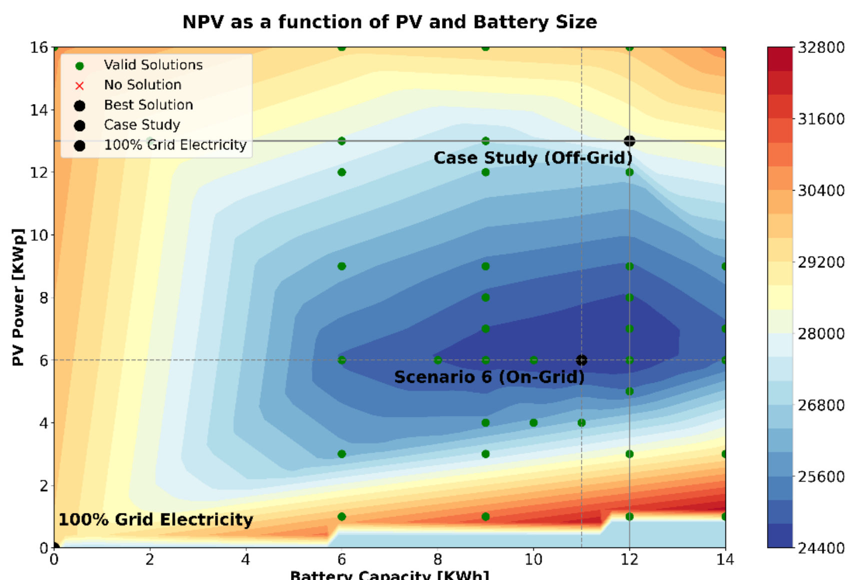
Solar-Powered Cold Rooms: Best Design Practices



2025 Edition

FOREWORD

Since 2021, Solar Cooling Engineering GmbH and the Carl von Ossietzky University of Oldenburg have collaborated—supported by Efficiency for Access—to develop innovative design methods for solar-powered cold rooms. This partnership has led to the creation of practical tools and methodologies for calculating the energy demand of cooling systems and determining the corresponding solar energy requirements. In addition, the tools support the optimization of key design variables—including insulation thickness, PV and battery capacity, and the grid electricity rate for on-grid systems—based on project-specific cost parameters.

This handbook presents the best practices derived from this work, offering a structured approach to designing solar-powered cold rooms that are technically sound, economically viable, and adapted to local conditions.

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INTRODUCTION

DESCRIPTION OF THE TOOL USED

The methods shown in this handbook are implemented in a simulation model developed in Python 3.10.9, to determine the best configuration of a solar-powered cold room system, combining PV power, a battery bank, and 2 different technologies: Ice Thermal Storage and Monoblock cooling units. The model includes a high-level detail of thermal load calculations and integrates the possibility of connecting to the electricity grid, allowing more reliable systems and enabling the evaluation of hybrid systems powered by solar energy, batteries, and grid electricity.

One-year simulations can be performed for various combinations of PV panels, batteries, and cooling units. A sensitivity analysis is conducted to evaluate the impact of different operational conditions on the cold room's performance and cost. Based on these simulations, an objective function is defined to identify the optimal system configuration that minimizes cooling costs while ensuring the cooling demand is met.

The simulation model enables the evaluation and comparison of different cold room designs and operational scenarios, supporting informed decision-making to achieve an energy-efficient and cost-effective system that can operate autonomously or with grid support, and is adaptable to various implementation needs.

COLD ROOMS

Cold rooms or also walk-in cold rooms refer to temperature-controlled storage units. These cold rooms are designed to maintain specific temperatures, vital to protecting goods or enabling processes [1], [9]. For agricultural applications, controlling the temperature and humidity of products is crucial to ensure their good quality for human consumption.

Depending on the temperature range at which the cold rooms operate, there are three types of cold rooms: [1], [9]

- **Storage or positive-temperature cold rooms:** Are designed for product conservation, maintaining temperatures between 0 and 10°C.

- **Freezer or negative-temperature cold rooms** Are designed to maintain temperatures below freezing, normally between 0 and-28°C.

- **Blast Freezers:** Are especially designed for rapid freezing. In this type of cold room, the aim is to quickly reduce the temperature of the product to reduce the risk of contamination and to be able to preserve them for longer without losing their properties. Temperatures normally reach -30 ºC to -40 ºC and are mostly used in the food industry.

Depending on the size of the cold room, cold rooms can also be divided into: [1]

- **Small-sized cold rooms:** Up to 30 m^3.
- **Medium-sized cold rooms:** Up to 200 m^3.
- **Large industrial cold rooms:** Up to 3000 m^3.

A basic cold room design consists of an insulating structure that allows the required internal conditions to be maintained without being significantly affected by the external temperature. The heart of the cooling process is a refrigeration system and a temperature and humidity control system that are also essential for monitoring internal conditions.

Figure 1. Main components of a cold room. (Source[9]).

MONOBLOCK COOLING UNITS

Monoblock units are well known for being all-in-one-design, facilitating their installation and operation. The equipment can be wall-mounted or ceiling-mounted, and its design minimizes energy losses, resulting in significant savings on power consumption. This technology is perfectly suitable for small to mid-size cold rooms, offering high versatility and working with eco-friendly refrigerants like R290, ensuring exceptional cooling performance and aligning with sustainable practices. [9]

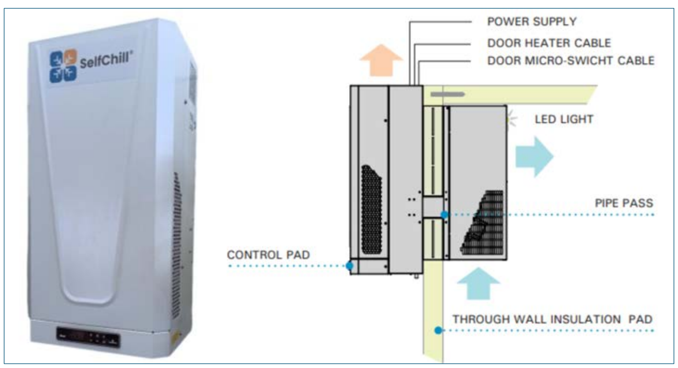

Figure 2. Monoblock Freezing Unit Phaesun Self Chill AC 0,48 kW -20°. (Source [18])

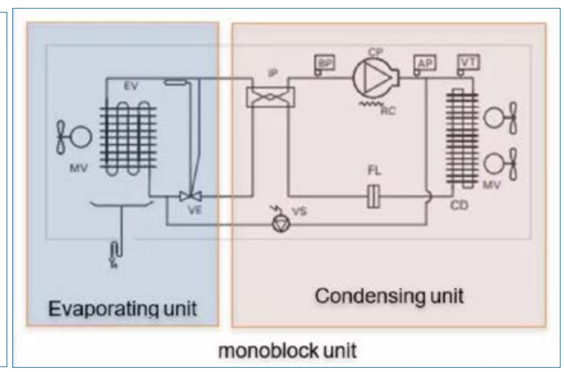

Figure 3. Diagram of a Monoblock unit. (Source[9])

METHODOLOGY

SYSTEM DESCRIPTION

The simulation models for a solar-powered cooling systems were studied for two different configurations:

Monoblock: Is based on a solar-powered cold room with AC cooling units of the 'Monoblock' type. This system can be powered by a photovoltaic (PV) module or can be also connected to the electrical grid. It includes AC power inverters and a large battery bank to convert the available solar energy into AC power.

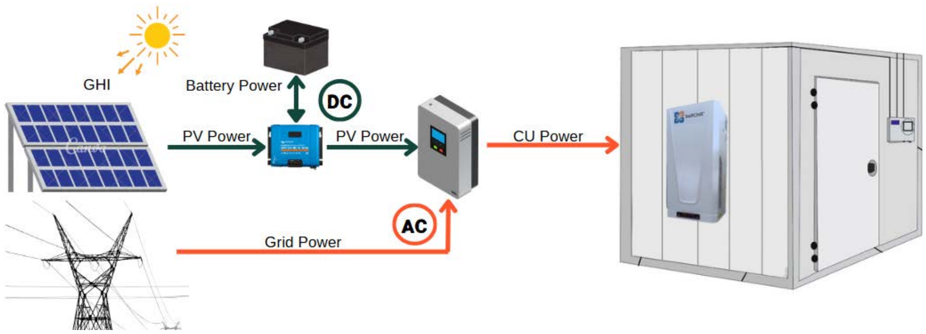

*Figure 4. **Monoblock**: Schematic diagram of the hybrid solar/grid cold room with Monoblock cooling AC units. PV power and battery power are DC, and Grid Power is AC.*

Self-Chill with Ice Thermal Storage: Based on DC CUs that can be directly powered by a PV module and equipped with AC power inverters and large battery banks. This solution integrates thermal storage based on the temperature reduction of a cooling medium (water) and the formation of ice around the evaporator plates. The evaporator plates of the CUs are placed inside a thermally insulated water tank (also known as a water chiller). An ultra-low power DC pump circulates water through the heat exchanger circuit, which then distributes cold air inside the cold room using a fan. [34]. This technology is only suitable for applications requiring positive temperatures unless antifreeze additives, such as glycol, are used.

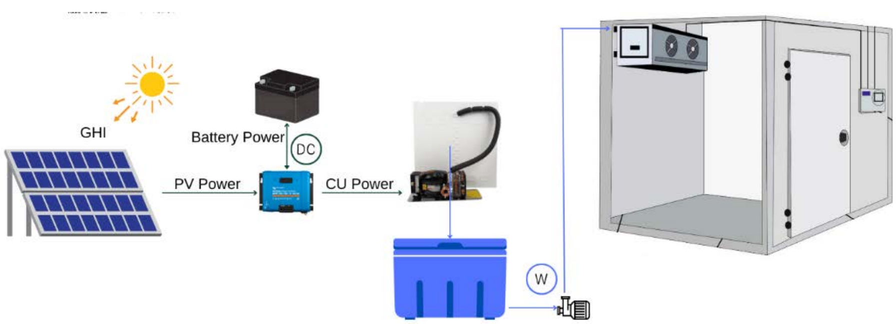

*Figure 5. **Self-Chill with Ice Thermal Storage**: Schematic diagram of the solar-powered cold room with thermal and electrical storage system, using DC cooling units.*

THERMAL LOADS

All the thermal loads involved in a cold room represent the total cooling demand which represents the total amount of energy that needs to be removed from the cold room to keep the products at the desired temperature [35]. Heat loads come from many sources such as transmission through walls due the solar radiation, air infiltration, heat from fan motors and lights, defrost, heat load from the product, including respiration heat, heat from equipment and heat from staff.

To estimate a more accurate cooling demand, a higher level of detail considering hourly calculations for all the thermal loads was developed, using all thermodynamic and environmental properties. The total heat load $\dot{Q}_{TOTAL}$ of the cold room is given by Equation (1) and is shown in Figure 6.

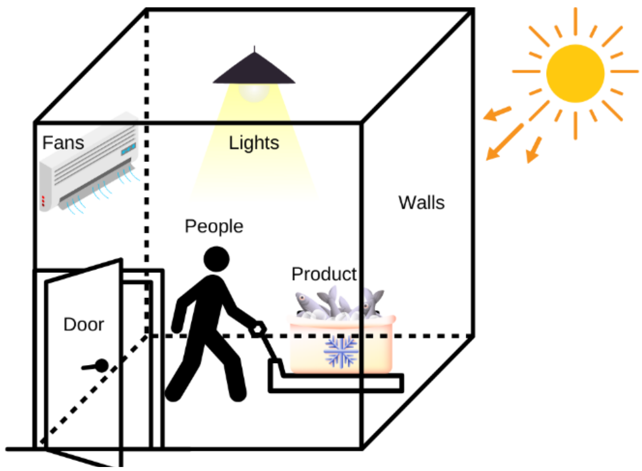

Figure 6 . Thermal loads in a cold room

$$\dot{Q}_{TOTAL} = \dot{Q}_{walls} + \dot{Q}_{infiltation} + \dot{Q}_{people} + \dot{Q}_{product} + \dot{Q}_{respiration} + \dot{Q}_{lights} + \dot{Q}_{fans} + \dot{Q}_{defrost} \quad (1)$$

Where:

- ✓ $\dot{Q}_{walls}$ is the heat load received from the walls due to solar radiation. $[W]$
- ✓ $\dot{Q}_{infiltration}$ is the heat load received from the mass flow of air through the door.$[W]$
- ✓ $\dot{Q}_{people}$ is the heat load received from people inside the cold room (Staff).$[W]$
- ✓ $\dot{Q}_{respiration}$ is the heat load received from the respiration of the product.$[W]$
- ✓ $\dot{Q}_{lights}$ is the heat load received from the lights of the cold room.$[W]$
- ✓ $\dot{Q}_{fans}$ is the heat load received from the fans inside the cold room.$[W]$
- ✓ $\dot{Q}_{defrost}$ is the heat load received from the system used to defrost the evaporator.$[W]$

Heat load from walls

The heat load received from the walls depends on the heat transfer between the ambient temperature and the internal temperature in the cold room. Additionally, the heat transfer coefficient is considered related to the thermal resistance (R) from insulation panels.[35]

$$\dot{Q}_{walls} = \frac{T_{amb} - T_{CR}}{R_{wall}} \quad (2)$$

Where:

- ✓ T_{amb} is the ambient temperature (Outside the cold room) $[°C]$
- ✓ T_{CR} is the temperature inside the cold room $[°C]$
- ✓ R_{wall} is the thermal resistance of the walls $[°C/W]$

Heat load from air infiltration

For small cold rooms, air infiltration should be considered. This heat load corresponds to the sensible and latent heat exchange caused by the mass flow of air that enters the cold room and is the sum of Q_{do} and Q_{ds} as is shown in Equation (3), where Q_{do} is the infiltration heat load during opening the door and Q_{ds} is the infiltration heat load through the seals when the door is closed [35].

$$\dot{Q}_{infiltration} = \dot{Q}_{do} + \dot{Q}_{ds} \quad (3)$$

$$\dot{Q}_{do} = m_{do} * \Delta h \quad (4)$$

$$\dot{Q}_{ds} = m_{ds} * \Delta h \quad (5)$$

- ✓ m_{do} is the mass flow of air through the door when it is open. $[Kg/s]$
- ✓ m_{ds} is the mass flow of air through the seal of the door when it is closed. $[Kg/s]$
- ✓ Δh is the enthalpy difference between external and internal conditions. $[KJ/Kg]$

m_{do} and m_{ds} are defined by Equation (6) and Equation (7), while Δh should be calculated based on the ambient conditions, the temperature and the humidity desired in the cold room.

$$m_{do} = (1 - E) * 0.221 * A_d * \rho_i * \left(1 - \frac{\rho_o}{\rho_i}^{0.5}\right) * (g * H_d)^{0.5} * \left(2\left(1 + \left(\frac{\rho_i}{\rho_o}\right)^3\right)\right)^{1.5} \quad (6)$$

$$m_{ds} = (v_f * \rho_o) \quad (7)$$

- ✓ E is the effectiveness of door protection or blockage. $[-]$
- ✓ A_d is the area of the door. $[m^2]$
- ✓ ρ_i is the density of the air inside the cold room. $[Kg/m^3]$
- ✓ ρ_o is the density of the air outside the cold room. $[Kg/m^3]$
- ✓ g is the acceleration due to gravity (9.81). $[m/s^2]$
- ✓ H_d is the height of the cold room door. $[m]$
- ✓ v_f is the volume flow rate through seals per meter of seal length $[m^2/s]$

Air is a physical mixture of various gases and water vapor. This mixture is studied by Psychrometry, including moisture content, humidity and temperature; and the use of these properties to analyze humid air conditions and processes. Thus, they can be used in building science for a wide range of applications, especially for mechanical heating, ventilation and air conditioning (HVAC) system design [36]. An example of a Psychrometric chart is shown in Figure 7 and Table 1 specifying some typical values for internal and external conditions of a cold room for calculating enthalpy.

Table 1. Psychrometric properties for internal and external conditions of the cold room.

PSYCHROMETRIC PROPERTIES			
	Cold Room	Outdoor	Units
Dry bulb temperature	10	32	°C
Air relative humidity	80	60	%
Mass enthalpy	25.46	78.52	KJ/Kg

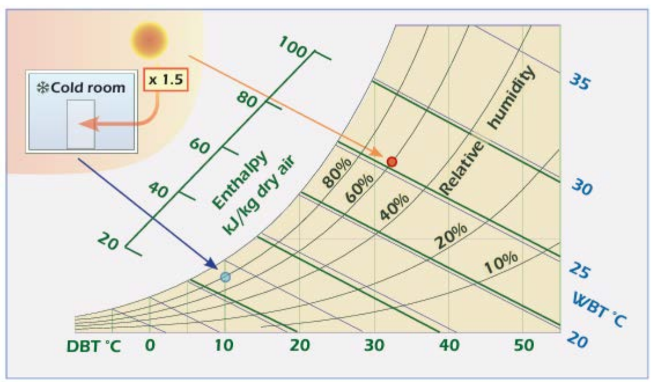

Figure 7 . Psychrometric chart for enthalpy calculation. (Source [35])

Internal conditions for internal enthalpy are calculated using the set point temperature and the humidity required in the cold room. For the calculation of external air conditions, the following method was implemented within the model for the calculation of enthalpy:

a. Calculate the saturation vapor pressure P_{ws} $[Pa]$ at the actual dry bulb temperature using Equation (8), where the temperature should be in Kelvin $[K]$ and using the given constants in SI units. This is the vapor pressure at the maximum content of water gas in air before it starts to condense out as liquid water.

$$\ln(P_{ws}) = \frac{C8}{T_{[K]}} + C9 + C10 * T_{[K]} + C11 * T_{[K]}^2 + C12 * T_{[K]}^3 + C13 * \ln(T) \quad (8)$$

$$C8 = -5800.22060$$
$$C9 = 1.3914993 C10 = -0.048640239$$

$C11 = 0.000041764768$
$C12 = -0.000000014452093$
$C13 = 6.5459673$

b. The relative humidity ratio (RH) is obtained from the location data and represents the ratio of vapor partial pressure P_w in the air to the saturation vapor partial pressure P_{ws} that would be in the mixture if it were saturated at the actual dry bulb temperature. Using Equation (9), the vapor partial pressure is calculated.

$$RH = \frac{P_w}{P_{ws}} * 100\% \quad [\%] \tag{9}$$

c. Calculate the dry air pressure $P_{da}[Pa]$ using the molar fractions of dry air (X_{da}) in Equation (10) and the molar fraction of the water vapor (X_w) in Equation (11), where P_{atm} $[Pa]$ is the atmospheric pressure.

$$X_{da} = \frac{P_{da}}{P_{da} + P_w} = \frac{P_{da}}{P_{atm}} \quad [-] \tag{10}$$

$$X_w = \frac{P_w}{P_{da} + P_w} = \frac{P_w}{P_{atm}} \quad [-] \tag{11}$$

d. The humidity ratio or specific humidity(W) represents the ratio of the mass of water vapor to the mass of dry air in a given volume and is explained by Equation (12).

$$W = 0.622 * \frac{x_w}{X_{da}} \quad \left[\frac{kg_w}{kg_{da}}\right] \tag{12}$$

e. Finally, the specific enthalpy for moist air is calculated using Equation (13).

$$h = Cp_{air} * T_{amb} + W * Q_{lv} + (1.86 * T_{amb}) \tag{13}$$

Where:

Cp_{air} is the specific heat capacity of the air at constant pressure. $[J/kg * K]$

Q_{lv} is the latent heat of vaporization. [J]

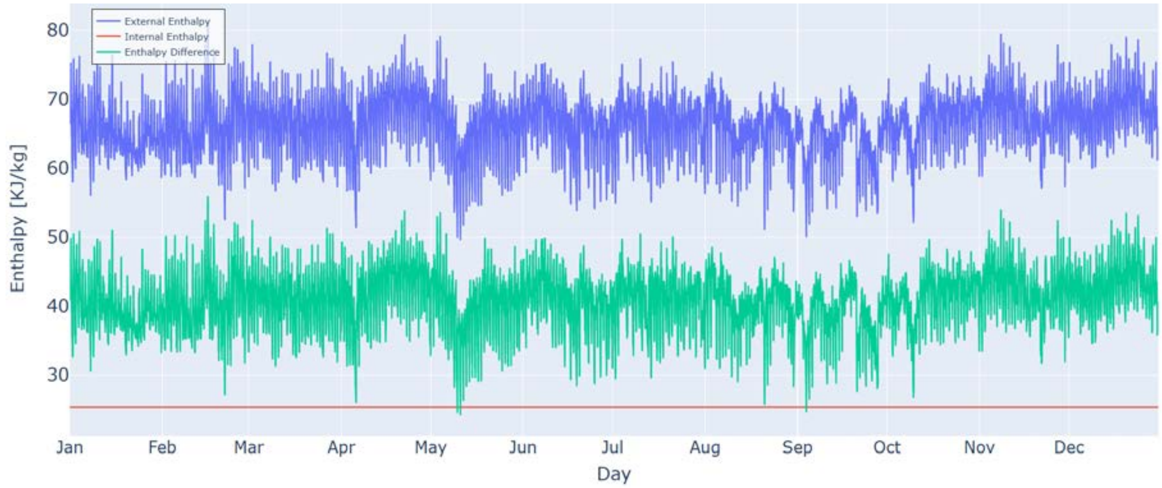

Figure 8. Enthalpy Difference: Internal vs External Enthalpy Over a Typical Year (Inlet Temperature: 10°C)

Heat load from people

A person in a cold room emits around 270 W of heat, and this can be added up to the number of people and the duration of their time inside the cold room. The heat load (per person in W) for the period in which the person is in the cold room can be calculated using Equation (14) (ASHRAE, 2022). It means that 270W is the reference value for the thermal load of a person in a cold room when the temperature is 0°C, and it decreases by 6 watts for each °C of the cold room.

$$\dot{Q}_{people} = (270 - (6 * T_{CR})) * t_p * N_p \tag{14}$$

Where:

- ✓ t_p is the duration time of one person inside the cold room. $[s]$
- ✓ N_p is the number of people inside the cold room. $[-]$
- ✓ T_{CR} is the temperature inside the cold room $[°C]$

Heat load from product respiration

The heat of respiration is calculated using Equation (15); where a and b are respiration coefficients derived from line fits using data from *ASHRAE (2022*).

$$\dot{Q}_{respiration} = a * e^{T_{CR} * b} \tag{15}$$

Heat load from fans

Monoblock cooling units have a fan integrated to circulate air through the evaporator and facilitate the cooling process. The heat of the fans is related to the CU operation and corresponds to approximately 10% of the power consumption of the compressor.

$$\dot{Q}_{fans} = P_{CU_{real}} * \frac{P_{fan}}{P_{CU_{nominal}}} * CU \tag{16}$$

Where:

- ✓ P_{CU} is the real power consumption of the cooling unit $[W]$
- ✓ P_{CU} is the nominal power of the cooling units $[W]$
- ✓ P_{fan} is the power of the fan of the cooling unit $[W]$
- ✓ CU is the number of cooling units $[-]$

Heat load from lights

Lighting has a direct effect (through the electrical energy used to power the lights) and an indirect effect through the heat generated from the lights that is a heat load on the cold store. The heat load from lighting is generally calculated as being equal to the power of the lights multiplied by a time factor related to usage of the lights [35]. Heat load from the lights is calculated from the luminous flux distributed evenly over the floor and walls divided by the efficacy of the lamps.

$$\dot{Q}_{lights} = LF * \frac{A_f + A_w}{e_l} * t_l \tag{17}$$

Where:

- ✓ LF is the luminous flux distributed evenly over the floor and walls. $[lm/m^2]$
- ✓ A_f is the floor area of the cold room. $[m^2]$
- ✓ A_w is the walls area of the cold room. $[m^2]$
- ✓ e_l is the efficacy of lighting lamps. $[lm/W]$
- ✓ t_l is the time the lights are on. $[s]$

Heat load from defrost

For cooling units operating below freezing cold rooms require a system for defrosting the evaporator. Its heat load is equal to the amount of heat required to melt all the frozen water entering the room through the door (air infiltration) or from the product [1]. This system commonly works with electrical resistance.

$$\dot{Q}_{defrost} = P_{defrost} * t_D * n_{cycle} \tag{18}$$

Where:

- ✓ $P_{defrost}$ is the power of the defrost system $[W]$
- ✓ t_D is the duration of the defrost system operating. $[s]$
- ✓ n_{cycle} is the number of cycles that the defrost system operates during the day. $[-]$

COOLING PRODUCTS

Energy Balance of the System

The energy balance for the cold room consists of the heat supplied by the cooling unit and the total thermal load that needs to be removed from the cold room, including the thermal load of the product, as shown in Figure 9. The cooling system must extract exactly the amount of heat that enters the cold room minus the heat that is transferred to the product. For the system in equilibrium, there is no change in the temperatures with time and the general energy balance is given by the equation (19) :

$$\dot{Q}_{cooling} = \dot{Q}_{thermal\_load} + \dot{Q}_{product} \tag{19}$$

Where:

- ✓ $\dot{Q}_{cooling}$ is the thermal power extracted by the cooling unit. [W]
- ✓ $\dot{Q}_{thermal\_load}$ is the total thermal load of the cold room, without considering the product.[W]
- ✓ $\dot{Q}_{product}$ is the thermal load associated with the cooling/freezing of the product. [W]

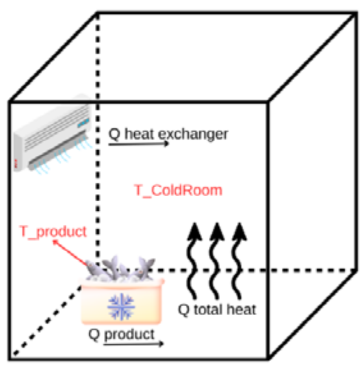

Figure 9. Energy balance of the cold room.

For the transient system, temperature changes over time must be considered, obtaining the final energy balance in Equation (20). The product only interacts with air, therefore $\dot{Q}_{thermal\_load} = 0$, $\dot{Q}_{cooling} = 0$ and is given by Equation (21).

$$\dot{Q}_{cooling} = \dot{Q}_{thermal\_load} + \dot{Q}_{product} - (Cp_{air} * m_{air}) * \frac{dT_{air}}{dt} - (Cp_{product} * m_{product}) * \frac{dT_{product}}{dt} \tag{20}$$

$$\dot{Q}_{product} = \frac{T_{air} - T_{product}}{R_{(air-prod)}} \tag{21}$$

Where:

- ✓ Cp_{air} is the specific heat capacity of the air inside the cold room. $[J/kg * K]$
- ✓ m_{air} is the mass flow of air inside the cold room. $[Kg/s]$
- ✓ $Cp_{product}$ is the specific heat capacity of the product. $[J/kg * K]$
- ✓ $m_{product}$ is the mass flow of product. $[Kg/s]$
- ✓ T_{air} is the temperature of the air inside the cold room. $[°C]$
- ✓ $T_{product}$ is the temperature of the product. $[°C]$
- ✓ $R_{air-product}$ is the thermal resistance between the air and the product. $[°C/W]$
- ✓ $\frac{dT_{air}}{dt}$ is the variation of the air temperature as a function of time $[°C/s]$
- ✓ $\frac{dT_{product}}{dt}$ is the variation of the product temperature as a function of time $[°C/s]$

Finally, the equations of interest to see the variation in air temperature and product temperature as a function of time, is formulated by Equation (22) and Equation (23). To solve these differential equations, the Runge Kutta method is used.

$$\frac{dT_{air}}{dt} = \frac{\dot{Q}_{themal\_load} - \dot{Q}_{cooling} + \frac{T_{air} - T_{product}}{R_{(air-prod)}}}{Cp_{air} * m_{air}} \tag{22}$$

$$\frac{dT_{product}}{dt} = \frac{\frac{T_{air} - T_{product}}{R_{(air-prod)}}}{Cp_{product} * m_{product}} \tag{23}$$

Runge-Kutta Fourth Order Method

"The Runge-Kutta methods are an important family of iterative methods for the approximation of solutions of ordinary differential equation ODE's, that were developed around 1900 by the German mathematicians C. Runge (1856–1927)and M.W. Kutta (1867–1944)" [37]. The fourth order method or RK4, is one of the most used Runge Kutta methods to find the solution of a differential equation, providing a finite difference method that discretizes the differential equations into small time steps [37]. The Runge-Kutta method was used for its accuracy and efficiency in approximating the solution of differential equations. The function f() is evaluated multiple times around a known value from the previous time step. The method computes the solution for the next time by taking a weighted average of the values found in the evaluation. The Runge-Kutta method is used to solve differential equations with $\Delta t = h = 20\ seg$ and the respective equations are shown in Table 2.

$$y1 = y0 + (1/6)(k1 + 2k2 + 2k3 + k4) \quad (24)$$

- $k1 = hf(x0, y0)$
- $k2 = hf[x0 + (1/2)h, y0 + (1/2)k1]$
- $k3 = hf[x0 + (1/2)h, y0 + (1/2)k2]$
- $k4 = hf(x0 + h, y0 + k3)$

Table 2. Runge Kutta method applied to the differential equations for air and product temperature.

AIR TEMPERATURE (COLD ROOM)	PRODUCT TEMPERATURE
$\boldsymbol{k1 = f\left(T_{air,_{i-1}}, T_{product,_{i-1}}\right)}$	$k1 = f\left(T_{air,_{i-1}}, T_{product,_{i-1}}\right)$
$\boldsymbol{k2 = f\left(T_{air,_{i-1}} + h * \frac{k1}{2}, T_{product,_{i-1}} + h * \frac{k1}{2}\right)}$	$k2 = f\left(T_{air,_{i-1}} + h * \frac{k1}{2}, T_{product,_{i-1}} + h * \frac{k1}{2}\right)$
$\boldsymbol{k3 = f\left(T_{air,_{i-1}} + h * \frac{k2}{2}, T_{product,_{i-1}} + h * \frac{k2}{2}\right)}$	$k3 = f\left(T_{air,_{i-1}} + h * \frac{k2}{2}, T_{product,_{i-1}} + h * \frac{k2}{2}\right)$
$\boldsymbol{k4 = f\left(T_{air,_{i-1}} + h * k3, T_{product,_{i-1}} + h * k3\right)}$	$k4 = f\left(T_{air,_{i-1}} + h * k3, T_{product,_{i-1}} + h * k3\right)$
$\mathbf{T_{air,_i} = T_{air,_{i-1}} + \frac{h}{6} * (k1 + 2 * k2 + 2 * k3 + k4)}$	$\mathrm{T_{product,_i} = T_{product,_{i-1}} + \frac{h}{6}(k1 + 2 * k2 + 2 * k3 + k4)}$

Figure 11 and Figure 12 show an example of the Runge Kutta methos results, presenting the relation between air and product temperature and the influence of them in the cooling power consumed for the cooling units of the system, during 1 hour with steps of 20 seconds.

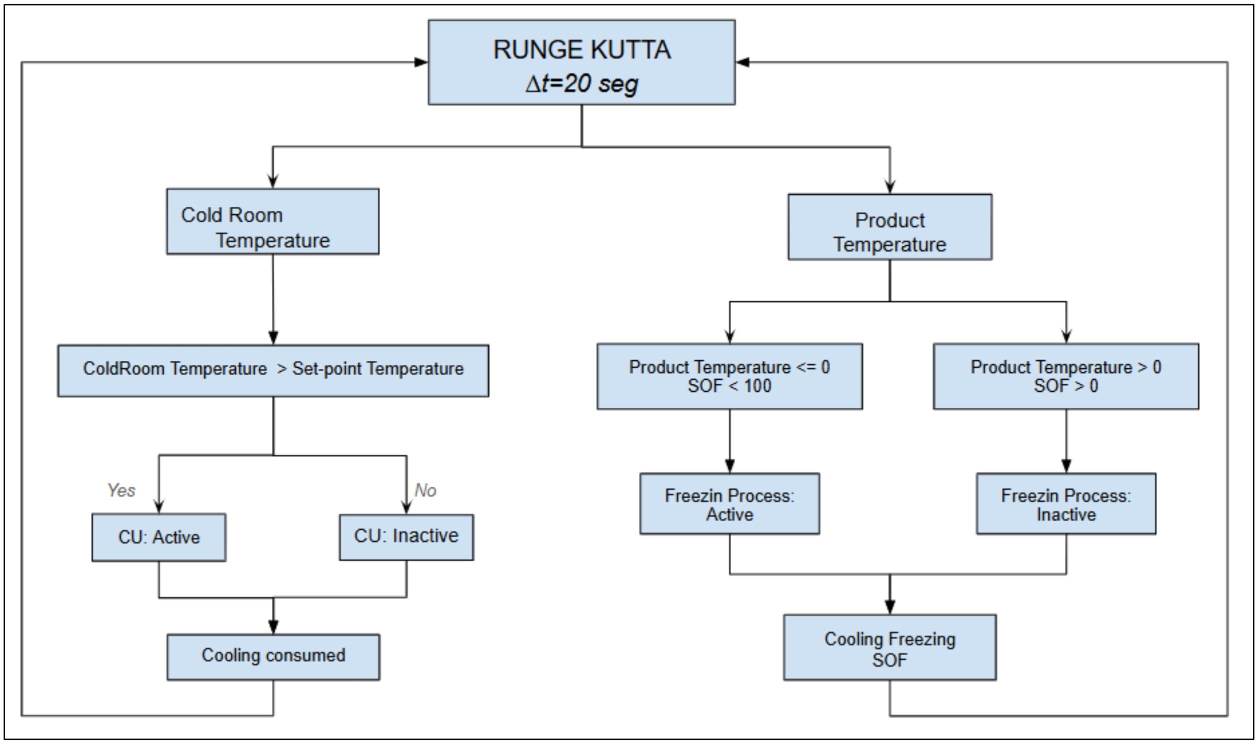

Figure 10. Runge Kutta flowchart.

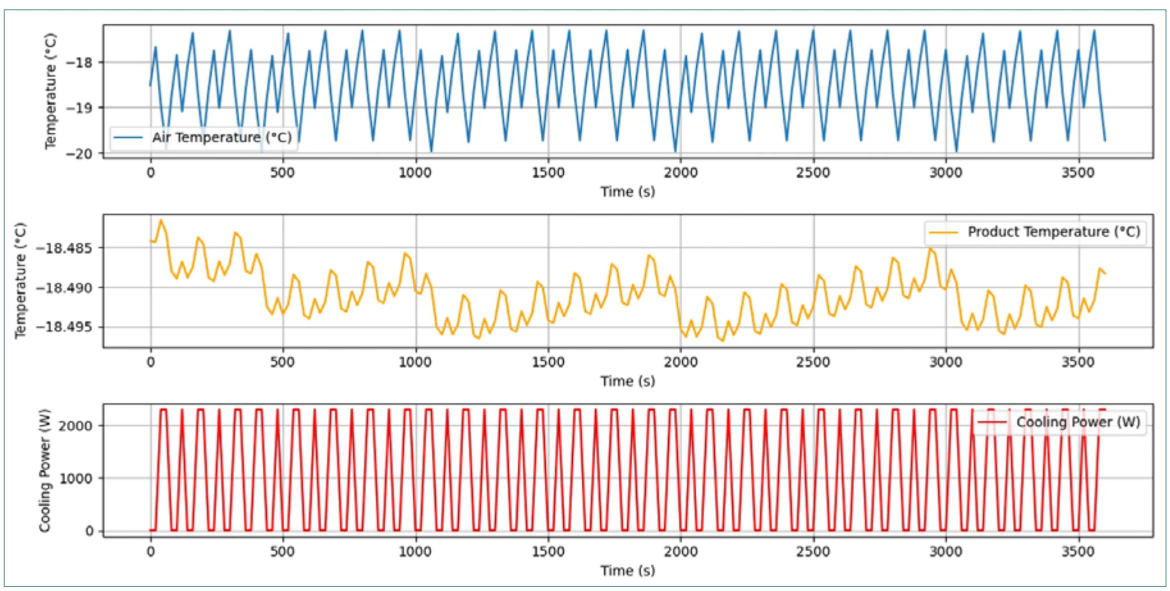

Figure 11. Runge-Kutta method for air and product temperatures when both are within the desired range or cold room set point.

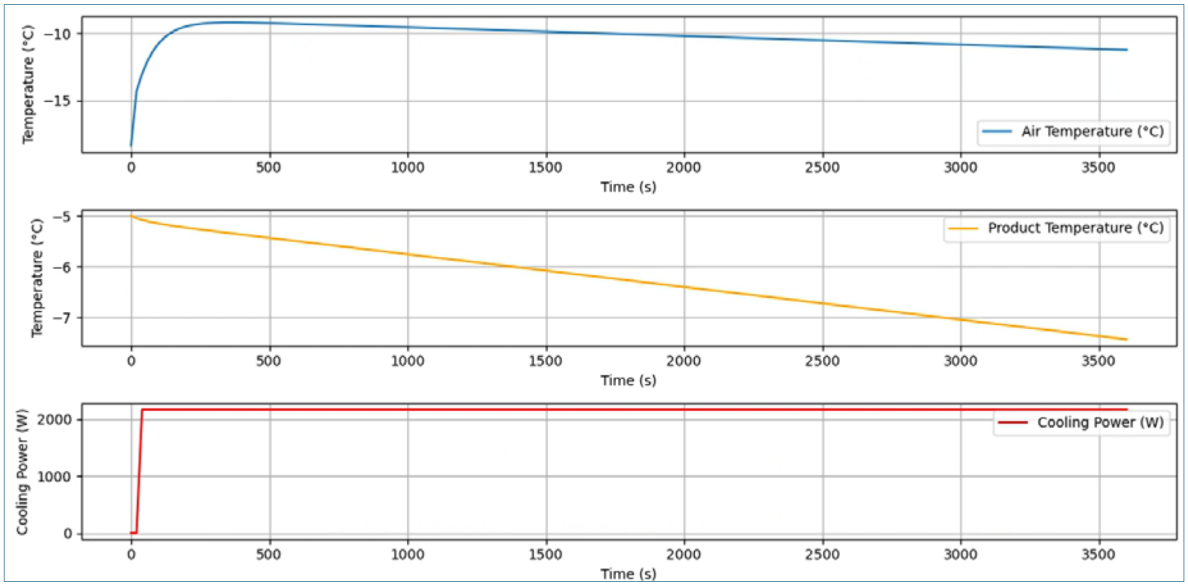

Figure 12. Runge-Kutta method for air and product temperature dynamics when new product at -5°c enters cold room, causing air temperature to rise due to high thermal load, requiring continuous cooling to reach set point.

Freezing Process

When the product entering the cold room is above the freezing point, usually above 5°C, and its temperature must be reduced below 0°C, the product needs to go through the freezing process. As shown in Figure 13**Error! Reference source not found.**, products do not freeze at a single temperature but gradually change their state into solid frozen. The energy required for freezing depends on the latent heat of fusion (L_f), which is defined by the water content (X_{water}) of the product [35].

$$\dot{Q}_{freezing} = m_{product} * L_{f,product} = m_{product} * (X_{water} * L_{f,water}) \quad (25)$$

Where:

- ✓ $m_{product}$ is the mass of product entering the cold room. $[Kg]$
- ✓ $L_{f,product}$ is the latent heat of fusion of the product $[J/kg]$
- ✓ X_{water} is the water content in the product $[Fraction]$
- ✓ $L_{f,water}$ is the latent heat of fusion of water $[J/kg]$

The freezing process was incorporated into the cooling products class. For this, a frozen state indicator (SOF) defined by Equation (26), indicates when the product is not frozen (0%) and when it is completely frozen (100%).

$$SOF[i] = SOF[i-1] - \left(T_{product,i}\right) * \frac{Cp}{h_{latent}} \qquad (26)$$

Where:

- ✓ $SOF[i]$ is the state of freezing of the product at iteration i. [%]
- ✓ $SOF[i-1]$ is the state of freezing of the product at the previous iteration $i-1$. [%]
- ✓ Cp_{water} is the specific heat capacity of the product $[J/kg \cdot K]$
- ✓ h_{latent} is the latent heat of freezing of the product $[J/kg]$

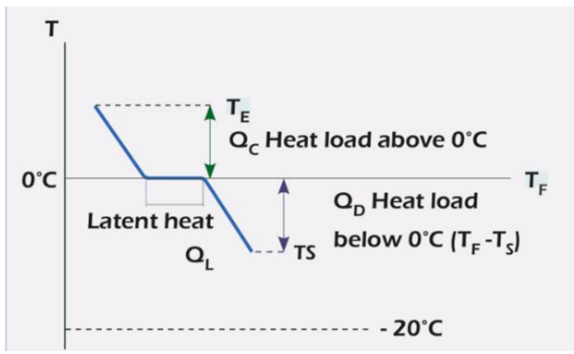

Figure 13. Product Freezing Load Profile. (Source [35])

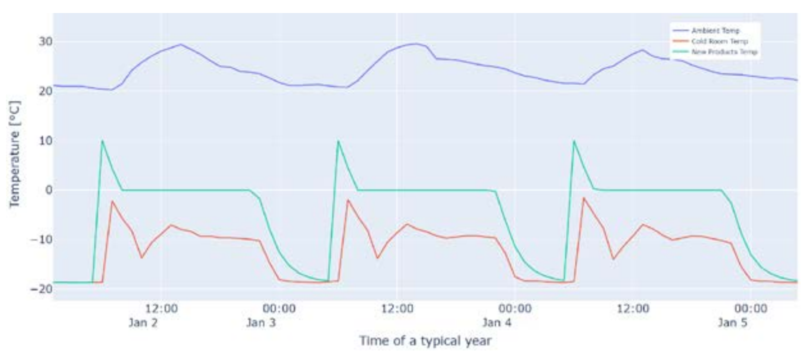

Figure 14. Freezing Process: Product Enters Cold Room at 10°C, Cooled to Below 0°C, and Maintains 0°C Until Freezing Energy is Reached, Then Continues Cooling to Set Point.

PV GENERATION

Solar radiation data

To obtain the solar radiation data, "Photovoltaic Geographical Information System (PVGIS)" was used. PVGIS is a web application open source, that provides information on solar radiation and photovoltaic system performance for any location in the world [38].

For this simulation, the data from a Typical Meteorological Year (TMY) was used. The data set contains hourly data of the following variables that were used in the model: Date and time,

Global horizontal irradiance, Direct normal irradiance, Diffuse horizontal irradiance, Dry bulb temperature, and Relative humidity.

The data set has been produced by choosing for each month the most "typical" month out of the full time period available e.g. 16 years (2005-2020). The variables used to select the typical month are global horizontal irradiance, air temperature, and relative humidity [39].

Solar irradiance components

The term solar irradiance represents the power from the sun that reaches a surface per unit area. Direct irradiance is the part of the solar irradiance that directly reaches a surface; diffuse irradiance is the part that is scattered by the atmosphere; global irradiance is the sum of both diffuse and direct components reaching the same surface.[40]

Solar irradiance is divided in 3 components as follows:

- GHI, Global Horizontal Irradiation
- DNI, Direct Normal Irradiation
- DIF, Diffuse Horizontal Irradiation

GHI and DIF are referred to a surface horizontal to the ground, while DNI is referred to a surface perpendicular to the Sun. Higher values of DIF/GHI ratio represent a higher occurrence of clouds, higher atmospheric pollution or higher water vapor content. [39]

Irradiance Plane of array (POA) and Module Temperature

The amount of sunlight collected by a PV panel depends on how well the panel orientation matches incoming sunlight. To calculate the solar irradiance on the plane, a library in Python called “pvlib” was used. This is an open-source library that provides implementations of PV system models [39].

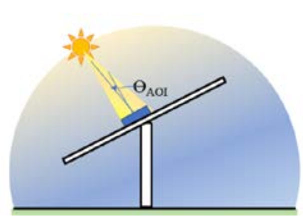

Figure 15. Plane of Array (POA) Irradiance. (Source [2])

To calculate the POA is important to define the panel orientation. For that, tilt and azimuth angles are needed and calculated as follows:

- Tilt: This angle indicates the inclination of the panel from the horizontal. A flat panel is at tilt=0 and a vertical panel has tilt=90 [39].
- Azimuth: Is measured in degrees from North and indicates the direction along the horizon the panel is facing. N=0, E=90, S=180, W=270 [39].

For the model, the Tilt angle and the Azimuth can be supplied as input parameters, or select the angles recommended by the model, which are calculated as follows:

- Tilt angle = abs(Latitude)
- Azimuth angle= 0 for latitude < 0 (southern hemisphere)– North-facing panel
- Azimuth angle = 180 for latitude > 0 (northern hemisphere) – South-facing panel

Another important parameter that has a significant effect on solar radiation is the temperature of the cell. Parameter values covering the common system designs are provided with pvlib [41]

For this model, the temperature is calculated using Sandia Array Performance Model (sapm) and an open rack glass-glass configuration.

Solar time and Local time

The data obtained from PVGIS uses Coordinated Universal Time (UTC). For the calculation of solar radiation, it is necessary to calculate the local time and the solar time. To find the shifted time, the hour with maximum radiation is calculated, and then, this hour is converted to the solar noon, which occurs when the Sun is at its highest point in the sky, which corresponds to the maximum irradiance.

$$Time\ Difference = 12 - hour_{\mathrm{Max}\,Radiation}\ [h] \tag{27}$$

GRID CONNECTION

Having a fully autonomous system powered by solar energy represents a highly sustainable solution, as it relies entirely on renewable energy. However, this can also result in high investment costs and lower system reliability, particularly in regions where solar energy is not sufficient throughout the year or in applications where continuous operation is critical. These challenges can be significantly minimized by implementing a hybrid system, which allows refrigeration units to be powered by both solar energy and the electrical grid, ensuring greater reliability and operational stability.

The logic of the energy flow depends on the battery's state of charge (SOC). When PV power is available, the system is powered by solar energy. When PV power is unavailable, it starts consuming the stored energy from the batteries until it reaches the minimum allowed state of charge. At that point, the system connects to the grid and starts consuming electricity from it. Once solar energy becomes available again, the system is powered by PV first. If there is excess solar energy, the battery starts charging, and finally, when the battery reaches its optimal state of charge, the system disconnects from the grid. The operation of the system when connected to the grid is better explained in Figure 16.

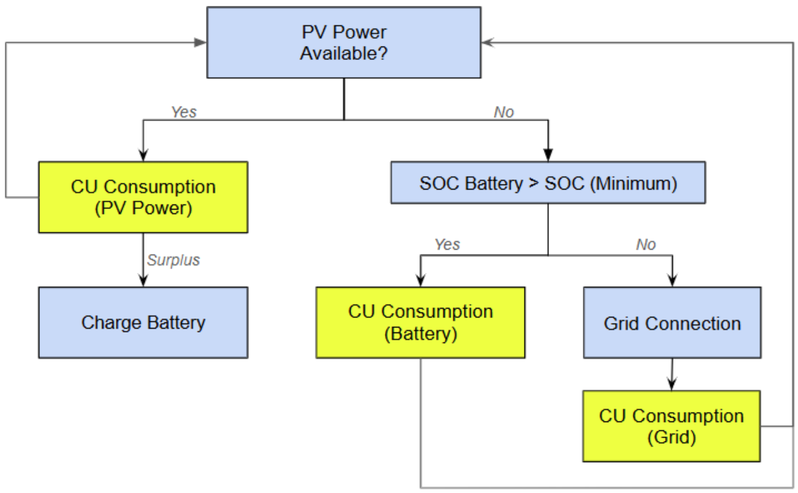

Figure 16. PV, Battery, and Grid Flowchart

IMPLEMENTATION OF THE SIMULATION

The simulation model in Python is based on object-oriented programming (OOP). Its modularity and structure offer better performance and make implementation and obtaining results easier. Additionally, the OPP makes the model reusable and scalable.

Input Data

An input parameter interface must be filled in with all required parameter values necessary for simulations to be carried out, allowing the user to select different types of technology and adapt the simulations to their parameters' design.

Table 3 shows the input parameters required for the cold room design. These parameters include sections such as battery, cold room, product, costs, insulation, thermal loads and the desired set points.

Additionallly, the following parameters should be selected:

Objective function for the optimization: CAPEX, OPEX, LCOC or NPV

Location of the project to obtain the accurate environmental and psychrometric properties.

Type fo system: Thermal Storage or Monoblock.

Table 3. Input data parameters of the model.

COSTS	PV Cost [€/kW]	BATTERY	Nominal Voltage [V]	THERMAL LOADS	Time persons into the room [s]
	CU Cost [€/und]		Maximum DOD [%]		Number of people into the room [-]
	Battery Cost [€/kWh]	PRODUCT	Diameter [m]		Respiration coefficients ASHRAE [m W/kg]
	Grid Cost [€/kWh]		Heat Transfer Coefficient [W/(m^2·K)]		Respiration coefficients ASHRAE (2022) [-]
	Installation Costs [€]		Product Density [Kg/m3]		Fan Power [W]
	PV Lifetime [Year]		Mass of the product [Kg]		Luminous Flux [lm.m-2]
	CU Lifetime [Year]		Specific Heat Capacity [J/kg K)]		Floor Area [m2]
	Battery Lifetime [Year]		Frequency of product storage [days]		Wall Area [m2]
	Insulation Lifetime [Year]		Time of introduction of products into the CR [h]		Efficacy of lighting lamps [lm.W-1]
	Project Lifetime [Year]		Total Mass of product into the CR [Kg]		Time lights are on [h]
	Discount Rate of the project [%]		Temperature inlet of product into the CR [°C]		Door Area [m2]
COLD ROOM	Length [m]	INSULATION	Thickness Insultation [m]		Door Height [m]
	Width [m]		Material Insulation		Effectiveness of door protection [%]
	Height [m]		Thermal Conductivity [W/m K]		Length of seal [m]
	Low Set Point of the CR [°C]		Insulation Cost [€]		Time open door [s]
	High Set Point of the CR [°C]				Times that door is open in one day [s]

1-Year Simulation

The model algorithm is shown in Figure 17. Based on the input parameters, it computes all the necessary characteristics of the cold room and the other system components. This information, combined with geographical data, is then used to calculate the hourly thermal load. Finally, using an energy balance, the energy required for the product cooling process is determined. The simulation is carried out for the entire year, and the results for each configuration of PV, Battery and CU are obtained and stored in a dictionary, with the most relevant annual values such as power electricity of the CU, power thermal of the cold room, total Grid Power consumption, solar fraction, NPV, OPEX, CAPEX, LCOC and others.

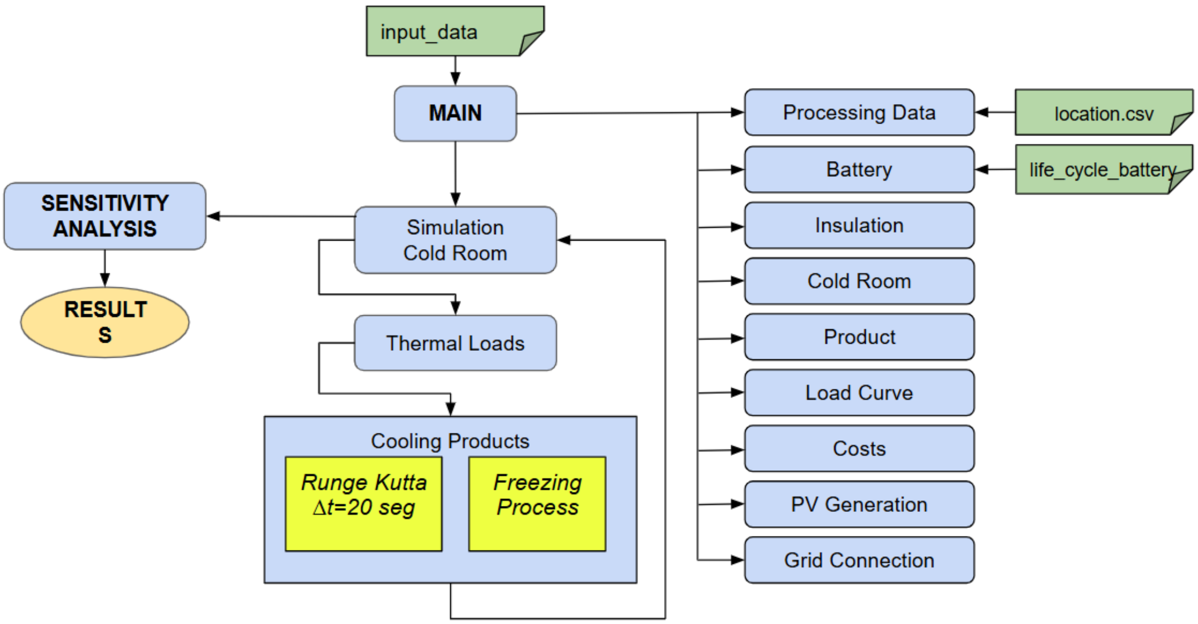

Figure 17. Flowchart and class structure diagram explaining the code logic and execution sequence.

Sensitivity analysis

Sensitivity analysis is a powerful financial modeling technique that allows decision-makers to assess the impact of changes in key input variables on the outcome of financial models [42].

By conducting a sensitivity analysis, the optimal solution is identified from a range of possible alternatives. These solutions are determined by the sizing of the PV system, battery, and CU, while the best option is selected based on any of the annual parameters stored in the final dictionary. Depending on the study's focus, the sensitivity analysis can identify the optimal solution based on criteria such as minimum cost. This analysis is performed over the project's lifetime.

Design selection criteria and cost analysis

Investment decisions are made based on financial analysis or capital budgeting. Since solar-powered cold rooms are considered capital-intensive, long-term investments are used for these projects. The study includes the total capital expenditure (CAPEX), that is the initial investment for the cold room construction (Cold room installation including the insulation, cooling units, batteries and PV panels). Operational expenditure (OPEX) should be also considered, especially for the lifetime of the components that could be replaced during the lifetime of the project. OPEX also includes electricity consumption in case the system is connected to the grid. [43]

Net Present Value (NPV) is a fundamental concept in finance and investment and a key factor for decision-making. *It represents the difference between the present value of cash inflows and the present value of cash outflows over a period of time. By discounting future cash flows to their present value, NPV allows investors and businesses to assess the profitability of an investment or project. [43]*

The levelized cost of energy (LCOE), or in this case referred to as the levelized cost of cooling (LCOC), measures lifetime costs divided by energy production and allows the comparison of different technologies. LCOC is calculated using Equation (28) and includes all the costs related to CAPEX and OPEX, lifetime project(n) considering each year (i), rate of discount (r) and the total output of energy or cooling generation ($Q_{cooling}$).

Table 4. Capex and Opex considered for solar-powered cold room projects

CAPEX	OPEX
Total Battery Cost	Battery Cost / Year
Total PV Array Cost	PV Array Cost / Year
Total Cooling Unit Cost	Cooling Unit Cost / Year
Total Cold Room Cost	Insulation Cost / Year
Total Installation Cost	Grid Cost / Year

$$LCOC = \frac{NPV\ (of\ total\ cost\ over\ life-time)}{NPV\ (of\ electrical\ energy\ produced\ over\ life-time)} \quad \left[\frac{€}{kWh}\right] \qquad (28)$$

$$LCOC = \frac{\sum_{i=1}^{N} \frac{(CAPEX + OPEX)}{(1+r)^{i+1}}}{\sum_{i=1}^{N} \frac{\dot{Q}_{cooling}}{(1+r)^{i+1}}} \quad \left[\frac{€}{kWh}\right] \qquad (29)$$

PRACTICAL EXAMPLE

Example of a Solar Powered Cold Storage for a typical tropical location:

Understanding the climate conditions is essential for the successful development of the project. The data is obtained from PVGIS to determine the behavior of the ambient temperature, relative humidity and solar radiation during a typical year, which are shown in Figure 18, Figure 19 and Figure 20.

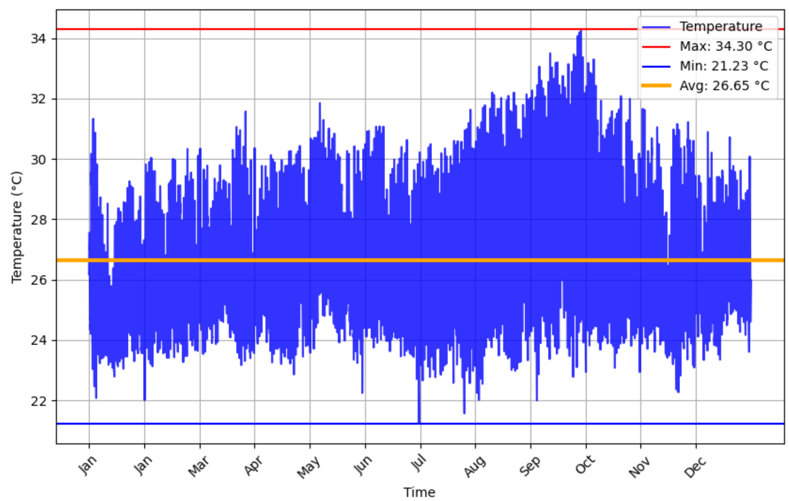

Figure 18. Ambient temperature during a typical year in Jakarta, Indonesia

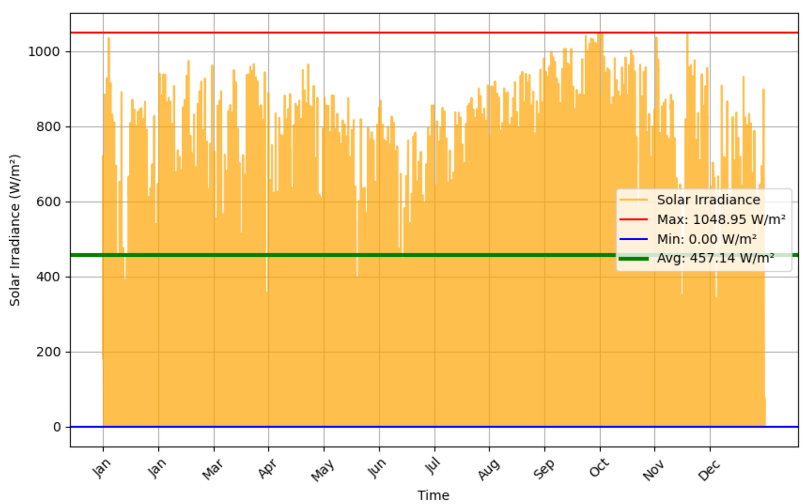

Figure 19. Solar irradiance during a typical year in Jakarta, Indonesia

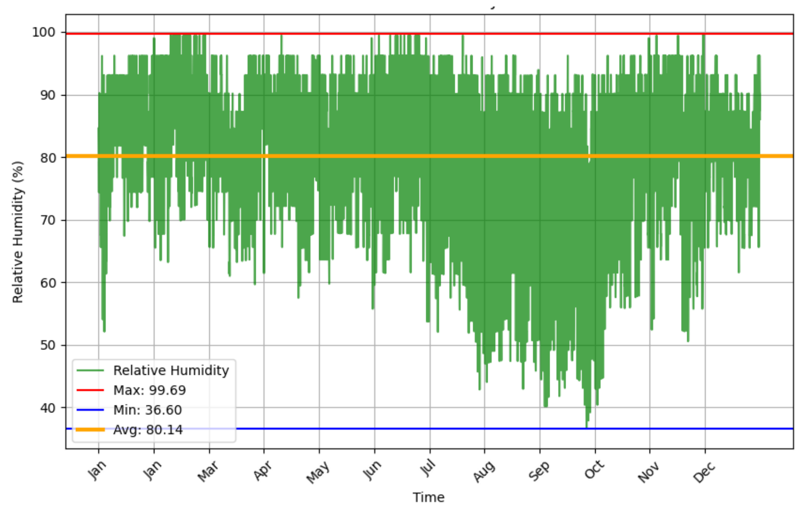

Figure 20. Relative humidity during a typical year in Jakarta, Indonesia

Heatmaps

Heatmap graphs are generated for better visualization of simulation data, such as ambient temperature, cooling demand, COP, cold room temperature, global horizontal irradiance, ice mass, state of charge, and thermal power.

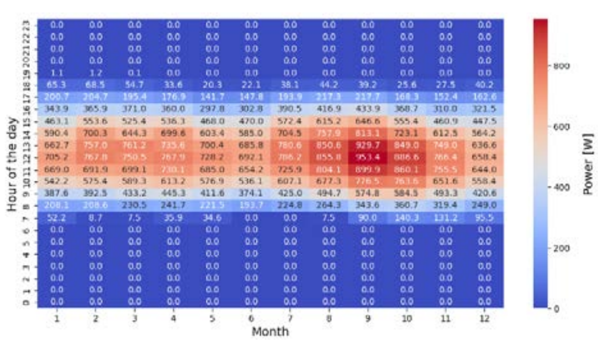

Figure 21. Monthly average ambient temperature per hour of the day

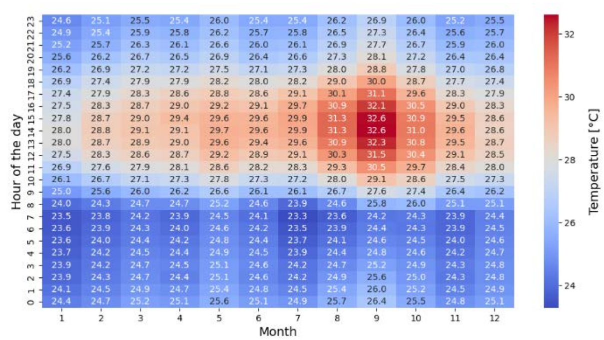

Figure 22. Monthly average GHI per hour of the day

Results of a practical application are shown for a typical small cold room, with solar panels installed on the roof, a Monoblock cooling unit embedded in the wall of the cold room, a battery system and a controller/inverter. (Figure 23). Table 5 shows the main characteristics of the cold room.

Additionally, the costs considered for this practical application are shown in Table 6 and Table 7, for CAPEX and OPEX.

Figure 23. AC cooling unit with Li-ion battery bank and controller/inverter unit. (Source [35])

Table 5. Characteristics of the cold room used during the sensitivity analysis simulations.

DESIGN PARAMETERS		
Variable	Value	Unit
Cold room Length	5	[m]
Cold room Width	2.3	[m]
Cold room Height	2.3	[m]
Insulation Thickness	150	[mm]
Product	Fish	[-]
Cold Room Temperature	-18	[°C]
Product Inlet Temperature	-5	[°C]
Specific heat capacity	3.3	[KJ/(Kg K)]
Heat transfer coefficient	13.1	[W/m2]
Total mass	500	[Kg]
Storage frequency	1	[day]
Time storage	13	[h]
Lifetime project	20	[years]

Table 6. Capital expenditure of the case study project

CAPEX	PRICE	
Battery Cost	271	[€/kWh]
PV Array Cost	500	[€/kW]
Cooling Unit Cost	1105	[€/kW]
Cold Room Cost	88.26	$[€/m^2]$
Installation Cost	9,263.77	[€]

Table 7. Operational expenditures of the case study

OPEX	LIFETIME	
Battery Cost / Year	10	[Years]
PV Array Cost / Year	20	[Years]
Cooling Unit Cost /Year	10	[Years]
Insulation Cost / Year	30	[Years]
Grid Cost	0.07	[€/kW]

The results of the sensitivity analysis for the practical application are presented in Figure 24, which shows a three-dimensional plot considering PV system size, battery capacity, and the Net Present Value (NPV) over the project's lifetime. The optimal configuration is selected based on the lowest total cost while ensuring that performance requirements are met. Green circles represent all feasible system configurations, whereas red "X" marks indicate configurations that are invalid. These invalid configurations fail to meet the system's operational criteria—such as achieving the target cold room temperature within the required time frame, rendering them unsuitable. Table 8 summarizes the optimal configuration identified for the case study, including the corresponding lifetime NPV.

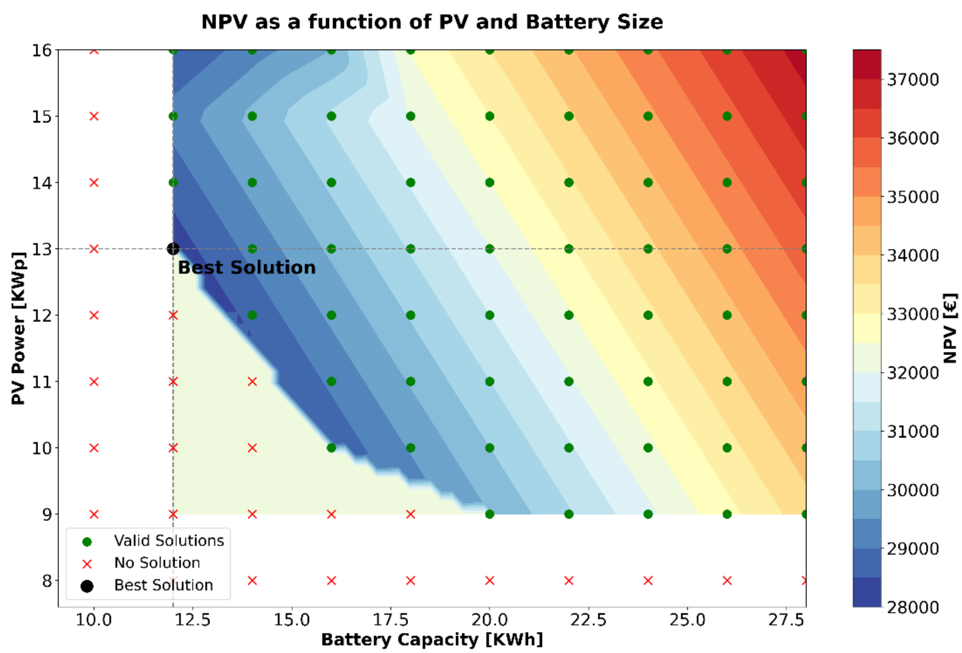

Figure 24. NPV as a function of PV and Battery size

Table 8. Best configuration of PV and Battery size for the case study based on the lowest cost.

BEST CONFIGURATION –		
PV	13,000	[Wp]
BATTERY	12,000	[Wh]
COOLING UNIT	1,615	[W]
COST (NPV)	28,213	[€]

The results also include the following graphs, which illustrate the system's performance throughout the entire year, highlighting key parameters such as temperatures and thermal loads.

Electrical distribution

The system's power distribution is made up of the energy generated by solar panels, the energy stored in the batteries and subsequently consumed by the system, and the energy consumed by the cooling units.

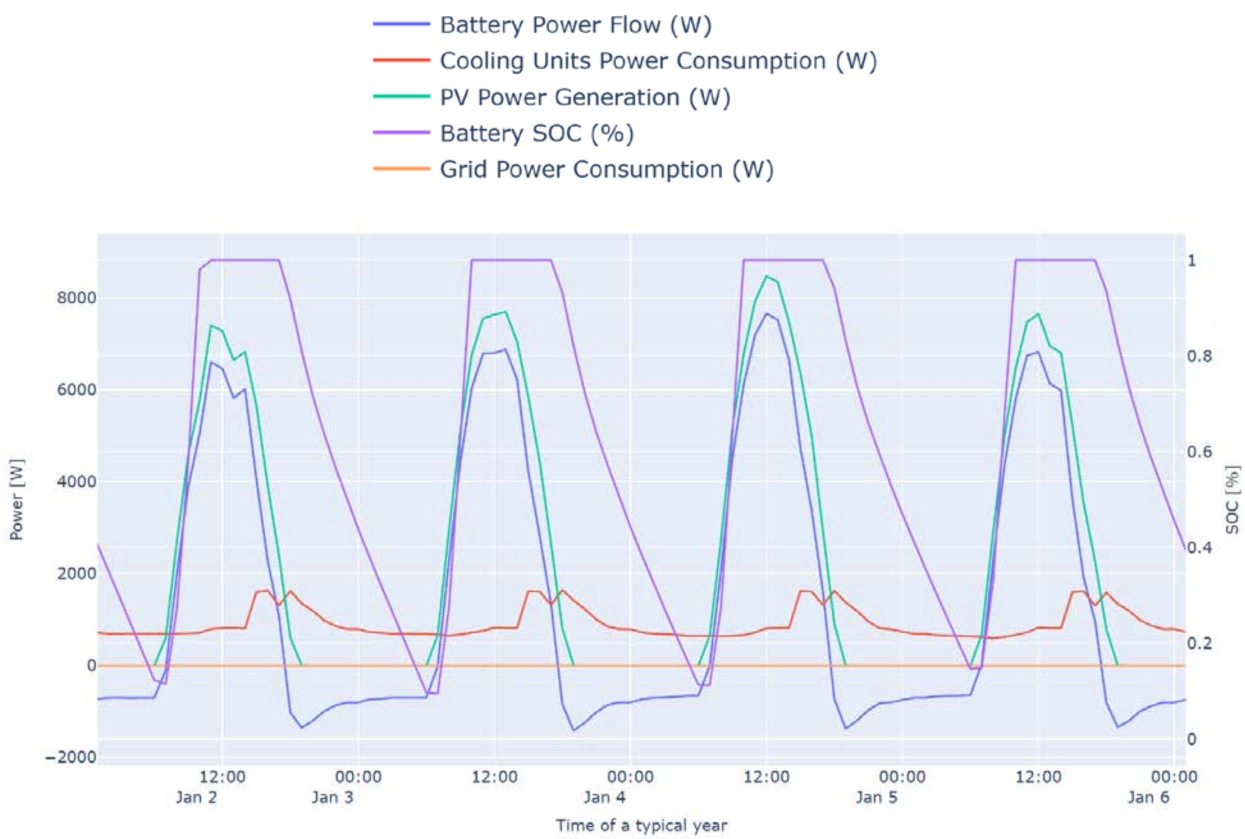

Figure 25. SOC of the Battery and Energy Distribution: PV Power generated, Power consumed by the CU, Power flow of the battery and power consumed from the grid

Cooling load distribution

Figure 26 shows the power consumed by the cold room and the power generated by the cooling unit (Total energy demand and total energy generation). The total energy demand is made up of the total heat load plus the product heat load.

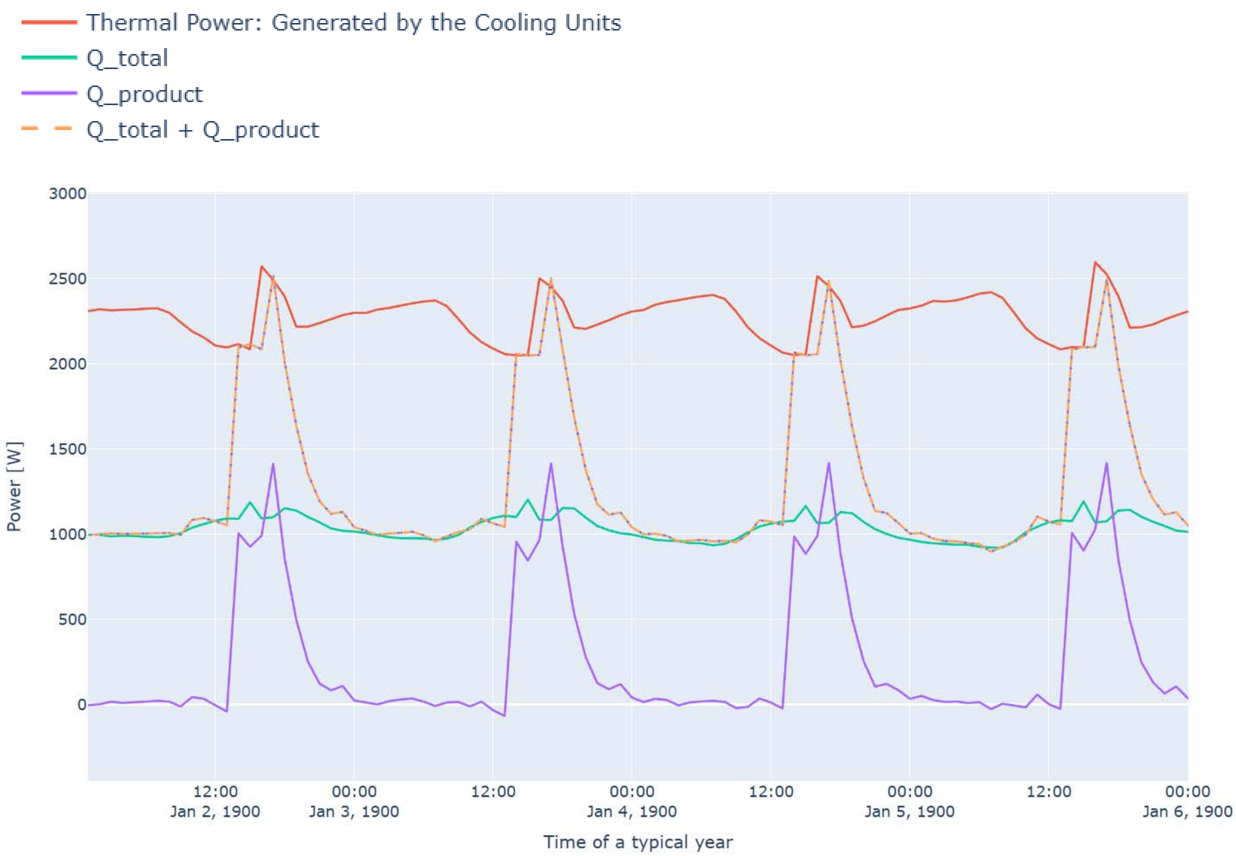

Figure 26. Thermal Power consumed by the cold room (Total Thermal Load) and Thermal power generated by the Cooling Units. Total Heat load is the sum of the Q total and Q product

Temperatures

Figure 27 shows the temperatures of the System: Ambient temperature, the temperature of the air inside the cold room and the temperature of the product.

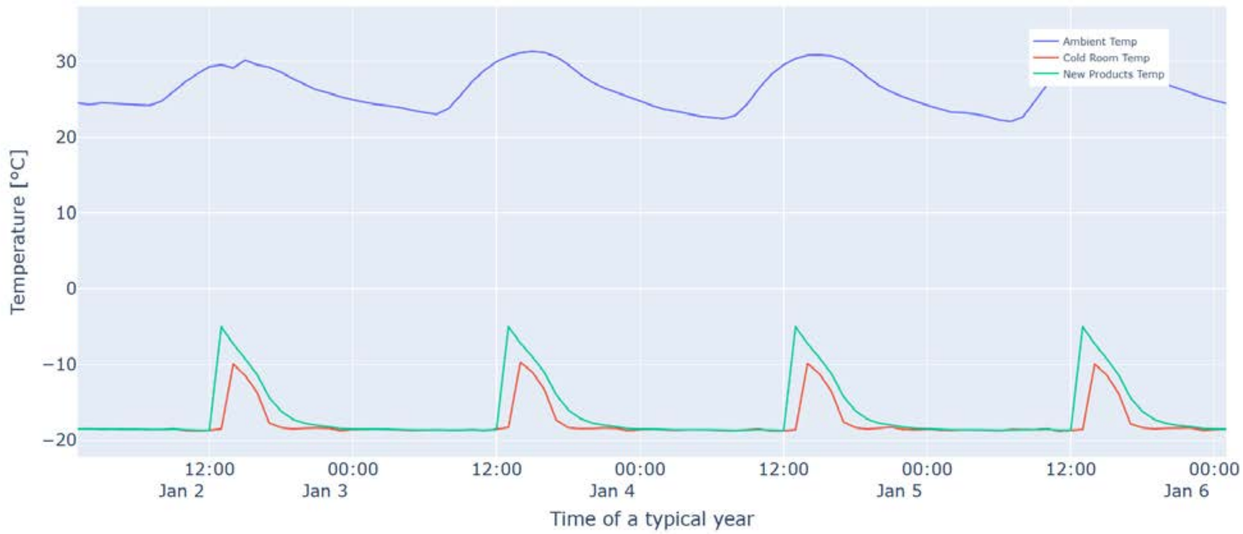

Figure 27. Ambient temperature, cold room temperature and product temperature.

Thermal Loads

The total heat load is the sum of all the loads described before.

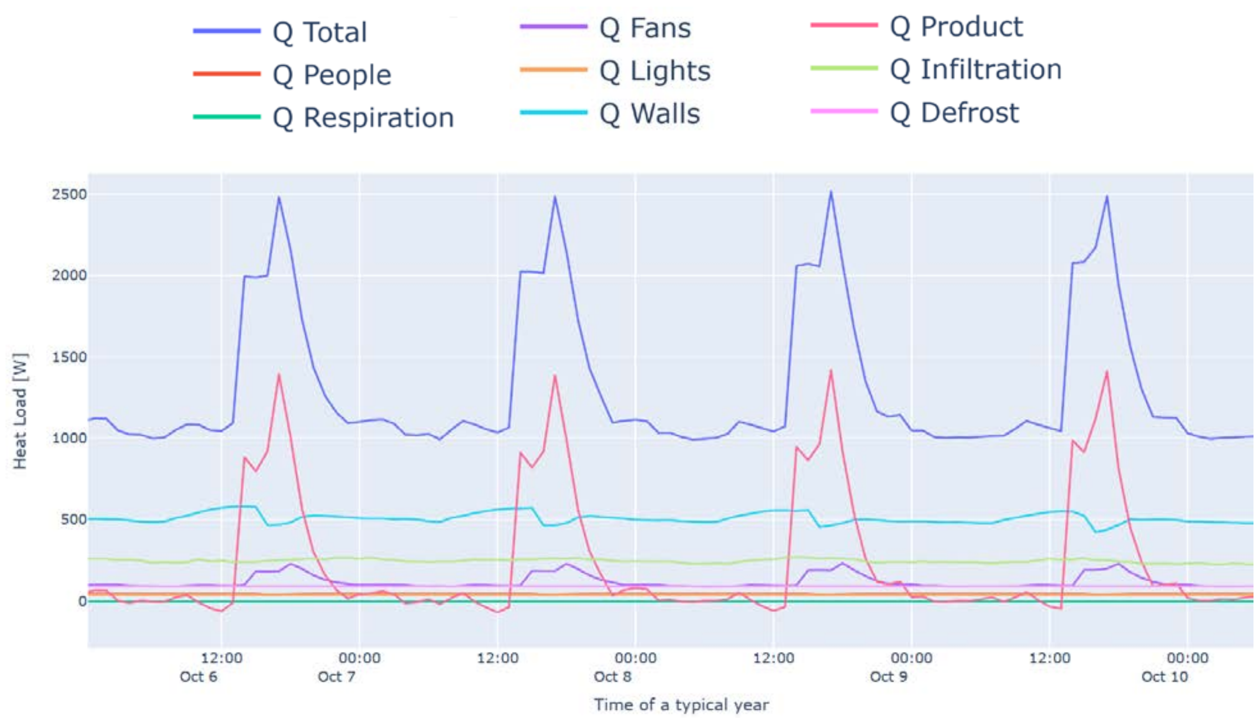

Figure 28. Total thermal loads received for the cold room, including heat load from product.

System Configuration

Additionally, the model allows us to analyze different configurations such as 100% on grid or hybrid Solar-Grid system, which is mostly powered by solar energy, but it can also be powered by grid electricity. This analysis aims to find the optimal solar fraction, based on costs and performance.

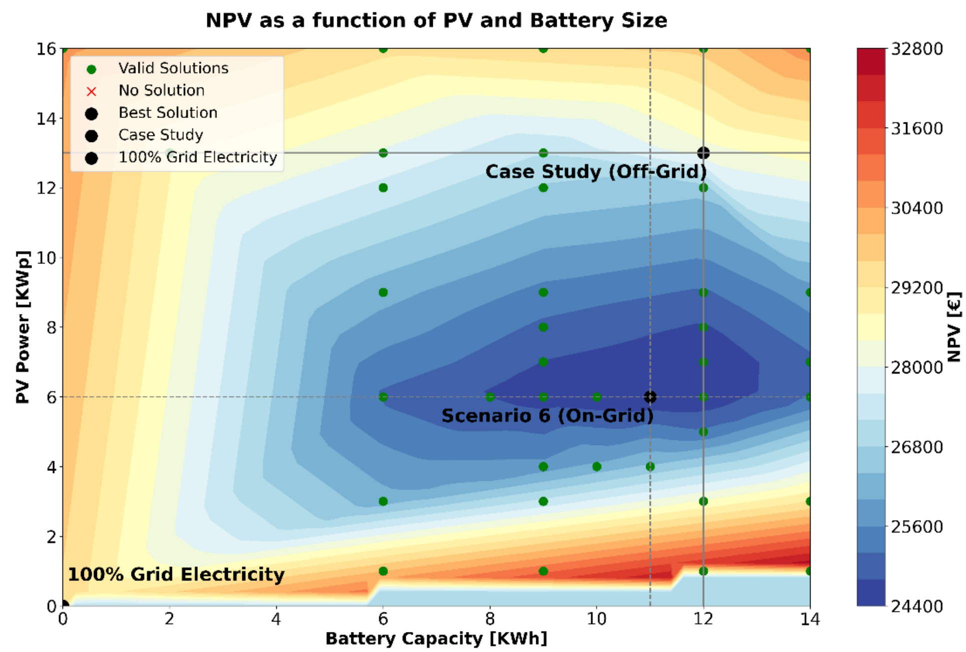

Figure 29. NPV as a function of PV and Battery size for case study connected to the electrical grid.

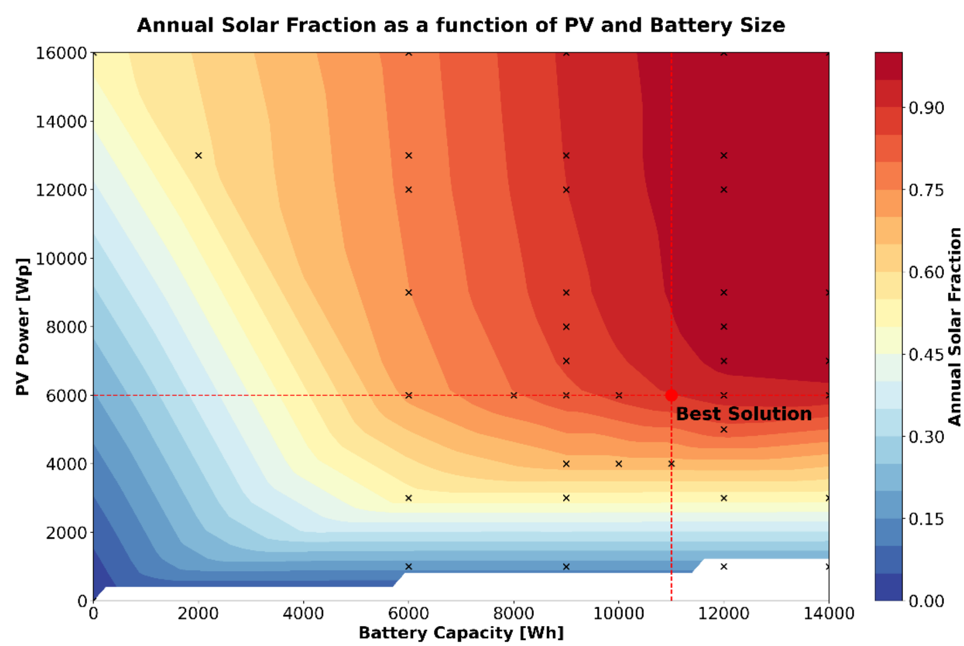

Figure 30. Average solar fraction for case study on-grid

FINAL REPORT:

All results obtained through the simulation model can compiled into a comprehensive final report as is shown below. The report provides a detailed summary of the cold room's design characteristics, including thermal behavior, operating conditions, and system configuration. Additionally, it presents the outcomes of the optimization process, highlighting the most efficient solution identified based on the selected performance criteria. The report also includes a collection of the most relevant performance graphs and visualizations, offering insights into the system's behavior throughout the year. These graphical results support a clearer understanding of key parameters such as energy demand, thermal load distribution, and cooling efficiency, which are essential for evaluating system effectiveness and guiding future improvements.