climatic conditions, and the effects of selected design and operating parameters. Finally, Chapter 5 summarises the main conclusions and provides recommendations for further model development, validation, and research.

Component Modelling Methodology

This chapter describes the methodology used to assess and improve the component-level representations within the SOLSTICE model. As stated in Chapter 1, Research Objective 1 is to assess the existing component models in SOLSTICE and adapt or develop them where necessary to improve their physical representation. These improvements are introduced while preserving the transparency and ease of use of the model. The simplified component models implemented in SOLSTICE are therefore examined to determine whether they sufficiently capture the dominant physical behaviour relevant to the present study.

To achieve this, the original model representations of the main system components are first described and analysed. Their assumptions, governing equations, and interactions are then compared with insights from literature and with the physical requirements of the integrated system considered in this thesis. Where the original formulation is considered insufficient for a realistic representation of system behaviour, model adaptations are introduced. Where the existing representation is considered sufficiently suitable for the present study, it is retained. In this way, the chapter distinguishes clearly between existing SOLSTICE component models and the modifications or newly developed equations implemented in this work, while remaining consistent with the broader objective of improving the model only where necessary.

The chapter is structured as follows. Section 2.1 discusses the solar energy system components, including the existing PV, ST, and PVT representations and the newly developed irradiance model based on POA irradiance. Section 2.2 presents the HP model, first describing the original SOLSTICE formulation and subsequently the adapted model with separate source and sink temperatures for different thermal duties. Section 2.3 addresses the EB storage model, including the original idealised formulation and the adapted representation with charging and discharging efficiencies. Section 2.4 discusses the ATES model, beginning with the original SOLSTICE representation and then introducing the developed HT-ATES formulation with explicit hot- and cold-well temperatures and a recovery-efficiency constraint. Finally, Section 2.5 summarises the main findings of the component-level assessment and the resulting model improvements.

2.1. Solar energy system components

This section describes the modelling approach used for the solar energy components within the SOLSTICE framework, namely PV modules, ST collectors, and PVT collectors. Because the performance of all three components depends directly on the incident solar irradiance, the improved solar irradiance model is presented first. Subsequently, the existing PV, ST, and PVT component models are described together with their underlying assumptions. The existing equations for the solar component models presented in the following subsections correspond to the original SOLSTICE implementation developed by Pourbarghisofiyani [12].

In Subsection 2.1.1, the developed solar irradiance model is introduced, in which global horizontal irradiance is converted to POA irradiance. The existing PV model is then presented in Subsection 2.1.2, followed by the ST collector model in Subsection 2.1.3 and the PVT collector model in Subsection 2.1.4.

2.1.1. Solar irradiance model - developed

The baseline PV model implemented in the SOLSTICE framework computes electrical power generation directly from GHI. While this approach captures the primary dependency of PV output on solar availability, it neglects the influence of module tilt and orientation on the incident irradiance. As a result, seasonal and diurnal variations in PV yield are systematically misrepresented, particularly for non-horizontal installations.

To improve physical realism while preserving the accessibility of the Excel-based model, the PV formulation is extended to account for POA irradiance. This is achieved using a transposition approach that resolves the geometric relationship between the sun and the tilted module surface at each timestep. The components of POA irradiance considered in this model are illustrated in Figure 2.1.

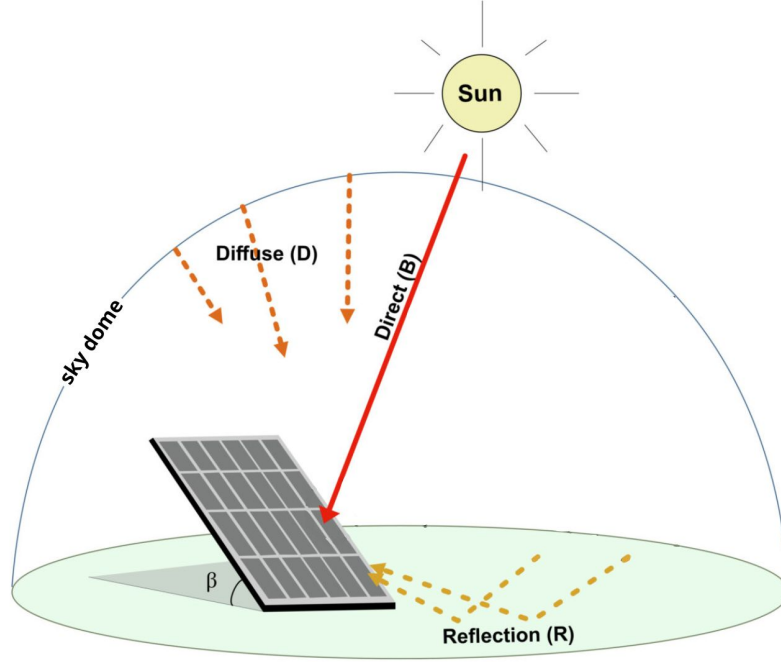


Figure 2.1: Schematic representation of the components of POA irradiance, including direct beam, diffuse radiation, and ground-reflected radiation on a tilted surface. Adapted from Applied Energy (KTH Royal Institute of Technology), CC BY 4.0.

Hourly irradiance data, including GHI, DNI, and DHI, are obtained from the Copernicus Atmosphere Monitoring Service (CAMS) radiation dataset [33]. Solar position parameters (solar elevation and azimuth) are calculated using the Solar Position Algorithm (SPA) developed by the National Renewable Energy Laboratory (NREL) [34].

In the improved formulation, the direct beam component incident on the tilted PV surface is calculated as:

$$G_{\text{beam,POA}} = \text{DNI} \max(0, \cos \theta_i), \quad (2.1)$$

where θ_i is the angle of incidence between the solar beam and the module surface normal. The angle of incidence is determined from the solar position and the module orientation (tilt and azimuth). The use of $\max(0, \cos \theta_i)$ ensures that only radiation incident on the front surface of the module contributes to the direct component.

The diffuse component on the tilted plane is estimated using the isotropic sky assumption:

$$G_{\text{diffuse,POA}} = \text{DHI} \frac{1 + \cos \beta}{2}, \quad (2.2)$$

where β is the module tilt angle.

Ground-reflected irradiance is included as:

$$G_{\text{ground,POA}} = \rho_g \text{GHI} \frac{1 - \cos \beta}{2}, \quad (2.3)$$

where ρ_g is the ground albedo, assumed constant.

The total POA irradiance is then obtained as:

$$G_{\text{POA}} = G_{\text{beam,POA}} + G_{\text{diffuse,POA}} + G_{\text{ground,POA}} \quad (2.4)$$

The POA irradiance is computed at hourly resolution in the SOLSTICE V2 workbook (POA-calculator sheet), where solar position and module orientation are evaluated for each timestep. This enables the model to capture the temporal variation of incident irradiance throughout the day and across seasons.

Alternatively, users may obtain location-specific POA irradiation data directly from the PVGIS tool [35], which provides precomputed irradiance values for optimally tilted PV systems. This offers a simplified input option when detailed irradiance decomposition and transposition are not required.

The computed G_{POA} replaces GHI in the PV power calculation (Equation 2.7), while the temperature-dependent efficiency formulation remains unchanged. This modification enables the model to account for the effects of module orientation and tilt on PV electricity generation, resulting in a more realistic representation of both diurnal and seasonal PV output.

The isotropic sky model is selected to balance model fidelity and transparency. Although more advanced transposition models exist, this approach provides a clear and computationally efficient improvement without introducing excessive complexity or additional data requirements. Remaining limitations include the neglect of circumsolar diffuse effects, detailed shading, and angle-of-incidence optical losses, which are considered acceptable within the scope of the present system-level analysis.

2.1.2. PV model -- existing

The PV module model implemented in the original SOLSTICE framework developed by Pourbarghisofiyani [12] represents electrical power generation using a simplified steady-state formulation that accounts for solar irradiance and temperature-dependent efficiency. In the original model, GHI was applied directly. In this work, the component equations are retained, but the irradiance input is replaced by the POA irradiance calculated using the model developed in Subsection 2.1.1. This adaptation allows module tilt and orientation to be represented while preserving the simplicity of the original PV model.

The PV module temperature is estimated using a linear heat balance between absorbed solar radiation and heat losses to the ambient environment. The module temperature T_m is calculated as:

$$T_m = T_{\text{amb}} + \frac{\alpha G_{\text{POA}}}{U_{\text{PV}}}, \quad (2.5)$$

where T_{amb} is the ambient air temperature, G_{POA} is the POA irradiance incident on the module surface, α is the effective solar absorption coefficient of the module, and U_{PV} is an overall heat-loss coefficient accounting for convective and radiative heat transfer to the surroundings. The equation represents a steady-state heat balance and therefore does not account for the transient thermal capacitance of the module.

The electrical efficiency of the PV module is corrected for operating temperature using a linear temperature coefficient:

$$\eta_{\text{PV}} = \eta_{\text{ref}} (1 + \gamma (T_m - 25)), \quad (2.6)$$

where η_{ref} is the reference efficiency at a module temperature of 25 °C and γ is the temperature coefficient of electrical efficiency. The value of $\gamma = -0.003 \text{ K}^{-1}$ is taken as a default representative for monocrystalline silicon PV modules, which are assumed in the present model.

The instantaneous electrical power output of the PV array is calculated as:

$$P_{\text{PV}} = G_{\text{POA}} A_{\text{PV}} \eta_{\text{PV}}, \quad (2.7)$$

where A_{PV} is the total PV module area. The PV power output is therefore directly coupled to ambient conditions through the intermediate estimation of module temperature. The module area is a user-defined input parameter and can be adjusted depending on the selected system configuration or case study. The parameter values used in the solar component models are summarised in Table 2.1.

Several simplifying assumptions are inherent to this PV model. The main limitations of the PV model are:

- convective and radiative heat transfer are combined into the constant overall heat-loss coefficient U_{PV} ;
- shading, angle-of-incidence losses, and spectral effects are neglected;
- inverter, cabling, and partial-load electrical losses are not modelled explicitly.

Table 2.1: Overview of parameters used in the solar energy component models

Component	Parameter	Description	Value
PV	A_{PV}	PV module area	25*
	η_{ref}	Reference efficiency at 25°C	0.20
	γ	Temperature coefficient (Mono-Si)	-0.003 K ⁻¹
	α	Absorption coefficient	0.7
	U	Heat loss coefficient	20 W/m ² K
ST	A_{ST}	Collector area	25*
	$\eta_{0,ST}$	Zero-loss optical efficiency (y-intercept)	0.757
	$a_{1,ST}$	Linear heat-loss coefficient (slope parameter)	1.553 W/m ² K
	T_{house}	Indoor temperature	20°C*
	$\Delta T_{inside,heating}$	Heating offset	70 K*
PVT	A_{PVT}	PVT collector area	25*
	α	Absorption coefficient	same as PV
	U_{PVT}	Heat loss coefficient	15 W/m ² K
	ΔT_{PVT}	Module–fluid temperature difference	5 K

* User-defined input parameter. The value shown corresponds to the reference case and can be adapted to the selected system design and operating conditions.

Despite these simplifications, the model captures the primary dependence of PV electricity generation on irradiance level and operating temperature, which is sufficient for system-level analysis within the integrated SOLSTICE framework.

2.1.3. ST collector model -- existing

The ST collector model implemented in the original SOLSTICE framework represents thermal energy generation using a simplified steady-state formulation based on incident solar irradiance and a linear heat-loss term. The objective of this model is to capture the dominant contribution of ST collectors to the system heat supply at hourly resolution while maintaining low computational complexity suitable for system-level simulations. For a general illustration of an ST collector and its physical structure, Figure 1.5 in Chapter 1 was already introduced.

The instantaneous thermal power output of the ST collector is calculated using a first-order collector efficiency model in which only linear thermal losses are included:

$$P_{ST} = \max [A_{ST} (\eta_{0,ST} G_{POA} - a_{1,ST} (T_{op} - T_{amb})), 0], \quad (2.8)$$

where A_{ST} is the collector area, G_{POA} is the POA irradiance incident on the collector surface, T_{op} is the assumed collector operating temperature, and T_{amb} is the ambient air temperature. As illustrated by the thermal-efficiency curves in Figure 1.6, $\eta_{0,ST}$ represents the y-intercept of the collector efficiency curve, corresponding to the zero-loss optical efficiency, while $a_{1,ST}$ determines its negative slope and therefore represents the linear heat-loss coefficient. The parameters and representative values used in the ST collector model are summarised in Table 2.1. The $\max(\cdot, 0)$ operator ensures that negative heat production is avoided under unfavourable operating conditions.

In the original SOLSTICE implementation, the collector operating temperature is not calculated dynamically from fluid flow or storage conditions. Instead, it is approximated using the required heating supply temperature in the system. This is expressed as:

$$T_{op} = T_{house} + \Delta T_{inside,heating}, \quad (2.9)$$

where T_{house} is the indoor or house temperature and $\Delta T_{inside,heating}$ is a fixed temperature offset representing the temperature lift required for useful heating delivery.

The hourly thermal energy supplied by the ST collector is then obtained by converting the thermal power output to energy over the one-hour timestep:

$$E_{ST,supply} = \frac{P_{ST}}{1000}, \quad (2.10)$$

where $E_{ST, \text{supply}}$ is expressed in kWh_{th} for an hourly timestep.

The main assumptions and limitations of the ST collector model are:

- the collector is represented by a steady-state energy balance, so thermal mass effects are neglected;
- the collector operating temperature is prescribed rather than calculated from collector inlet and outlet temperatures, mass flow rate, or buffer storage conditions;
- only a first-order heat-loss term is included, while second-order losses are neglected;
- hydraulic losses, pump electricity demand, and heat losses in connecting pipes are not included.

Despite these simplifications, the model captures the first-order dependence of ST output on irradiance level, ambient temperature, and required operating temperature. This makes it suitable for the system-level analyses performed in the original SOLSTICE framework, but it provides only a simplified representation of actual collector behaviour.

2.1.4. PVT collector model -- existing

The PVT collector model implemented in the original SOLSTICE framework by Pourbarghisofiyani [12] extends the PV formulation described in Section 2.1.2 by incorporating thermal energy extraction from the module. The electrical performance is therefore evaluated using the same temperature-dependent efficiency relation (Equation 2.6) and power calculation (Equation 2.7) as for the PV model. Consequently, the distinction between PV and PVT operation lies primarily in the determination of the module temperature. The general configuration of a PVT collector was introduced in Figure 1.7 in Chapter 1.

In contrast to the standalone PV model, for which the module temperature is calculated using Equation 2.5, the PVT module temperature is reduced by heat extraction through the circulating fluid. In the original SOLSTICE formulation, this effect is represented by modifying the module heat balance as:

$$T_{m, \text{PVT}} = T_{\text{amb}} + \frac{\alpha G_{\text{POA}} - q_{\text{cool}}}{U_{\text{PVT}}}, \quad (2.11)$$

where T_{amb} is the ambient air temperature, α is the effective solar absorption coefficient, G_{POA} is the POA irradiance incident on the collector surface, U_{PVT} is the overall heat-loss coefficient, and q_{cool} is the cooling heat flux extracted from the collector. The original SOLSTICE model used GHI as its irradiance input, whereas the present implementation uses the calculated POA irradiance.

The cooling heat flux is written as:

$$q_{\text{cool}} = \frac{P_{\text{surplus}} (\text{COP} - 1)}{A_{\text{PVT}}}, \quad (2.12)$$

where P_{surplus} is the available surplus electrical power supplied to the HP, COP is the corresponding COP, and A_{PVT} is the PVT collector area. The term $P_{\text{surplus}} (\text{COP} - 1)$ represents the source-side heat absorbed by the HP, corresponding to the part of the delivered thermal power that is extracted from the PVT collector rather than supplied electrically. Dividing by A_{PVT} expresses this heat extraction as a cooling heat flux acting on the module surface.

The thermal output of the PVT collector is therefore determined by operation of the HP, rather than by an independently prescribed fluid mass flow or collector outlet temperature. This is consistent with the supply-driven operation of the integrated system, in which surplus solar electricity operates the HP and thereby determines the amount of heat extracted from the collector.

In the original formulation, the temperature of the PVT fluid supplied to the source side of the HP is calculated using a constant module-to-fluid temperature difference:

$$T_{\text{source, PVT}} = T_{m, \text{PVT}} - \Delta T_{\text{PVT}}, \quad (2.13)$$

where ΔT_{PVT} is assumed constant. The corresponding COP is calculated using the existing HP formulation presented in Equation 2.17. Because the source temperature affects the COP, while the COP determines the cooling heat flux, the PVT and HP calculations are coupled. The fixed temperature difference does not, however, account for variations in the heat-extraction rate or the internal heat transfer between the module and the working fluid. The source-temperature relation was therefore adapted in this work.

2.1.5. PVT collector model -- adapted

The adapted PVT formulation extends the source-side heat-extraction term of the original model to account for the different active HP duties. In the original formulation, this heat extraction was represented by the cooling heat flux in Equation 2.12. In the adapted model, this term is replaced by the total source-side thermal power extracted from the PVT collector, calculated by summing the heat requirement of each active HP duty:

$$\dot{Q}_{\text{src,PVT}} = \sum_i P_{\text{HP},i} (\text{COP}_i - 1), \quad (2.14)$$

where $P_{\text{HP},i}$ is the electrical power consumed by the HP for thermal duty i , and COP_i is the corresponding COP. The considered duties include SH, DHW, and HT-ATES charging. The duty-specific COP values are calculated using the adapted HP formulation presented in Equation 2.23.

The adapted PVT module temperature is subsequently calculated as:

$$T_{\text{m,PVT}} = T_{\text{amb}} + \frac{\alpha G_{\text{POA}} - \dot{Q}_{\text{src,PVT}}/A_{\text{PVT}}}{U_{\text{PVT}}}, \quad (2.15)$$

where $\dot{Q}_{\text{src,PVT}}/A_{\text{PVT}}$ represents the source-side thermal power extracted per unit collector area. In addition to this duty-specific representation of heat extraction, the original constant module-to-fluid temperature difference in Equation 2.13 is replaced by a heat-extraction-dependent temperature difference. The temperature of the fluid supplied by the PVT collector to the source side of the HP is therefore calculated as:

$$T_{\text{source,PVT}} = T_{\text{m,PVT}} - \min \left(\frac{\dot{Q}_{\text{src,PVT}}}{A_{\text{PVT}} h_{\text{int}}}, \Delta T_{\text{PVT,max}} \right), \quad (2.16)$$

where h_{int} is the effective internal heat-transfer coefficient between the module and the working fluid, and $\Delta T_{\text{PVT,max}}$ is the maximum permitted module-to-fluid temperature difference. Values of $h_{\text{int}} = 50 \text{ W m}^{-2} \text{ K}^{-1}$ and $\Delta T_{\text{PVT,max}} = 5 \text{ K}$ are applied. The temperature difference therefore increases at high heat-extraction rates, while the upper limit prevents unrealistically large module-to-fluid temperature differences at high extraction rates.

The main assumptions and limitations of the adapted PVT collector model are:

- the collector is represented using a steady-state energy balance, so its thermal mass and sub-hourly temperature dynamics are not resolved;
- the thermal output of the PVT collector is determined by the source-side heat requirement of the HP, rather than by an independently modelled fluid mass flow or collector-control strategy;
- internal module-to-fluid heat transfer is represented by the lumped coefficient h_{int} and a maximum temperature difference, rather than by a detailed hydraulic and thermal collector model;
- fluid-pumping electricity, pressure losses, pipework heat losses, and detailed fluid-temperature dynamics are not modelled explicitly.

Despite these simplifications, the adapted formulation captures the main interaction between PVT cooling, electrical efficiency, HP source temperature, and source-side heat extraction while retaining the transparent structure required for the system-level SOLSTICE model.

2.2. Heat pump model -- existing

In the SOLSTICE framework, the heat pump (HP) is represented as a quasisteady-state energy converter that upgrades heat from a low-temperature source to a higher-temperature sink using electrical input. A schematic overview of the working principle of a HP was already shown in Figure 1.8 in Chapter 1. The model does not resolve detailed thermodynamic cycle states, part-load behaviour, or capacity constraints. Instead, the performance is described using a Carnot-based coefficient of performance (COP), which depends on the temperature lift between the source and sink. The structure of the existing HP model as implemented in SOLSTICE is illustrated in Figure 2.2. The equations presented below correspond to the original SOLSTICE implementation by Pourbarghisofiyani [12].

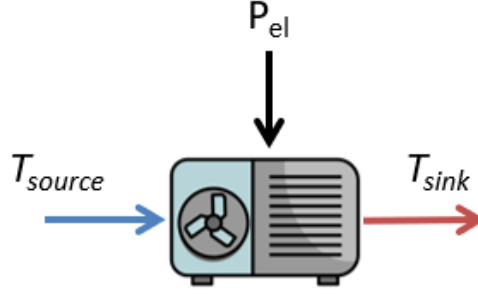


Figure 2.2: Simplified representation of the existing HP model in SOLSTICE, showing the electrical input, a single effective source temperature, and a single effective sink temperature used to determine the COP.

The COP is calculated as:

$$COP = \eta_{hp} \frac{T_{sink,K}}{\Delta T_{lift}}, \quad (2.17)$$

where $T_{sink,K}$ is the sink temperature in Kelvin and η_{hp} is an efficiency factor representing deviations from ideal Carnot performance. The effective temperature lift is defined as:

$$\Delta T_{lift} = \max(T_{sink} - T_{source}, \Delta T_{min}), \quad (2.18)$$

where T_{source} and T_{sink} are expressed in degrees Celsius and ΔT_{min} is a minimum temperature difference imposed to prevent unrealistically high COP values at small temperature lifts.

Depending on the system configuration, the source temperature may be provided by ambient air, the PVT collector, or the ATES system, while the sink temperature corresponds to the required supply temperature for SH and DHW.

The electrical input required to meet the heating demand is calculated as:

$$P_{el,heat} = \frac{\dot{Q}_{SH} + \dot{Q}_{DHW}}{COP}, \quad (2.19)$$

where $\dot{Q}_{SH}$ and $\dot{Q}_{DHW}$ represent the SH and DHW demands, respectively.

Cooling operation is represented using the same COP formulation, but with source and sink temperatures defined according to the cooling configuration. In this case, heat is removed from the building and rejected to a lower-temperature sink such as ambient air or the ATES system. The cooling COP is calculated directly from the corresponding temperatures and is not derived from the heating COP.

Several simplifying assumptions are inherent to the HP model:

- the HP is represented using a steady-state formulation at hourly resolution, so transient effects are neglected;
- the COP is based on a simplified Carnot relation using one effective source temperature and one effective sink temperature;
- no explicit limits are imposed on HP capacity or part-load performance;
- auxiliary electricity consumption, such as pumping or control losses, is not modelled explicitly and is assumed to be included implicitly in the efficiency factor η_{hp} ;
- the model does not resolve detailed thermodynamic cycle states of the refrigerant.

Despite these simplifications, the model captures the primary dependence of HP performance on temperature lift, which is the dominant factor governing system behaviour in the SOLSTICE framework.

2.2.1. Heat pump model -- adapted

The original HP model in the SOLSTICE framework represents the HP using a single sink temperature for all operating conditions. In this formulation, the COP is determined from one source and one sink temperature, after which the required electrical input is calculated from the aggregated thermal demand. While this approach is transparent and computationally efficient, it does not reflect that different thermal streams, such as SH, DHW, and HT-ATES charging, operate at different temperature levels. As the COP is highly sensitive to the temperature lift, this simplification may lead to inaccuracies in the estimation of electrical consumption and system performance.

To improve the physical consistency of the model, the HP formulation is extended such that separate source and sink temperatures are assigned to each thermal stream. The adapted model distinguishes between three HP duties: SH, DHW, and HT-ATES charging. For each duty i , an effective source temperature and an effective sink temperature are defined, from which an individual temperature lift and COP are calculated. In this representation, T_{source} denotes the temperature of the active heat source selected by the system configuration, while T_{sink} denotes the temperature level required by the thermal duty under consideration.

The source temperature is selected through configuration-dependent logic implemented in the Excel model. In the PV-based configurations, ambient air is used as the heat source. In the PVT-based configuration, the fluid outlet temperature of the PVT collector is used. Because the PVT source temperature and HP COP are mutually dependent, the source temperature calculated during the preceding hour is used after the initial timestep to avoid a direct same-hour circular dependency. When this calculated source temperature falls below 0 °C, the HP switches to an auxiliary cold-water source at 2 °C, and heat extraction from the PVT collector is disabled during that hour. The HT-ATES cold well is therefore not used as a HP source in the configurations assessed in this thesis. The structure of the adapted HP model is illustrated in Figure 2.3.

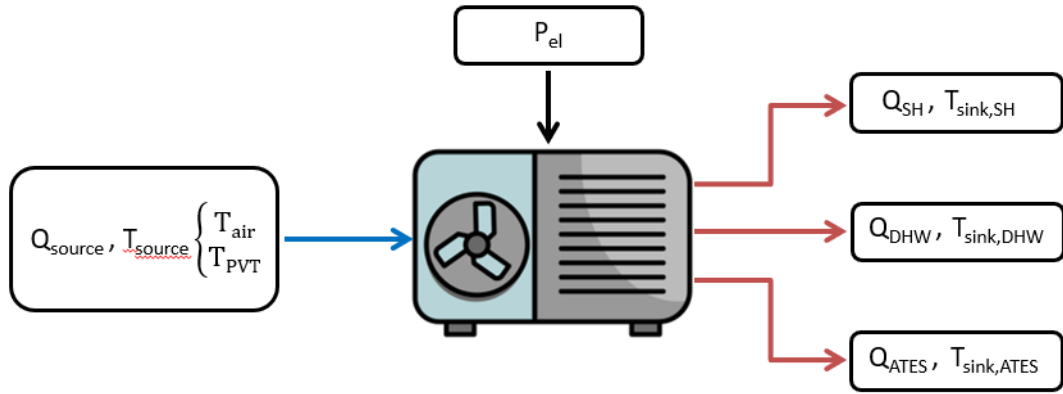


Figure 2.3: Schematic representation of the adapted HP model, showing the electrical input, configuration-dependent heat source, and multiple thermal sinks. Ambient air is used in the PV-based configurations, while the PVT fluid loop is used in the PVT-based configuration. The sink temperatures correspond to SH, DHW, and HT-ATES charging.

The effective sink temperature is given by:

$$T_{\text{sink,eff},i} = T_{\text{sink},i} + \Delta T_{\text{sink}}, \quad (2.20)$$

where $T_{\text{sink},i}$ is the nominal sink temperature and ΔT_{sink} represents the temperature difference between the delivered heat and the effective condensation temperature. A fixed sink-side offset of 5 K is applied to all three heating duties.

The effective source temperature is defined as:

$$T_{\text{source,eff},i} = T_{\text{source},i} - \Delta T_{\text{source}}, \quad (2.21)$$

where $T_{\text{source},i}$ is the selected source temperature and ΔT_{source} accounts for the temperature difference between the external source and the effective evaporator temperature. A source-side offset of 8 K is applied during air-source operation, whereas an offset of 4 K is used during PVT-coupled water-source operation. The temperature levels and offsets used in the adapted HP model are summarised in Table 2.2.

Table 2.2: Overview of temperature parameters used in the adapted HP model

Parameter	Description	Applied value
$T_{\text{sink,SH}}$	SH supply temperature	40 °C
$T_{\text{sink,DHW}}$	DHW temperature	60 °C
$T_{\text{sink,HTATES}}$	HT-ATES charging temperature	90 °C
$T_{\text{source,air}}$	Ambient-air source temperature	T_{amb}
$T_{\text{source,PVT}}$	PVT fluid outlet temperature	$T_{\text{source,PVT},t-1}$
$T_{\text{source,fallback}}$	Auxiliary cold-water source	2 °C
ΔT_{sink}	Sink-side temperature offset	5 K
$\Delta T_{\text{source,air}}$	Air-source temperature offset	8 K
$\Delta T_{\text{source,PVT}}$	Water-source temperature offset	4 K
ΔT_{min}	Minimum temperature lift	15 K

For each duty i , the effective temperature lift is calculated as:

$$\Delta T_{\text{lift},i} = \max(T_{\text{sink,eff},i} - T_{\text{source,eff},i}, \Delta T_{\text{min}}), \quad (2.22)$$

where a minimum temperature lift of 15 K prevents unrealistically high COP values when the source and sink temperatures approach each other.

The COP is then obtained using:

$$\text{COP}_i = \eta_{\text{hp}} \frac{T_{\text{sink,eff},K,i}}{\Delta T_{\text{lift},i}}, \quad (2.23)$$

where $T_{\text{sink,eff},i}$ is converted to Kelvin, consistent with the Carnot-based COP formulation. After determining the COP for each duty, the total electrical input is calculated as:

$$P_{\text{el,HP}} = \frac{\dot{Q}_{\text{SH}}}{\text{COP}_{\text{SH}}} + \frac{\dot{Q}_{\text{DHW}}}{\text{COP}_{\text{DHW}}} + \frac{\dot{Q}_{\text{HTATES}}}{\text{COP}_{\text{HTATES}}}. \quad (2.24)$$

This formulation captures the influence of different temperature levels and heat sources on HP performance while maintaining the simplified steady-state structure of the original SOLSTICE model.

Despite this improvement, part-load behaviour, transient effects, HP capacity constraints, and defrost cycles are not modelled. Furthermore, the source- and sink-side offsets are represented by fixed values rather than being derived from detailed heat-exchanger or thermodynamic-cycle calculations.

2.3. Electrical battery storage model -- existing

EB storage in the SOLSTICE framework is represented using a simplified energy balance that tracks the stored battery energy based on hourly charging and discharging at the household level. The model is intended to capture the primary effect of short-term electrical storage on self-consumption and grid interaction, while remaining computationally efficient and transparent for Excel-based implementation.

In the original SOLSTICE formulation, the EB is represented as an ideal, lossless storage system. This existing formulation is based on the original SOLSTICE implementation by Pourbarghisofiyani [12]. As a result, no charging, discharging, or round-trip efficiency losses are included. The stored battery energy is updated at each timestep using a direct energy balance:

$$E_{\text{bat},t+1} = E_{\text{bat},t} + E_{\text{ch},t} - E_{\text{dis},t}, \quad (2.25)$$

where $E_{\text{bat},t}$ is the electrical energy stored in the EB at timestep t , and $E_{\text{ch},t}$ and $E_{\text{dis},t}$ are the electrical energies charged to and discharged from the battery during timestep t , respectively. Because the original formulation assumes lossless storage, all charging energy is added to the stored-energy inventory, while the energy withdrawn from the battery is equal to the useful electricity delivered to the system.

The stored battery energy is constrained by the nominal storage capacity:

$$0 \leq E_{\text{bat},t} \leq E_{\text{bat},\text{max}}, \quad (2.26)$$

where $E_{\text{bat},\text{max}}$ is the nominal energy capacity of the EB.

Battery operation is governed by the instantaneous electrical balance of the system. When on-site electricity generation exceeds demand, the resulting surplus electricity is used to charge the EB, subject to the available storage capacity. Conversely, when demand exceeds generation, the EB is discharged to cover part of the deficit, limited by the electrical energy available in the battery. Charging and discharging are mutually exclusive within each timestep, and no optimisation with respect to electricity prices or forecast information is implemented. The operational logic of the EB, including charging during surplus conditions and discharging during periods of deficit, is illustrated in Figure 2.4.

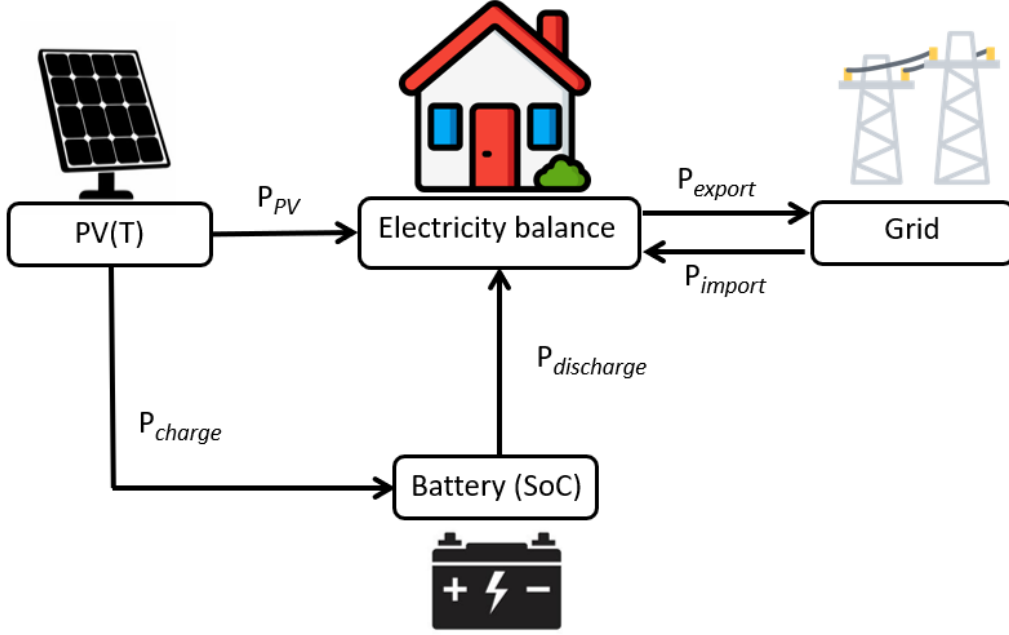


Figure 2.4: Schematic representation of the battery model within the SOLSTICE framework. Electricity generated by the PV system is first used to meet household demand. Surplus electricity is directed to the EB for charging, while electricity deficits are covered by battery discharge or grid import.

The interaction with the grid is handled at the system level. After battery charging or discharging has been determined, any remaining electricity surplus or deficit is exchanged with the grid or allocated to other system components, such as the HP or thermal storage.

Several simplifying assumptions are inherent to this representation:

- the EB is represented as an ideal storage system without efficiency losses in the original formulation;
- battery degradation and self-discharge are neglected;
- charging and discharging power limits and dynamic response are not included;
- the EB is assumed to respond instantaneously within each hourly timestep;
- no optimisation with respect to electricity prices, forecasting, or control strategy is implemented.

Despite these simplifications, the model captures the dominant influence of short-term electrical storage on household electricity flows within the integrated SOLSTICE framework.

2.3.1. Electrical battery storage model -- adapted

Although the original SOLSTICE battery model is suitable for first-order system analysis, the assumption of lossless storage is not physically realistic. In practice, electrical batteries exhibit losses during charging and discharging, resulting in a round-trip efficiency below unity. To improve the physical realism of the model, the battery formulation is therefore adapted to include these losses through the round-trip efficiency.

The stored battery energy is updated according to:

$$E_{\text{bat},t+1} = E_{\text{bat},t} + \sqrt{\eta_{\text{rt}}} E_{\text{ch},t} - \frac{E_{\text{dis},t}}{\sqrt{\eta_{\text{rt}}}}, \quad (2.27)$$

where $E_{\text{bat},t}$ is the electrical energy stored in the EB at timestep t , $E_{\text{ch},t}$ is the electricity supplied to the battery for charging, $E_{\text{dis},t}$ is the useful electricity delivered from the battery to the system, and η_{rt} is the battery round-trip efficiency. A round-trip efficiency of $\eta_{\text{rt}} = 0.90$ is assumed.

The storage-capacity constraint given in Equation 2.26 remains unchanged, and the charging and discharging logic is identical to that of the original model. The adaptation therefore affects only the stored-energy balance and the associated storage losses, while preserving the overall control structure of the SOLSTICE framework.

This modification improves the realism of the EB representation without substantially increasing model complexity. At the same time, the model remains simplified, as self-discharge, degradation, temperature effects, power limits, and power-dependent efficiency variations are still neglected.

2.4. HT-ATES model -- existing

Seasonal thermal energy storage in the SOLSTICE framework is represented as an aquifer thermal energy storage (ATES) “thermal battery” that shifts surplus summer energy to periods of winter heat demand. In line with the simplified modelling philosophy of SOLSTICE, the ATES is not represented using explicit groundwater flow, thermal stratification, or heat losses to the surrounding geology. Instead, the storage is modelled as a single hourly energy buffer with an imposed round-trip efficiency. The equations presented below correspond to the original SOLSTICE implementation developed by Pourbarghisofiyani [12].

In configurations that include ATES, surplus electrical power remaining after meeting the instantaneous electrical demand and battery charging is converted into thermal energy by operating the HP in a supply-driven mode. The corresponding thermal energy supplied by the HP during a one-hour time step is calculated as:

$$E_{\text{HP},\text{supply}} = P_{\text{surplus}} \text{COP}, \quad (2.28)$$

where P_{surplus} is the available electrical surplus power and COP is the coefficient of performance of the HP. For the PVT configuration, this COP is calculated hourly, while in simpler configurations it is prescribed or fixed.

The hourly thermal demand is defined as the sum of the SH and DHW demands:

$$E_{\text{heat},\text{dem}} = Q_{\text{SH}} + Q_{\text{DHW}}, \quad (2.29)$$

where Q_{SH} and Q_{DHW} are the thermal demands. At each time step, the model compares $E_{\text{HP},\text{supply}}$ and $E_{\text{heat},\text{dem}}$ to determine whether the ATES is charged or discharged.

Storage losses are represented through a round-trip efficiency η_{heat} , which is applied symmetrically to charging and discharging by using $\sqrt{\eta_{\text{heat}}}$. The effective energy added to storage is given by:

$$E_{\text{add}} = \sqrt{\eta_{\text{heat}}} \max(E_{\text{HP},\text{supply}} - E_{\text{heat},\text{dem}}, 0) \quad (2.30)$$

and the effective energy extracted from storage is:

$$E_{\text{extract}} = \frac{\max(E_{\text{heat},\text{dem}} - E_{\text{HP},\text{supply}}, 0)}{\sqrt{\eta_{\text{heat}}}} \quad (2.31)$$

The state of charge of the ATES is tracked as stored thermal energy and updated hourly according to:

$$E_{\text{store},t+1} = E_{\text{store},t} + E_{\text{add},t} - E_{\text{extract},t} \quad (2.32)$$

In this representation, the ATES is charged whenever heat supply exceeds heat demand and discharged whenever demand exceeds supply. By applying $\sqrt{\eta_{\text{heat}}}$ to both charging and discharging, the overall round-trip efficiency of the storage equals η_{heat} .

Several simplifying assumptions are inherent to this representation:

- the hot and cold wells are not represented explicitly as separate temperature reservoirs;
- the ATES is modelled as a single energy buffer with a constant round-trip efficiency;
- groundwater flow, thermal stratification, and heat losses to the surrounding geology are not represented explicitly;
- standing losses, pumping power, and maximum charge and discharge capacities are neglected;
- the energy-based state of charge may become negative, which indicates an energy deficit relative to the assumed storage boundary rather than a physically realistic aquifer state.

Despite these simplifications, the model captures the first-order role of seasonal storage in shifting heat from periods of summer surplus to periods of winter demand within the SOLSTICE framework.

2.4.1. HT-ATES model -- developed

The original SOLSTICE ATES model represents seasonal storage as a single thermal-energy buffer with a fixed round-trip efficiency. Although this approach is suitable for first-order system simulations, it does not relate the available stored heat to the aquifer volume or operating-temperature range. In addition, long-term storage performance is prescribed independently of the aquifer properties and operating conditions. The model was therefore extended to represent the HT-ATES system through a bounded useful hot-well energy inventory and its corresponding lumped temperature.

The developed model retains a simplified, system-level representation of the aquifer. The hot well is represented as a spatially uniform thermal volume, whereas the cold-well and heating-return temperature are prescribed at 30 °C. The cold-well temperature is therefore not updated through a separate energy balance. Detailed groundwater flow, thermal-front development, buoyancy-driven plume migration and hydraulic-pressure changes are outside the scope of the model. The seasonal charging and discharging processes represented in the developed HT-ATES model are illustrated in Figure 2.5.

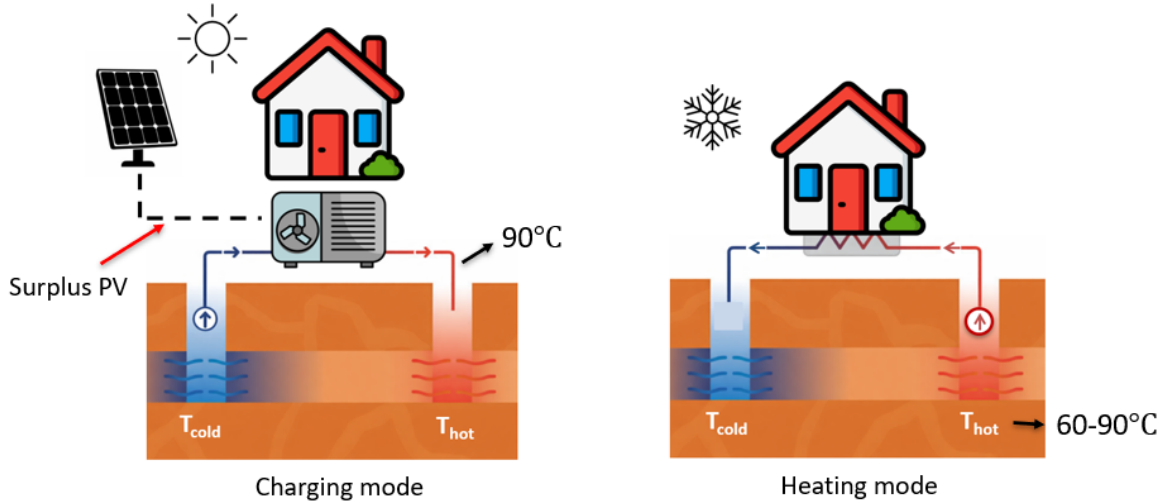


Figure 2.5: Schematic representation of the developed HT-ATES model. During charging operation (left), surplus solar electricity operates the HP to heat water transferred from the cold well to the hot well. During discharging operation (right), useful heat is extracted from the hot well to supply SH and DHW, after which the cooled return water is reinjected into the cold well.

The thermal storage capacity is determined from the volumetric heat capacity of the saturated aquifer. Both the pore water and the surrounding geological matrix contribute to the storage of thermal energy:

$$c_{aq} = (1 - \phi)\rho_r c_r + \phi\rho_w c_{p,w}, \quad (2.33)$$

where ϕ is the aquifer porosity, ρ_r and c_r are the density and specific heat capacity of the solid aquifer matrix, and ρ_w and $c_{p,w}$ are the corresponding properties of water. A water density of $\rho_w = 970 \text{ kg m}^{-3}$ is used as a representative value for the HT-ATES operating-temperature range. This is consistent with thermodynamic property data, which indicate liquid-water densities of approximately 972 kg m^{-3} at 80°C and 965 kg m^{-3} at 90°C [36].

Only heat stored above the minimum temperature for direct heat supply is included in the useful hot-well inventory, where inventory refers to the amount of stored thermal energy that is available for useful recovery:

$$E_{\text{use},t} = V_{\text{hot}} c_{\text{aq,kWh}} (T_{\text{hot},t} - T_{\text{min,ATES}}), \quad (2.34)$$

where V_{hot} is the effective hot-well volume, $T_{\text{hot},t}$ is the lumped hot-well temperature at timestep t , and T_{min} is the minimum temperature at which stored heat can directly supply the modelled thermal demand. The useful inventory is evaluated within the operating range between $T_{\text{min}} = 60^\circ\text{C}$ and the charging temperature $T_{\text{ch}} = 90^\circ\text{C}$.

For configurations using PV or PVT, the electrical power available for charging is the surplus solar electricity remaining after direct electricity demand and EB charging have been supplied. The potential thermal energy delivered by the HP to the HT-ATES during one timestep is:

$$Q_{\text{ch,pot},t} = P_{\text{sur},t} \text{COP}_{\text{ch},t} \Delta t, \quad (2.35)$$

where $P_{\text{sur},t}$ is the available surplus electrical power, $\text{COP}_{\text{ch},t}$ is the COP of the HP when supplying heat at the HT-ATES charging temperature, and $\Delta t = 1 \text{ h}$ is the simulation timestep. The actual charged energy, $Q_{\text{ch},t}$, cannot exceed either the potential charging energy or the remaining thermal capacity of the hot well.

During discharge, heat from the hot well is supplied directly to the combined SH and DHW demand. The discharged energy, $Q_{\text{dis},t}$, is limited by the instantaneous thermal demand and the useful energy remaining in the hot well. When the available useful inventory is insufficient to supply the complete demand, the remaining SH and DHW loads are supplied through the auxiliary HP operation described in Chapter 3.

Long-term subsurface losses are included through the recovery efficiency η_r . The useful hot-well inventory is updated hourly according to:

$$E_{\text{use},t+1} = E_{\text{use},t} + \eta_r Q_{\text{ch},t} - Q_{\text{dis},t}, \quad (2.36)$$

where $\eta_r Q_{\text{ch},t}$ is the recoverable fraction of the thermal energy charged during timestep t , and $Q_{\text{dis},t}$ is the useful heat supplied from storage. The updated inventory is constrained by the operating-temperature limits listed in Table 2.3. Charging is curtailed when the hot well reaches T_{ch} , while discharge cannot exceed the useful energy remaining above T_{min} .

After the useful inventory has been updated, the corresponding lumped hot-well temperature is calculated as:

$$T_{\text{hot},t+1} = T_{\text{min}} + \frac{E_{\text{use},t+1}}{V_{\text{hot}} c_{\text{aq,kWh}}}, \quad (2.37)$$

where the resulting temperature remains bounded between T_{min} and T_{ch} . The prescribed cold-well and heating-return temperature remains constant at 30°C throughout the simulation.

The recovery efficiency used in Equation 2.36 represents the fraction of injected thermal energy that remains recoverable after seasonal subsurface losses. The calculation is based on the modified Rayleigh-number approach originally developed by Schout et al. [37] and later extended to higher-temperature conditions by Sheldon et al. [38]. In the present model, the refined screening relation proposed by Geerts et al. [39] is used because it can be evaluated directly from the aquifer properties and annual injected water volume.

The characteristic thermal radius of the injected volume is calculated as:

$$R_{\text{th}} = \sqrt{\frac{c_w V_i}{c_{\text{aq}} \pi H_{\text{aq}}}}, \quad (2.38)$$

where $c_w = \rho_w c_{p,w}$ is the volumetric heat capacity of water, V_i is the annual injected water volume, and H_{aq} is the aquifer thickness. The corresponding modified Rayleigh number is:

$$Ra^* = \frac{\alpha_f \rho_w g H_{\text{aq}}^2 c_{\text{aq}} \sqrt{k_h k_v} \Delta T}{\mu \lambda_{\text{aq}} R_{\text{th}}}, \quad (2.39)$$

where α_f is the thermal expansion coefficient of water, g is the gravitational acceleration, k_h and k_v are the horizontal and vertical permeabilities, ΔT is the difference between the injection and undisturbed ground

temperatures, μ is the dynamic viscosity, and λ_{aq} is the thermal conductivity of the saturated aquifer. The water density and dynamic viscosity are evaluated at the average temperature between the injection and ground temperatures.

Using Ra^* and V_i , the recovery efficiency is calculated with the fitted screening relation of Geerts et al. [39]:

$$\eta_r = \left(0.406 - \frac{2.02 \times 10^3}{V_i}\right) \exp \left[Ra^* \left(\frac{2.46}{V_i} - 2.62 \times 10^{-4} \right) \right] + \left(0.500 - \frac{1.37}{V_i}\right) \exp \left[Ra^* \left(-\frac{3.92 \times 10^{-2}}{V_i} - 3.25 \times 10^{-4} \right) \right]. \quad (2.40)$$

The annual injected volume V_i is expressed in m^3 in the fitted relation. The resulting value is physically restricted to the range between zero and one. The recovery efficiency is calculated in the HT-ATES screening sheet and subsequently applied as a fixed scenario-level parameter in the hourly inventory balance.

The principal parameters used in the developed HT-ATES model and the recovery-efficiency calculation are summarised in Table 2.3. The values shown correspond to the reference case implemented in the present study. Within the SOLSTICE model, users can adjust selected design and location-dependent inputs, including the effective storage volume, annual injected volume, aquifer properties, operating temperatures, and initial hot-well temperature. The volumetric heat capacity and recovery efficiency are subsequently calculated from these inputs.

Table 2.3: Reference parameters used in the developed HT-ATES model and recovery-efficiency screening

Parameter	Description	Unit	Value
ϕ	Aquifer porosity	—	0.25
ρ_r	Density of aquifer matrix	$kg\ m^{-3}$	2640
c_r	Specific heat capacity of aquifer matrix	$J\ kg^{-1}\ K^{-1}$	710
ρ_w	Representative water density	$kg\ m^{-3}$	970
$c_{p,w}$	Specific heat capacity of water	$J\ kg^{-1}\ K^{-1}$	4183
$c_{aq,kWh}$	Volumetric heat capacity of saturated aquifer	$kWh\ m^{-3}\ K^{-1}$	0.672
T_{ch}	HT-ATES charging temperature	$^{\circ}C$	90
$T_{min,ATES}$	Minimum useful hot-well temperature	$^{\circ}C$	60
$T_{hot,0}$	Initial hot-well temperature	$^{\circ}C$	75
T_{cold}	Cold-well and heating-return temperature	$^{\circ}C$	30
T_g	Undisturbed ground temperature	$^{\circ}C$	10
ΔT	Injection-ground temperature difference	K	80
V_{hot}	Effective hot-well volume	m^3	Case-specific
V_{cold}	Reference cold-well volume	m^3	Case-specific
V_i	Annual injected water volume	$m^3\ yr^{-1}$	Case-specific
H_{aq}	Aquifer thickness	m	60
α_f	Thermal expansion coefficient of water	K^{-1}	3.00×10^{-4}
μ	Dynamic viscosity at average temperature	Pa s	5.50×10^{-4}
λ_{aq}	Thermal conductivity of saturated aquifer	$W\ m^{-1}\ K^{-1}$	2.5
k_h	Horizontal permeability	m^2	2.88×10^{-11}
k_v	Vertical permeability	m^2	5.75×10^{-13}
η_r	Calculated recovery efficiency	—	Case-specific

The developed HT-ATES model remains a simplified representation. The hot well is treated as a spatially uniform thermal inventory, while the cold-well temperature is prescribed rather than calculated dynamically. Thermal-plume development, groundwater flow, stratification, dispersion, detailed well hydraulics, operational flow limitations, pressure losses and pumping electricity are not evaluated explicitly. Seasonal subsurface losses are instead represented through the scenario-level recovery efficiency. Nevertheless, compared with the original SOLSTICE ATES model, the developed formulation provides a more physically constrained representation by relating the useful stored heat to the aquifer volume, operating-temperature range, initial thermal inventory and aquifer-specific recovery efficiency.

2.5. Conclusion

This chapter addressed Research Objective 1 by evaluating the component-level representations within the SOLSTICE model. The objective was to assess the existing component models and adapt or develop them where necessary to improve their physical representation, while maintaining the transparency and usability of the framework.

The assessment showed that the original SOLSTICE model provides a suitable basis for system-level analysis, but that several component equations required refinement to better represent seasonal energy interactions. In particular, targeted improvements were introduced for the solar irradiance model, the PVT model, the HP model, the battery model, and the ATES representation. These adaptations improved the physical consistency of the model while preserving its simplified structure.

At the same time, the methodology confirmed that not all original component models required modification. The existing PV and ST equations remained suitable for the purposes of this thesis once combined with the improved irradiance treatment. This selective approach is consistent with Research Objective 1, as the purpose was to improve the component models where necessary rather than to replace the SOLSTICE framework with a more complex model.

Research Objective 1 has therefore been achieved by assessing the existing component models and introducing adapted or newly developed equations where the original representations were considered insufficient. The resulting set of component models forms the methodological basis for the integrated system analysis presented in the following chapters.

3

System-Level Operation and Simulation Methodology

Chapter 2 described the component-level modelling approach used in SOLSTICE V2, including the existing component models, the adapted equations, and the newly developed HT-ATES representation. However, the performance of an integrated residential energy system is not determined by the component models alone. It also depends on how these components are combined, how the input data are processed, and how energy flows are prioritised during each timestep.

This chapter addresses Research Objective 2, which is to integrate the component models into SOLSTICE V2 using hourly input data, defined system configurations, and rule-based operational modes. The chapter therefore describes the system-level simulation methodology through which the model is applied. In particular, it explains how weather data, residential electricity demand, thermal demand, building parameters, and energy prices are implemented. It also describes the selected system configurations, operational modes, energy-flow priorities, and main modelling assumptions. A visual overview of the main SOLSTICE V2 workbook sheets and their workflow is provided in Appendix B.

By establishing a consistent simulation setup, this chapter ensures that the later comparison between configurations and climatic conditions is based on the same modelling structure and input-processing approach. The chapter therefore forms the methodological link between the component-level model development in Chapter 2 and the system-performance results presented in Chapter 4.

3.1. Integrated SOLSTICE V2 System

SOLSTICE V2 represents an integrated residential energy system in which solar generation, HP (HP) operation, electrical storage, seasonal thermal storage, and grid interaction are combined. The model is used to simulate the hourly operation of a representative household over a full year. Its purpose is to evaluate how different combinations of PV(T) collectors, EB storage, HP operation, and HT-ATES affect self-consumption, grid dependency, heat demand coverage, and energy costs.

Figure 3.1 shows a simplified representation of the integrated system. The system boundary includes the household electricity demand, thermal demand, PV(T) collectors, EB, HP, HT-ATES, and the electricity grid. Weather data and electricity prices are treated as external inputs to the model.

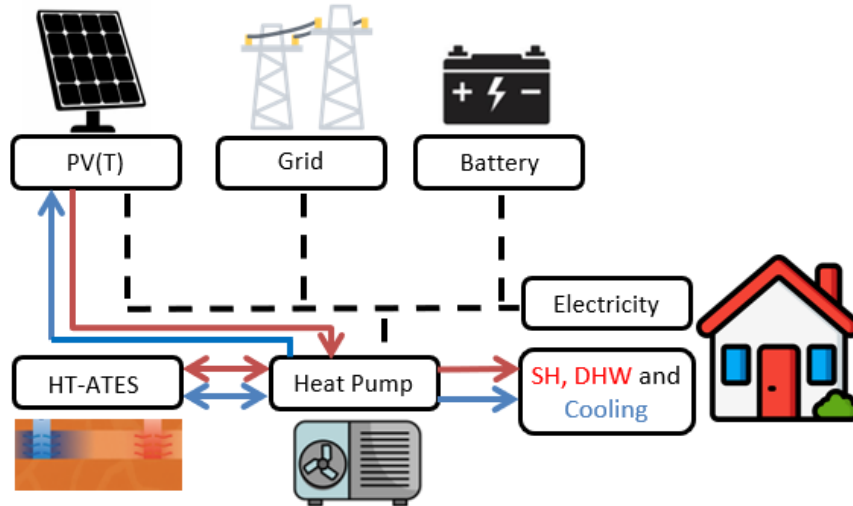


Figure 3.1: Simplified SOLSTICE V2 system layout, showing PV(T) generation, grid interaction, EB storage, HP operation, and HT-ATES. Dashed black arrows indicate electrical flows; red and blue arrows indicate thermal flows.

The electrical subsystem consists of PV(T) electricity generation, appliance electricity demand, HP electricity consumption, EB storage, and grid import or export. Locally generated electricity can be used directly, stored in the battery, used to operate the HP, or exported to the grid depending on the selected system configuration and operating mode.

The thermal subsystem consists of SH, DHW production, HP operation, and HT-ATES. Thermal demand can be supplied directly by the HP or by stored heat from HT-ATES, depending on the available storage state and the selected operational mode.

The HP forms the main coupling between the electrical and thermal subsystems. It allows electricity, including surplus solar electricity, to be converted into useful heat. When combined with HT-ATES, this enables part of the solar energy generated during periods of high availability to be shifted to periods with higher heating demand. The detailed hourly operation of these interactions is described in Section 3.4.

3.2. Model Inputs

The model requires a set of hourly and user-defined input parameters to simulate the operation of the residential energy system over a full year. In this thesis, the simulations are performed using hourly data for the year 2023. This includes hourly weather conditions, electricity prices, and demand profiles where applicable. Using data from the same historical year preserves the temporal relationship between solar irradiance, wind conditions, electricity demand, and electricity prices. This is important because periods of high renewable electricity generation can coincide with low or negative electricity prices, which directly affects the operation and economic performance of the system.

All household demand values are scaled to a standardised representative household of 2.5 persons. This is done to enable a consistent comparison between countries and system configurations. Since average household size differs between countries, using country-specific average households would introduce demographic differences into the comparison. By scaling appliance electricity demand and DHW demand to the same 2.5-person reference household, differences in model output can be interpreted primarily as the result of climate, energy prices, and system configuration rather than household size.

The following subsections describe the main input categories used in the model: weather data, residential appliance electricity demand, thermal demand and building parameters, and energy price data.

3.2.1. Weather data

Hourly weather data are used as external boundary conditions for the simulations. The required weather variables include ambient air temperature, wind speed, and solar irradiance data. Ambient temperature is used to determine building heat losses, HP source conditions, and solar module temperatures, while solar irradiance determines the available solar energy for the PV, ST, and PVT models.

For the solar irradiance input, SOLSTICE V2 provides two possible approaches. First, users can use the plane-of-array (POA) calculator implemented in the workbook. In this approach, global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) are obtained from the CAMS radiation dataset [33] and converted to POA irradiance using solar-position calculations based on the Solar Position Algorithm (SPA) [34]. The detailed transposition method was described in Section 2.1.1. Second, users can directly import POA irradiance data from PVGIS [35], which provides location-specific solar irradiation data for defined module orientations.

In this thesis, the POA calculator implemented in SOLSTICE V2 is used to generate the irradiance input for the selected locations. The same weather-data structure is applied to each location, so that differences in model output can be attributed to climatic conditions and system configuration rather than to differences in data processing. The weather inputs used in the model are illustrated in Figure 3.2, which shows both the detailed time-series structure for one location and the annual weather indicators used for comparison between locations.

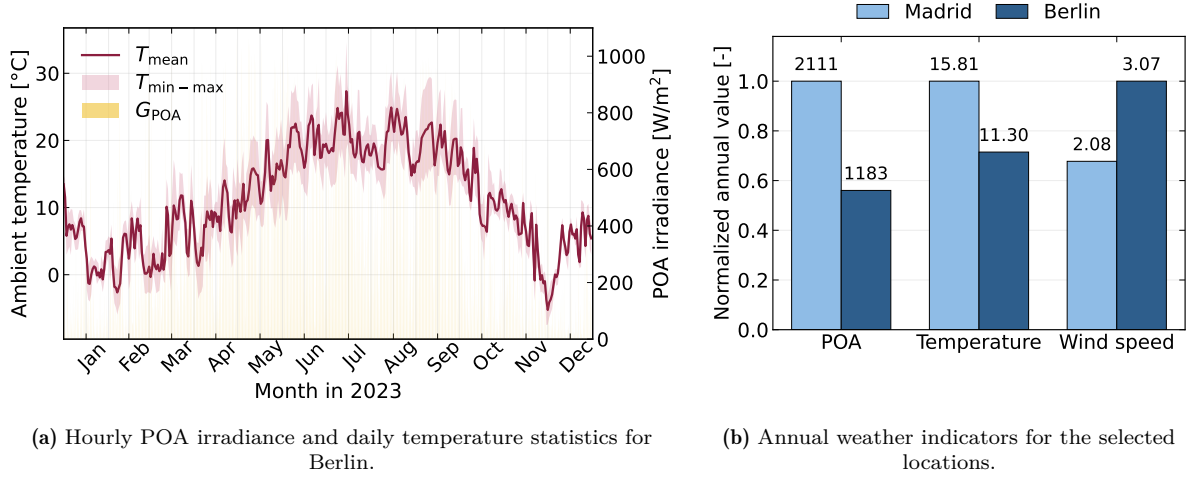


Figure 3.2: Weather input data used in the model: (a) detailed Berlin time series and (b) annual comparison of selected weather indicators.

3.2.2. Residential electricity demand

Residential electricity demand refers to the non-heating electrical demand of the household, referred to as appliance electricity demand in the model. SH and DHW are not included in this input category, because they are represented as thermal demands and are supplied through the HP or thermal storage depending on the system configuration.

Country-specific hourly appliance electricity profiles are used to represent differences in household electricity-use behaviour. For Germany, the updated standard load profile from the German Association of Energy and Water Industries (BDEW) was used, specifically the H25 household profile [40]. For Spain, the household electricity profile was based on the SPAHOUSEC III study by IDAE [41], which provides measured information on residential energy consumption, equipment, and household energy-use behaviour in Spain. This distinction is included to capture differences in daily demand patterns between countries, such as the later and more distributed electricity-use profile observed for Spain.

The profiles are expressed as hourly fractions of the daily appliance electricity demand. The daily appliance electricity demand is set to 5.0 kWh/day for Berlin and 7.64 kWh/day for Madrid. These values are used to scale the hourly profiles while preserving the country-specific distribution of electricity use over the day. The resulting profiles used for Germany and Spain are shown in Figure 3.3.

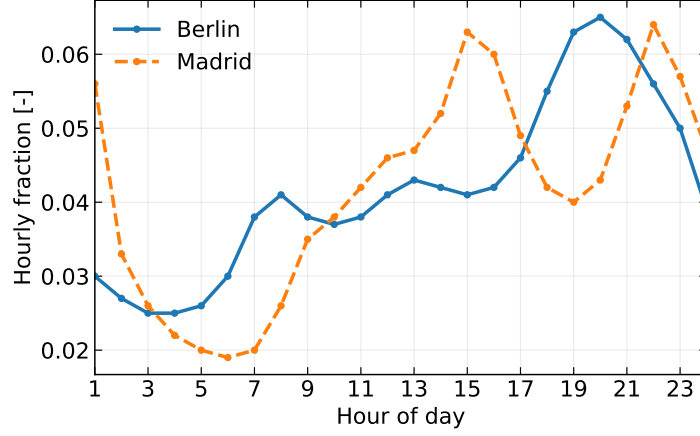


Figure 3.3: Hourly appliance electricity demand profiles for Germany and Spain. The profiles are expressed as hourly fractions of the daily appliance electricity demand and are scaled to 5.0 kWh/day for Berlin and 7.64 kWh/day for Madrid.

3.2.3. Thermal demand and building parameters

The thermal demand of the household consists of SH, cooling, and DHW. These demands are treated separately from the residential appliance electricity demand. Appliance electricity demand is prescribed as an electrical load profile, while SH, cooling, and DHW are represented as thermal energy requirements. The electricity required to supply these thermal demands is calculated within the model from the HP operation and the COP.

SH and cooling demand are calculated dynamically from the indoor temperature balance of the building. The simplified building model accounts for heat exchange with the outdoor environment, solar gains through windows, and the thermal mass of the building. The main building parameters are the heat loss coefficient, effective sun-facing window area, thermal mass, number of households, and indoor temperature setpoints. The values used in this thesis are summarised in Table 3.1.

Table 3.1: Building parameters used for the SH and cooling demand calculation.

Parameter	Value	Unit
Minimum room temperature	20	°C
Maximum room temperature	25	°C
Thermal mass of house	30×10^6	J/°C
Heat loss coefficient	100	W/°C
Effective sun-facing window area	3	m ²

For each hourly timestep, the indoor temperature is first updated based on the passive temperature response of the building. This is calculated as:

$$T_{\text{end},t} = T_{\text{start},t} + \frac{[(T_{\text{out},t} - T_{\text{start},t})H + G_{\text{POA}}A_{\text{win}}]\Delta t}{C_{\text{th}}}, \quad (3.1)$$

where $T_{\text{start},t}$ and $T_{\text{end},t}$ are the indoor temperatures at the start and end of timestep t , $T_{\text{out},t}$ is the ambient temperature, H is the heat loss coefficient, G_{POA} is the plane-of-array irradiance, A_{win} is the effective sun-facing window area, Δt is the timestep duration, and C_{th} is the thermal mass of the house.

After the passive indoor temperature response is calculated, SH or cooling demand is generated if the resulting indoor temperature falls outside the comfort temperature range. If the indoor temperature after the passive response is below the lower comfort setpoint, the hourly SH demand is calculated as:

$$Q_{\text{SH},t} = \frac{C_{\text{th}} \max(T_{\text{min,room}} - T_{\text{end},t}, 0)}{3.6 \times 10^6}, \quad (3.2)$$

Conversely, if the indoor temperature after the passive response exceeds the upper comfort setpoint, the hourly cooling demand is calculated as:

$$Q_{\text{cool},t} = \frac{C_{\text{th}} \max(T_{\text{end},t} - T_{\text{max,room}}, 0)}{3.6 \times 10^6}, \quad (3.3)$$

where $Q_{\text{SH},t}$ and $Q_{\text{cool},t}$ are the hourly SH and cooling demands, and $T_{\text{min,room}}$ and $T_{\text{max,room}}$ are the lower and upper indoor temperature setpoints, respectively. The factor 3.6×10^6 converts joules to kWh. Since the model uses hourly time steps, the resulting hourly energy demand is numerically equivalent to the average thermal power in kW_{th} over that time step.

The resulting SH and cooling demand profiles are shown in Figure 3.4. The detailed profile for Berlin illustrates the hourly and seasonal variation in thermal demand, while the bar chart compares the annual SH and cooling demand between the selected locations.

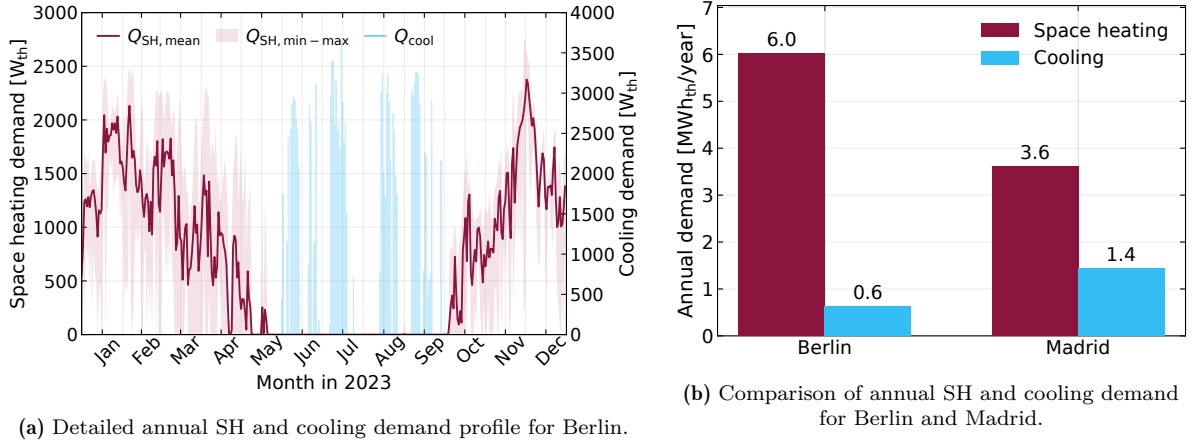


Figure 3.4: SH and cooling demand inputs: (a) detailed Berlin profile and (b) annual demand comparison between selected locations.

DHW demand is included separately as a daily thermal energy requirement. Country-specific DHW values are based on Fuentes et al. [42]. A representative realistic hourly draw-off profile from this source is shown in Figure 3.5 for comparison, but is not used directly in the simulations. Instead, SOLSTICE V2 assumes that DHW is supplied through a storage tank that is charged by the HP during a fixed midday period. The daily DHW demand is set to 8.36 kWh/day for Berlin and 3.92 kWh/day for Madrid. These values are distributed evenly over four hours, from 11:00 to 14:00, with each hour representing 25% of the daily DHW energy demand. This simplified profile represents scheduled tank charging rather than instantaneous hot-water draw-off behaviour. It preserves the daily DHW energy requirement while aligning DHW production with hours of relatively high solar electricity generation. Figure 3.5 compares the realistic draw-off profile with the simplified charging profile.

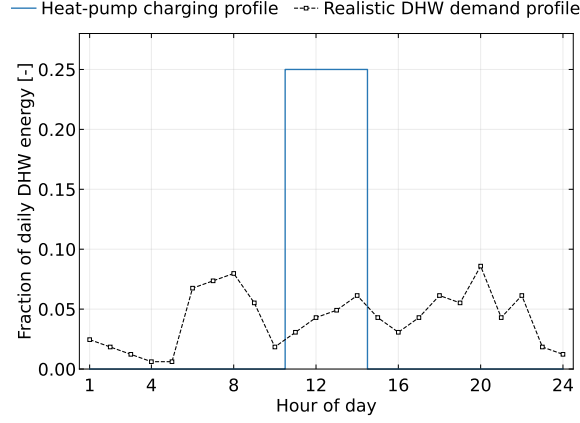


Figure 3.5: DHW draw-off profile and the simplified charging profile. In the simplified profile, the daily DHW demand is distributed evenly over four midday hours, with each hour representing 25% of the daily energy requirement.

3.2.4. Energy price data

Hourly electricity price data are used to evaluate the operational electricity costs of the different system configurations. Electricity import prices are derived from the European wholesale day-ahead electricity price dataset published by Ember [43]. The hourly wholesale prices capture the temporal variation of the electricity market, including periods of high, low, and negative prices. However, they do not include the network charges, taxes, and levies paid by residential consumers.

To obtain representative residential import prices, a constant country-specific correction is added to every hourly wholesale price. This correction is selected such that the resulting annual average equals the corresponding average household electricity price reported by Eurostat [44]. This approach preserves the hourly variation of the wholesale market while adjusting the overall price level to represent residential electricity costs. The resulting annual average import prices are approximately 0.387 €/kWh for Berlin and 0.287 €/kWh for Madrid.

Electricity exported to the grid is treated separately from electricity imported from the grid. The export remuneration of residential PV electricity is country-specific and depends on national support schemes, market rules, and supplier contracts. Therefore, a fixed export price is assigned per country rather than assuming that exported electricity is remunerated at the adjusted hourly import price.

For Germany, a fixed export remuneration of 0.084 €/kWh is applied, based on the German EEG feed-in remuneration for small residential PV systems in the relevant size range [45]. For Spain, residential PV surplus electricity is compensated through supplier-based surplus-compensation schemes rather than through a single regulated feed-in tariff. A representative fixed export price of 0.065 €/kWh is therefore applied for Madrid [46].

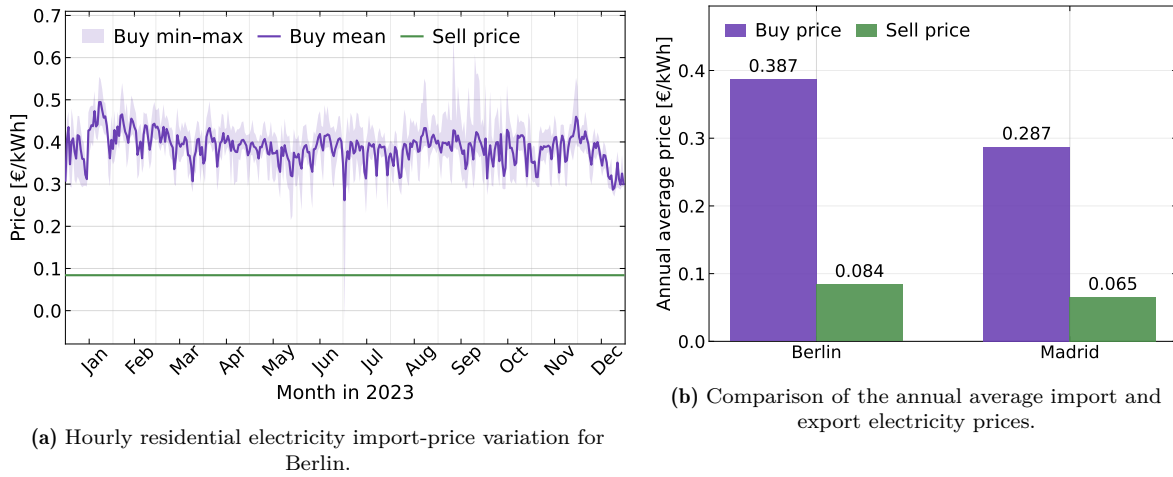


Figure 3.6: Electricity price inputs used in SOLSTICE V2. The detailed Berlin plot illustrates the hourly variation in the residential import price throughout 2023, while the comparison plot shows the annual average import and fixed export prices for both selected locations.

This treatment separates the time-varying residential cost of imported electricity from the fixed remuneration received for exported solar electricity. The model can therefore evaluate the economic value of self-consumption while accounting for differences in residential electricity-price levels and export-compensation conditions between the selected countries.

3.3. System Configurations

The SOLSTICE V2 model includes six residential energy system configurations. Configurations 1–5 form the main comparative set evaluated in Chapter 4, while Configuration 6 is retained as an additional model option but is not included in the main results comparison. The configurations are introduced stepwise, starting from a HP-only reference case and gradually adding PV generation, EB storage, HT-ATES, PVT collectors, and ST collectors. This stepwise structure makes it possible to evaluate the added value of each component separately while keeping the system comparison transparent. A similar configuration-based approach is used in the original SOLSTICE framework, where different combinations of PV, PVT, HPs, batteries, and seasonal storage are compared to assess their effect on energy flows and grid interaction.

Configuration 1: HP

Configuration 1 represents the reference electrified heating system. In this configuration, the household is connected to the electricity grid, which supplies both the appliance electricity demand and the electricity required by the HP. The HP supplies the thermal demand for SH, DHW, and cooling. No local electricity generation, electrical storage, or seasonal thermal storage is included.

Configuration 2: HP + PV

Configuration 2 extends the reference case by adding PV generation. The generated PV electricity can be used directly to supply appliance electricity demand and HP electricity consumption. When PV generation is insufficient, the remaining electricity demand is supplied by the grid. When PV generation exceeds the instantaneous demand, the surplus electricity is exported to the grid, since no electrical or thermal storage is included in this configuration.

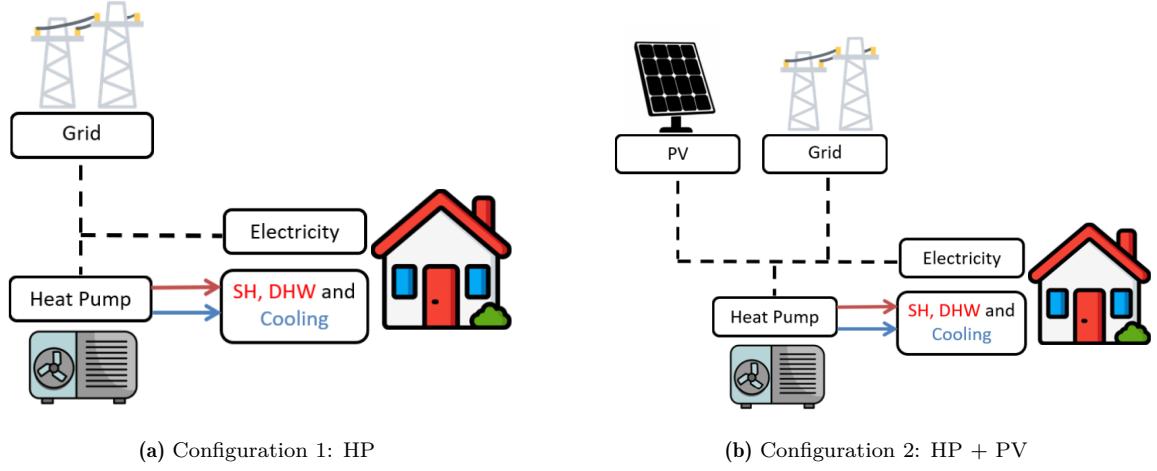


Figure 3.7: System configurations 1 and 2. Configuration 1 represents a HP-only system supplied by the electricity grid, while Configuration 2 adds PV generation for direct electricity use and possible grid export.

Configuration 3: HP + PV + EB

Configuration 3 adds an EB to the PV and HP system. The battery is used for short-term electricity storage. When PV generation exceeds the instantaneous electricity demand, the surplus electricity can be stored in the battery. During periods when PV generation is insufficient, the battery can discharge to supply part of the appliance electricity demand or HP electricity demand. If the battery is full, remaining surplus electricity is exported to the grid. If the battery is empty, remaining electricity demand is supplied by grid import.

Configuration 4: HP + PV + EB + HT-ATES

Configuration 4 adds HT-ATES to Configuration 3. In this configuration, the system can store surplus solar electricity seasonally by converting it into heat using the HP. During periods with excess PV electricity, the HP can charge the HT-ATES by producing heat at the required storage temperature. During periods with thermal demand, stored heat from the HT-ATES can be used to supply SH and DHW demand. This configuration therefore combines short-term electrical storage with seasonal thermal storage.

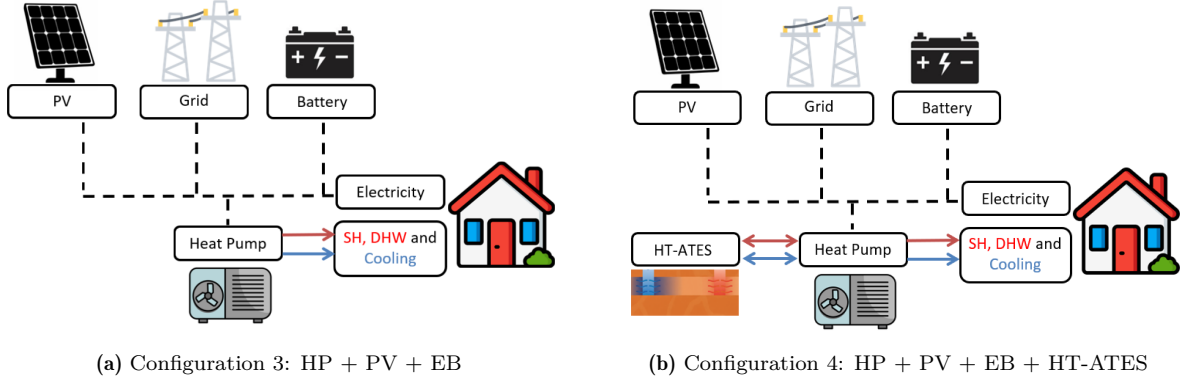


Figure 3.8: System configurations 3 and 4. Configuration 3 includes EB storage for short-term electricity balancing, while Configuration 4 additionally includes HT-ATES for seasonal thermal storage.

Configuration 5: HP + PVT + EB + HT-ATES

Configuration 5 replaces the PV modules with PVT collectors and represents the most integrated system layout considered in this thesis. The electrical output of the PVT collectors is treated in the same way as PV electricity and can be used for direct demand supply, battery charging, HP operation, or grid export. In addition, the thermal side of the PVT collector is coupled to the HP source loop. Heat extracted from the PVT module lowers the module temperature, which can improve electrical efficiency, while simultaneously increasing the source temperature of the HP. This reduces the temperature lift between source and sink and can therefore

increase the COP. The PVT–HP coupling is not defined as a separate operational mode, but as a configuration-specific source pathway that is active whenever the HP operates in this configuration.

Configuration 6: PV + EB + ST + HT-ATES

Configuration 6 represents an alternative solar-thermal configuration. Instead of using an HP as the main conversion unit for thermal storage charging, the system combines PV electricity generation with ST collectors, an EB, and HT-ATES. In this configuration, PV generation supplies the electrical demand and can charge the battery, while ST collectors provide thermal energy for storage or direct thermal use. This configuration is included to compare the HP-based storage pathway with a solar-thermal-based storage pathway.

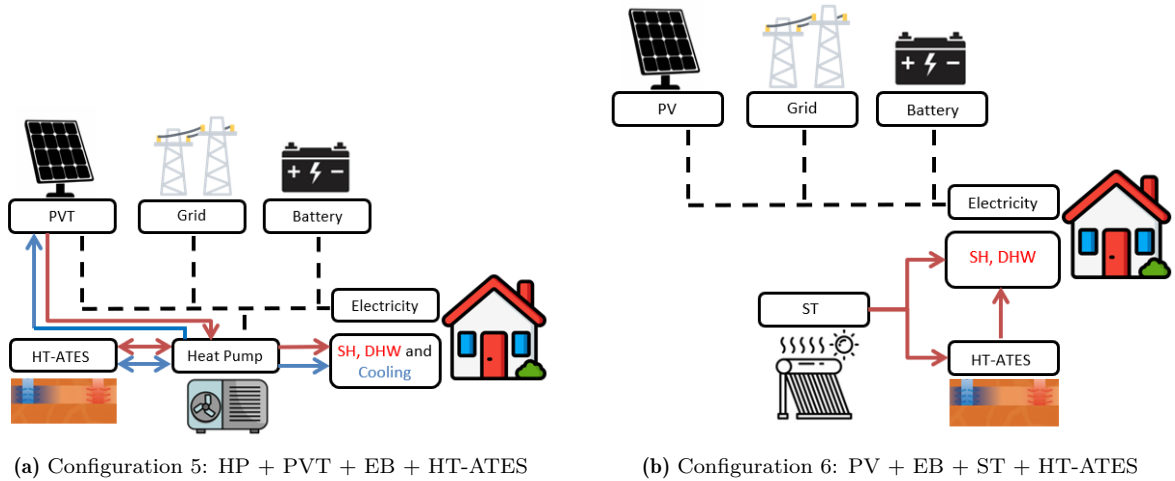


Figure 3.9: System configurations 5 and 6. Configuration 5 uses PVT collectors coupled to an HP and HT-ATES, while Configuration 6 combines PV, EB storage, ST collectors, and HT-ATES.

3.4. Operational Modes

The hourly operation of SOLSTICE V2 is represented by five operational modes that describe the main electrical and thermal energy-flow pathways within the system. The applicable pathways depend on the selected system configuration, the instantaneous balance between solar electricity generation and household demand, the state of charge of the EB, and the available temperature and recoverable energy in the HT-ATES system. The modes represent individual energy-flow routes rather than fully independent system states. Consequently, several modes may occur during the same hourly time step. For example, household appliance demand may be supplied according to Mode I while stored heat from HT-ATES is simultaneously used according to Mode V. The submodes indicated by (a), (b), and (c) describe the priority order or alternative pathways within each mode. In the following figures, dashed black arrows indicate electrical energy flows, while coloured solid arrows indicate thermal energy flows. Cooling is not presented as a separate operational mode because it does not introduce an additional supply or storage pathway. When cooling demand occurs, it is supplied by the HP, while the corresponding electrical demand is covered by solar generation, the EB, or the electricity grid according to the same electrical priority used elsewhere in the model.

3.4.1. Mode I: Direct Household Electricity Supply

Mode I describes how household appliance electricity demand is supplied. Locally generated solar electricity is used first, followed by electricity discharged from the EB. Grid import acts as the final backup source when local generation and stored electricity are insufficient. The three supply pathways are illustrated in Figure 3.10.

Mode Ia: Direct Solar Electricity Supply

In Mode Ia, electricity generated by the PV system, or by the electrical part of the PVT system, is used directly to supply household appliance demand. Direct use is prioritised because it avoids battery conversion losses and reduces both grid import and grid export.

Mode Ib: Electrical Battery Supply

If solar electricity is insufficient to fully supply the appliance demand, the remaining demand can be supplied by the EB in Mode Ib. Battery discharge is limited by the available state of charge and the discharging efficiency of the battery.

Mode Ic: Grid Electricity Supply

If appliance demand remains after direct solar supply and EB discharge, the remaining electrical demand is supplied by the electricity grid in Mode Ic. Grid import therefore acts as the final pathway that ensures that appliance demand can always be met. If solar generation exceeds the instantaneous appliance electricity demand, the remaining electricity is treated as surplus and passed to Mode II.

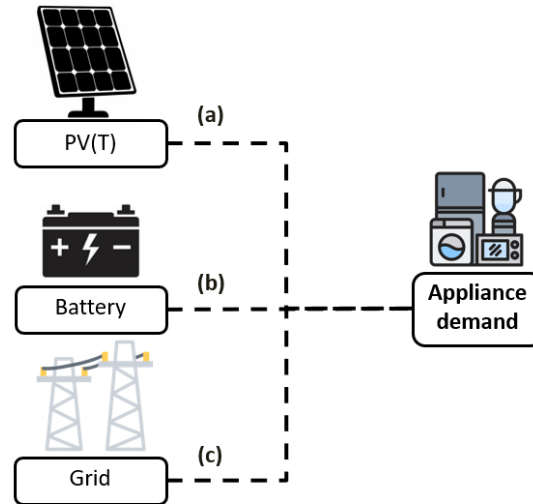


Figure 3.10: Mode I: direct household electricity supply. Appliance demand is supplied by (a) direct PV(T) electricity, followed by (b) EB discharge and, if required, (c) electricity imported from the grid.

3.4.2. Mode II: Electricity Surplus Operation

Mode II describes the allocation of solar electricity that remains after household appliance demand has been supplied. The surplus electricity is first used to charge the EB. When additional surplus remains, it can be used to operate the HP for HT-ATES charging in configurations with conventional PV. Electricity that cannot be used or stored locally is exported to the grid. These pathways are shown in Figure 3.11.

Mode IIa: Electrical Battery Charging

In Mode IIa, surplus solar electricity is used to charge the EB when storage capacity is available. This allows electricity generated during periods of high solar availability to be shifted to later hours and increases the local use of solar electricity.

Mode IIb: PV-Driven HT-ATES Charging

When surplus PV electricity remains after EB charging, it can be used to operate the HP for HT-ATES charging in Mode IIb. In the conventional PV configuration, the HP uses ambient air as its thermal source and upgrades this heat to the required HT-ATES charging temperature. The HP therefore operates in a supply-driven manner. Its operation is initiated by the availability of surplus PV electricity rather than by an immediate household heat demand. In this way, surplus electricity that would otherwise be exported can be converted into thermal energy and stored for later use.

Mode IIc: Grid Export

If surplus electricity remains after EB charging and possible PV-driven HT-ATES charging, the remaining electricity is exported to the grid in Mode IIc. Grid export therefore represents the final surplus pathway when no further local use or storage capacity is available.

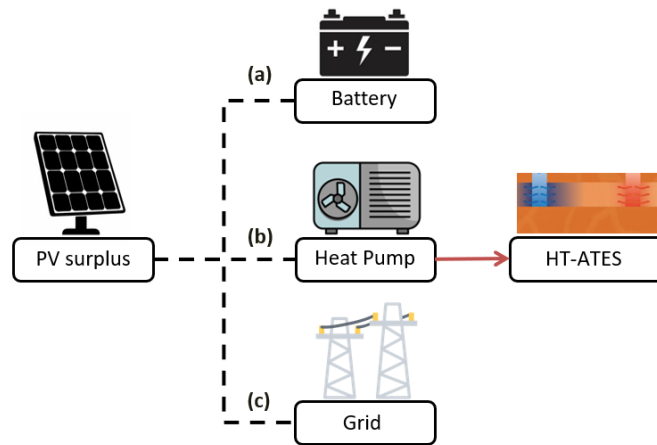


Figure 3.11: Mode II: electrical surplus operation. After direct demand has been supplied, remaining PV electricity is allocated to: (a) EB charging, (b) HP operation for ATES charging, and (c) grid export.

3.4.3. Mode III: Electricity Shortage Operation

Mode III describes auxiliary HP operation when SH or DHW demand cannot be fully supplied by HT-ATES. This can occur when the storage contains insufficient recoverable thermal energy or when the hot-well temperature is below the temperature required by the thermal demand. The remaining heating demand is then supplied by the HP using electricity from the EB or the grid, as illustrated in Figure 3.12.

Mode IIIa: Battery-Powered Heat-Pump Operation

In Mode IIIa, electricity discharged from the EB is used to operate the HP. The HP converts the stored electricity into useful heat and supplies part or all of the remaining SH and DHW demand. Battery operation reduces the amount of grid electricity required for auxiliary heating.

Mode IIIb: Grid-Powered Heat-Pump Operation

If the EB cannot provide sufficient electricity, the remaining HP electricity demand is supplied by the grid in Mode IIIb. This pathway acts as the final backup and ensures that the thermal demand can always be met. Grid-powered HP operation is generally avoided where possible because the purpose of HT-ATES is to reduce HP electricity consumption during periods of high heating demand. However, this pathway remains necessary when insufficient usable heat is available from storage.

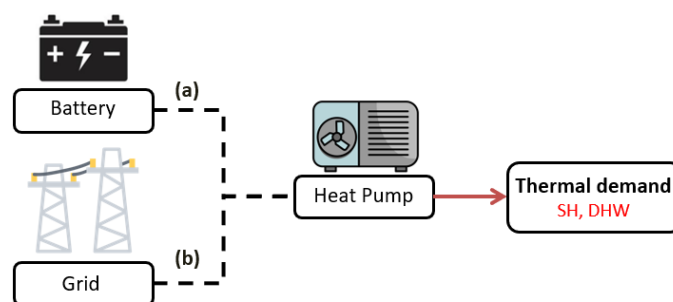


Figure 3.12: Mode III: electrical shortage operation. When PV generation is insufficient, the remaining demand is handled through: (a) EB discharging, (b) grid import.

3.4.4. Mode IV: Solar-Assisted HT-ATES Charging

Mode IV describes HT-ATES charging in configurations that include PVT or ST collectors. In contrast to Mode IIb, the solar collector does not only provide, or support, the electrical input to the HP. Thermal energy recovered from the collector is also supplied to the source side of the HP. The HP then upgrades this heat to the required storage temperature and injects it into the hot well. As in Mode IIb, the HP operates in a supply-driven

manner. Charging is initiated when sufficient solar energy and storage capacity are available, rather than in response to an immediate household heating demand. The PVT- and ST-assisted charging routes are illustrated in Figure 3.13.

Mode IVa: PVT-Assisted HT-ATES Charging

In Mode IVa, the PVT collector simultaneously generates electricity and supplies low-temperature thermal energy to the source side of the HP. Surplus PVT electricity can operate the HP, while heat extraction from the collector increases the available source temperature and cools the PVT module. The HP upgrades the recovered heat to the HT-ATES charging temperature before injection into the hot well.

Mode IVb: Solar-Thermal-Assisted HT-ATES Charging

In Mode IVb, thermal energy generated by the ST collector is supplied to the source side of the HP. The electrical input required by the HP is provided by the electrical subsystem of the corresponding configuration. The HP upgrades the collector heat to the required storage temperature and injects it into the hot well.

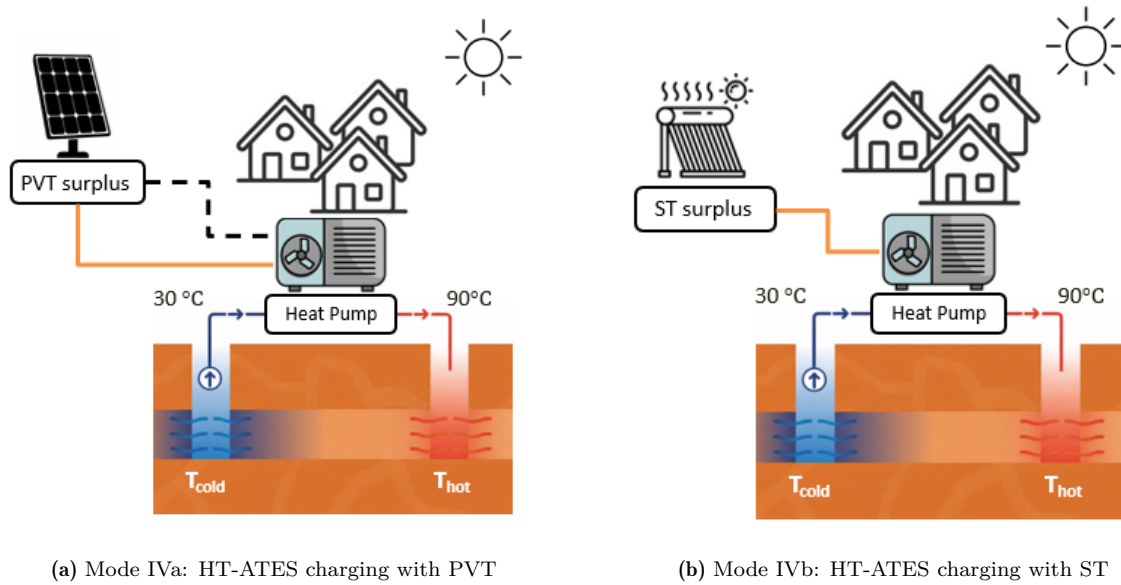


Figure 3.13: Mode IV: Solar-assisted HT-ATES charging. Thermal energy from the PVT or ST collector is used as a heat source for the HP. The HP upgrades the heat to the required storage temperature and injects it into the hot well.

3.4.5. Mode V: Direct HT-ATES Heat Supply

Mode V describes the direct supply of heating demand using thermal energy recovered from the HT-ATES hot well. This mode is active when SH or DHW demand is present and sufficient recoverable energy is available at a suitable hot-well temperature. In contrast to the charging modes, the HP is not used during direct HT-ATES discharge. Water is extracted from the hot well and its thermal energy is transferred to the building heating system. The available heat is allocated to SH and DHW according to the instantaneous demand and the applicable supply-temperature requirements. After heat delivery, the cooled return water is directed back to the cold well, thereby completing the ATES discharge cycle. Direct discharge reduces HP operation and associated electricity demand during the heating season. If the available storage temperature or recoverable thermal energy is insufficient, the remaining heating demand is passed to Mode III and supplied by auxiliary HP operation. The complete Mode V discharge pathway is illustrated in Figure 3.14

generation, demand, and electricity price fluctuations, but also means that the results are specific to the selected year.

- **Repeated daily demand profiles:** Appliance electricity demand and DHW demand are represented using fixed daily profiles that are repeated throughout the year. This preserves the daily energy demand and typical intraday structure, but does not capture weekday–weekend differences, holidays, occupancy variation, or behavioural randomness.
- **Representative building across locations:** The same reference building parameters are used for the selected locations. This isolates the effect of climate on system performance, but does not account for differences in national building stock, insulation levels, dwelling size, or occupant practices.
- **Simplified building thermal demand:** SH and cooling demand are calculated using a simplified indoor temperature balance with fixed building parameters, including thermal mass, heat loss coefficient, effective sun-facing window area, and comfort setpoints.
- **Fixed comfort settings:** Indoor temperature setpoints are kept constant throughout the year. Adaptive comfort behaviour, night setback, thermostat schedules, and occupant-controlled heating or cooling adjustments are not included.
- **Heat pump performance:** The HP COP is calculated from source and sink temperatures using a simplified Carnot-based formulation. Compressor maps, part-load behaviour, cycling losses, defrost operation, auxiliary electricity use, and HP capacity limits are not included.
- **HT-ATES representation:** HT-ATES is represented using simplified energy and volume balances, a lumped dynamic hot-well temperature, a fixed cold-well/heating-return temperature, and a recovery-efficiency constraint.
- **Component degradation:** Long-term degradation of system components is not considered. This includes PV and PVT module degradation, battery ageing, HP performance degradation, and possible long-term changes in thermal storage performance.
- **Energy transfer losses:** Additional distribution losses, such as pipe heat losses, inverter losses, cable losses, and auxiliary pumping electricity, are not explicitly modelled unless represented indirectly through simplified efficiency factors.
- **Heat pump operation:** A single equivalent high-temperature HP is assumed to serve SH, DHW production, and HT-ATES charging by operating at the corresponding duty-specific sink temperatures. The detailed hydraulic switching between these duties and the physical HP architecture are not modelled explicitly.
- **System control:** Operation follows predefined rule-based control logic. The model does not perform predictive optimisation and therefore does not necessarily represent the optimal control strategy.

These assumptions are consistent with the purpose of SOLSTICE V2 as a simplified system-level model. The results should therefore be interpreted as indicative outcomes for comparing system configurations and climatic conditions, rather than as detailed design predictions for individual components or site-specific installations.

3.7. Conclusion

This chapter addressed Research Objective 2 by presenting the system-level simulation methodology used in SOLSTICE V2. While Chapter 2 focused on the formulation and improvement of the individual component models, this chapter described how these components are integrated into complete residential energy-system configurations and operated at hourly resolution.

First, the main model inputs were introduced. Hourly weather data provide ambient temperature, wind speed, and POA irradiance. Residential appliance electricity demand is represented using country-specific daily load profiles scaled to the selected daily demand. Thermal demand is divided into SH, cooling, and DHW. The SH and cooling demands are calculated dynamically using a simplified building-temperature balance, while DHW is represented as a scheduled thermal load supplied during a fixed midday charging period.

Second, the selected system configurations and sizing parameters were defined. These configurations represent different combinations of PV, PVT, HP operation, EB storage, and HT-ATES. Their operation was described through five rule-based operational modes, which together define the overall supply-driven and demand-driven energy-flow structure of the system. This structure determines how electricity and heat are supplied, stored, exchanged with the grid, or transferred between the system components during each timestep.

Finally, the main modelling assumptions were summarised. These assumptions clarify the intended scope of SOLSTICE V2 as a transparent, early-stage system-assessment tool rather than a detailed component-design model. They also provide the context required to interpret the results presented in the following chapter.

Research Objective 2 has therefore been achieved by integrating the component models with hourly input data, defined system configurations, energy-flow priorities, and rule-based operational modes. The resulting methodology provides a consistent simulation framework for comparing system configurations and climatic conditions in Chapter 4.

Results and Discussion

This chapter presents the simulation results obtained with SOLSTICE V2. While Chapters 2 and 3 defined the component models, input data, system configurations, and operational logic, this chapter applies the resulting framework to evaluate the performance and behaviour of the considered residential energy systems. The aim is to determine how PV generation, electrical battery storage, HT-ATES, and PVT collectors influence grid interaction, HP operation, seasonal thermal storage, and operational electricity costs. Although six configurations are available within SOLSTICE V2, the analysis in this chapter focuses on Configurations 1–5. These configurations form a stepwise comparative sequence, beginning with the HP-only reference case and subsequently introducing PV, EB, HT-ATES, and PVT. The alternative PV + EB + ST + HT-ATES configuration remains available within the model but is not evaluated further, as the comparative analysis of this thesis focuses on the PV- and PVT-based system pathways.

The analysis first considers the Berlin base case. The behaviour of the individual components and their interaction within the integrated system are examined first. This includes the operation of the PV and PVT collectors, the HP, the EB, HT-ATES, the operational pathways, and the resulting thermal-demand coverage. These detailed results are subsequently synthesised through an annual comparison of the system configurations. The analysis is then extended to Madrid to evaluate how the same system design performs under different location-specific weather, demand, and electricity-price conditions. Since the fixed Berlin design is not necessarily suitable for Madrid, a climate-adapted Madrid case is subsequently analysed.

Finally, a sensitivity analysis is performed to determine how the results are affected by key design and operating parameters. The investigated parameters include collector area, HT-ATES volume, recovery efficiency, building heat loss, and HT-ATES charging temperature. Together, these results identify which system-performance outcomes are strongly influenced by component sizing and operating assumptions and which conclusions remain consistent across the investigated cases. To further support the interpretation of the results, selected component outputs are compared with literature and independent reference data in Appendix A. A full system-level validation is not performed, as sufficiently comparable monitored data for the complete integrated system were not available. The broader implications and limitations of these findings are discussed in Chapter 5.

The chapter is structured as follows. Section 4.1 defines the simulation case and performance indicators. Section 4.2 analyses the component behaviour and integrated system operation. Section 4.3 compares the annual performance of the system configurations. Section 4.4 examines the influence of climate and location. Section 4.5 presents the sensitivity analysis. Finally, Section 4.6 summarises the main findings of the chapter.

4.1. Simulation Case and Performance Indicators

The Berlin base case is used as the starting point for the configuration comparison, location comparison, and sensitivity analysis. Berlin is selected because its relatively cold winters and pronounced seasonal mismatch between solar generation and heating demand provide a relevant case for evaluating electrical storage, HP operation, and seasonal thermal storage. The simulation uses hourly weather, demand, and electricity-price data for 2023.

The model represents a residential community of 1000 identical households. Unless stated otherwise, all results are reported per household. System parameters that are common to multiple configurations are retained at the same value to isolate the effect of adding PV generation, electrical battery storage, HT-ATES, or PVT collectors. When a component is present, the reference collector area is 25 m² per household and the electrical

battery capacity is 10 kWh per household. The HT-ATES system is represented at community scale, with the corresponding useful stored energy reported on a per-household basis. The principal parameters of the Berlin base case are summarised in Table 4.1.

Table 4.1: Principal parameters of the Berlin base case.

Parameter	Reference value
Location	Berlin
Simulation year	2023
Number of households	1000
Reporting basis	Per household unless stated otherwise
PV/PVT collector area	25 m ² ($\approx$ 5 kWp) per household
Electrical battery capacity	10 kWh per household
Effective hot-well volume	230,000 m ³
HT-ATES recovery efficiency	0.833
HT-ATES charging temperature	90 °C
Initial useful HT-ATES inventory	2319 kWh _{th} per household
HT-ATES cyclicity tolerance	5% of initial useful inventory

Cyclicity is evaluated by comparing the initial and final useful HT-ATES inventory. A case is considered approximately cyclic when the absolute end-of-year inventory difference remains within 5% of the initial useful inventory. System performance is evaluated using annual grid import and export, peak hourly grid import and export, solar self-consumption, electrical self-sufficiency, operational electricity cost, and energy-weighted HP COP. For configurations containing HT-ATES, useful heat supplied from storage and the end-of-year inventory difference are also considered.

4.2. Component Behaviour and System Operation

Before comparing the annual performance of the complete system configurations, this section examines the component behaviour and integrated system operation for the Berlin base case. Unless stated otherwise, the component results are obtained from the two fully integrated configurations, HP + PV + EB + HT-ATES and HP + PVT + EB + HT-ATES, using the reference component sizes defined in Table 4.1. The analysis builds on the system configurations and operational logic defined in Section 3.3 and Section 3.4. It follows the main energy pathway through the system: first the behaviour of the PV and PVT collectors, followed by the performance of the HP, the operation of the EB, the HT-ATES storage cycle, and finally the operation of the integrated system.

4.2.1. Solar Collector Behaviour

This subsection compares the module temperature, electrical efficiency, and electricity generation of the PV and PVT collectors. Both collector types use the same collector area, irradiance input, reference electrical efficiency, and temperature coefficient. The reference electrical efficiency, η_{ref} , is set to 20% at a module temperature of 25 °C, as defined in Table 2.1. Differences in electrical performance therefore mainly result from differences in the calculated module temperature.

As described in Equation 2.15, the PVT collector includes a cooling heat flux associated with heat extraction by the HP source loop. Since this heat extraction depends on system operation, the cooling effect varies throughout the year. Figure 4.1 compares the resulting collector behaviour during representative weeks in January and July.

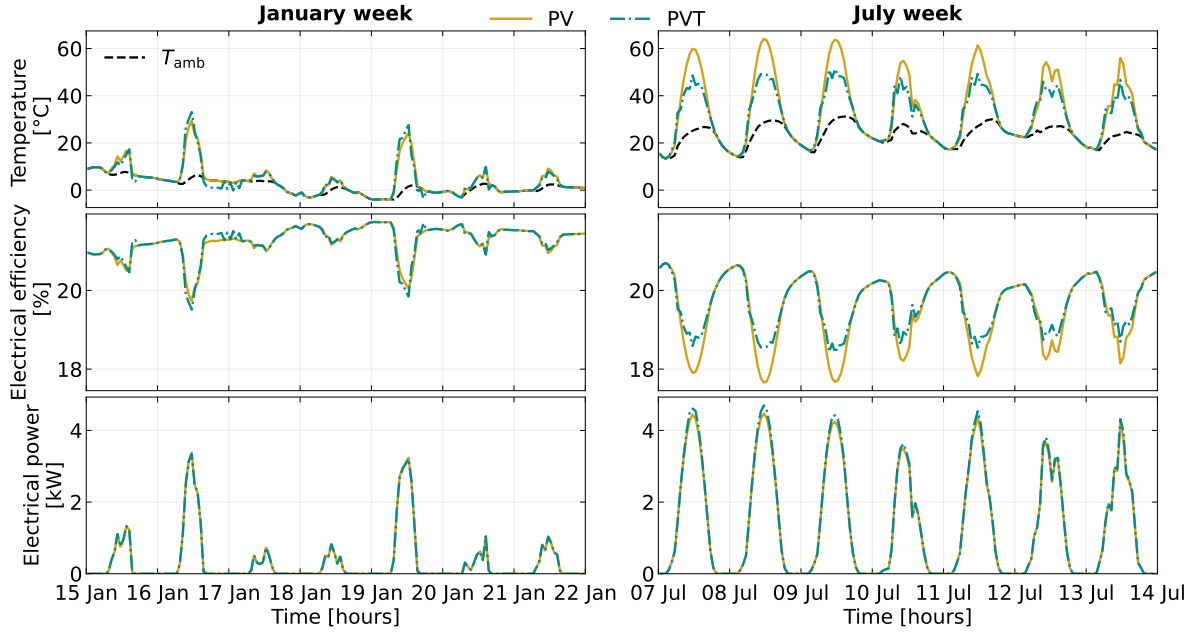


Figure 4.1: Hourly comparison of PV and PVT collector behaviour during representative weeks in January and July for the Berlin base case. The upper panels show the calculated temperature, including the ambient-air temperature for reference, the middle panels show the temperature-corrected electrical efficiency, and the lower panels show the electrical power output.

During the January week, the PV and PVT module temperatures remain relatively close, and the corresponding differences in electrical efficiency and generation are small. Both collectors mostly operate close to ambient temperature, with only short irradiated periods reaching approximately 25–30 °C. The PVT module temperature is occasionally slightly higher than the PV module temperature during these short winter peaks. This occurs because solar-assisted heat extraction is limited in winter, so the PVT cooling term is small or inactive during many hours. The small January differences therefore mainly reflect the coupled PVT–HP operating logic, rather than strong thermal cooling of the collector.

The difference becomes clearer during the July week. Under high irradiance, the standalone PV module exceeds 60 °C during several midday periods, whereas the PVT module generally remains around 45–50 °C during comparable peaks. This lower operating temperature reduces the temperature-related efficiency loss of the PVT collector. In the hottest periods of the July week, the PV electrical efficiency decreases to approximately 18%, while the PVT efficiency remains closer to 18.5–19%. Through the temperature-dependent efficiency relation in Equation 2.6, this results in a slightly higher electrical power output for the PVT collector during high-irradiance hours.

Over the full year, the PVT collector generates 5805 kWh per household, compared with 5731 kWh for PV. This corresponds to an increase of 74 kWh, or approximately 1.3%. The direct electrical benefit of PVT is therefore modest in the present simulation. Its main system-level contribution is related to the heat extracted from the collector and the resulting source temperature supplied to the HP, which is analysed in Subsection 4.2.2.

4.2.2. Heat Pump Behaviour

The HP supplies three different thermal duties: SH, DHW, and HT-ATES charging. These duties operate at different sink temperatures and therefore require different temperature lifts, as described in the adapted HP model in Subsection 2.2.1. In the PV-based configuration, ambient air is used as the heat source. In the PVT-based configuration, the PVT collector loop provides the source temperature available to the HP. The PVT source temperature therefore depends on both solar availability and HP operation.

Figure 4.2 compares the annual energy-weighted COP values during active HP operation. For the air-source HP, the weighted COP decreases from 3.29 for SH to 2.94 for DHW and 2.24 for HT-ATES charging. This follows from the increasing sink temperature required for each duty. Coupling the HP to the PVT collector increases the weighted COP for all three duties. The SH COP increases from 3.29 to 3.66, the DHW COP from 2.94 to 3.83, and the HT-ATES charging COP from 2.24 to 2.76.

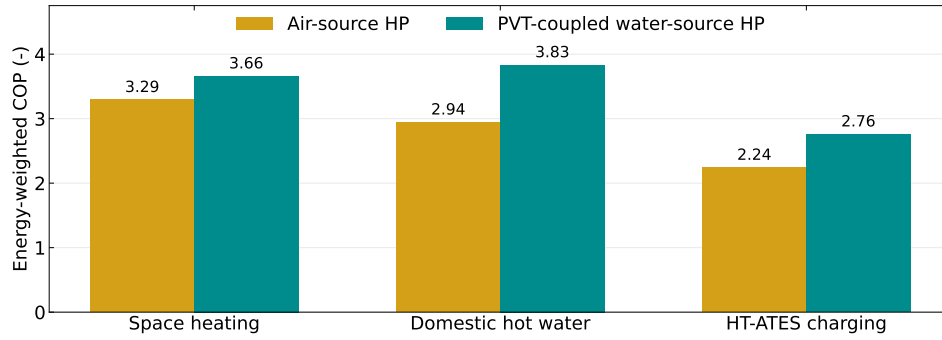


Figure 4.2: Energy-weighted COP of the air-source and PVT-coupled HP for SH, DHW, and HT-ATES charging.

The temporal COP profiles in Figure 4.3 show that the PVT benefit varies throughout the year. During winter, the PVT-coupled HP still improves the COP, but the difference remains moderate because irradiance is limited and the PVT source temperature is not continuously elevated. During summer, the PVT-coupled HP reaches substantially higher COP values, especially for DHW and HT-ATES charging. These duties occur more often during irradiated periods, when the PVT collector can provide a warmer source temperature.

The distinction between all calculated hours and active operating hours is important for interpreting the profiles in Figure 4.3. The red, black, and green lines represent the COP for SH, DHW, and HT-ATES charging, respectively. Thin lines show the calculated COP for all hours, including periods when the corresponding HP duty is not active, while thick line segments indicate the hours that actually contribute to the energy-weighted COP values in Figure 4.2. Some of the highest COP values, particularly for SH during solar-rich periods, occur when there is little or no SH demand. These values therefore represent favourable theoretical temperature-lift conditions in the model rather than delivered heating performance.

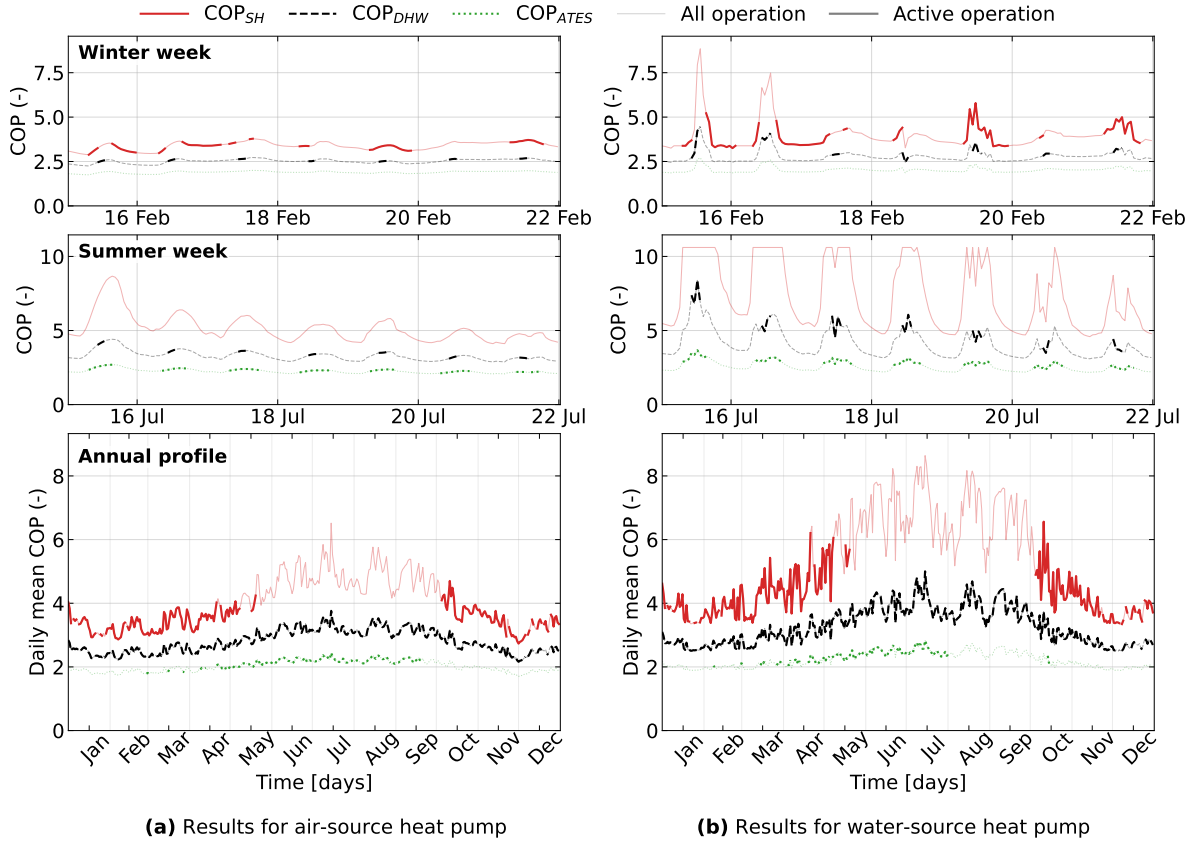


Figure 4.3: Comparison of HP COP behaviour for the PV- and PVT-based configurations during representative winter and summer weeks and over the full simulation year. Thin lines show the calculated COP during all hours, while thick line segments indicate periods in which the corresponding HP duty is active.

The source-temperature profiles in Figure 4.4 explain the higher COP values of the PVT-coupled HP. During the winter week, the ambient-air source temperature mostly remains between approximately -5 and 10 °C. The PVT source temperature is also low during non-irradiated periods, but it can rise above 20 °C during short irradiated intervals. This explains why the annual SH COP improves, while the improvement remains smaller than for DHW and HT-ATES charging.

During the summer week, the source-temperature difference becomes much larger. The ambient-air source temperature generally varies between approximately 15 and 35 °C, while the PVT source temperature frequently reaches 30 – 50 °C during irradiated hours. These higher source temperatures reduce the temperature lift required by the HP, especially for DHW production and HT-ATES charging. This explains the stronger COP improvement for these duties in Figure 4.2. The lower limit visible in the winter week follows from the fallback-source assumption introduced in Subsection 2.2.1. When the calculated PVT source temperature becomes negative, the HP does not use the PVT loop as its source. Instead, it switches to the auxiliary 2 °C water source. This explains why the active source temperature in Figure 4.4 remains at 2 °C during several winter periods, even when the calculated PVT source temperature would otherwise fall below 0 °C.

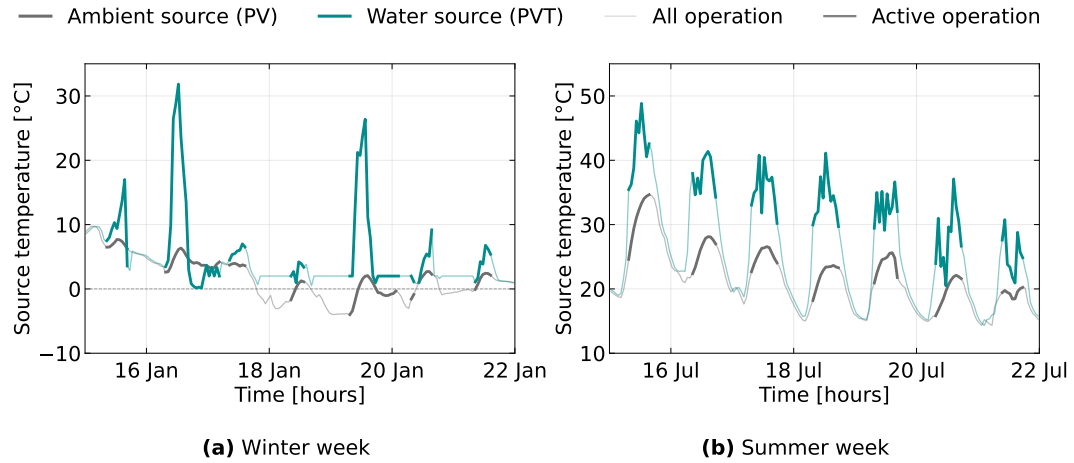


Figure 4.4: Ambient-air and PVT source temperatures available to the HP during representative winter and summer weeks. Thick segments indicate periods when DHW production is active.

The improved HP performance also affects the annual system results. In the PV-based HT-ATES configuration, annual HP electricity consumption is 4092 kWh per household. In the PVT-based HT-ATES configuration, this decreases to 3353 kWh per household, a reduction of 739 kWh or approximately 18%. The lower HP electricity demand is the main reason why the PVT-based configuration achieves a lower net annual electricity cost, even though its grid import is only slightly lower than that of the PV-based HT-ATES configuration.

4.2.3. Electrical Battery Operation

The EB addresses the short-term mismatch between solar electricity generation and electricity demand according to the surplus and shortage logic introduced in Section 3.4. In the Berlin base case, the EB capacity is 10 kWh per household. Figure 4.5 shows the EB charging and discharging power during representative winter, spring, and summer weeks, together with the annual state-of-charge profile. The irradiance profile is included in the weekly panels to provide context for the timing of solar electricity availability, although the EB itself is controlled by the residual electricity surplus or deficit.

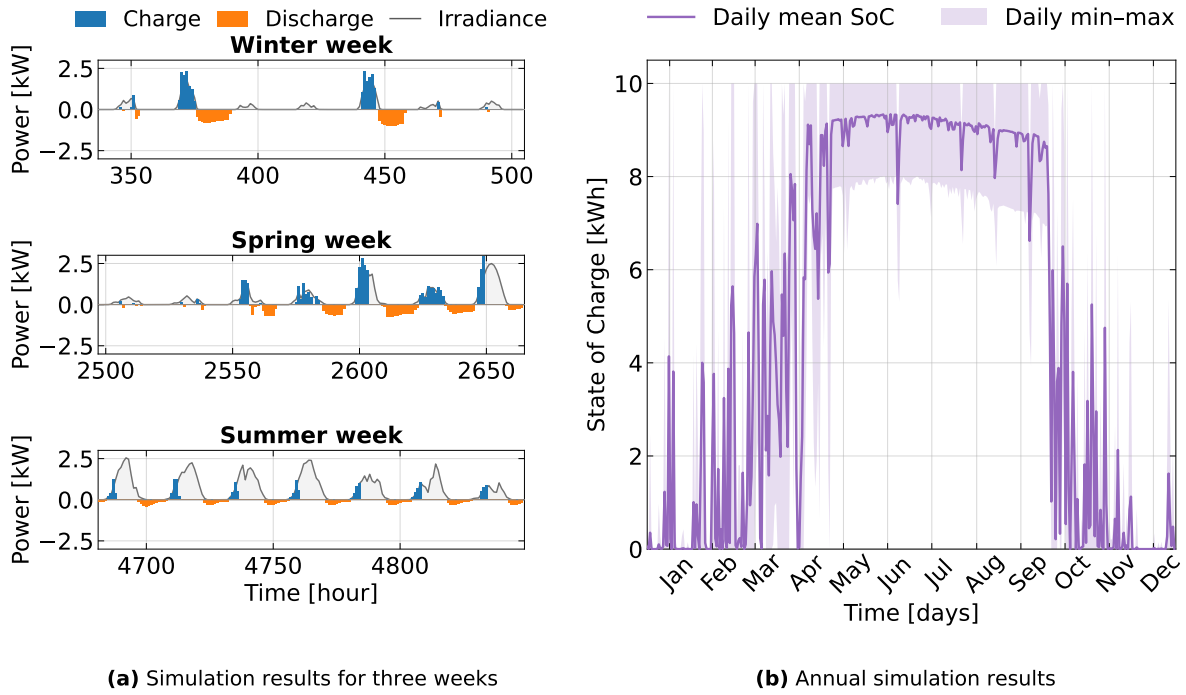


Figure 4.5: Electrical battery charging and discharging during representative winter, spring, and summer weeks, together with the annual daily mean and minimum-maximum state of charge for the Berlin base case. The irradiance profile indicates the timing of solar availability, while battery operation is governed by the residual electricity balance.

During the winter week, charging opportunities are limited because solar irradiance, daylight duration, and solar electricity generation are low. At the same time, heating demand is high, so most available electricity is used directly by the HP and household loads rather than stored in the EB. The EB is therefore frequently discharged and often approaches 0 kWh in the annual state-of-charge profile. More regular daily cycling occurs during spring, when irradiance and daylight hours increase while heating demand decreases. This creates more recurring daytime solar surplus, allowing the battery to charge during the day and discharge later over intraday timescales. During the summer week, the EB also charges during daytime surplus periods and discharges later in the day, but the annual profile shows that it often remains close to its 10 kWh capacity limit. Once the EB is full, additional solar electricity must be allocated to other pathways, such as HT-ATES charging or grid export.

The seasonal state-of-charge behaviour therefore shows that the EB improves the short-term match between solar generation and electricity demand. However, because it is frequently depleted during winter and frequently close to full during summer, it cannot transfer the seasonal solar surplus to the winter heating period. The resulting effect on annual grid import, grid export, self-consumption, and self-sufficiency is quantified in Section 4.3.

4.2.4. HT-ATES Operation

HT-ATES provides seasonal thermal storage by transferring heat from periods of high solar availability to periods with high residential heating demand. During charging, surplus solar electricity operates the HP and raises the hot-well temperature. During discharge, useful heat is extracted directly from the hot well to supply SH and DHW demand. The storage state is governed by the balance between thermal charging, useful heat extraction, and the recovery-efficiency constraint introduced in Subsection 2.4.1.

Figure 4.6 compares the annual hot-well temperature and useful stored thermal energy for the PV- and PVT-based HT-ATES configurations. Both configurations show a clear seasonal cycle. Stored energy decreases during the first months of the year as heat is extracted to meet winter demand. In the PV-based configuration, the useful inventory decreases from 2319 kWh_{th} at the start of the year to a minimum of 28 kWh_{th} near the end of winter. In the PVT-based configuration, the minimum useful inventory remains higher, at 234 kWh_{th}, because the storage is recharged more effectively during the transition towards spring.

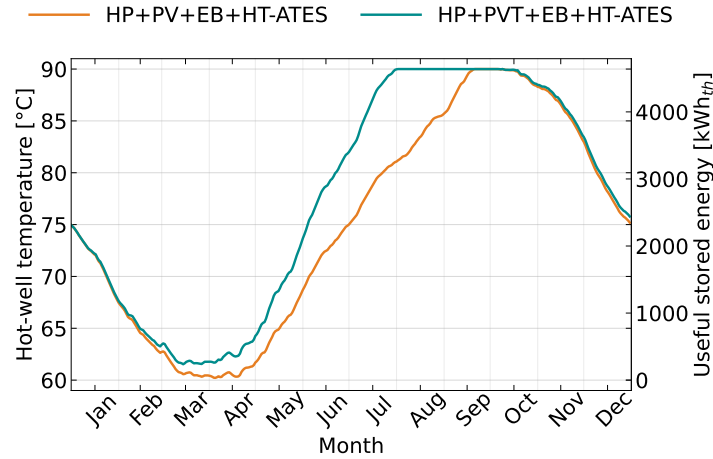


Figure 4.6: Annual HT-ATES operation for the PV- and PVT-based configurations under the Berlin base conditions, hot-well temperature and useful stored thermal energy.

The PVT-based configuration rebuilds its thermal inventory more rapidly during spring and reaches the upper storage level earlier than the PV-based configuration. This follows from the higher HP COP during HT-ATES charging identified in Subsection 4.2.2. The extent of this difference also depends on the installed collector area, as examined further in Subsection 4.5.1. Both configurations reach the maximum useful inventory of 4639 kWh_{th} and the imposed hot-well temperature limit of 90 °C during the charging season. Once this limit is reached, further charging is constrained by the storage capacity, which explains why the profiles become similar during the solar-rich period.

The hot-well temperature follows the same seasonal pattern. In the PV-based configuration, the temperature decreases from approximately 75 °C at the start of the year to a minimum of 60.2 °C near the end of winter. In the PVT-based configuration, the minimum temperature is higher, at 61.5 °C, and the temperature recovers earlier during spring. Both configurations end close to their initial temperature, with final hot-well temperatures of 75.1 °C for the PV-based case and 75.7 °C for the PVT-based case.

This seasonal storage behaviour demonstrates the mechanism through which HT-ATES can reduce grid interaction. By converting summer solar surplus into useful stored heat, HT-ATES reduces the need for HP operation during the winter heating period. Its effect on annual and peak grid import is quantified in Section 4.3. The near-cyclic storage behaviour of the base case is reflected in the end-of-year inventory changes of 0.5% for the PV-based configuration and 4.5% for the PVT-based configuration, as reported in Table 4.6.

4.2.5. Integrated System Operation

This subsection combines the component results by examining the activation of the operating modes defined in Section 3.4 and the resulting thermal-supply pathways. Figure 4.7 shows the operating-mode activation during representative winter, spring, and summer weeks and over the full simulation year.

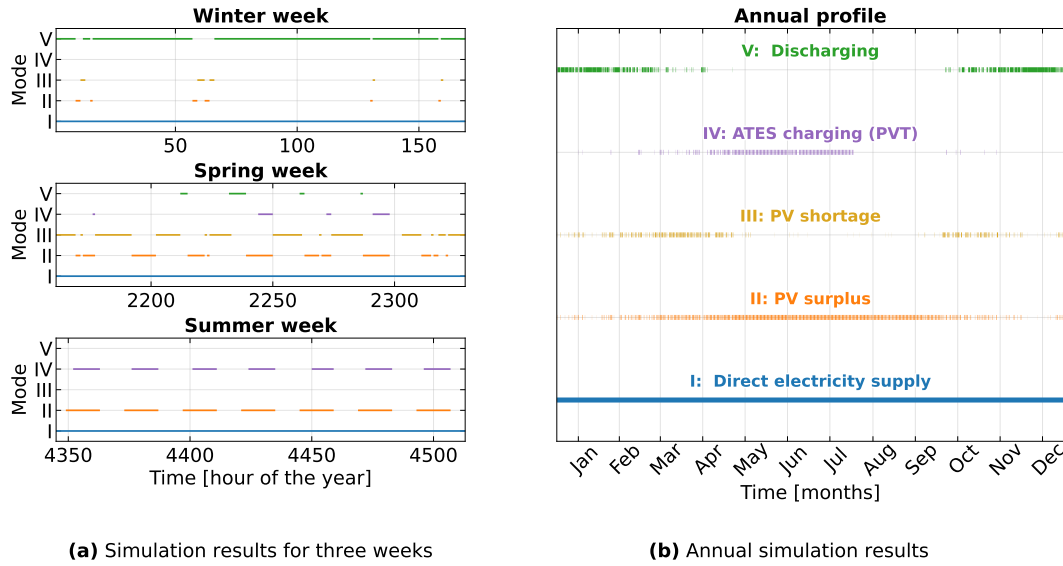


Figure 4.7: Operating modes during representative winter, spring, and summer weeks and over the full simulation year for the Berlin reference case.

Mode I remains active throughout the year because household electricity demand is always present. During the winter week, Mode V is active for extended periods, indicating direct heat supply from HT-ATES. Shorter periods of Mode III represent auxiliary HP operation when stored heat is insufficient or unavailable at the required temperature. During spring, both discharge and charging occur as the system transitions between the heating season and the solar-rich period. During summer, Mode V is largely absent and Mode IV becomes the main thermal-storage pathway as solar surplus is converted into stored heat.

The annual activation pattern confirms that HT-ATES discharge is concentrated in winter and late autumn, whereas HT-ATES charging occurs mainly between spring and early autumn. The overlap between modes also confirms that the operating modes represent energy-flow pathways rather than mutually exclusive system states, as described in Section 3.4.

The resulting heat-supply contributions are shown in Figure 4.8. HP output is attributed to either direct solar electricity or electricity discharged from the EB, while HT-ATES represents direct thermal supply from seasonal storage. SH is supplied predominantly by HT-ATES during the winter months, with additional HP support from direct solar and EB electricity. EB-supported HP operation is most visible during spring and autumn, when solar generation and heating demand only partly overlap.

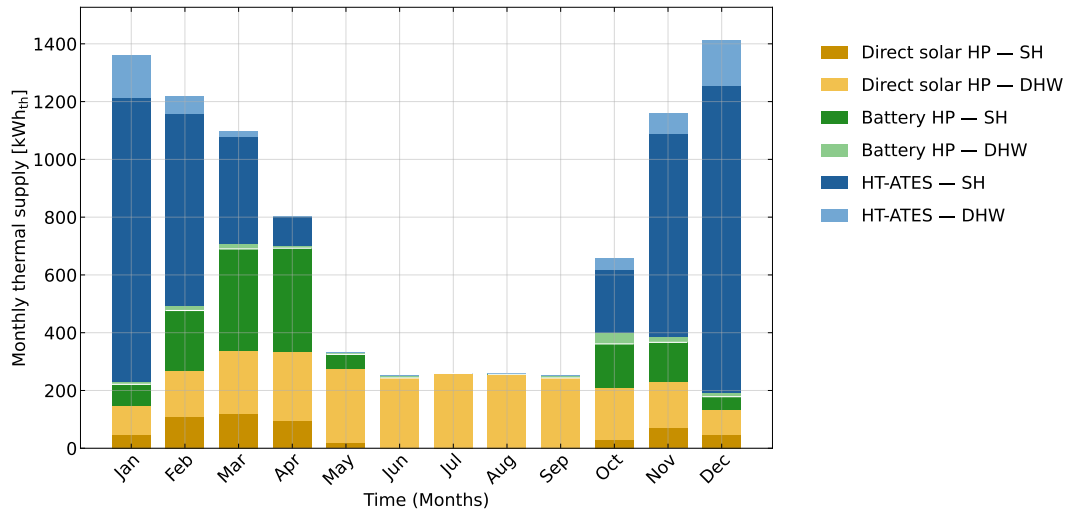


Figure 4.8: Monthly thermal-supply pathways for SH and domestic hot water in the HP+PV+EB+HT-ATES configuration. HP output is attributed to direct solar or battery electricity, while HT-ATES represents direct thermal supply from seasonal storage.

DHW demand remains present throughout the year. During the solar-rich months, it is supplied mainly by the HP using direct solar electricity, while HT-ATES contributes more strongly during winter. Together, Figure 4.7 and Figure 4.8 show how the EB and HT-ATES perform complementary roles. The EB shifts electricity over short timescales, while HT-ATES shifts solar energy seasonally from the charging period to the heating season. These component interactions provide the physical explanation for the differences between the annual system configurations examined in the following section.

4.3. Annual Configuration Performance

Having established the behaviour of the individual components and their interaction within the integrated system, this section compares the annual performance of the five HP-based configurations for the Berlin base case. The configurations are evaluated incrementally to identify the effect of adding PV generation, EB storage, HT-ATES, and PVT collectors. Figure 4.9 shows the resulting annual grid import and export.

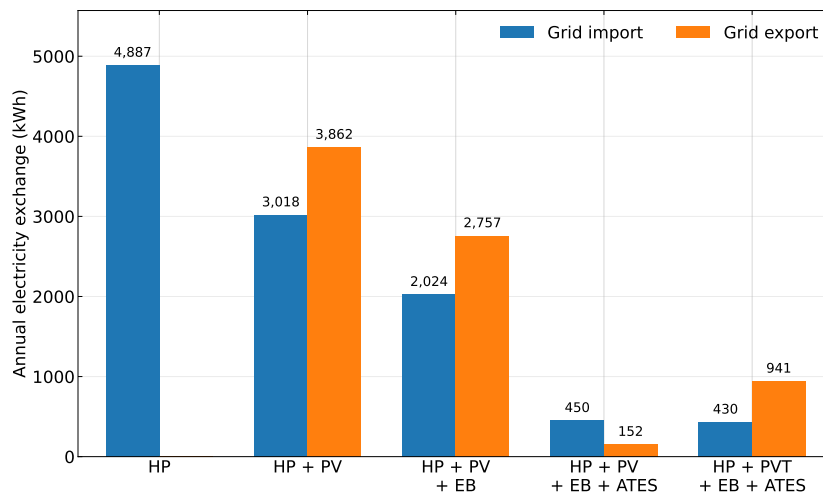


Figure 4.9: Annual grid import and export for the system configurations under the Berlin base-case conditions. Results are reported per household.

The main annual performance indicators are summarised in Table 4.2. These indicators synthesise the collector, HP, EB, HT-ATES, and integrated-system behaviour examined in Section 4.2.

Table 4.2: Main annual performance indicators for the Berlin base case, reported per household.

Configuration	Solar electricity generation (kWh)	Grid import (kWh)	Grid export (kWh)	Peak import (kW)	Self-consumption (%)	Self-sufficiency (%)	Net annual cost (€)
HP	0	4887	0	1.9	–	0	1902
HP + PV	5731	3018	3862	1.8	33	38	878
HP + PV + EB	5731	2024	2757	1.8	52	59	573
HP + PV + EB + HT-ATES	5731	450	152	0.3	97	92	163
HP + PVT + EB + HT-ATES	5805	430	941	0.3	84	92	89

The HP reference configuration requires 4887 kWh of annual grid import. Adding 25 m² of PV collectors reduces this to 3018 kWh, a reduction of approximately 38%. However, the PV configuration also exports 3862 kWh. Although annual PV generation exceeds the annual electricity demand of the household, the self-consumption value of 33% shows that much of the generation is not available at the time it is needed.

Adding the EB of 10 kWh improves the short-term use of solar electricity. Annual grid import decreases further to 2024 kWh, while grid export decreases to 2757 kWh. Self-consumption and self-sufficiency increase to 52% and 59%, respectively. However, the peak grid import remains close to that of the PV-only configuration. The EB therefore reduces the annual amount of electricity exchanged with the grid, but does not resolve the seasonal mismatch between solar generation and heating demand.

The largest reduction in grid dependence occurs when HT-ATES is added. Annual grid import decreases from 2024 kWh in the HP+PV+EB configuration to 450 kWh, while grid export decreases from 2757 to 152 kWh. Self-consumption and self-sufficiency increase to 97% and 92%, respectively, and the peak grid import decreases to 0.3 kW. This reduction in peak electricity demand may also help limit pressure on local distribution networks during periods of high winter demand, although grid congestion is not modelled explicitly in SOLSTICE. This shows that HT-ATES provides the main seasonal-balancing function by allowing summer solar surplus to be converted into useful heat for later use.

Replacing PV with PVT slightly increases annual solar electricity generation from 5731 kWh to 5805 kWh. The annual grid import decreases only modestly, from 450 kWh to 430 kWh. The more important difference is observed in HP operation and cost: annual HP electricity consumption decreases from 4092 kWh in the PV-based HT-ATES configuration to 3353 kWh in the PVT-based configuration, while the net annual electricity cost decreases from € 163 to € 89. At the same time, grid export increases to 941 kWh and self-consumption decreases to 84%, because less solar electricity is required for HP operation. The main benefit of PVT in the annual results is therefore not a large additional reduction in grid import, but improved HP performance and lower operational electricity cost.

In summary, PV reduces annual grid import but introduces substantial electricity export, while the EB improves short-term solar utilisation. HT-ATES has the strongest effect on annual and peak grid import because it addresses the seasonal imbalance between solar generation and heating demand. The PVT-based configuration further improves the integrated system by reducing HP electricity use and operational cost, although this also leaves more electricity available for grid export.

4.4. Influence of Climate and Location

The Berlin base case represents a climate with relatively cold winters and a strong seasonal mismatch between solar generation and heating demand. To assess whether the results are transferable to a different location, the system is also evaluated for Madrid. The comparison uses the location-specific weather, demand, and electricity-price inputs introduced in Section 3.2. Madrid has higher solar availability and ambient temperatures, lower SH and DHW demand, higher cooling demand, and different electricity price conditions than Berlin.

The analysis is performed in two steps. First, the Berlin component sizes and control settings are applied unchanged to Madrid. This fixed-design comparison evaluates how the same system design behaves under different location-specific conditions. Second, the fixed-design results are used to define a climate-adapted Madrid case, in which the collector area and hot-well volume are reduced to better match the lower heating demand and higher solar availability.

4.4.1. Fixed-Design Location Comparison

The fixed-design comparison applies the Berlin component sizes and control settings unchanged to Madrid. The PV/PVT collector area remains 25 m² per household, the EB capacity remains 10 kWh per household, and

the effective hot-well volume remains 230,000 m³. The comparison therefore evaluates the transferability of the same system design, rather than a location-specific optimum. The Berlin results shown in this subsection are the same Berlin base-case results introduced in Section 4.1 and analysed in Section 4.3. They are repeated here only to provide a direct reference for the fixed-design comparison with Madrid.

Figure 4.10 compares the annual grid import and export for Berlin and Madrid. The same 25 m² PV area produces 9935 kWh per household in Madrid, compared with 5731 kWh in Berlin. As a result, grid import is lower for all solar-based configurations in Madrid, but grid export is substantially higher.

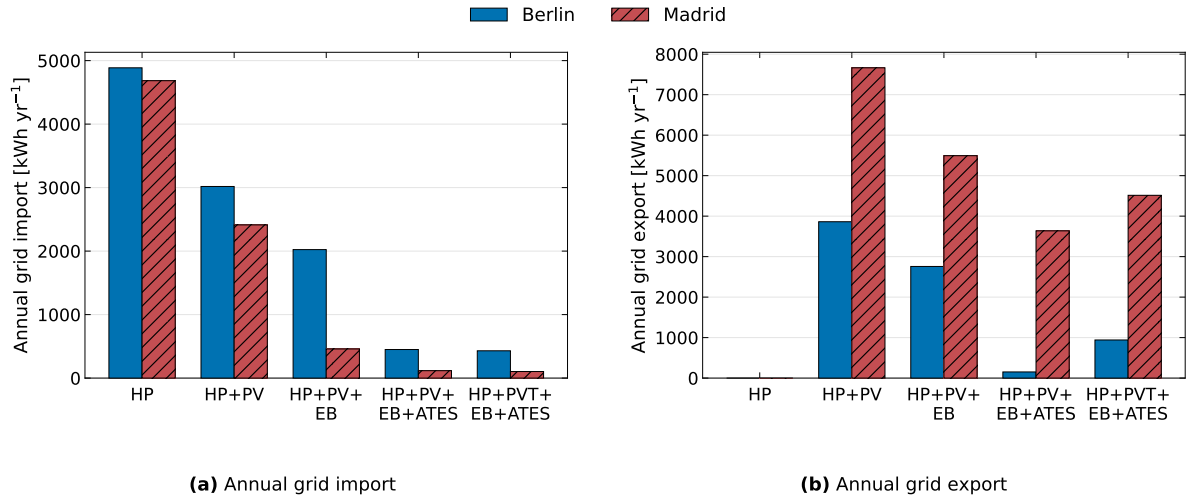


Figure 4.10: Annual grid import and export for the fixed-design Berlin and Madrid cases. The Berlin component sizes and control settings are applied unchanged in both locations.

The fixed-design performance indicators are summarised in Table 4.3. For the HP+PV configuration, Madrid exports 7664 kWh, compared with 3862 kWh in Berlin. Adding the EB reduces Madrid grid import from 2413 to 459 kWh, showing that the larger solar surplus improves the potential for short-term electricity shifting. Adding HT-ATES reduces grid import further to 117 kWh, but the system still exports 3636 kWh. The fixed Madrid design therefore achieves high electrical self-sufficiency, but at the expense of large electricity export and lower solar self-consumption.

Table 4.3: Main annual performance indicators for the fixed-design Berlin and Madrid cases, reported per household. Identical component sizes and control settings are applied in both locations.

Configuration	Location	Solar electricity generation (kWh)	Grid import (kWh)	Grid export (kWh)	Peak import (kW)	Self-consumption (%)	Self-sufficiency (%)	Net annual cost (€)
HP	Berlin	0	4887	0	1.9	—	0	1902
	Madrid	0	4684	0	1.4	—	0	1335
HP + PV	Berlin	5731	3018	3862	1.8	33	38	878
	Madrid	9935	2413	7664	1.2	23	49	213
HP + PV + EB	Berlin	5731	2024	2757	1.8	52	59	573
	Madrid	9935	459	5493	1	45	90	-230
HP + PV + EB + HT-ATES	Berlin	5731	450	152	0.3	97	92	163
	Madrid	9935	117	3636	0.5	63	98	-205
HP + PVT + EB + HT-ATES	Berlin	5805	430	941	0.3	84	92	89
	Madrid	10108	111	4350	0.5	57	98	-253

The PVT-based HT-ATES configuration follows the same general pattern. In Madrid, it reduces annual grid import slightly further than the PV-based HT-ATES configuration, from 117 to 111 kWh. However, grid

export increases from 3636 to 4350 kWh and solar self-consumption decreases from 63% to 57%. The net annual electricity cost decreases from -€ 205 to -€ 253, mainly because the remaining import cost is low while substantial export remuneration is still obtained. These values should therefore be interpreted as operational electricity costs under the selected import and export price assumptions, not as full system costs.

The HT-ATES storage behaviour in Figure 4.11 shows that the main issue in Madrid is not insufficient solar supply, but excess charging potential relative to the heating demand available for seasonal discharge. In Berlin (blue line), both the PV- and PVT-based HT-ATES configurations follow a clear seasonal cycle: the useful inventory decreases during winter, recharges during spring and summer, and finishes close to its initial value. In Madrid (red line), the storage is only slightly discharged during winter and reaches the maximum useful inventory and the 90 °C hot-well temperature limit already during spring.

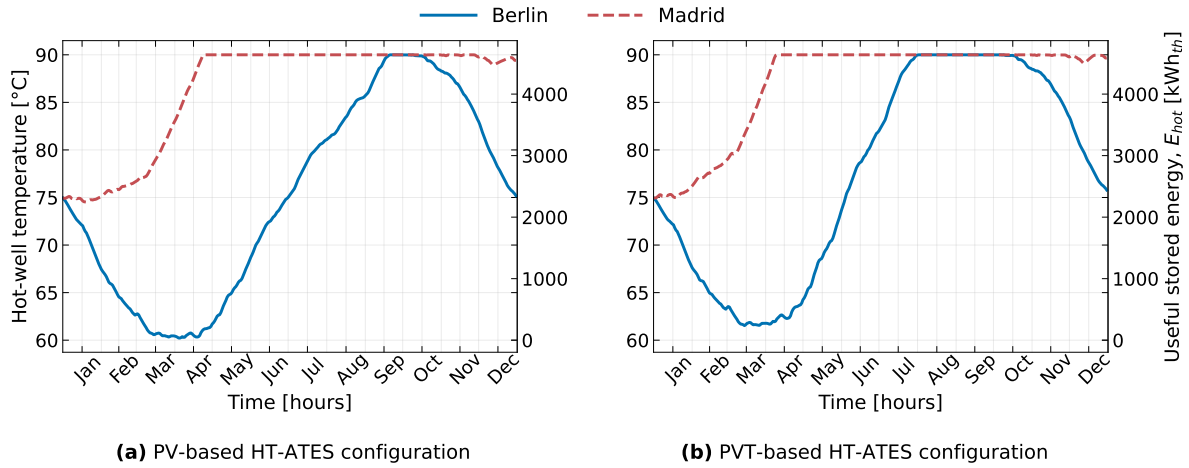


Figure 4.11: Annual hot-well temperature and useful stored thermal energy for Berlin and Madrid using the same HT-ATES size and control settings.

For the PV-based Madrid system, the useful inventory ends the year at 4543 kWh_{th} per household, compared with an initial inventory of 2319 kWh_{th}. This corresponds to an end-of-year inventory surplus of 2224 kWh_{th}, or 96% of the initial useful inventory. The minimum useful inventory remains high at 2235 kWh_{th}, showing that the storage is barely depleted during winter before reaching the maximum useful inventory of 4639 kWh_{th} during spring.

The PVT-based Madrid system shows the same behaviour. Its useful inventory ends the year at 4592 kWh_{th}, corresponding to an inventory surplus of 2273 kWh_{th}, or 98% of the initial useful inventory. Its minimum useful inventory is 2299 kWh_{th}, which is even higher than in the PV-based case. The fixed Madrid design is therefore strongly non-cyclic for both collector technologies and oversized relative to the local balance between solar availability and heating demand. This motivates the climate-adapted Madrid sizing analysed in the following subsection.

4.4.2. Climate-Adapted Madrid Case

The fixed-design comparison shows that the Berlin base-case system provides more solar generation and HT-ATES capacity than can be effectively used in Madrid. A climate-adapted Madrid case is therefore defined by reducing the PV/PVT collector area and hot-well volume. The EB capacity, hot-well temperature limits, and control logic are retained. The same adjusted sizing is applied to the PV- and PVT-based configurations to preserve a controlled comparison between the two collector technologies.

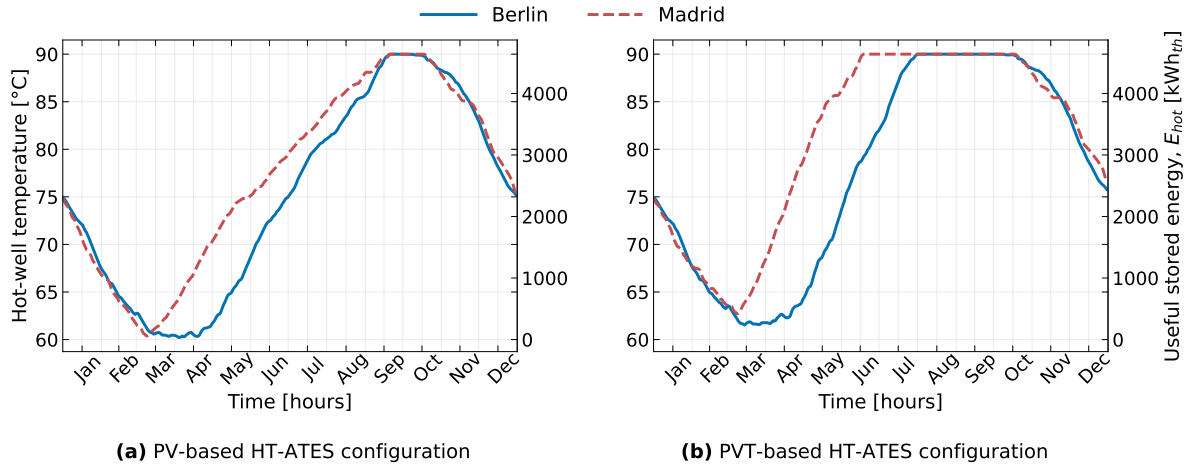
The adjusted design parameters are summarised in Table 4.4. The collector area is reduced from 25 to 13 m² per household, while the effective hot-well volume is reduced from 230,000 to 100,000 m³. This reduces the maximum useful HT-ATES inventory from 4639 to 2017 kWh_{th} per household.

Table 4.4: Adjusted design parameters and resulting HT-ATES characteristics for the Berlin base case and climate-adapted Madrid case.

Parameter	Berlin base case	Climate-adapted Madrid
PV/PVT collector area per household	25 m ² ($\approx 5 \text{ kW}_p$)	13 m ² ($\approx 2.6 \text{ kW}_p$)
effective hot-well volume	230,000 m ³	100,000 m ³
Injection volume V_i	90,000 m ³	43,000 m ³
Calculated HT-ATES recovery efficiency	83.3%	79.1%
Maximum useful HT-ATES inventory per household	4639 kWh _{th}	2017 kWh _{th}

The recovery efficiency is recalculated for the adjusted storage design rather than retained from the Berlin base case. The lower injection volume in the Madrid case changes the calculated recovery efficiency from 83.3% to 79.1%. The climate-adapted case therefore changes both the storage capacity and the storage recovery characteristics.

Figure 4.12 compares the resulting HT-ATES behaviour with the Berlin base case. After resizing, the Madrid storage profiles again show a seasonal discharge and recharge cycle. In the PV-based Madrid case, the useful inventory decreases from 1008 kWh_{th} to a minimum of 25 kWh_{th} during winter, reaches the maximum value of 2017 kWh_{th} during the charging season, and ends the year at 1024 kWh_{th}. This corresponds to an end-of-year inventory difference of 1.5%. The PVT-based Madrid case is depleted less deeply, with a minimum useful inventory of 180 kWh_{th}, but ends the year with a larger surplus of 10.2%. In both configurations, the hot-well temperature remains within the imposed 60–90 °C operating range.

**Figure 4.12:** Annual hot-well temperature and useful stored thermal energy for the Berlin base case and climate-adapted Madrid case: (a) PV-based HT-ATES configuration and (b) PVT-based HT-ATES configuration.

The annual performance of the climate-adapted Madrid case is summarised in Table 4.5. Reducing the collector area lowers annual solar generation in Madrid from 9935 to 5166 kWh for the PV-based system and from 10108 to 5189 kWh for the PVT-based system. Despite this lower solar generation, the Madrid systems require less HP electricity than the Berlin base case because of the lower heating demand and more favourable source temperatures.

Table 4.5: Annual performance of the PV- and PVT-based HT-ATES configurations for the Berlin base case and climate-adapted Madrid case.

Configuration	Location	Solar generation (kWh)	HP electricity consumption (kWh)	Weighted COP for HT-ATES charging	Grid import (kWh)	Grid export (kWh)	Self-consumption (%)	Self-sufficiency (%)	Net annual cost (€)
HP + PV + EB + HT-ATES	Berlin	5731	4092	2.24	450	152	97	92	163
	Madrid	5166	2339	2.39	295	157	97	94	70
HP + PVT + EB + HT-ATES	Berlin	5805	3353	2.76	430	941	84	92	89
	Madrid	5189	1827	3.22	265	656	87	94	30

For the PV-based HT-ATES configuration, HP electricity consumption decreases from 4092 kWh in Berlin to 2339 kWh in the climate-adapted Madrid case. For the PVT-based configuration, it decreases from 3353 to 1827 kWh. The weighted HT-ATES charging COP also increases, from 2.24 to 2.39 for the PV-based system and from 2.76 to 3.22 for the PVT-based system.

Grid import is lower in the climate-adapted Madrid case than in Berlin for both integrated configurations, reaching 295 kWh for the PV-based system and 265 kWh for the PVT-based system. The corresponding net annual electricity costs are also lower, at € 70 and € 30, respectively. Compared with the PV-based Madrid system, the PVT-based system reduces HP electricity consumption by 511 kWh and lowers the net annual electricity cost by € 41, although grid export increases from 157 to 656 kWh.

In summary, the location comparison shows that directly transferring the Berlin design to Madrid results in a mismatch between solar-energy supply and heating demand, evident from the limited winter discharge, early saturation of the HT-ATES, and substantial end-of-year inventory surplus. After adapting the collector area and storage volume, the Madrid case becomes more balanced and retains the main benefits of the integrated PV/PVT, EB, HP, and HT-ATES system. The results therefore show that system performance depends not only on the selected technologies, but also on matching the component sizes to the local balance between solar availability and heating demand.

4.5. Sensitivity Analysis

The sensitivity analysis evaluates how the main design and operating parameters influence HT-ATES behaviour and overall system performance. Unless stated otherwise, the Berlin reference case is used and all parameters remain at their base-case values except for the parameter under investigation. The charging-temperature cases form an exception, as the collector area, hot-well volume, and recovery efficiency are adjusted together to obtain corresponding system designs.

The seasonal storage profiles are used to explain the physical response of the system, while the main annual indicators are summarised in Table 4.6. Particular attention is given to unmet thermal demand and the end-of-year inventory difference, since reductions in electricity consumption or cost are not considered beneficial when they result from incomplete demand supply or non-cyclic storage operation.

4.5.1. Collector-area sensitivity

The collector-area sensitivity evaluates reductions from the base value of 25 m² to 22.5 and 20 m². The resulting HT-ATES profiles are shown in Figure 4.13.

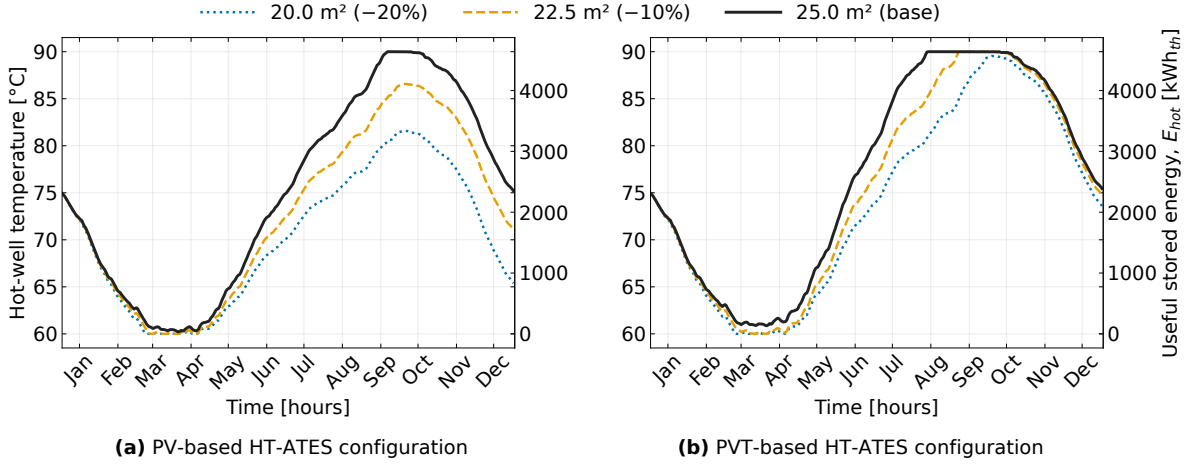


Figure 4.13: Annual hot-well temperature and equivalent useful stored thermal energy for different PV/PVT collector areas: (a) PV-based configuration and (b) PVT-based configuration.

Reducing the collector area decreases the available solar electricity and delays the seasonal recharge of HT-ATES. This effect is strongest for the PV-based configuration. At 22.5 m², the PV system reaches full storage depletion and ends the year with an inventory change of -27%, together with 177 kWh_{th} of unmet thermal demand. At 20 m², the maximum useful inventory only reaches 3336 kWh_{th}, and the end-of-year inventory change decreases further to -65%, with 399 kWh_{th} of unmet demand.

The PVT-based system is less sensitive to the area reduction because of its higher HT-ATES charging COP. At 22.5 m², it remains almost cyclic, with an inventory change of -0.2% and no unmet demand. At 20 m², the storage also reaches depletion, but the inventory change remains limited to -5.6% and unmet demand is 166 kWh_{th}. The lower electricity use and cost in reduced-area cases therefore have to be interpreted together with thermal-demand coverage and cyclic storage operation.

4.5.2. HT-ATES storage-size sensitivity

The hot-well storage volume is varied by -20% and +20% relative to the base value of 230,000 m³. The corresponding annual useful-inventory profiles are presented in Figure 4.14.

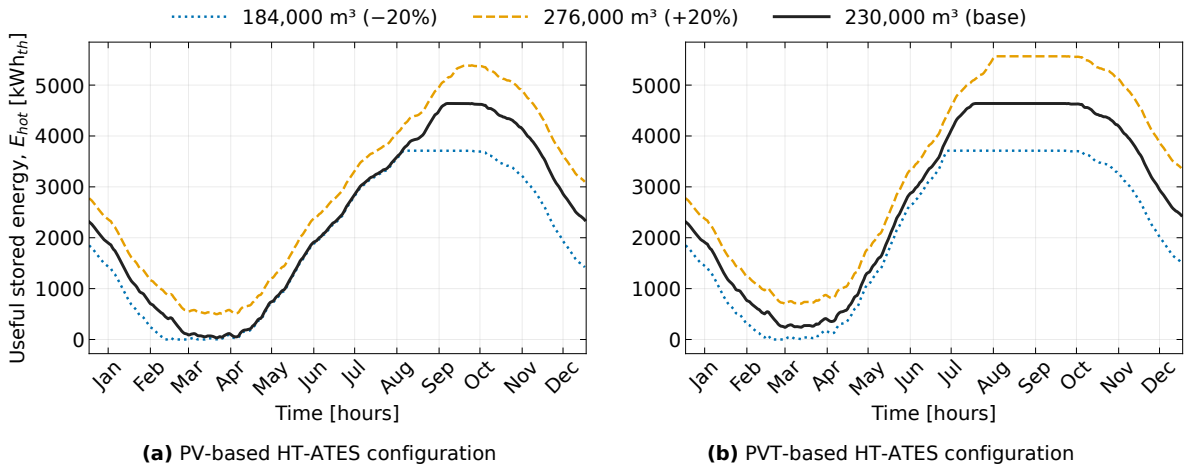


Figure 4.14: Annual useful thermal energy stored in hot-well for different storage volumes: (a) PV-based configuration and (b) PVT-based configuration.

Reducing the storage volume to 184,000 m³ causes the available thermal inventory to be depleted during the heating season. The maximum useful inventory is reduced to 3711 kWh_{th}, and both configurations reach full

depletion. The PV- and PVT-based configurations consequently show unmet thermal demands of 436 and 230 kWh_{th}, with end-of-year inventory changes of -24.4% and -19.4%, respectively.

Increasing the volume to 276,000 m³ prevents unmet demand, but the larger storage is not fully discharged over the annual cycle. The minimum useful inventory remains 492 kWh_{th} for the PV-based case and 697 kWh_{th} for the PVT-based case, while the end-of-year inventory changes increase to +10.7% and +20.4%, respectively. The base storage volume therefore provides a closer match between the available charging energy, useful storage capacity, and annual thermal demand.

4.5.3. HT-ATES recovery-efficiency sensitivity

The influence of HT-ATES recovery efficiency is evaluated by reducing η_r from the base value of 0.83 to 0.75 and 0.65. The resulting seasonal storage profiles are shown in Figure 4.15.

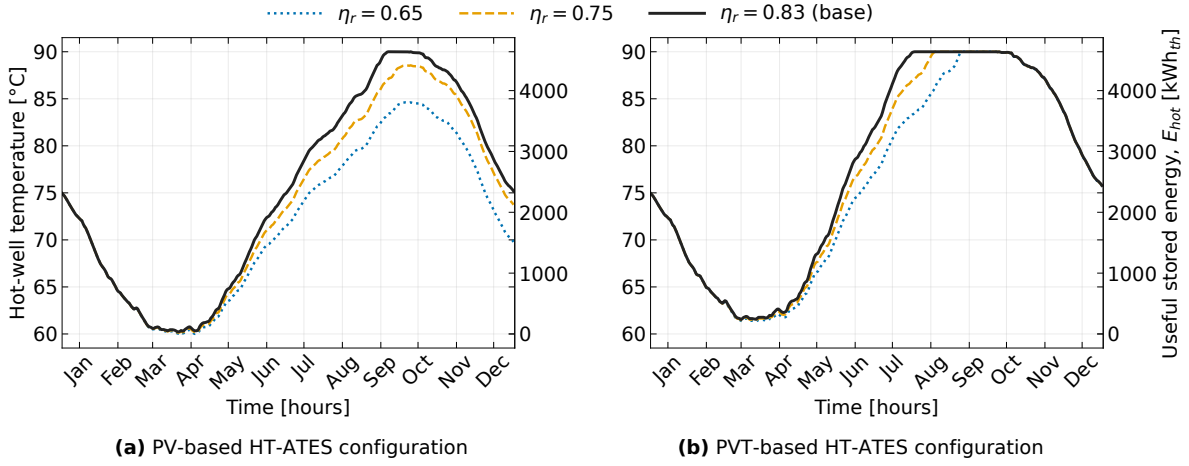


Figure 4.15: Annual HT-ATES hot-well temperature and equivalent useful stored thermal energy for different thermal recovery efficiencies: (a) PV-based configuration and (b) PVT-based configuration.

A lower recovery efficiency reduces the fraction of charged heat that can be supplied usefully during the heating season. The PV-based configuration is particularly sensitive to this reduction. At $\eta_r = 0.75$, thermal demand remains fully supplied, but the minimum useful inventory decreases to 15 kWh_{th} and the annual inventory change becomes -9.2%. At $\eta_r = 0.65$, the storage reaches full depletion, the inventory change decreases to -35.5%, and 8 kWh_{th} of unmet thermal demand occurs.

The PVT-based system maintains full thermal-demand coverage at both reduced efficiencies. The end-of-year inventory change remains close to cyclic operation, at +4.4% for $\eta_r = 0.75$ and +4.2% for $\eta_r = 0.65$. However, the lower recovery efficiency still increases HP electricity consumption and cost: for the PVT case, annual HP electricity use rises from 3576 to 3905 kWh when η_r decreases from 0.75 to 0.65.

4.5.4. Building Heat-Loss Sensitivity

The influence of the building heat-loss coefficient is evaluated for $H = 75, 100$, and 150 W K^{-1} . The value of 100 W K^{-1} represents the Berlin base case, while the lower and higher values represent buildings with reduced and increased heat losses, respectively. All other building and system parameters, including the collector area, volume, recovery efficiency, battery capacity, and control settings, are retained at their base-case values. The DHW demand also remains unchanged.

Figure 4.16 compares the resulting annual SH and cooling demands. Increasing the heat-loss coefficient raises annual SH demand from 4.2 MWh_{th} at 75 W K^{-1} to 6 MWh_{th} in the base case and 9.8 MWh_{th} at 150 W K^{-1} . Cooling demand changes in the opposite direction, decreasing from 0.9 to 0.4 MWh_{th}.

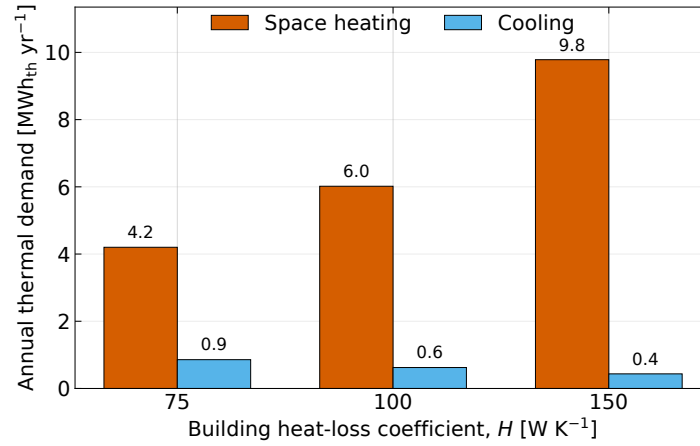


Figure 4.16: Annual SH and cooling demand for different building heat-loss coefficients. DHW demand remains unchanged between the cases.

The corresponding effect on seasonal thermal storage is shown in Figure 4.17. At 75 W K^{-1} , the lower heat demand leaves unused stored heat at the end of the year, with inventory changes of +27.3% for the PV-based case and +30.2% for the PVT-based case. At 150 W K^{-1} , both configurations reach storage depletion and become strongly non-cyclic, with inventory changes of -55.5% for PV and -50.4% for PVT. The corresponding unmet thermal demands are 1751 and 1417 kWh_{th} , respectively.

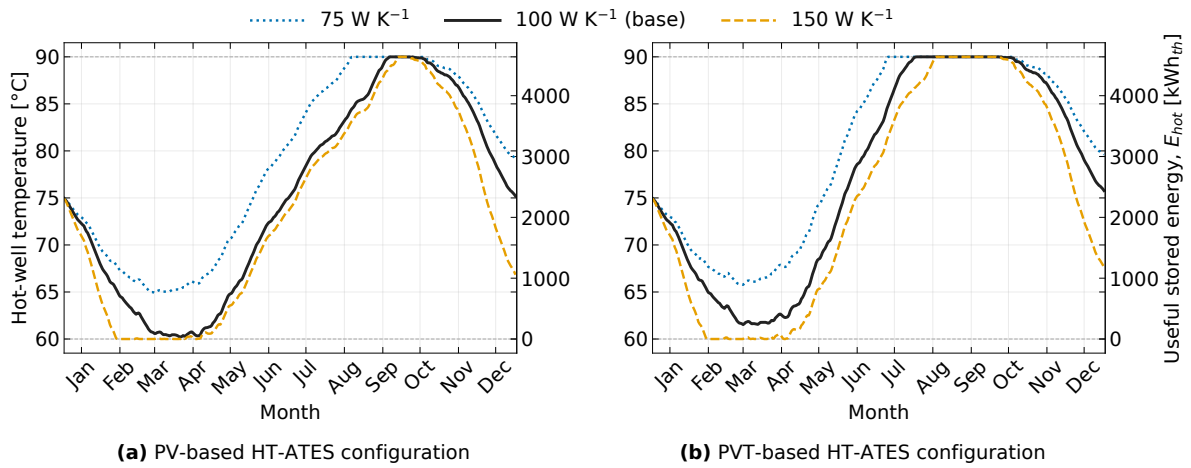


Figure 4.17: Annual HT-ATES hot-well temperature and equivalent useful stored thermal energy for different building heat-loss coefficients: (a) PV-based configuration and (b) PVT-based configuration.

4.5.5. HT-ATES charging-temperature sensitivity

The charging-temperature cases differ from the preceding sensitivities because the charging temperature is not varied independently. If the base-case collector area and hot-well volume are retained, lowering the charging temperature leads to an unbalanced storage profile, as shown in Appendix C. The storage charges and depletes rapidly, indicating that the original sizing is no longer suitable for the lower storage-temperature range. For this reason, the 70 and 80 $^{\circ}\text{C}$ cases are treated as coupled redesign cases, in which the collector area, hot-well volume, injection volume, and resulting recovery efficiency are adjusted together.

The resulting PVT-based storage behaviour is shown in Figure 4.18. Compared with the 90 $^{\circ}\text{C}$ base case, the hot-well volume increases from 230,000 to 400,000 m^3 at 80 $^{\circ}\text{C}$ and to 820,000 m^3 at 70 $^{\circ}\text{C}$. At the same time, the PVT collector area is reduced from 25 to 20 m^2 at 80 $^{\circ}\text{C}$ and to 18 m^2 at 70 $^{\circ}\text{C}$. These design changes produce storage profiles that remain closer to an annual balance, with cyclic inventory changes of +9.3% at 80 $^{\circ}\text{C}$ and -5% at 70 $^{\circ}\text{C}$, compared with +4.5% for the 90 $^{\circ}\text{C}$ base case.

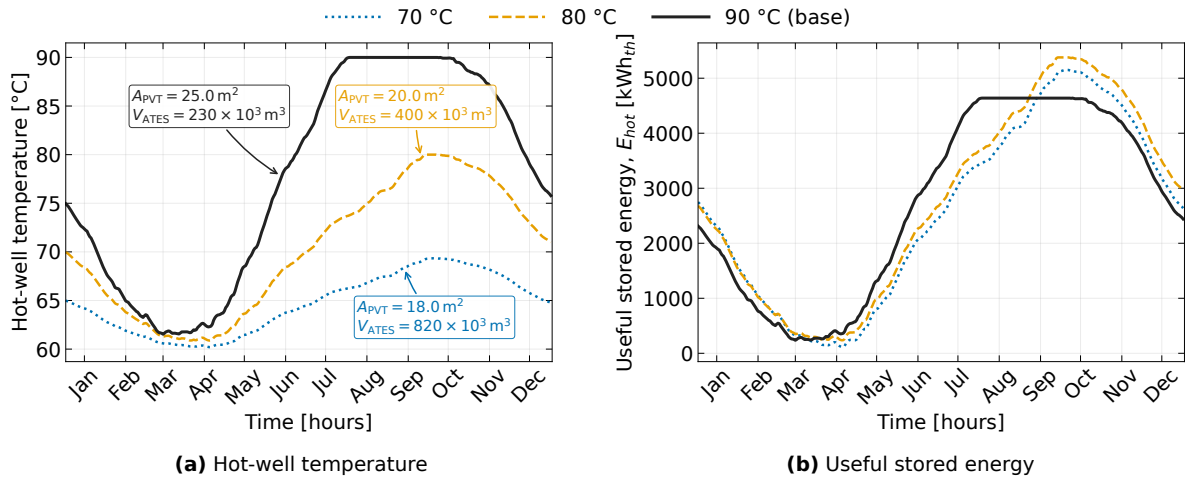


Figure 4.18: Annual HT-ATES behaviour for the coupled PVT-based charging-temperature redesign cases: (a) hot-well temperature and (b) useful stored thermal energy. The collector area, hot-well volume, and calculated recovery efficiency are adjusted for each charging-temperature design.

Reducing the charging temperature decreases the required HP temperature lift and therefore increases the HT-ATES charging COP. This effect is illustrated in Figure 4.19. For the PVT-based system, the annual weighted charging COP increases from 2.76 at 90 °C to 3.16 at 80 °C and 3.62 at 70 °C. The same trend is visible for the PV-based system, where the charging COP increases from 2.24 to 2.49 and 2.82, respectively. The PVT-coupled HP therefore retains a clear COP advantage at all charging temperatures.

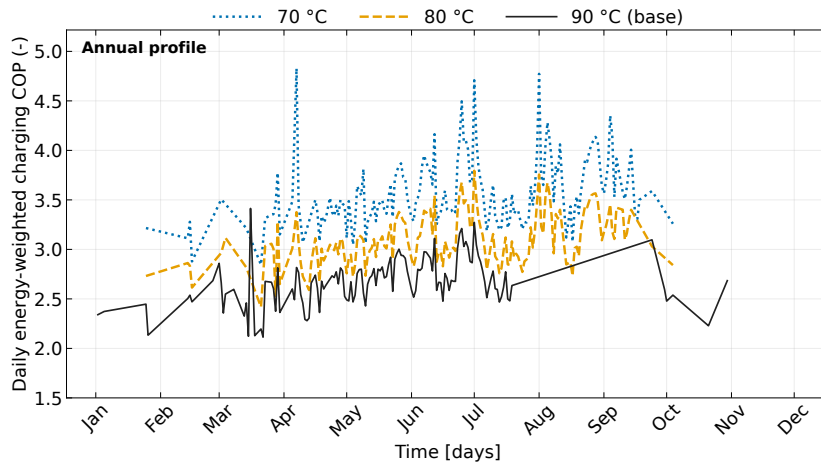


Figure 4.19: Daily energy-weighted HP COP during HT-ATES charging for the coupled PVT-based charging-temperature redesign cases.

The improved COP does not automatically translate into lower grid import or cost, because the system sizing also changes. For the PVT-based cases, annual HP electricity consumption decreases from 3353 kWh in the 90 °C base case to 3177 kWh at 80 °C and 2793 kWh at 70 °C. However, grid import increases to 483 and 511 kWh, respectively, because the redesigned systems use smaller PVT collector areas. The charging-temperature cases therefore show that lower storage temperatures can improve HP performance, but that the overall result depends on the complete system design rather than on the charging temperature alone.

4.5.6. Overall sensitivity comparison

The principal annual results of all sensitivity cases are summarised in Table 4.6. In addition to the system-performance indicators, unmet thermal demand and the end-of-year HT-ATES inventory change are included to distinguish genuine performance improvements from cases that do not provide repeatable annual operation.

Table 4.6: Sensitivity-analysis results for the PV- and PVT-based HT-ATES configurations.

Sensitivity group	Case	Config.	Collector area [m ²]	Hot-well volume [10 ³ m ³]	Recovery efficiency [–]	Charging temperature [°C]	Charging COP [–]	HP electricity [kWh]	Grid import [kWh]	Net cost [EUR]	ATES heat supplied [kWh _{th}]	Unmet thermal demand [kWh _{th}]	Cyclic inventory change [%]
Base case	Base	PV	25	230	0.833	90	2.24	4092	450	163	4855	0	0.5
Base case	Base	PVT	25	230	0.833	90	2.76	3353	430	89	4608	0	4.5
Collector area	22.5 m ²	PV	22.5	230	0.833	90	2.25	3758	531	208	4931	177	-27
Collector area	22.5 m ²	PVT	22.5	230	0.833	90	2.79	3318	454	142	4867	0	-0.2
Collector area	20 m ²	PV	20	230	0.833	90	2.25	3292	631	248	4981	399	-65
Collector area	20 m ²	PVT	20	230	0.833	90	2.84	3241	530	207	4987	166	-5.6
Hot-well volume	184 × 10 ³ m ³	PV	25	184	0.833	90	2.22	3771	594	183	4419	436	-24.4
Hot-well volume	184 × 10 ³ m ³	PVT	25	184	0.833	90	2.75	3125	499	92	4377	230	-19.4
Hot-well volume	276 × 10 ³ m ³	PV	25	276	0.833	90	2.24	4243	450	176	4855	0	10.7
Hot-well volume	276 × 10 ³ m ³	PVT	25	276	0.833	90	2.76	3555	430	106	4608	0	20.4
ATES efficiency	0.75	PV	25	230	0.75	90	2.24	4243	450	176	4855	0	-9.2
ATES efficiency	0.75	PVT	25	230	0.75	90	2.76	3576	430	108	4608	0	4.4
ATES efficiency	0.65	PV	25	230	0.65	90	2.24	4246	452	177	4847	8	-35.5
ATES efficiency	0.65	PVT	25	230	0.65	90	2.78	3905	430	136	4608	0	4.2
Building heat loss	75 W K ⁻¹	PV	25	230	0.833	90	2.22	3616	414	112	3421	0	27.3
Building heat loss	75 W K ⁻¹	PVT	25	230	0.833	90	2.72	2971	395	46	3253	0	30.2
Building heat loss	150 W K ⁻¹	PV	25	230	0.833	90	2.25	4810	1063	422	6209	1751	-55.5
Building heat loss	150 W K ⁻¹	PVT	25	230	0.833	90	2.78	4037	892	295	6215	1417	-50.4
Charging temperature	80 °C	PV	23	400	0.847	80	2.49	3809	470	184	5056	0	-0.5
Charging temperature	80 °C	PVT	20	400	0.847	80	3.16	3177	483	186	5153	0	9.3
Charging temperature	70 °C	PV	22	820	0.86	70	2.82	3595	482	189	5161	0	7.1
Charging temperature	70 °C	PVT	18	820	0.86	70	3.62	2793	511	200	5391	0	-5

Notes: Annual energy and cost values are reported per household. The cyclic inventory change is expressed relative to the initial useful HT-ATES inventory. The charging-temperature cases are coupled system redesigns in which the collector area, hot-well volume, recovery efficiency, and charging temperature were changed simultaneously.

Colour coding: Light colours in the first three columns distinguish the sensitivity groups. For unmet thermal demand, green indicates zero unmet demand, yellow indicates up to 10 kWh_{th}, and red indicates more than 10 kWh_{th}. For cyclic inventory change, green indicates an absolute deviation of at most 5%, yellow indicates a deviation between 5% and 20%, and red indicates a deviation above 20%.

Overall, Table 4.6 shows that system performance is mainly determined by the balance between solar charging potential, HT-ATES storage capacity, and annual heat demand. Cases that disturb this balance show either storage depletion and unmet demand or excess end-of-year inventory. This is most visible for the reduced collector-area, reduced storage-volume, and high heat-loss cases. For example, reducing the PV collector area to 20 m² results in 399 kWh_{th} of unmet thermal demand and an inventory change of -65%, while increasing the building heat-loss coefficient to 150 W K⁻¹ leads to 1751 kWh_{th} of unmet demand in the PV-based case and 1417 kWh_{th} in the PVT-based case.

The PVT-based configuration is generally more robust than the PV-based configuration because of its higher HT-ATES charging COP. This is especially clear in the collector-area and recovery-efficiency sensitivities. At 22.5 m², the PVT-based case remains almost cyclic, with an inventory change of -0.2% and no unmet demand, whereas the corresponding PV-based case has an inventory change of -27% and 177 kWh_{th} of unmet demand. Similarly, when the recovery efficiency is reduced to 0.65, the PVT-based case still supplies the full thermal demand and remains close to cyclic operation, while the PV-based case reaches -35.5% inventory change.

The charging-temperature redesign cases show that lower storage temperatures improve HP performance, but not independently of system sizing. For the PVT-based system, the weighted charging COP increases from 2.76 at 90 °C to 3.16 at 80 °C and 3.62 at 70 °C. However, these cases also require different collector areas and much larger hot-well volumes. The resulting performance therefore depends on the complete system design rather than on charging temperature alone.

The sensitivity analysis therefore confirms that apparent reductions in electricity consumption or operational cost cannot be interpreted as improvements by themselves. They must be evaluated together with unmet thermal demand and the end-of-year HT-ATES inventory balance. Within the simplified SOLSTICE V2 framework, the best-performing cases are those that maintain full thermal-demand coverage while remaining close to cyclic storage operation.

4.6. Conclusion

This chapter addressed Research Objective 3 by evaluating the integrated SOLSTICE V2 system under different climatic conditions and design settings. For the Berlin base case, adding PV, a 10 kWh EB, and subsequently HT-ATES reduced annual grid import from 4887 to 450 kWh per household and increased electrical self-sufficiency to 92%. Replacing PV with PVT resulted in a similar grid import of 430 kWh but reduced annual HP electricity use from 4092 to 3353 kWh, mainly due to the improved HP source conditions and higher HT-ATES charging COP.

The climate comparison showed that the Berlin design could not be transferred directly to Madrid. After climate-specific resizing, however, approximately 94% electrical self-sufficiency was achieved with a reduced collector area of 13 m² per household and a smaller HT-ATES volume of 100 000 m³. The sensitivity analysis further showed that collector area, storage volume, recovery efficiency, and building heat loss strongly influence storage cyclicity and thermal-demand coverage.

Overall, the results demonstrate that high system performance depends on matching solar generation, seasonal-storage capacity, and thermal demand to the local conditions. Research Objective 3 was therefore achieved by identifying how climate and selected design parameters influence the integrated system performance.

Conclusion and Recommendations

5.1. Conclusion

This thesis further developed and applied the SOLSTICE modelling framework for the assessment of integrated solar-based residential energy systems with seasonal HT-ATES. The primary objective was to determine whether a transparent, hourly Excel-based model can provide physically plausible and practically useful comparisons of systems combining solar generation, heat pumps, electrical storage, and seasonal thermal storage. To achieve this goal, three research objectives were addressed:

- **Research Objective 1:** The existing component models were critically assessed and retained, adapted, or newly developed where necessary to improve their physical consistency while preserving the transparent structure of SOLSTICE (Chapter 2).
- **Research Objective 2:** A consistent integrated-system simulation methodology was developed by defining common input processing, system configurations, operational modes, and energy-flow priorities (Chapter 3).
- **Research Objective 3:** The integrated methodology was applied to compare system configurations under different climatic conditions and to assess the influence of key design and operating parameters (Chapter 4).

5.1.1. Summary of key findings

The main findings of this thesis are summarised as follows:

- **Component and framework development:** The irradiance, PVT, HP, EB, and HT-ATES representations were adapted or developed where required, while the existing PV and ST models were retained as suitable first-order representations. The main improvements include POA irradiance, duty-specific HP operation, battery losses, improved PVT-HP coupling, and a bounded useful-energy representation of HT-ATES.
- **Integrated system methodology:** The developed hourly methodology combines solar generation, residential demand, HP operation, electrical and seasonal thermal storage, and grid exchange within a consistent energy-balance framework. Defined system configurations and rule-based operational modes allow the contribution of individual components and energy-flow pathways to be compared transparently.
- **Technical system performance:** For the Berlin reference case, adding PV, a 10 kWh EB, and HT-ATES reduced annual grid import from 4887 to 450 kWh per household and increased electrical self-sufficiency to approximately 92%.
- **Role of PVT:** Replacing PV with PVT increased annual electrical generation by only approximately 1.3%, but improved the heat-source conditions of the HP. This increased the energy-weighted HT-ATES charging COP from 2.24 to 2.76 and reduced annual HP electricity consumption from 4092 to 3353 kWh per household.
- **Climate, sizing, and sensitivity:** The system design must be adapted to local solar availability and thermal demand. In Madrid, approximately 94% electrical self-sufficiency was maintained after reducing the collector area from 25 to 13 m² per household and the effective hot-well volume from 230 000 to 100 000 m³. The sensitivity analysis further showed that collector area, storage size, recovery efficiency, building heat loss, and charging temperature strongly influence thermal-demand coverage and annual HT-ATES cyclicality.
- **Economic assessment:** The calculated annual net electricity cost decreased from approximately € 1902 for the Berlin HP-only case to € 163 and € 89 for the corresponding PV- and PVT-based HT-ATES systems.

These values represent operational electricity costs only and therefore do not establish overall economic feasibility.

5.1.2. Final conclusion

This thesis demonstrates that combining solar generation, short-term electrical storage, HP operation, and seasonal HT-ATES can substantially reduce residential grid dependence when the system is appropriately sized for local climatic and demand conditions. The EB primarily addresses daily electricity balancing, while HT-ATES enables summer solar surpluses to be shifted to winter heat demand, and PVT further improves performance by providing more favourable heat-source conditions for the HP. Under the investigated climate-adapted cases, electrical self-sufficiency above 90% was achieved while meeting the annual thermal demand. SOLSTICE V2 therefore provides a transparent and accessible framework for early-stage comparison of integrated residential energy systems, while detailed design and economic feasibility assessment require further validation, site-specific modelling, and techno-economic analysis.

5.2. Recommendations

Based on the findings and limitations of this thesis, the following recommendations are proposed for the further development and application of SOLSTICE V2.

1. **Further develop the HT-ATES representation.**

Include a simplified cold-well energy balance, charging and discharging flow limits, and groundwater pumping electricity. The relationship between storage volume, injected water volume, and recovery efficiency should also be treated more consistently.

2. **Perform a complete techno-economic and LCOH assessment.**

Extend the economic assessment beyond electricity import and export costs by including investment, maintenance, replacement, and financing costs. The resulting LCOH should be compared with suitable reference heating systems.

3. **Apply SOLSTICE to a wider range of climates and locations.**

Evaluate additional climates, particularly colder regions with a stronger seasonal mismatch between solar generation and heat demand. System sizing and aquifer parameters should be adapted to the local conditions for each case.

4. **Further improve the user-friendliness of SOLSTICE V2.**

The developed input sheets, results summary, and dashboard improve accessibility, but further work could simplify model interaction, navigation, and the presentation of assumptions and warnings.

5. **Further develop the ST system integration.**

The ST model should be coupled more explicitly with the HP, allowing solar-thermal energy to act as a lower-temperature heat source before being upgraded to the required HT-ATES charging temperature.

6. **Separate the model and location data.**

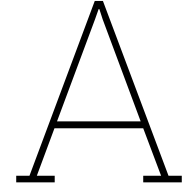
Future versions could store location-specific weather, irradiance, demand, and electricity-price data in a separate data file and import only the selected location into SOLSTICE V2. This would limit workbook size and simplify the addition, updating, and management of a larger number of locations.

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Component-Level Validation

A targeted comparison was performed to assess whether selected component outputs of SOLSTICE V2 are consistent with independent reference data and literature. Percentage differences are only reported where the model and reference values represent sufficiently comparable quantities and operating conditions.

Table A.1: Targeted comparison of SOLSTICE V2 component behaviour with independent reference data and literature.

Component	Quantity	SOLSTICE (current study)	V2	Literature	Difference / comparison	Source
PV	Annual irradiation, Berlin	1183 kWh m ⁻² yr ⁻¹		1303 kWh m ⁻² yr ⁻¹	-9.2%	PVGIS [35]
PV	Annual irradiation, Madrid	2111 kWh m ⁻² yr ⁻¹		2152 kWh m ⁻² yr ⁻¹	-1.9%	PVGIS [35]
PVT	Summer module-temperature reduction	approx. 10–15 °C		11.9–18.9 °C	Comparable range	Han et al. [47]
PVT	Effect on HP COP	2.53 → 3.13		3.06 → 3.46	Same trend; different system	Han et al. [47]
HP	COP at 0 °C source and 40 °C sink	3.00		2.79	+7.6%	Ruhnau et al. [48]
HP	COP at 0 °C source and 60 °C sink	2.32		2.11	+9.9%	Ruhnau et al. [48]
HT-ATES	Recovery-efficiency formulation	Geerts relation; $\eta_r = 0.833$ in reference case		Screening relation fitted to numerical HT-ATES simulations	No direct percentage comparison	Geerts et al. [39]

The comparisons support the use of the simplified component models for first-order system analysis. However, they do not constitute validation of a complete integrated installation.

B

SOLSTICE V2 Workbook Interface

This appendix provides an overview of the main worksheets of the developed SOLSTICE V2 workbook. The figures illustrate the workflow from defining the simulation inputs and inspecting the underlying data to calculating the solar irradiance, evaluating system performance, comparing configurations, and inspecting the hourly energy-flow calculations. The screenshots are intended to demonstrate the structure and transparency of the Excel-based framework rather than to provide additional quantitative results.

B.1. Input sheet

The *Input* sheet forms the main user interface for defining a SOLSTICE V2 simulation. It combines the active location and demand data with the principal building, solar, electrical-storage, and HT-ATES parameters. The user can select the location, number of households, system configuration, and irradiance source and can modify the main model inputs without directly accessing the underlying hourly calculation sheets. Supporting plots provide immediate feedback on the selected demand, solar-resource, and seasonal thermal-demand conditions.

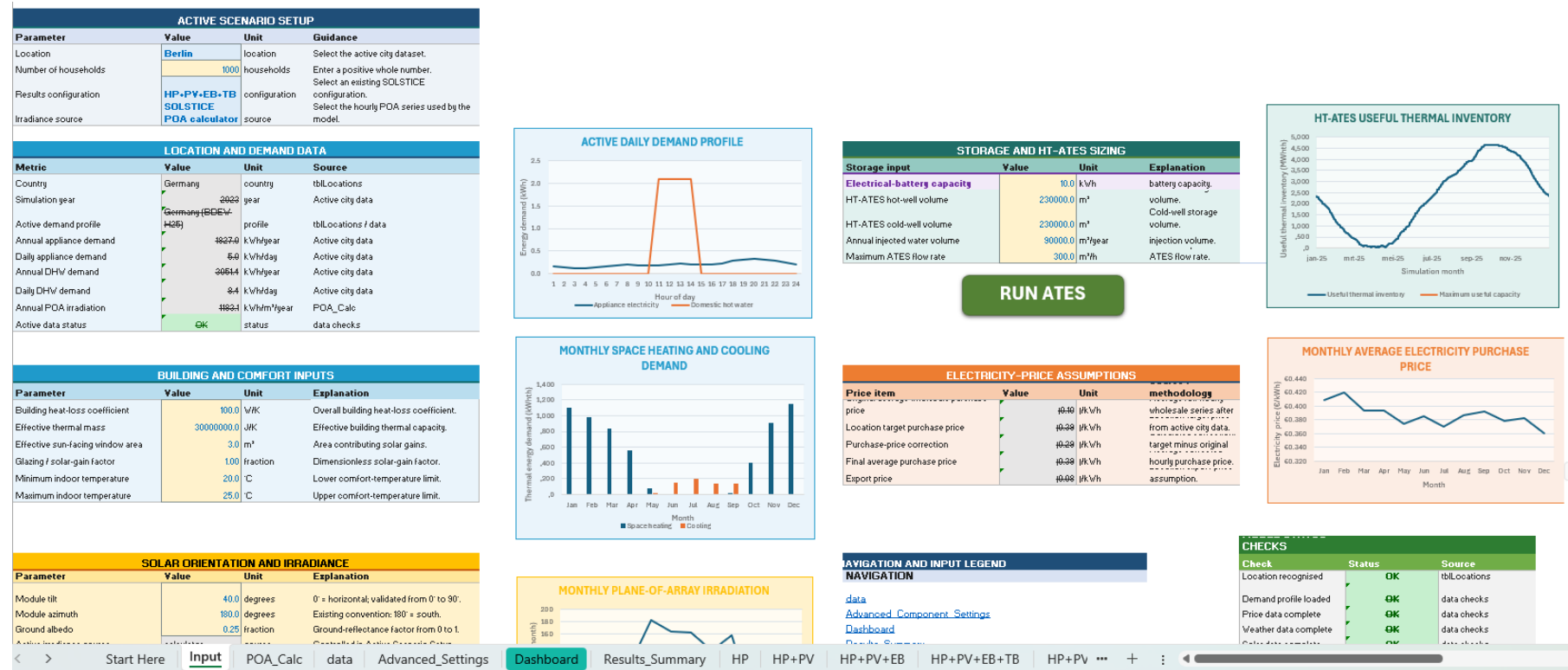


Figure B.1: SOLSTICE V2 *Input* sheet showing the active scenario setup, location and demand data, building parameters, solar inputs, storage sizing, electricity-price assumptions, and supporting visualisations.

B.2. Location and hourly input data

The *Data* sheet contains the location-dependent information used by the hourly simulation. The selected location determines the corresponding electricity-price data, weather conditions, residential demand profiles, and solar-resource data. Data-completeness checks verify that the required hourly series and demand profiles are available before the simulation is evaluated. The visible data structure allows the user to inspect the underlying input series used throughout the model.

SOLSTICE — LOCATION AND HOURLY INPUT DATA

ACTIVE LOCATION SETUP

Setting / Parameter

Selection / Value

Unit

Simulation year

2023

year

Selected location

Berlin

location

Demand profile

Germany (BDEW H25)

profile

Target buy price

0.39

€/kWh

Export price

0.08

€/kWh

Annual appliance demand

1827.0

kWh/year

Annual DHW demand

3051.4

kWh/year

Daily appliance demand

5.0

kWh/day

Daily DHW demand

8.4

kWh/day

TARGET PURCHASE-PRICE COMPATIBILITY

Country

Location

Target price (€/kWh)

Germany

Berlin

60.39

Spain

Madrid

60.29

LOCATION SELECTOR SUPPORT

Location

Demand profile

Named range

input_Location_List

Berlin

Germany (BDEW H25)

Madrid

Spain (IDAE)

DATA COMPLETENESS CHECKS

Check

Count / Value

Required

Status

Source

Notes

Location exists

1 / 1

OK

tblLocations

Selected city

Demand profile exists

24 / 24

OK

tblDemandProf

24-hour profile

Appliance demand available

1827.0 > 0

OK

tblLocations

kWh/year

DHW demand available

3051.4 > 0

OK

tblLocations

kWh/year

Wholesale-price records

8760 / 8760

OK

tblHourlyLocations

W/m²

Temperature records

8760 / 8760

OK

tblHourlyLocations

°C

Wind-speed records

8760 / 8760

OK

tblHourlyLocations

m/s

GHI records

8760 / 8760

OK

tblHourlyLocations

W/m²

DNI records

8760 / 8760

OK

tblHourlyLocations

W/m²

DHI records

8760 / 8760

OK

tblHourlyLocations

W/m²

Solar-azimuth records

8760 / 8760

OK

tblHourlyLocations

degrees

Solar-zenith records

8760 / 8760

OK

tblHourlyLocations

degrees

PVGIS POA records

Optional unless 0

OK

tblHourlyLocations

No populated source series in current workbook

Appliance fraction total

100.0% / 1

OK

tblDemandProf

100% target

DHW fraction total

100.0% / 1

OK

tblDemandProf

100% target

Overall data status

OK

All required checks

OK

Selected location OK only when required data pass

ACTIVE ELECTRICITY-PRICE DATA

Complete 8,760-hour wholesale purchase and export-price series used by SOLSTICE.

Hour

Wholesale purchase price (€/MWh)

Export price (€/kWh)

1

-8.41

0.08

2

-15.70

0.08

3

-17.51

0.08

4

-17.21

0.08

5

-13.82

0.08

6

-12.26

0.08

7

-9.65

0.08

8

-11.29

0.08

9

-0.27

0.08

10

-0.33

0.08

11

-0.31

0.08

12

4.10

0.08

13

5.68

0.08

14

10.24

0.08

ACTIVE WEATHER DATA

Complete 8,760-hour ambient-temperature and wind-speed series used by SOLSTICE.

Hour

Ambient temperature (°C)

Wind speed (m/s)

1

14.9

6.4

2

14.9

6.3

3

14.7

6.2

4

14.4

6.0

5

14.2

5.7

6

13.9

5.5

7

14.0

5.8

8

14.3

6.1

9

14.1

6.1

10

14.2

6.1

11

14.5

6.1

12

14.7

6.1

13

14.8

5.7

14

14.7

5.2

ACTIVE DEMAND PROFILE

Selected 24-hour appliance and domestic-hot-water profile.

Hour

Appliance fraction

DHW fraction

Appliance energy (kW)

DHW energy (kWh)

1

3.0%

0.0%

0.2

0.0

2

2.7%

0.0%

0.1

0.0

3

2.5%

0.0%

0.1

0.0

4

2.5%

0.0%

0.1

0.0

5

2.6%

0.0%

0.1

0.0

6

3.0%

0.0%

0.2

0.0

7

3.8%

0.0%

0.2

0.0

8

4.1%

0.0%

0.2

0.0

9

3.8%

0.0%

0.2

0.0

10

3.7%

0.0%

0.2

0.0

11

3.8%

25.0%

0.2

2.1

12

4.1%

25.0%

0.2

2.1

13

4.3%

25.0%

0.2

2.1

14

4.2%

25.0%

0.2

2.1

ACTIVE SOLAR AND POA DATA

Raw solar inputs, calculated SOLSTICE POA, optional PVGIS POA, and final irradiance used.

Hour

GHI (W/m²)

DNI (W/m²)

DHI (W/m²)

Solar azimuth (°)

Solar zenith (°)

Calculated SOLAR (W/m²)

1

0.0

0.0

0.0

22.9

143.0

0.0

2

0.0

0.0

0.0

46.2

143.8

0.0

3

0.0

0.0

0.0

64.3

136.3

0.0

4

0.0

0.0

0.0

78.8

127.6

0.0

5

0.0

0.0

0.0

91.3

118.6

0.0

6

0.0

0.0

0.0

102.7

109.5

0.0

7

0.0

0.0

0.0

113.8

100.9

0.0

8

9.3

37.2

7.4

125.2

92.9

0.0

9

52.4

140.7

38.1

137.2

85.9

0.0

10

94.5

15.7

91.2

150.0

80.6

0.0

11

119.6

8.3

117.6

163.6

77.0

0.0

12

102.9

11.2

100.2

177.7

75.5

0.0

13

125.2

44.4

115.4

191.9

76.2

0.0

14

80.3

29.0

76.5

205.7

79.2

0.0

Start Here

Input

POA_Calc

data

Advanced_Settings

Dashboard

Results_Summary

HP

HP+PV

HP+PV+EB

HP+PV+EB+TB

HP+PV

+

:

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Figure B.2: SOLSTICE V2 *Data* sheet containing the active location setup, data-completeness checks, electricity-price series, weather data, residential demand profiles, and solar-resource inputs.

B.3. Plane-of-array irradiance calculator

The *POA_Calc* sheet determines the solar irradiance incident on the selected collector plane. The user specifies the location, module tilt, module azimuth, ground albedo, and irradiance source. Hourly global horizontal irradiance, direct normal irradiance, diffuse horizontal irradiance, and solar-position data are then used to determine the direct, diffuse, and ground-reflected contributions to the plane-of-array irradiance. The resulting irradiance series provides the common solar input for the photovoltaic, photovoltaic-thermal, and solar-thermal component models. Alternatively, an externally supplied PVGIS plane-of-array irradiance series can be selected.

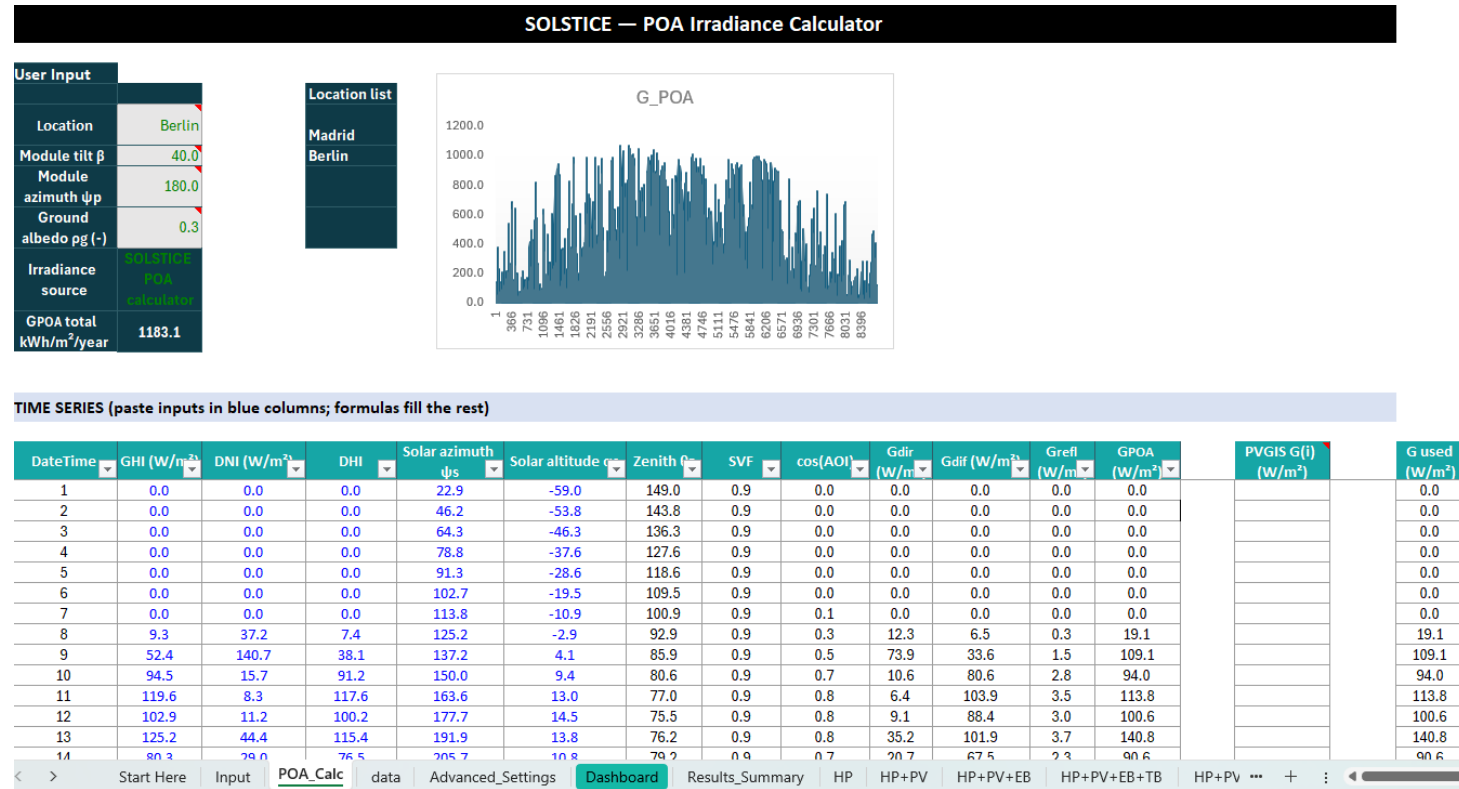


Figure B.3: SOLSTICE V2 *POA_Calc* sheet showing the user-defined collector orientation, hourly solar-resource inputs, calculated plane-of-array irradiance components, and alternative PVGIS irradiance input.

B.4. Dashboard

The *Dashboard* provides a compact visual overview of the active simulation. It combines the main annual performance indicators with monthly and hourly results for grid exchange, electricity cost, self-consumption, self-sufficiency, heat-pump performance, thermal supply, solar-collector behaviour, and HT-ATES operation. Key indicators and model-status checks are displayed directly alongside the figures to enable rapid assessment of the selected scenario.



Figure B.4: SOLSTICE V2 *Dashboard* providing a visual overview of the principal system-performance indicators and the behaviour of the electrical and thermal subsystems.

B.5. Results summary

The *Results_Summary* sheet collects the principal performance indicators of the available system configurations in a single overview. The comparison includes solar generation, electricity consumption, annual and peak grid exchange, solar self-consumption, electrical self-sufficiency, heat-pump electricity consumption and coefficient of performance, and operational electricity costs. For configurations containing HT-ATES, additional diagnostics are provided for recovery efficiency, useful thermal inventory, unmet thermal demand, and annual storage cyclicality.

SOLSTICE V2 — Results Summary

Note: After changing the location, ATES inputs, or solar collector area, fully recalculate the workbook and run the Update ATES Results macro before using the ATES results.

SECTION 1 — RUN INFORMATION

Active locationBerlinLinked to existing selector / source

Simulation year2023Derived from input time series

Number of household:1000.0Linked to HT-ATES input

Active weather dataset = Table4(Ambi)Formula source used for weather rows

Electricity-price counGermanyMapped from active location

Date/time last review Updates on recalculation

ATES cyclic-balance1.0%Editable screening tolerance, not a physical model parameter

SECTION 2 — CONFIGURATION COMPARISON

Configuration	Solar collector type	Total solar collector area [m²]	Electrical battery capacity [kWh]	Annual solar electricity generation [kWh]	Annual total electricity consumption [kWh]	heat-pump electricity consumption [kWh]	Annual grid import [kWh]	Annual grid export [kWh]	Peak hourly grid import [kW]	Peak hourly grid export [kW]	Solar self-consumption [%]	Electrical self-sufficiency [%]	Weighted COP for space heating [-]	Weighted COP for domestic hot water	Weighted COP for ATES charging [-]	Average import price [€/kWh]	Annual import cost [€]	Annual export revenue [€]	Net annual electricity cost
HP	-	-	-	0.0	4893.5	3066.5	4893.5	0.0	1.9	0.0	-	0.0%	3.2	2.3	-	10.39	11901.70	10.00	11901.70
HP+PV	PV	25.0	-	5730.8	4893.5	3066.5	3014.9	3852.1	1.7	4.2	32.8%	36.4%	3.2	2.3	-	10.40	11200.13	1323.58	11876.54
HP+PV+EB	PV	25.0	10.0	5730.8	4893.5	3066.5	2019.0	2745.6	1.7	4.2	52.1%	58.7%	3.2	2.3	-	10.40	11802.20	1230.63	11571.57
HP+PV+EB+TB	PV	25.0	10.0	5730.8	5332.8	4105.8	450.0	137.4	0.3	3.5	97.6%	92.4%	3.3	2.3	2.2	10.39	1176.23	111.54	1164.69
HP+PVT+EB+TB	PVT	25.0	10.0	5827.8	5250.4	3423.4	428.4	891.2	0.3	3.7	84.7%	91.8%	3.7	3.8	2.8	10.39	1167.63	174.86	1182.77
PV+EB+ST+TB	PV+ST	30.0	10.0	3438.5	1954.5	0.0	251.0	1643.4	0.3	2.8	52.2%	87.2%	-	-	-	10.39	1197.24	1138.05	-140.81

Note: Electricity consumption, grid import and electricity-cost results for PV+EB+ST+TB remain provisional until the auxiliary electric-heating logic in column AEA1 is finalized.

SECTION 3 — ATES DIAGNOSTICS

Configuration	ATES recovery efficiency [%]	Initial useful thermal inventory [kWh]	Actual annual heat charged [kWh]	Recoverable annual charged heat [kWh]	Useful heat supplied from ATES [kWh]	Final useful thermal inventory [kWh]	Cyclic-balance difference [kWh]	Cyclic-balance difference [%]	Minimum useful inventory [kWh]	um useful inventory	Remainin g unmet thermal demand [kWh]	Cyclic-status
HP+PV+EB+TB	83.3%	2319.3	5845.8	4866.8	4855.0	2331.2	11.8	0.5%	27.8	4638.7	0.0	PASS
HP+PVT+EB+TB	83.3%	2319.3	5845.8	4866.8	4855.0	2331.2	11.8	0.5%	27.8	4638.7	0.0	PASS
PV+EB+ST+TB	83.3%	2319.3	5845.8	4866.8	4855.0	2331.2	11.8	0.5%	27.8	4638.7	0.0	PASS

SECTION 4 — VALIDATION CHECKS

Configuration	Electrical energy-balance error [kWh]	Battery minimum state of charge [kWh]	Battery maximum state of charge [kWh]	Hours battery SOC < 0	Hours battery SOC > capacity	PVT convergence error	ATES snapshot status
HP	0.0	-	-	-	-	-	NOT ACTIVE
HP+PV	0.0	-	-	-	-	-	NOT ACTIVE
HP+PV+EB	0.0	0.0	10.0	0.0	0.0	0.0	NOT ACTIVE
HP+PV+EB+TB	0.0	0.0	10.0	0.0	0.0	0.0	CURRENT
HP+PVT+EB+TB	0.0	0.0	10.0	0.0	0.0	0.0	NOT ACTIVE
PV+EB+ST+TB	0.0	0.0	10.0	0.0	0.0	-	NOT ACTIVE
Number of formula-en	0.0						

SECTION 4 — JULY / DECEMBER GRID IMPORT / EXPORT [kWh]

Configuration	July Import	July Export [kWh]	December Import [kWh]	December Export [kWh]
HP	272.6	0.0	626.5	0.0
HP+PV	272.6	0.0	626.5	0.0
HP+PV+EB	272.6	0.0	626.5	0.0
HP+PV+EB+TB	272.6	0.0	626.5	0.0
HP+PVT+EB+TB	272.6	0.0	626.5	0.0
PV+EB+ST+TB	272.6	0.0	626.5	0.0

< > Start Here Input POA,Calc data Advanced Settings Dashboard

Results_Summary HP HP+PV HP+PV+EB HP+PV+EB+TB HP+PV ... + : ◀

Figure B.5: SOLSTICE V2 *Results_Summary* sheet showing the configuration comparison, HT-ATES diagnostics, and model-consistency checks.

B.6. Configuration-level hourly calculations

Each system configuration is represented by a dedicated worksheet containing the underlying hourly energy-flow calculations. Figure B.6 shows the PV, EB, HP, and HT-ATES configuration. The worksheet exposes the hourly household electricity demand, solar generation, battery charging and discharging, HP operation, HT-ATES charging and heat supply, and electricity exchange with the grid. This structure enables individual energy flows to be traced directly and preserves the transparent spreadsheet-based character of SOLSTICE V2.

hour	ELECTRICITY CONSUMPTION			SOLAR GENERATION			BATTERY						ATES INPUTS / REMAINING HEAT						HT-ATES outputs HP+PV+EB+TB snapshot from ATES_model						GRID & COSTS				
	Pappl (W_e)	Pcool (W_e)	total_direct (W_e)	T_modul (C)	eff. (%)	Psolar (W_e)	Pnet_before (W_e)	Pcharged (W_e)	discharged (W_e)	Estored (W_e)	afid_after (W_e)	EB (W_e)	Psurplus (W_e)	ATES_chable (W_e)	afid_DHW (W_e)	SH_dhw (W_e)	rem_t_remain (W_e)	ATES_disc (W_e)	SH_unm (W_e)	DHW_unm (W_e)	IP_unmet (W_e)	P_unmet (W_e)	ATES_use (W_e)	T_hot_end (C)	Pgrid_imp (W_e)	cost_imp (C)	Pgrid_exp (W_e)	revenue_exp (C)	
1-jan 00:30	150.2	0.0	150.2	14.9	20.6%	0.0	-150.2	0.0	0.0	0.0	150.2	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	2318.8	75.0	150.2	10.04	0.0	10.00	
1-jan 01:30	135.1	0.0	135.1	14.9	20.6%	0.0	-135.1	0.0	0.0	0.0	135.1	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	2318.3	75.0	135.1	10.04	0.0	10.00	
1-jan 02:30	125.1	0.0	125.1	14.7	20.6%	0.0	-125.1	0.0	0.0	0.0	125.1	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	2317.8	75.0	125.1	10.03	0.0	10.00	
1-jan 03:30	125.1	0.0	125.1	14.4	20.6%	0.0	-125.1	0.0	0.0	0.0	125.1	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	2317.2	75.0	125.1	10.03	0.0	10.00	
1-jan 04:30	130.1	0.0	130.1	14.2	20.6%	0.0	-130.1	0.0	0.0	0.0	130.1	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	2316.6	75.0	130.1	10.04	0.0	10.00	
1-jan 05:30	150.2	0.0	150.2	13.9	20.7%	0.0	-150.2	0.0	0.0	0.0	150.2	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	2316.0	75.0	150.2	10.04	0.0	10.00	
1-jan 06:30	190.2	0.0	190.2	14.0	20.7%	0.0	-190.2	0.0	0.0	0.0	190.2	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	2315.4	75.0	190.2	10.05	0.0	10.00	
1-jan 07:30	205.2	0.0	205.2	15.0	20.6%	98.5	-106.7	0.0	0.0	0.0	106.7	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	2314.9	75.0	106.7	10.03	0.0	10.00	
1-jan 08:30	190.2	0.0	254.2	17.9	20.4%	557.2	303.0	303.0	0.0	0.3	0.0	0.0	0.0	0.0	367.0	0.0	64.0	0.0	0.0	0.0	0.0	0.0	2314.3	75.0	0.0	10.00	0.0	10.00	
1-jan 09:30	185.2	0.0	258.4	17.5	20.5%	480.4	222.0	222.0	0.0	0.5	0.0	0.0	0.0	0.0	567.3	0.0	73.2	0.0	0.0	0.0	0.0	0.0	2314.9	75.0	0.0	10.00	0.0	10.00	
1-jan 10:30	190.2	0.0	365.0	18.5	20.4%	580.2	384.8	0.0	384.8	0.1	0.0	0.0	0.0	0.0	662.5	723.5	51.2	0.0	0.0	0.0	0.0	0.0	2314.9	75.0	0.0	10.00	0.0	10.00	
1-jan 11:30	205.2	0.0	600.8	18.2	20.4%	513.0	-87.7	0.0	87.7	0.0	0.0	0.0	0.0	0.0	395.5	395.5	0.0	0.2	0.7	1.2	0.0	0.0	2313.8	75.0	0.0	10.00	0.0	10.00	
1-jan 12:30	215.2	0.0	715.0	19.8	20.3%	715.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	493.7	493.7	0.0	0.6	0.1	0.7	0.0	0.0	2313.0	75.0	0.0	10.00	0.0	10.00	
1-jan 13:30	210.2	0.0	462.5	17.9	20.4%	462.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	252.3	252.3	0.0	1.4	0.3	1.6	0.0	0.0	2311.4	74.9	0.0	10.00	0.0	10.00	
1-jan 14:30	205.2	0.0	275.1	17.6	20.4%	496.7	221.6	221.6	0.0	0.2	0.0	0.0	0.0	0.0	291.5	0.0	63.8	0.0	0.0	0.0	0.0	0.0	2311.4	74.9	0.0	10.00	0.0	10.00	
1-jan 15:30	210.2	0.0	210.2	13.5	20.7%	0.0	-210.2	0.0	193.5	0.0	10.8	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.0	0.0	2310.7	74.9	10.8	10.00	0.0	10.00
1-jan 16:30	230.3	0.0	230.3	12.7	20.7%	0.0	-230.3	0.0	0.0	0.0	230.3	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.0	0.0	2310.0	74.9	230.3	10.08	0.0	10.00	
1-jan 17:30	275.3	0.0	275.3	12.0	20.8%	0.0	-275.3	0.0	0.0	0.0	275.3	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2309.2	74.9	275.3	10.10	0.0	10.00	
1-jan 18:30	315.3	0.0	315.3	11.4	20.8%	0.0	-315.3	0.0	0.0	0.0	315.3	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2308.4	74.9	315.3	10.11	0.0	10.00	
1-jan 19:30	325.4	0.0	325.4	11.4	20.8%	0.0	-325.4	0.0	0.0	0.0	325.4	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2307.5	74.9	325.4	10.11	0.0	10.00	
1-jan 20:30	310.3	0.0	310.3	11.5	20.8%	0.0	-310.3	0.0	0.0	0.0	310.3	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2306.7	74.9	310.3	10.10	0.0	10.00	
1-jan 21:30	280.3	0.0	280.3	11.6	20.8%	0.0	-280.3	0.0	0.0	0.0	280.3	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2305.8	74.9	280.3	10.09	0.0	10.00	
1-jan 22:30	250.3	0.0	250.3	11.4	20.8%	0.0	-250.3	0.0	0.0	0.0	250.3	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2305.0	74.9	250.3	10.08	0.0	10.00	
1-jan 23:30	195.2	0.0	195.2	11.2	20.8%	0.0	-195.2	0.0	0.0	0.0	195.2	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2304.1	74.9	195.2	10.06	0.0	10.00	
2-jan 00:30	150.2	0.0	150.2	11.1	20.8%	0.0	-150.2	0.0	0.0	0.0	150.2	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2303.2	74.9	150.2	10.05	0.0	10.00	
2-jan 01:30	135.1	0.0	135.1	11.0	20.8%	0.0	-135.1	0.0	0.0	0.0	135.1	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2302.3	74.9	135.1	10.04	0.0	10.00	
2-jan 02:30	125.1	0.0	125.1	11.0	20.8%	0.0	-125.1	0.0	0.0	0.0	125.1	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2301.4	74.9	125.1	10.04	0.0	10.00	
2-jan 03:30	125.1	0.0	125.1	11.3	20.8%	0.0	-125.1	0.0	0.0	0.0	125.1	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2300.5	74.9	125.1	10.04	0.0	10.00	
2-jan 04:30	130.1	0.0	130.1	11.2	20.8%	0.0	-130.1	0.0	0.0	0.0	130.1	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2299.6	74.9	130.1	10.05	0.0	10.00	
2-jan 05:30	150.2	0.0	150.2	11.1	20.8%	0.0	-150.2	0.0	0.0	0.0	150.2	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2298.7	74.9	150.2	10.06	0.0	10.00	
2-jan 06:30	190.2	0.0	190.2	11.4	20.8%	0.0	-190.2	0.0	0.0	0.0	190.2	0.0	0.0	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	2297.9	74.9	190.2	10.08	0.0	10.00	
2-jan 07:30	205.2	0.0	205.2	11.9	20.8%	0.0	-199.3	0.0	0.0	0.0	199.3	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2297.1	74.9	199.3	10.08	0.0	10.00	
2-jan 08:30	190.2	0.0	190.2	12.4	20.8%	45.1	-145.1	0.0	0.0	0.0	145.1	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2296.3	74.9	145.1	10.06	0.0	10.00	
2-jan 09:30	185.2	0.0	241.5	14.3	20.6%	241.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	56.3	0.0	0.4	0.4	0.0	0.0	2295.9	74.8	0.0	10.00	0.0	10.00	
2-jan 10:30	190.2	0.0	190.2	14.2	20.6%	142.1	-48.1	0.0	0.0	0.0	48.1	0.0	0.0	0.0	0.0	2.1	0.6	2.7	0.0	0.0	0.0	0.0	2293.3	74.8	48.1	10.02	0.0	10.00	
2-jan 11:30	205.2	0.0	205.2	14.6	20.6%	115.7	-89.5	0.0	0.0	0.0	89.5	0.0	0.0	0.0	0.0	2.1	0.6	2.6	0.0	0.0	0.0	0.0	2290.6	74.8	89.5	10.04	0.0	10.00	
2-jan 12:30	215.2	0.0	215.2	14.9	20.6%	99.8	-115.4	0.0	0.0	0.0	115.4	0.0	0.0	0.0	0.0	2.1	0.5	2.6	0.0	0.0	0.0	0.0	2288.0	74.8	115.4	10.05	0.0	10.00	
2-jan 13:30	210.2	0.0	281.7	15.5	20.6%	281.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.5	71.5	0.0	1.9	0.5	2.4	0.0	0.0	2285.6	74.8	0.0	10.00	0.0	10.00	
2-jan 14:30	205.2	0.0	205.2	13.4	20.7%	66.5	-138.7	0.0	0.0	0.0	138.7	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.0	0.0	2285.0	74.8	138.7	10.06	0.0	10.00	
2-jan 15:30	210.2	0.0	210.2	12.6	20.7%	0.0	-210.2	0.0	0.0	0.0	210.2	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	0.0	0.0	2284.2	74.8	210.2	10.09	0.0	10.00	
2-jan 16:30	230.3	0.0	230.3	12.0	20.8%	0.0	-230.3	0.0	0.0	0.0	230.3	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	2283.4	74.8	230.3	10.10	0.0	10.00	
2-jan 17:30	275.3																												

Supplementary Simulation Results

C.1. HT-ATES charging-temperature sensitivity

Figure C.1 shows the annual hot-well temperature and useful stored-energy profiles corresponding to the charging-temperature cases discussed in Section 4.5.5.

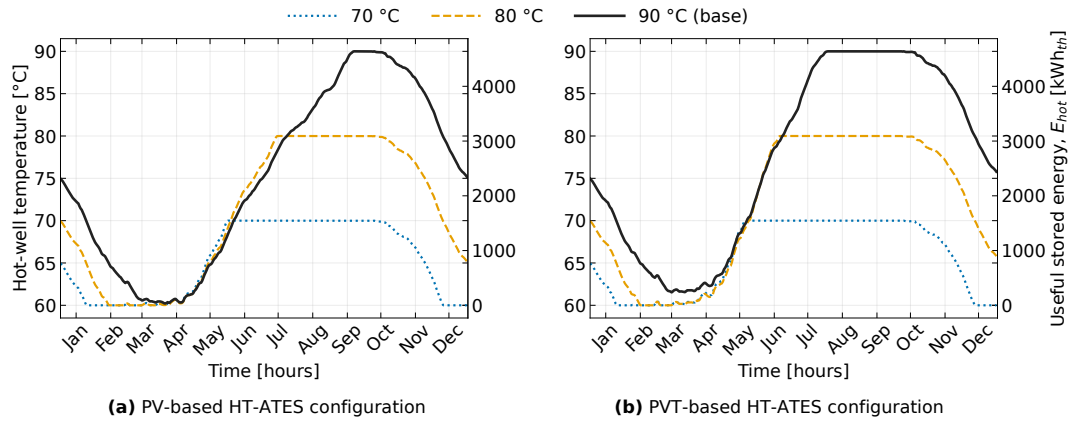


Figure C.1: Annual hot-well temperature and useful stored-energy profiles for HT-ATES charging temperatures of 70, 80 and 90 °C for the PV- and PVT-based configurations.