DELIVERABLE D.T3.1.3

Finalized software tools for energy management in HUC

Project summary:

It is challenging to provide a low carbon energy supply in cities with energy storages. Especially in historical urban centres it is very difficult to achieve these results, because interventions in this specific area meet strict architectural protection constraints, involve higher implementation costs and often come in conflict with town planning policies.

Therefore, the main objective is to improve and enrich energy and spatial planning strategies targeting historical city centres by focusing on integration of energy storage systems to enhance the public institutional and utility capabilities.

The pilot actions implemented in specific sites will demonstrate the various energy storages that can be adapted and transferred to other local or regional environments. The storages will provide good showcases to the local authorities which can benefit in sense of improved energy efficiency, increased usage of renewable energy sources and lower costs for energy. The transnational strategy will provide the recommendations for improving the energy and spatial planning. The energy management tool will enable to monitor all features that prove the effectiveness of the pilot installations. Additionally, the autarky rate tool will indicate the economic and reasonable utilisation of storages. By establishing the stakeholder deployment desk Store4HUC will reach the relevant players to share the knowledge and also transfer it to other additional audience. It will enable to gain wider consensus of the pilot instalment and further tool usage, especially with the signed memorandums of the future tool utilisation. The project approach foresees also peer review actions, mutual learning within project consortium and exchange of experiences and knowledge with target groups that can enhance the transnational added value. Innovative energy storage installation and storing of renewable energy determines the innovative aspect of Store4HUC.

WPT3 description:

In WPT3 the objective is to present the impact of integration of energy storage systems in HUC. Based on the technical & legal framework of integrating efficiently energy storage systems in HUC affordable solutions will be used to demonstrate the matured combination of renewable energy sources & energy storages. Both will be controlled via adapted EMS tool able to maintain & to balance the overall system. Available experiences of selected case study sites and of other running projects will be used in a consolidated way. This foremost relates to energy management software tools inherited by partners from preview projects like e.g. Interreg Danube 3Smart which is coordinated by this WP leader – PP9. The tools adaptation will be concepted, realized and finalized through pilot verifications and interactions, by development PPs (PP9, PP4). After that the establishment of a software tool to interpret autarky rates due to the integration of RES in HUC occurs. The autarky rate is interpreted with an additional checklist. Economical, technical and ecological impacts of the calculated autarky rate are evaluated. Furthermore, it will be examined which performance effects are generated from different renewable energy sources. The gathered information will then be presented via the online tool which will be available for the public for free. An online guide will be elaborated guiding the users through the relevant functions of the tool. Every partner will be trained in the use & all partners will afterwards organize training sessions with members of the deployment desks & invited external experts to educate them on the use & to show corresponding benefits. The acceptance and further usage of the tool will be agreed within the deployment desks and officially committed with the signed memorandum of understanding for the future use of the tools. It is anticipated to engage 8 additional institutions (public institutions, public utilities, etc.) applying for the tools via deployment desks.

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Notations and acronyms

EMS	Energy Management System
Autarky rate	Assessment of installation self-sufficiency
PV	Photo-voltaic
BESS	Battery energy storage system
DSO	Distribution System Operator
CHP	Combined Heat and Power
LP	Linear Program
SLP	Sequential Linear Program
MILP	Mixed-Integer Linear Program
HUC	Historical Urban Centre

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Executive summary

Energy management systems optimally reconcile conflicting requirements for utility and energy performance of systems. This is even harder and even more needed for different systems placed in historical urban centres where additional constraints are stemming from cultural heritage preservation regulations.

This is a design document for the software modules of the tool for energy management in historical urban centres, tailored for application on pilot sites of the Store4HUC project.

It relies on the previously developed concept of the energy management tool where several software modules are inherited from the preceding Interreg Danube project 3Smart and in general the tool is based on ideas from 3Smart. The design of new modules used on the pilot sites of the Store4HUC project is presented in this deliverable – foremost these are (i) module for optimal parametrization of the PV and battery storage system and (ii) module for optimal operation of the heat sources connected to a heat storage.

1. Introduction and general considerations on energy management systems

Energy management systems (EMSs) have in general the task to consolidate the operation of complex systems constituted of different energy-relevant parts, such that they optimally interact with each other from the point of view of energy they use.

The optimality of this interaction is set via goals for operation of the considered complex system expressed as objective function and via constraints on different physical quantities in that system that need to be obeyed.

The objective function and the mathematical constraints formulation constitute the mathematical optimization problem which is posed by specific software modules based on provided input data for the system in question. The software tools developed have the main purpose to efficiently construct the optimization problem from input data, call the appropriate solver to solve the optimization problem efficiently and process its output results to finally provide the advice for system parametrization or operation (off-line) or a direct command for operation to the automation system (on-line).

The concept of energy management tool for the historical urban site is developed within the previous deliverable D.T3.1.1 [1]. The tool developed for energy management of historical urban centres (HUCs) is tailored from the developed energy management tool of the Interreg Danube project 3Smart [2].

There are two new modules that were not part of 3Smart and that have arisen as a need for optimal parametrization, planning and operation of energy storages at HUCs, and the focus of this deliverable is put on them. They are [1]:

(1) module for optimal sizing of the investment in a renewable electricity source and electricity storage for a particular consumer with known electricity consumption profile under given condition of allowed return on investment period and HUC-specific constraints, with included profiling of optimal operation of the storage system;

(2) module for optimal operation of the combination of heat sources and a heat storage system for a particular consumer or producer with known heat demand and required temperature conditions in the heating medium storage (on-line operation of this module is module (12) from the concept).

Compared to the concept, for the case of module (2) parameterization of the heat storage is opted out due to revealed significant computational complexity behind that would prevent its usage in practice.

In the sequel of this deliverable first in Section 2 the design of modules (1) and (2) is presented, and then in Section 3 their application to the Store4HUC pilot sites is illustrated. Module (1) is applied to the pilot sites Bračak and Cuneo, while module (2) is applied to pilot sites of Bračak, Lendava and Weiz.

2. Design of the energy management tool adapted to historical urban centres

2.1. Module (1)

Module (1) of the energy management tool for historical urban centres is used for optimal sizing of the investment in a renewable electricity source and electricity storage for a particular consumer with known electricity consumption profile under given conditions of allowed return on investment period and HUC-specific constraints and with included profiling of optimal operation of the battery storage system.

Initial tool was described in **Napaka! Vira sklicevanja ni bilo mogoče najti.**, but upon implementation it was noted that computational requirements for running the tool were too large, i.e. a regular laptop or a PC would not be able to run the tool. Since the tool would require more than 64 GB of memory, changes were made in the mathematical operation of the tool to make it available for broader public. Final version is running for longer time, but it requires significantly less computational resources, 16 GB of memory, which makes it possible for the tool to be accessible to more users. Mathematical background of the final version of the tool is described in section 2.1.2. Usage of the tool and its user interface is presented in section 2.1.2.

2.1.1. Mathematical background

The currently designed procedure is tailored for the combination of a photovoltaic (PV) system and a battery energy storage system (BESS). Optimal size of the PV system in terms of its power production at STC (standard test conditions: 1000 W/m2 input irradiance and 25°C PV modules temperature) is provided, as well as the optimal size of the BESS in terms of its power converter power rating and the storage capacity. The mentioned optimal parameters are computed based on the measured electrical energy consumption at the consumer's grid connection point, and a PV energy production. As the PV system is yet to be installed, global solar irradiance measurements and sun angles (elevation and azimuth) during the year are used. Together with orientation and inclination angles of the planned PV solar arrays, a possible PV production profile, P_{PV}, is generated. Its peak power is $P_{PV,peak,nearby}$.

The electricity consumption profile, P_{dem}, is recorded with sampling time of $T_{s,ful} = 15$ min, but then it is resampled with sampling time $T_{s,res} = 1$ h, which makes it 4 times smaller and saves memory at the expense of the accuracy. However, consumption profile is resampled twice, once as average of 4 values during the same hour, and once as maximal of 4 values during the same hour:

$$P_{dem,avg}(k) = \text{mean}(P_{dem}[rk:r(k+1)]), \qquad k \in [0..N-1] \tag{2.1.1}$$

$$P_{dem,max}(k) = \text{max}(P_{dem}[rk:r(k+1)]), \qquad k \in [0..N-1] \tag{2.1.2}$$

where N is number of original samples, and:

$$r = \frac{T_{s,res}}{T_{s,ful}} = 4. \tag{2.1.3}$$

That way, the peak power is computed more accurately. The PV production profile, P_{PV}, is resampled only as average:

$$P_{PV,avg}(k) = \text{mean}(P_{PV}[rk:r(k+1)]), \qquad k \in [0..N-1] \tag{2.1.4}$$

because maximal values of PV production do not coincide with maximal values of electricity consumption.

Besides resampling, the calculation procedure was modified to use less computational resources. Instead of solving one large (linear programming) LP problem,

$$\text{Minimize } f^T x,$$

$$\text{subject to } A_{ineq}x \le b_{ineq},$$

$$A_{eq}x = b_{eq}, \tag{2.1.5}$$

$$x_{min} \le x \le x_{max},$$

the result is obtained by solving a series of smaller LP problems. This technique is called sequential (or successive) linear programming (SLP) and solving one LP is called iteration. Iterations are separated into 4 sections:

1.) Initial iteration (1 iteration),

2.) Efficiency and degradation iteration (1 iteration),

3.) Feed-in price iterations (>1 iterations),

4.) Converging iterations (>1 iterations).

The calculation process can be stopped at any iteration if the BESS is not economically viable.

Initial iteration

In the initial iteration, the state of charge of the battery, SoC, is influenced by charging (or discharging) power, P_{bat}, without efficiency included, i.e. it is considered that there is no energy loss:

$$SoC(k+1) = SoC(k) + P_{bat}(k)T_{s,res}, \tag{2.1.6}$$

where P_{bat} is positive while charging, and negative while discharging. Power exchange with the utility grid is calculated as

$$P_{grid,avg}(k) = P_{dem,avg}(k) + P_{bat}(k) - \alpha_{PV}P_{PV,avg}(k),$$

$$P_{grid,max}(k) = P_{dem,max}(k) + P_{bat}(k) - \alpha_{PV}P_{PV,avg}(k), \tag{2.1.7}$$

where α_{PV} is a scaling coefficient used to calculate the optimal peak power of the new PV system with respect to the one obtained from solar irradiance profile: $\alpha_{PV} = \frac{P_{PV,peak}}{P_{PV,peak,nearby}}$.

Cost function, $f(x)$, that is minimized by solving the LP depends on the user input, as the user can choose one of three options:

1.) Energy exchange with the grid, $f_1(x)$;

2.) Price of the energy exchanged with the grid, $f_2(x)$;

3.) Total price (price of the exchanged energy + yearly scaled investment + yearly maintenance), $f_3(x)$.

$$f_1(x) = \sum_{k=0}^{n-1} P_{grid,avg}(k)T_{s,res} \tag{2.1.F1}$$

$$f_2(x) = J_{yes,inv} \tag{2.1.F2}$$

$$f_3(x) = J_{yes,inv} + \frac{J_{inv}}{n_{payoff}} + J_{ym} \tag{2.1.F3}$$

where $J_{yes,inv}$ is the price of the energy exchange with the utility grid, J_{inv} is the cost of the investment, n_{payoff} is the number of years in which the investment must be paid off specified by the user, and J_{ym} is the cost of the yearly maintenance:

$$J_{yes,inv} = c_{grid}\sum_{k=0}^{n-1} P_{grid,avg}(k)T_{s,res} + c_{peak}\sum_{k=0}^{n-1} P_{peak}(k), \tag{2.1.8}$$

$$J_{inv} = c_{bat}SoC_{max} + c_{pc}P_{pc,max} + c_{PV}P_{PV,peak,nearby}\alpha_{PV}, \tag{2.1.9}$$

$$J_{ym} = \frac{c_{bat}}{n_{bat}}SoC_{max} + \frac{c_{pc}}{n_{pc}}P_{pc,max} + \frac{c_{pv}}{n_{PV}}P_{PV,peak,nearby}\alpha_{PV}. \tag{2.1.10}$$

In equations (2.1.11-13) n denotes number of samples in both electricity consumption and PV generation profiles after the resampling, c_{bat} is the price of the battery pack per unit of energy, SoC_{max} is the energy capacity of the battery, n_{bat} is the lifetime of the battery pack in years, c_{pc} is the price of the power converter per unit of power, $P_{pc,max}$ is the nominal power of the power converter, n_{pc} is the lifetime of the power converter in years, c_{PV} is the price of the PV system per unit of installed power, and n_{PV} is the lifetime of the PV system in years. The second term in the equation (2.1.8) is removed if the consumer does not have peak power billed.

In equations (2.1.8-10) x represents the optimization vector and it consists of:

- charging/discharging powers of the battery, $P_{bat}(k), k \in [0 \dots n-1]$;

- peak power of power exchange with the grid, $P_{peak}(k), k \in [1 \dots 12]$, which is present only if the peak power is billed;

- starting state of charge of the battery, $SoC(0)$;

- energy capacity of the battery pack, SoC_{max};

- nominal power of the power converter, $P_{pc,max}$;

- scaling coefficient of the PV system, α_{PV}.

To fully construct the LP problem (equation 2.1.5) and to fully describe the overall system mathematically, equality and inequality constraints must be posed. The only equality constraint makes sure that the calculated sequence is repeatable, i.e. the last instance of state of charge must be equal to the starting one:

$$SoC(0) = SoC(N). \tag{2.1.C1}$$

Inequality constraints, inter alia, make sure that

2.) the battery is never under- nor over-charged,

$$(1 - DoD)SoC_{max} \le SoC(k) \le SoC_{max}, \forall k \in [0 \dots n], \tag{2.1.C2}$$

3.) power converter operates within its limits,

$$-P_{pc,max} \le P_{bat}(k) \le P_{pc,max}, \forall k \in [0 \dots n], \tag{2.1.C3}$$

4.) the peak power is properly calculated even though it is not a linear function,

$$P_{peak}(l) \ge P_{grid,max}(k), \qquad \forall k \in month\ l \tag{2.1.C4}$$

5.) the total investment does not exceed the limit posed by the user,

$$J_{inv} \le J_{inv,max} \tag{2.1.C5}$$

6.) the investment is paid off within the number of years set by the user.

$$J_{no,inv} - J_{yes,inv} \ge \frac{J_{inv}}{n_{payoff}} + J_{ym} \tag{2.1.C6}$$

$J_{no,inv}$ is the price of energy exchange with the grid for the case of no investment, and DoD is the depth of discharge of the battery.

Upon constructing and solving the LP, (2.1.F1 - 2.1.F3) + (2.1.C1 - 2.1.C6), the results are saved and transferred to the next iteration.

Efficiency and degradation iteration

After having the solution of the initial iteration, efficiency of the BESS and degradation of the battery pack can be introduced. Since those functions are linear only if the $P_{bat}(k)$ does not change its sign, a new auxiliary variable $CoD(k)$, which determines if the battery charges or discharges at every timestamp k, is introduced: $CoD(k) = 1$ while charging, and $CoD(k) = -1$ while discharging. After the initial iteration it is calculated as:

$$CoD^0(k) = \begin{cases} 1, & when\ \text{sign}\big(P_{bat}^0(k)\big) = 0 \\ \text{sign}\big(P_{bat}^0(k)\big), & otherwise \end{cases}, \tag{2.1.11}$$

where $CoD^0(k) = 1$ if the battery was neither charged nor discharged. In further iterations, enumerated with i, the (dis)charging power $P_{bat}(k)$ should be able to change sign, and this is ensured by changing $CoD(k)$ from 1 to -1 when $P_{bat}(k)$ changes from positive value to zero, and from -1 to 1 when $P_{bat}(k)$ changes from negative value to zero:

$$CoD^i(k) = 2\ \text{sign}\left(P_{bat}^i(k)\right) - CoD^{i-1}(k). \tag{2.1.12}$$

Having the variable that determines the direction of the power flow to/from the battery, the efficiency of the BESS at timestamp k, $\eta(k)$, can be expressed as:

$$\eta(k) = \max\big(0, \eta_{ch}CoD(k)\big) - \min\left(0, \frac{1}{\eta_{dch}}CoD(k)\right), \tag{2.1.13}$$

where η_{ch} and η_{dch} are charging and discharging efficiencies defined by the user. Now, the state of charge of the battery can be expressed with a linear function:

$$SoC(k+1) = SoC(k) + \eta(k)P_{bat}(k)T_{s,res}. \tag{2.1.14}$$

The cost of the battery degradation is expressed per unit of energy that goes through it, and it is calculated as:

$$c_{deg} = \frac{c_{bat}}{2n_{cyc}DoD}, \tag{2.1.15}$$

where n_{cyc} is the number of cycles that the battery pack can go through without significantly reducing its capacity. With degradation cost defined, the cost of the yearly maintenance is now calculated as:

$$J_{ym} = c_{deg}T_{s,ext} \sum_{k=0}^{n-1} CoD(k)\eta(k)P_{bat}(k) + \frac{c_{pc}}{n_{pc}}P_{pc,max} + \frac{c_{pv}}{n_{pv}}P_{pv,peak,nearby}\alpha_{pv}. \tag{2.1.16}$$

Due to new definitions of $SoC(k)$ and J_{ym}, cost function (2.1.F3) and constraints (2.1.C1), (2.1.C2) and (2.1.C6) are updated. Furthermore, a new constraint is introduced. It makes sure that:

7.) the (dis)charging power of the battery does not change its sign.

$$P_{bat}(k) \geq 0\ when\ CoD(k) = 1,$$
$$P_{bat}(k) \leq 0\ when\ CoD(k) = -1. \tag{2.1.C7}$$

Feed-in price iterations

So far, the price of the energy exchanged with the utility grid was the same no matter the sign. For example, if the energy is going into the grid due to high PV production, price for it was the same as for buying the energy. However, feed-in prices are normally significantly lower than buying prices. Therefore, a new auxiliary variable $BoS(k)$, which determines whether the energy is bought or sold at timestamp k, is

introduced: $BoS(k) = 1$ when buying the energy, and $BoS(k) = -1$ when selling the energy. After the initial iteration it is calculated as:

$$BoS^0(k) = \begin{cases} 1, & \text{when } \text{sign}\left(P^0_{grid,avg}(k)\right) = 0 \\ \text{sign}\left(P^0_{grid,avg}(k)\right), & \text{otherwise} \end{cases}, \qquad (2.1.17)$$

where $BoS^0(k) = 1$ if the energy is neither bought nor sold. In further iterations the power exchanged with the grid $P_{grid,avg}(k)$ should be able to change sign, and this is ensured by changing $BoS(k)$ from 1 to -1 when $P_{grid,avg}(k)$ changes from positive value to zero, and from -1 to 1 when $P_{grid,avg}(k)$ changes from negative value to zero:

$$BoS^i(k) = 2 \, \text{sign}\left(P^i_{grid,avg}(k)\right) - BoS^{i-1}(k). \qquad (2.1.18)$$

Therefore, the cost of the energy exchange with the grid, c_{el}, can be defined depending on $P_{grid,avg}$:

$$c_{el}(k) = \max\left(0, c_{grid}BoS(k)\right) - \min\left(0, c_{feed}(k)BoS(k)\right), \qquad (2.1.19)$$

where c_{feed} is the feed-in price of the electrical energy. With the newly defined energy price, cost of energy exchange with the grid, equation (2.1.8), becomes:

$$J_{yes,inv} = \sum_{k=0}^{n-1} c_{el}(k)P_{grid,avg}(k)T_{s,res} + c_{peak}\sum_{k=0}^{n-1} P_{peak}(k), \qquad (2.1.20)$$

where the second term is removed if the consumer does not have peak power billed. Due to new definitions of $J_{yes,inv}$, cost functions (2.1.F1 – 2.1.F3) and constraint (2.1.C6) are updated. Furthermore, a new constraint is introduced. It makes sure that:

8.) the power exchange with the utility grid does not change its sign.

$$P_{grid,avg}(k) \geq 0 \text{ when } BoS(k) = 1,$$
$$P_{grid,avg}(k) \leq 0 \text{ when } BoS(k) = -1. \qquad (2.1.C8)$$

With newly formed LP it is not guaranteed that the solution will be feasible. Because of lowered feed-in price the revenue from selling the energy would be lowered which means lower investment possible, and with fixed directions of power flows between the consumer and the grid there could be no feasible solution. Therefore, the feed-in price c_{feed} is tweaked until the proper solution is found.

Firstly, the LP is formulated with proper feed-in price c_{feed}. If the solution is feasible than the procedure advances to the converging iterations. On the other hand, if the solution of this LP is infeasible, feed-in price is artificially brought halfway back to the buying price c_{grid} as $c_{feed,artificial} = (c_{grid} + c_{feed})/2$. If the solution is infeasible again, the halving of the interval between current feed-in price and the buying price is repeated until the feasible solution is found. After the feasible solution is found, the LP is formulated again with the proper feed-in price. This time, if the solution is infeasible, the new artificial feed-in price is brought halfway back to the feed-in price that resulted in feasible solution for the last iteration: $c_{feed,artificial} = \left(c^{i-1}_{feed} + c_{feed}\right)/2$. If the solution is infeasible again, the procedure of interval halving is repeated until feasible solution is obtained.

Converging iterations

The last set of iterations is carried out until the convergence. The LP problems have the same construction as the feed-in price iterations. The only difference is the feed-in price that is now fixed at the proper value. Every time the LP problem is solved auxiliary variables CoD and BoS are updated. Also, every time the LP is solved, the value of its cost function is compared with the minimal value so far. If it is less than the minimum so far, the procedure continues with further iterations. However, if the value of the cost function

is greater than the minimum so far, the counter for convergence increases by 1. When the counter reaches the setpoint number the procedure ends, and the optimal result is the one with minimal value of the cost function.

2.1.2. Optimal sizing calculator

Module (1) of the energy management tool for historical urban centres is made available for public use for free and it is called "Optimal sizing calculator". The calculator is downloadable from the project's website. It comes as a .zip file which contains everything necessary to run it and it does not require installation, i.e. it is ready to use just after unzipping the .zip file. The content of the .zip file is shown in Figure 1.
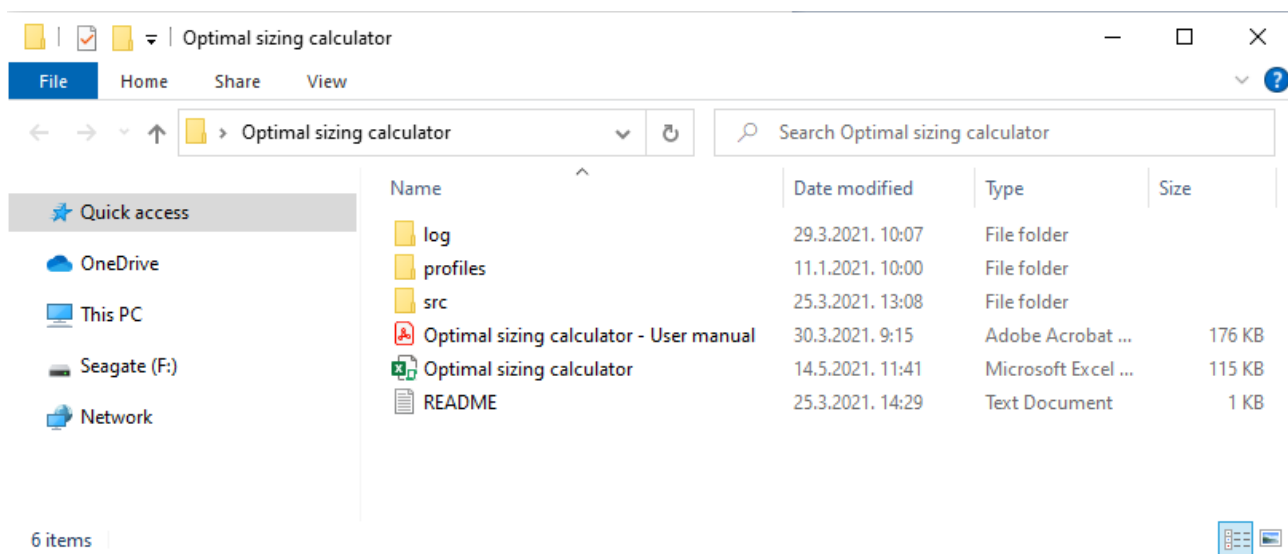
Figure 1. Folder content of the Optimal sizing calculator.

"README" file contains simple instructions on how to get started with the tool. The user interface (UI) is made in MS Excel®, and a screenshot of it is presented in Figure 2. The calculator UI is placed under the tab "Calculator", while the user manual is placed under the tab "User Manual". The same user manual is also placed in the root folder of the calculator as a .pdf file. It contains instructions on how to use the tool and explanation of all the parameters.

The calculation process is implemented in Python programming language with GLPK® as the solver for LP problems. To make the module useful on a computer without Python installed, a standalone executable file is created from the Python scripts. Resulting .exe file, with its auxiliary .dll files, can be executed on any computer with Windows operating system and it is positioned in the "src" folder.

For every calculation started there is a log file generated and placed into "log" folder. Log files contain details of every calculation. They might not be of much use for the user, but if an unexpected error occurs, the user can step in contact with the developers of the tool and provide the log file to quickly resolve the problem.

The folder "profiles" contains all pre-recorded electricity consumption profiles and solar irradiance profile. If a user wants to use a custom consumption profile, it must be placed in the same folder.

Figure 2. UI of the Optimal sizing calculator.

During calculation the calculator displays messages about the calculation progress. Messages can be of type *info*, *warning* or *error*. Info messages provide information about the computation process (e.g. *Data preprocessing finished. Formulating mathematical problem...*). Warning messages inform the user if something is wrong, but the computation can continue. Lastly, error messages inform the user if something is wrong and, in that case, the computation must terminate (e.g. *Parameters are missing. The calculator cannot continue.*). Every message contains a timestamp (date and time), message body (text), and type. By clicking on the *Calculate optimal sizes* button all the existing messages are deleted, and new ones are being displayed. An example of messages for a calculation is displayed in Figure 3.

33		
34	**Calculate optimal sizes**	Cancel calculation	Default values
35		
36		
37	**RESULTS**	
38	Optimal battery size	0.00 kWh
39	Optimal power converter	0.00 kW
40	Optimal PV size	10.00 kWp
41		
42		
43		
44	**MESSAGES**	
45		

	TIMESTAMP	MESSAGE	TYPE
46			
47	2021/10/05 15:18:17	Calculator started. Please be aware that the calculation process is time-consuming.Reading and preprocessing data...	info
48	2021/10/05 15:18:23	Data preprocessing finished. Formulating mathematical problem...	info
49	2021/10/05 15:22:01	Mathematical problem formulated. Solving initial iteration...	info
50	2021/10/05 15:24:05	Initial iteration solved. Current solution: Battery 0.96 kWh, Power converter 0.77 kW, PV 10.00 kWp.	info
51	2021/10/05 15:24:05	Calculation finished because the optimal solution was found. Battery storage is economically unviable.Final solution: Battery 0.00 kWh, Power converter 0.00 kW, PV 10.00 kWp.	info
52			
53			

Figure 3. Messages being displayed in the calculator.

2.2. Module (2)

Module (2) of the energy management tool for historical urban centres is the module for optimal operation of the combination of a heat source and a heat storage system, for a particular consumer or set of consumers connected to the storage, with known cumulative heat demand under required heating medium temperature conditions in the storage. The module results in profiling of optimal operation of the heat generation system that inject heat in the storage.

The procedure of finding the optimal profiles of heat sources engagement is based on the heating demand and disturbances. Since the module works for day-ahead operation, heating demand and disturbances must be predicted. To test functionality of the module in a simulation, one can use pre-recorded heating demand and disturbances. The main disturbance for a heat storage system is the temperature of air around the storage tank due to imperfect insulation. The length of profiles, both inputs and outputs, is 24 h, and the resolution of measurements is equal to 15 min, which is short enough to capture dynamic behaviour of the system, but also long enough not to make the module computationally too expensive.

2.2.1. Mathematical background

A heating system depicted in Fig. 1 is considered. It consists of a heat source, a thermal energy storage (TES), demand side, and an environment of the TES. The heat source provides power to the TES by heating up a heating medium. This medium is stored in the TES, and it is provided to the demand side only from the TES. Also, the TES has energy losses to the surrounding environment.
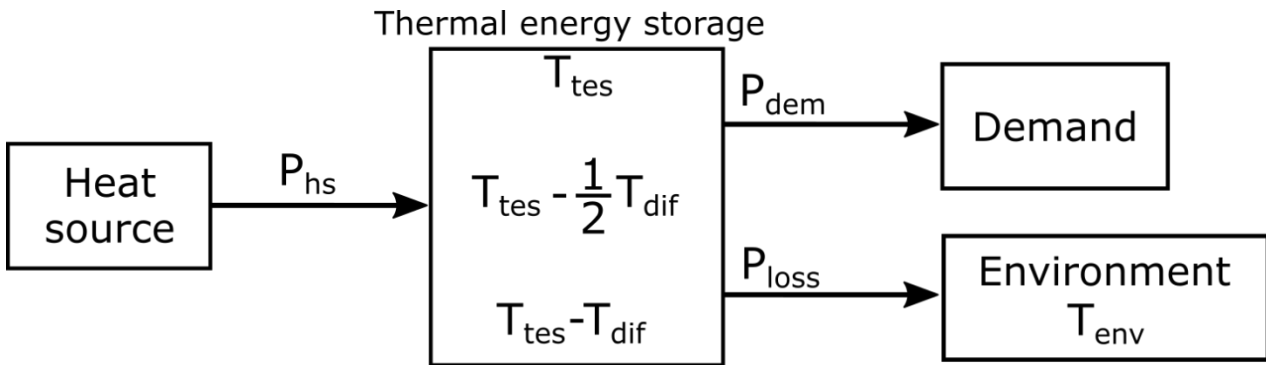

Figure 4. Heating system representation.

Heat source

Most of heat sources available on the market, such as boilers or combined heat and power (CHP), cannot have their power regulated from 0 % to 100 %. They have a minimal power they can operate with. Therefore, the heat source in this model is controlled in two ways: by turning it on and off, and by regulating its power output between its minimal, $P_{min} > 0$, and its maximal power, $P_{max} \geq P_{min}$. For turning the heat source on/off a binary variable is used, $\delta_{hs} \in \{0, 1\}$, while for regulating its power output a continuous variable is used, $P_{ref} \in [P_{min}, P_{max}]$. In total, a single variable can be used as the actual power reference for the heat source, $P_{act} = \delta_{hs} P_{ref}$. However, as such variable can take on values from a disjoint set, $P_{act} \in \{0\} \cup [P_{min}, P_{max}]$, all three variables ($\delta_{hs}$, P_{ref}, P_{act}) are used later in the optimization formulation.

Heat sources cannot respond to the reference power immediately. Therefore, the heating power coming to the TES from the heat source, P_{hs}, is modelled dynamically as:

$$\frac{dP_{hs}}{dt} = \frac{P_{act} - P_{hs}}{T_{hs}}, \tag{2.2.1}$$

where T_{hs} is the time constant of the heat source.

Another feature of the heat source is variable efficiency which refers to the ratio of obtained heating energy and primary energy used. It is usually written in the datasheet of the selected device as efficiency at the minimal power output, η_{min}, and efficiency at maximal power output, η_{max}. For all values of P_{ref} inbetween P_{min} and P_{max} the efficiency is calculated using linear interpolation between those two points:

$$\eta(P_{ref}) = k_\eta P_{ref} + l_\eta, \tag{2.2.2}$$

where k_η and l_η are slope and intercept of the affine function obtained from two points: $\eta_{min} = \eta(P_{min})$ and $\eta_{max} = \eta(P_{max})$.

Thermal energy storage

TES is a stratified storage tank containing heating medium. It is assumed that it has a constant temperature difference, T_{dif}, between the heating medium at the top and at the bottom of the tank. Since the medium is the hottest at the top and coldest at the bottom of the storage tank, the outlet pipe going to the demand side is always situated at the top of the tank. Therefore, the temperature at the top of the tank, T_{tes}, is the one that is modelled:

$$mc_p \frac{dT_{tes}}{dt} = P_{hs} - P_{dem} - P_{loss}, \tag{2.2.3}$$

where m is the mass of the heating medium in the tank, c_p is the specific heat capacity of the heating medium, P_{dem} is the heat demand, and P_{loss} is the storage loss due to temperature difference between heating medium and the surrounding environment of the storage tank.

Power demand profile is provided by the user of the tool, so in a mathematical sense it is assumed to be known. Storage loss is defined as:

$$P_{loss} = \lambda(T_{tes} - T_{env}), \tag{2.2.4}$$

where λ is the overall heat transfer coefficient, and T_{env} is the temperature of the environment surrounding the tank, provided by the user. The overall heat transfer coefficient depends on heating medium, construction material of the tank, insulation material, thickness of the insulation, surrounding environment and the overall area of the storage tank. In this tool it is assumed that the storage tank is made out of steel, it is filled with water, it is insulated, and it is placed in a boiler room where ambient temperature does not change significantly during a 24-h period. The overall heat transfer coefficient between water in the tank and outside air is calculated as:

$$\lambda = \frac{1}{\frac{1}{h_w} + \frac{d_i}{k_i} + \frac{1}{h_a}} A_{tank}, \tag{2.2.5}$$

where h_w is the heat transfer coefficient of water, d_i is the thickness of the insulation, k_i is the thermal conductivity of the insulation, h_a is the heat transfer coefficient of air, and A_{tank} is the surface area of the tank.

Discretization

Overall, the system defined with expressions (2.2.1) and (2.2.3) can be written in the matrix form:

$$\begin{bmatrix} \frac{dT_{tes}}{dt} \\ \frac{dP_{hs}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{\lambda}{mc_p} & \frac{1}{mc_p} \\ 0 & -\frac{1}{T_{hs}} \end{bmatrix} \begin{bmatrix} T_{tes} \\ P_{hs} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{T_{hs}} \end{bmatrix} P_{act} + \begin{bmatrix} -\frac{1}{mc_p} P_{dem} + \frac{\lambda}{mc_p} T_{env} \\ 0 \end{bmatrix}, \tag{2.2.6}$$

and generally as:

$$\dot{x} = A_{cont} x + B_{u,cont} u + B_{f,cont}, \tag{2.2.7}$$

where x is the vector of system variables (T_{tes}, P_{hs}), and u is the system input (P_{act}). To discretise such system with the zero-order hold (ZOH) transformation the constant element in equation (2.2.7), $B_{f,cont}$,

must be eliminated. This is done by combining matrices $B_{u,cont}$ and $B_{f,cont}$ into a single matrix B_{cont}. The system is then:

$$\dot{x} = A_{cont}x + [B_{u,cont} \quad B_{f,cont}]\begin{bmatrix} u \\ 1 \end{bmatrix} = A_{cont}x + B_{cont}v. \tag{2.2.8}$$

After performing ZOH transformation with sampling time of T_s, the discretized system is defined as:

$$x(k+1) = A_{disc}x(k) + B_{disc}v = A_{disc}x(k) + B_{u,disc}u(k) + B_{f,disc}. \tag{2.2.9}$$

Control formulation

The idea of this procedure is to optimally schedule a heat source for a certain horizon of length N. The obtained schedule represents a profile of actual reference powers for the heat source for each timestamp of the horizon, i.e. $P_{act}(k), \forall k \in \{0, 1, \dots, N-1\}$.

Power demand P_{dem} and environment temperature T_{env} can be seen as uncontrollable inputs, i.e. disturbances, but their profiles can be predicted and used as known values. Therefore, they are part of the inputs required from the user. To make it simpler for the user, environment temperature is represented as a single number rather than a profile.

The schedule is considered optimal if it uses the least amount of primary energy but satisfies all constraints. Therefore, the cost function of this problem is total amount of primary energy used by the heat source over the horizon of length NT_s:

$$J = \int_0^{NT_s} \frac{P_{act}(t)}{\eta\left(P_{ref}(t)\right)} dt. \tag{2.2.10}$$

Since the system model is discretized, the cost function can be written in a discrete form:

$$J = T_s \sum_{k=0}^{N-1} \frac{P_{ref}(k)}{k_\eta P_{ref}(k) + l_\eta} \delta_{hs}(k). \tag{2.2.11}$$

To minimize the cost function a successive/sequential linear programming (SLP) approach is utilized. In every iteration the cost function is linearized at the current point and the optimal solution is found around that point. The process is repeated until convergence, i.e. until there is no more improvement of the solution. The LP in each iteration is formulated as in (2.1.5). However, the model contains binary variables which makes this problem a mixed-integer linear programming (MILP) problem, which has the same formulation as a LP problem, but some of the variables are not continuous.

Linearization of the cost function

If the cost function is written as $J = \sum_{k=0}^{N-1} E_{prim}(k)$, primary energy spent during one sampling period, from kT_s to $(k+1)T_s$, is:

$$E_{prim}(k) = \frac{P_{act}(k)}{k_\eta P_{act}(k) + l_\eta} T_s. \tag{2.2.12}$$

Such function can be easily linearized by approximating it with the first order term of the Taylor series around the point x_0:

$$f(x) \approx \hat{f}(x) = f(x_0) + \frac{df}{dx}\bigg|_{x=x_0}(x - x_0), \tag{2.2.13}$$

where $\hat{f}(x)$ is a linear approximation of the function $f(x)$ around the point x. When the efficiency of the heat source is greater at higher reference power, $\eta_{max} > \eta_{min}$, the primary energy spent, $E_{prim}(k)$, is a concave function. When linearizing a concave function, the linear approximation of the function, $\hat{f}(x)$, will always be greater than the function $f(x)$ itself. This is shown in Figure 5. Therefore, in any SLP iteration the value of the cost function will be greater than the value of the nonlinear function. In other words, the

solution obtained by solving the MILP problem will result in more primary energy spent than necessary. Hence, the SLP procedure will be conservative with changing the input variables $P_{act}(k)$ and the procedure will converge to the solution steadily.
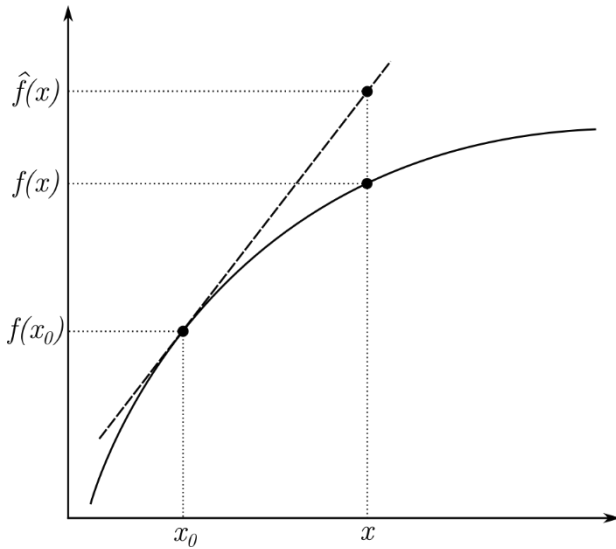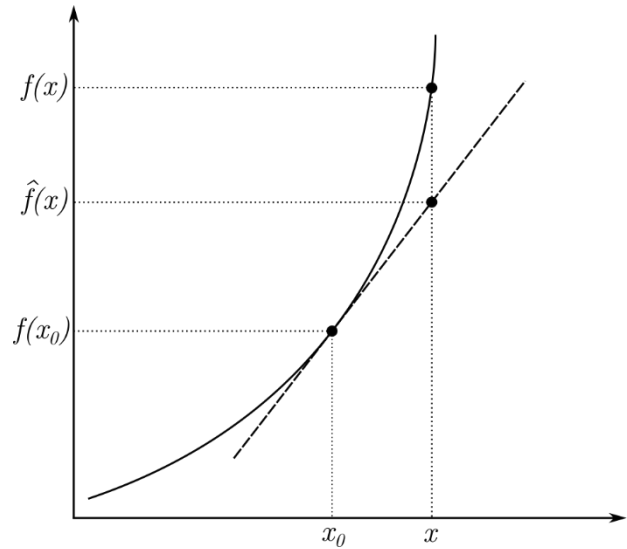

Figure 5. Linearizing a concave function.

Figure 6. Linearizing a convex function.

On the other hand, if the efficiency of the heat source is lower at higher reference power, $\eta_{max} < \eta_{min}$, the primary energy spent $E_{prim}(k)$ is a convex function. Linear approximation $\hat{f}(x)$ of a convex function will always be smaller than the function $f(x)$ itself. This feature is depicted in Figure 6. Therefore, the LP solver will find a solution that is overly optimistic in terms of primary energy usage. As a consequence, the SLP procedure will need to have a great number of iterations to converge, if the convergence is possible at all. To combat this issue, another type of linearization is introduced.

The primary energy expenditure $E_{prim}(k)$ is linearized with 2 lines, one connecting the linearization point and the minimal point, and the other one connecting linearization point and the maximal point. Such linearization is shown in Figure 7.
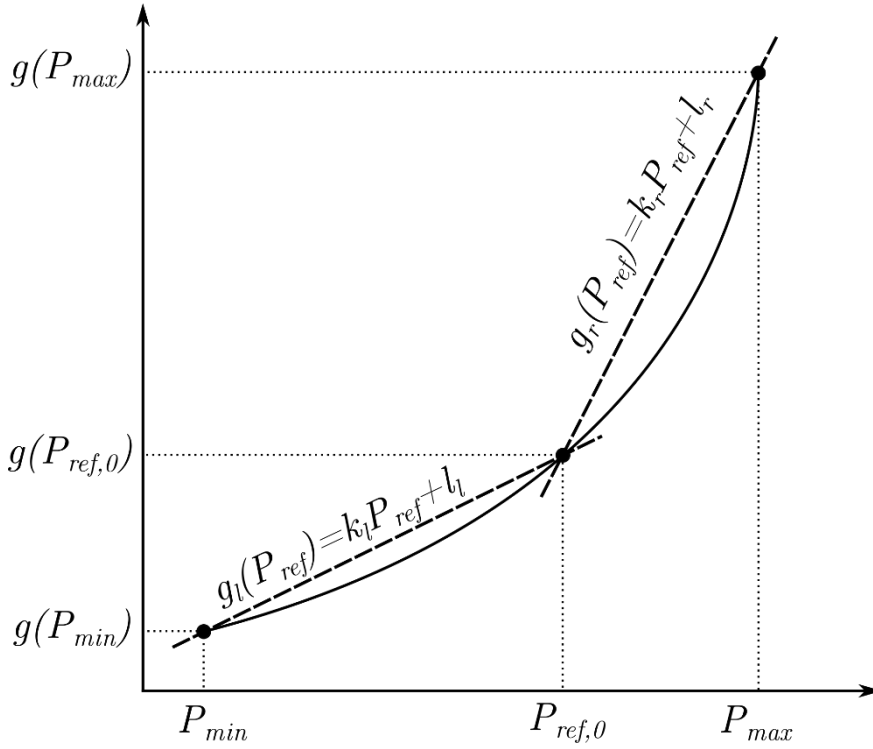
Figure 7. Linearization with two affine functions.

The function being linearized is:

$$g(P_{ref}) = \frac{P_{ref}}{\eta(P_{ref})} = \frac{P_{ref}}{k_\eta P_{ref} + l_\eta}, \tag{2.2.14}$$

and its approximation functions are $g_l(P_{ref}) = k_l P_{ref} + l_l$ and $g_r(P_{ref}) = k_r P_{ref} + l_r$. When the resulting reference power is greater than the reference power from the previous iteration, $P_{ref} > P_{ref,0}$, the right line, $g_r(P_{ref})$, is used as the approximation function, while in the case of $P_{ref} < P_{ref,0}$ the left line, $g_l(P_{ref})$, is used as the approximation function. To determine whether the reference power is greater or less than itself from the previous iteration, an additional binary variable is introduced:

$$\delta_{lr} = \begin{cases} 1, when\ P_{ref} \geq P_{ref,0} \\ 0, when\ P_{ref} < P_{ref,0} \end{cases}. \tag{2.2.15}$$

To define such expression in a MILP formulation, a set of linear inequalities must be posed. This is done by following guidelines from article [4]:

$$[f(x) \leq 0] \leftrightarrow [\delta = 1] \equiv \begin{cases} f(x) \leq M(1 - \delta) \\ f(x) \geq \varepsilon + (m - \varepsilon)\delta \end{cases}, \tag{2.2.16}$$

The primary energy consumption can be written as multiplication of affine functions $g_r(P_{ref})$ and $g_l(P_{ref})$, and binary variables δ_{lr} and δ_{hs}:

$$E_{prim} = T_s \frac{P_{ref}(k)}{k_\eta P_{ref}(k) + l_\eta} \delta_{hs} \approx T_s\big(g_l(P_{ref})(1 - \delta_{lr}) + g_r(P_{ref})\delta_{lr}\big)\delta_{hs}. \tag{2.2.17}$$

Since there is multiplication between continuous and two binary variables, additional auxiliary variables are introduced:

$$z_l = T_s g_l(P_{ref})(1 - \delta_{lr})\delta_{hs}, \tag{2.2.18}$$

$$z_r = T_s g_r(P_{ref})\delta_{lr}\delta_{hs}, \tag{2.2.19}$$

so that the primary energy consumption can be expressed linearly: $E_{prim} = z_l + z_r$. Definition of multiplication of a continuous and two binary variables in a MILP format is done by introducing a set of linear inequalities:

$$y = f(x)\delta_1\delta_2 \equiv \begin{cases} y \leq M\delta_1 \\ y \geq m\delta_1 \\ y \leq M\delta_2 \\ y \geq m\delta_2 \\ y \leq f(x) - m\big((1-\delta_1) + (1-\delta_2)\big) \\ y \geq f(x) - M\big((1-\delta_1) + (1-\delta_2)\big) \end{cases}, \qquad (2.2.20)$$

where M must be at least the maximum of $f(x)$, i.e. $M \geq \max(f(x))$, and m must be at least twice as small as minimum of $f(x)$, i.e. $m \leq \min(f(x))/2$. Furthermore, both parameters must have different signs, so if $M > 0$ then it must be $m \leq 0$ even if $\min(f(x)) > 0$. Therefore, values of the parameters for both cases, z_l and z_r, are: $M = \frac{P_{max}}{k_\eta P_{max} + l_\eta}$ and $m = 0$.

Constraints

To fully construct the LP/MILP problem (equation 2.1.5) and to fully describe the overall system mathematically, equality and inequality constraints must be posed. The only equality constraint makes sure that:

1.) the calculated sequence is repeatable, i.e. the last instance of state variables must be equal to the starting one:

$$x(0) = x(N). \qquad (2.2.C1)$$

Inequality constraints, inter alia, make sure that:

2.) the temperature of water at the top of the storage tank is always between user defined limits,

$$T_{min} \leq T_{tes}(k) \leq T_{max}, \qquad \forall k \in [0 \ldots N-1], \qquad (2.2.C2)$$

3.) the heat source is operated within its limits,

$$P_{min} \leq P_{ref}(k) \leq P_{max}, \qquad \forall k \in [0 \ldots N-1], \qquad (2.2.C3)$$

4.) the change of reference power is small enough to minimize the linearization error,

$$-\Delta P_{ref,max} \leq P_{ref}(k) - P_{ref,0}(k) \leq \Delta P_{ref,max}, \qquad \forall k \in [0 \ldots N-1]. \qquad (2.2.C4)$$

Move blocking

Sampling time used in this procedure equals to $T_s = 15\,\text{min}$ which with 24-h ahead operation makes the length of the horizon equal to $N = 96$. This means 96 values of reference powers for the heat source. Some heat sources should not be turned on or off too often, or they should not have their reference power changed too often. To tackle this issue, and to lower the computational complexity, a move blocking procedure is introduced. It means that the reference power does not change for a certain number of timestamps, which is set by the user.

2.2.2. Optimal heat source scheduler

Module (2) of the energy management tool for historical urban centres is made available for public use for free and it is called "Optimal heat source scheduler". The scheduler is downloadable from the project's website. It comes as a .zip file which contains everything necessary to run it and it does not require installation, i.e. it is ready to use just after unzipping the .zip file. The content of the .zip file is shown in Figure 8.
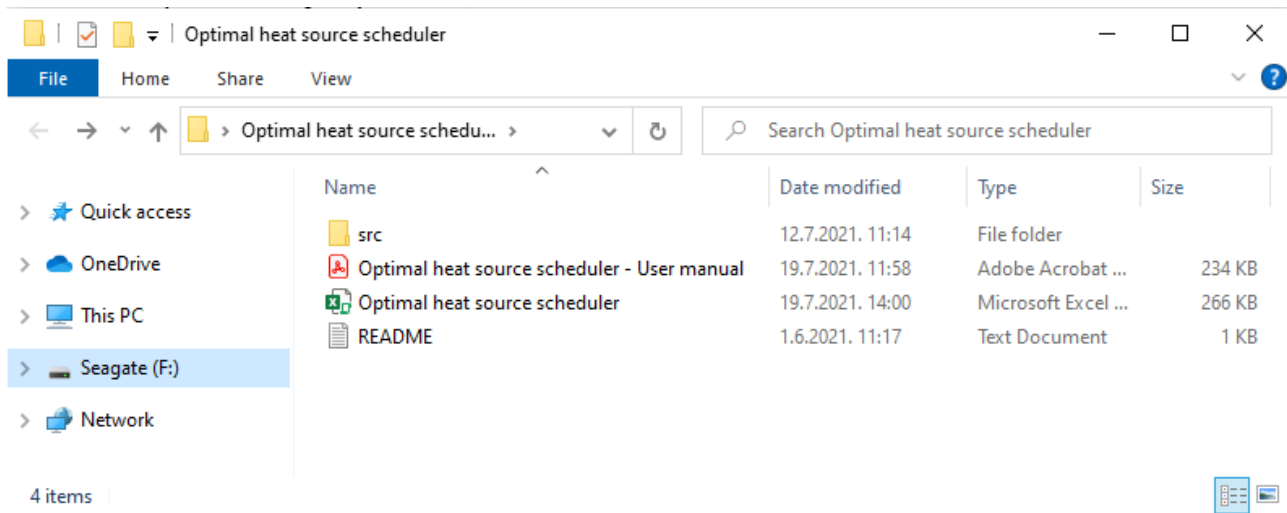
Figure 8. Folder content of the Optimal heat source scheduler.

"README" file contains simple instructions on how to get started with the tool. The user interface (UI) is made in MS Excel®, and a screenshot of it is presented in Figure 9. User enters data under the tab "Scheduler", while the results are presented under the tab "Results". The user manual is placed under the tab "User Manual". The same user manual is also placed in the root folder of the calculator as a .pdf file. It contains instructions on how to use the tool and explanation of all the parameters.

Results have two parts: analysis and data. Analysis compares energy requirements and energy losses between optimal schedule of the heat source and its classical control. There is also analysis of a case without a TES. Data part is a chart containing heating power demand, optimal schedule of the heat source, power profile obtained using classical control, and simulated temperatures of water at the top of the storage tank for both control techniques. The chart can be saved as an image while the data can be saved either as a .xlsx or a .csv file. An example of results is shown in Figure 10.
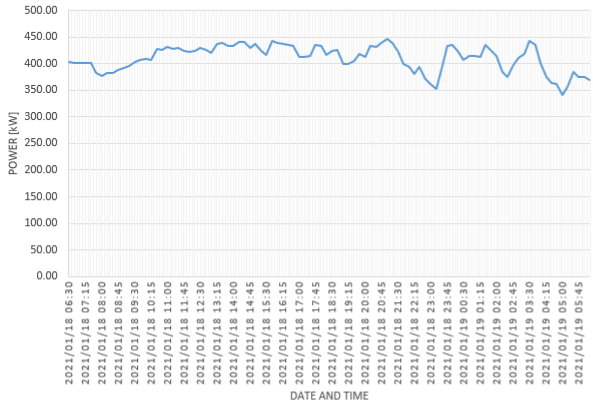
The calculation process is implemented in Python programming language with CBC® as the solver for MILP problems. To make the module useful on a computer without Python installed, a standalone executable file is created from the Python scripts. Resulting .exe file, with its auxiliary .dll files, can be executed on any computer with Windows operating system and it is positioned in the "src" folder.

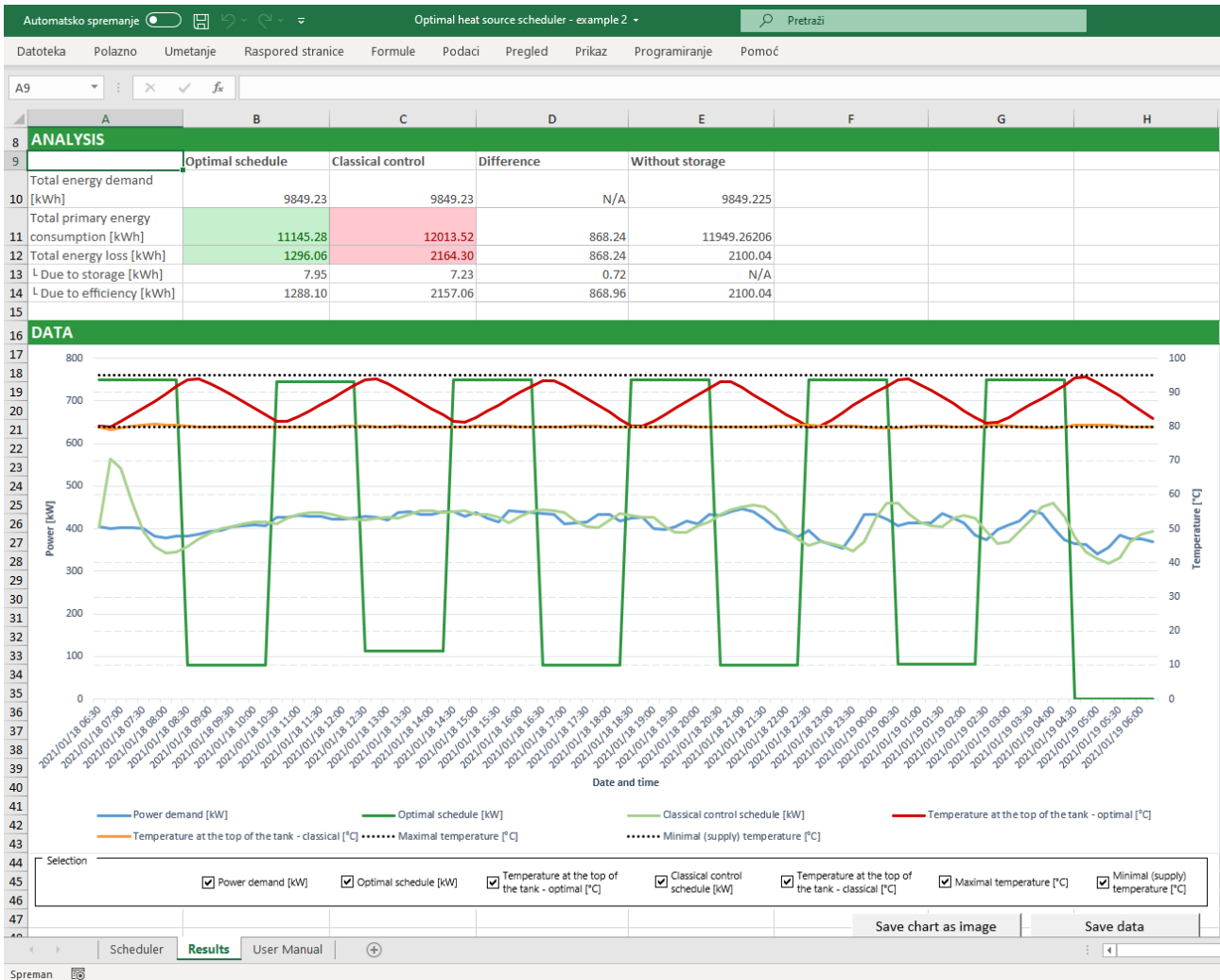**Figure 9. UI of the Optimal heat source scheduler.**

Figure 10. An example of results obtained from Optimal heat source scheduler.

3. Functioning of the energy management tool on the Store4HUC pilot sites

3.1. Croatian pilot site in Bračak

The pilot site in Bračak is an example of a historical urban site where recently significant integration and refurbishment efforts had been already done, making it a site with class A energy certificate even before the installation of PV + BESS. Still the site did not have a renewable electricity source or a storage. Thus, the investment in Bračak was made to:

- introduce renewable electrical energy in a form of a photovoltaic plant;
- introduce energy storage in terms of a battery system;

The following functionalities of the Store4HUC EMS are envisioned on the Bračak site.

Off-line:

1) planning the optimal investment in and operation of renewable energy source and storage by taking into account yearly energy consumption profiles of the existing HUC setup for different pre-determined return on investment periods, with respected HUC-induced constraints and interactions with the climate control system;

2) autarky rate assessment of the Bračak castle for the selected PV and battery system configuration.

Within this deliverable operation of the module (1) is shown. Autarky rate assessment is presented in deliverable D.T3.2.4.

3.1.1. Module (1) results for the Bračak pilot site

Energy consumption at the Bračak pilot site was metered at a single point (of total three points) where the PV system + BESS was installed. The power consumption profile is shown in Figure 11.

The canopy built at the site, where the PV array was installed, has south-west orientation, and it is inclined for 15°. With such orientation and inclination angles the possible PV production has a profile shown in Figure 12. This profile is scaled during the calculation process to find the optimal peak power of the PV system. Since the planned installation considered 10 kWp of PV arrays, this is also the maximal possible peak power of the PV system. Lifetime of the PV system is 25 years, which is a typical warranty time for solar panels. The Optimal sizing calculator is run for two different prices of the PV system: 1050 €/kWp, and 420 €/kWp which is the price with 60 % subsidies that are available in Croatia [5].

Chosen BESS parameters are the default ones from the Optimal sizing calculator:

- Number of cycles (n_{cyc}): 2000
- Depth of discharge (DoD): 0.8 (80%)
- Discharging efficiency (η_{dch}): 0.9 (90%)
- Charging efficiency (η_{ch}): 0.9 (90%)
- Lifetime of power converter (n_{PC}): 25 years
- Price of the new battery pack (c_{bat}): 770 €/kWh
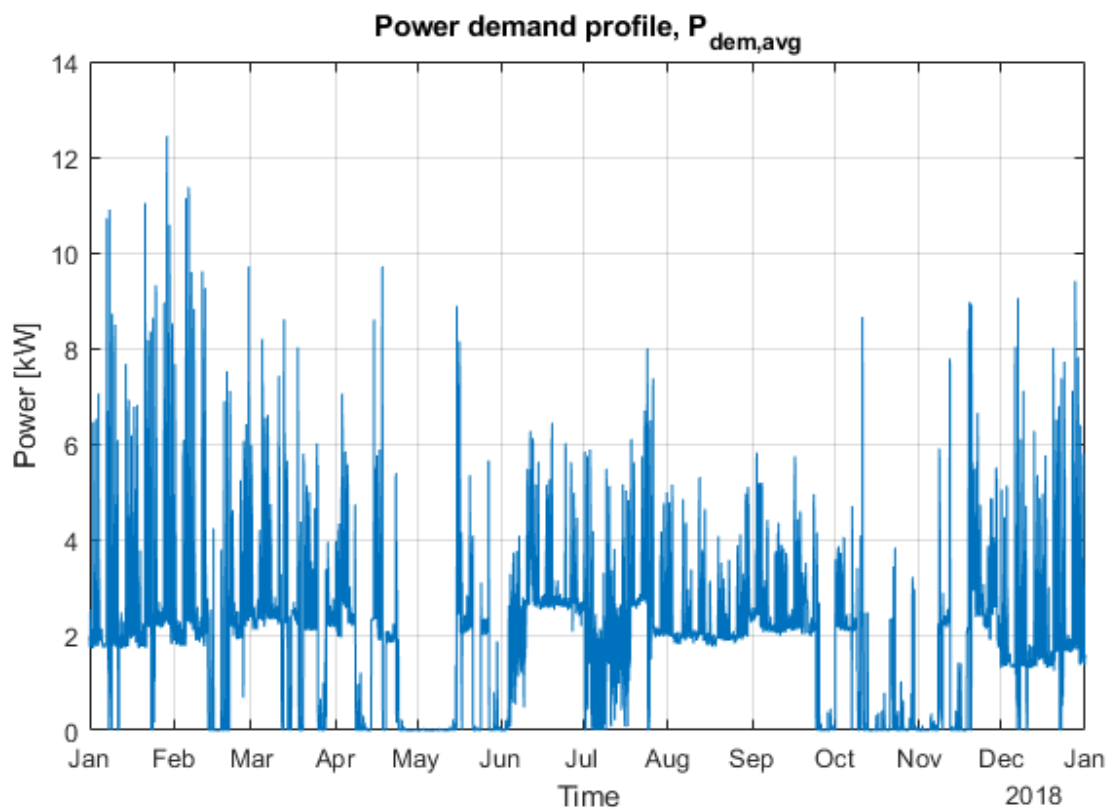- Price of the new power converter (c_{PC}): 660 €/kW

Figure 11. Resampled electrical power demand profile at Bračak site for year 2018.
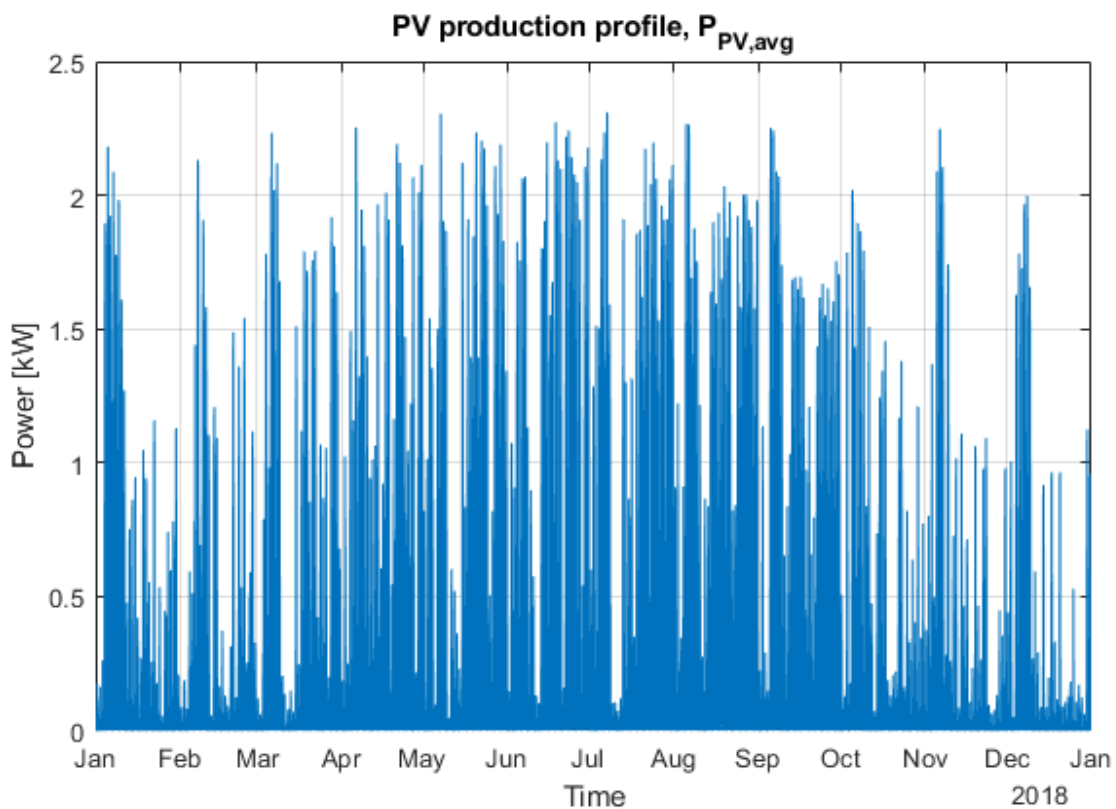

Figure 12. Possible PV production profile according to orientation and inclination angles of the Bračak pilot site.

The results are obtained for different duration of payoff period and for different optimality criterions. The results are presented in Table 1, Table 2, and Table 3.

Table 1. Optimal PV + BESS sizes for the Bračak pilot site, using yearly amount of energy taken from the grid (KPI$_1$) as the optimality criterion.

Investment payoff period [years]	10		15		20	
PV system subsidies	0 %	60 %	0 %	60 %	0 %	60 %
Battery capacity (SoC_{max}) [kWh]	0.00	2.60	0.00	3.23	0.00	4.93
Power converter power ($P_{pc,max}$) [kW]	0.00	1.91	0.00	1.65	0.00	3.17
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	9.97	10.00	10.00	10.00	10.00

Table 2. Optimal PV + BESS sizes for the Bračak pilot site, using yearly cost of energy exchanged with the grid (KPI2) as the optimality criterion.

Investment payoff period [years]	10		15		20	
PV system subsidies	0 %	60 %	0 %	60 %	0 %	60 %
Battery capacity (SoC_{max}) [kWh]	0.00	2.65	0.00	6.24	0.00	9.47
Power converter power ($P_{pc,max}$) [kW]	0.00	1.88	0.00	3.19	0.00	4.39
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	10.00	10.00	10.00	10.00	10.00

Table 3. Optimal PV + BESS sizes for the Bračak pilot site, using total yearly cost (energy cost + yearly scaled investment + yearly maintenance) (KPI3) as the optimality criterion.

Investment payoff period [years]	10		15		20	
PV system subsidies	0 %	60 %	0 %	60 %	0 %	60 %
Battery capacity (SoC_{max}) [kWh]	0.00	0.00	0.00	0.00	0.00	0.00
Power converter power ($P_{pc,max}$) [kW]	0.00	0.00	0.00	0.00	0.00	0.00
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	10.00	3.42	10.00	10.00	10.00

3.2. Italian pilot site in Cuneo

The sloping elevator in Cuneo was planned to be equipped with a BESS and a PV system.

The EMS tool should in this case decide what would be the optimal investment in terms of battery and PV system capacities as well as the optimized behaviour of the battery storage system considering a longer-term recorded electricity consumption of the sloping elevator. The battery system efficiency, its degradation characteristics and price, and the pricing conditions of electricity towards the grid will be taken into account.

The typical electricity demands for the elevator after the investment are assessed for working days, Saturdays, Sundays and holidays and then extrapolated for the whole year period.

The following functionalities of the Store4HUC EMS are envisioned on the Cuneo site.

Off-line:

1) planning the optimal investment in and operation of renewable energy source and storage by taking into account yearly energy consumption profiles of the existing HUC set-up for different pre-determined return on investment periods, with respected HUC-induced constraints;

Thus module (1) is applied on the Cuneo site.

3.2.1. Module (1) results for the Cuneo pilot site

For Cuneo pilot site energy metered on a typical working day, a typical Saturday and a typical Sunday was used. Firstly, the data is extrapolated to a full year, considering consumption on Italian national holidays same as on Sundays. Estimated yearly energy profile is shown in Figure 13Figure 13, while the typical weekly profile is shown in Figure 14. Unlike for Croatian pilot Bračak where the peak power is measured as a mean power in 15 min periods, peak power for pilot in Cuneo is measured every second. If every second in a year was modelled, the LP problem would have been too large to be solved on a regular computer. Therefore, a simplification is introduced. The data resampled to 1-h increments, $P_{dem,avg}$, was multiplied by a factor β_{peak} to be as close as possible to the real peak power. This β_{peak} is calculated as:

$$\beta_{peak} = \frac{mean(P_{dem,real})}{mean(P_{dem,avg})}, \qquad (3.2.1)$$

and it has a value of $\beta_{peak} = 10.3$. So, the power profile used for peak power billing is $P_{dem,max} = \beta_{peak}P_{dem,avg}$. Such data processing is done only for "Slope elevator" consumer type in the tool.

The structure built at the site, where the solar array was installed, has orientation of -20° (south-south-west), so the orientation towards South was entered as the parameter value in the tool. Inclination of the solar array is 70°. With such orientation and inclination angles the possible PV production has a profile shown in Figure 15. The maximal possible peak power of 10 kWp was chosen, as this was the consideration at the beginning of the project. Price of PV system is chosen as 1250 €/kWp, and the lifetime of the PV system is a typical warranty time for solar panels, 25 years. All simulations were carried out without subsidies for PV systems as there are no subsidies for PV systems on the national level.
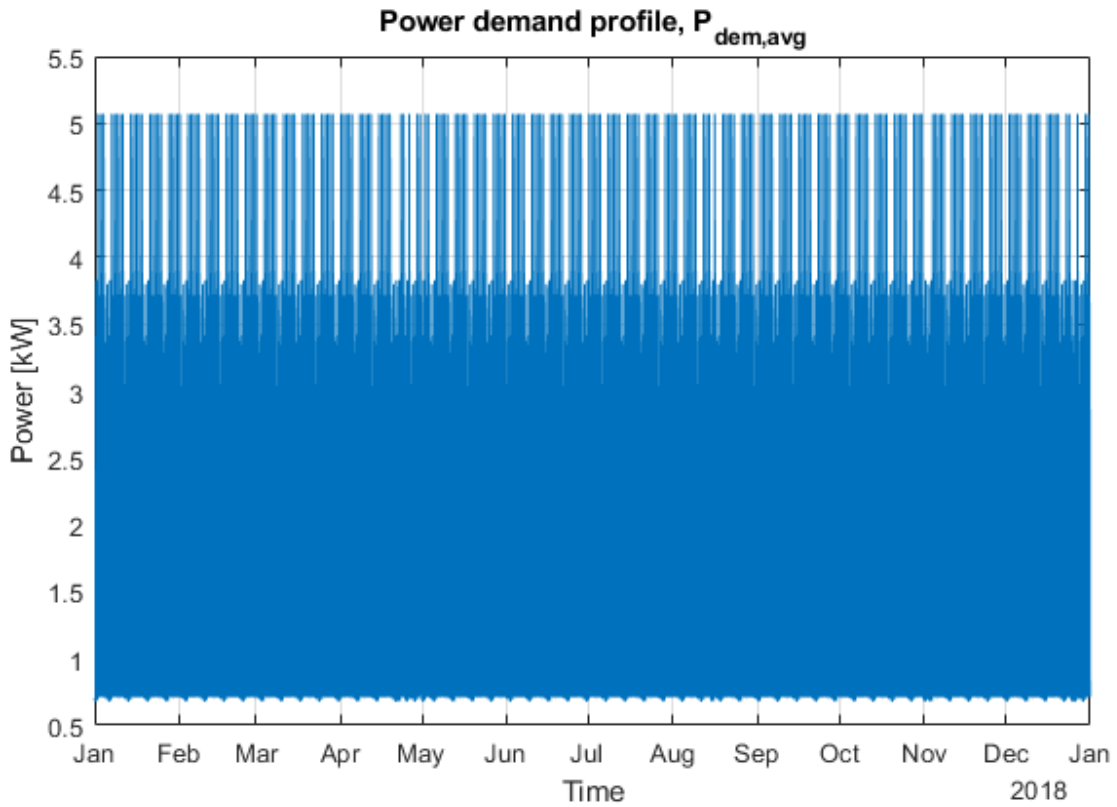
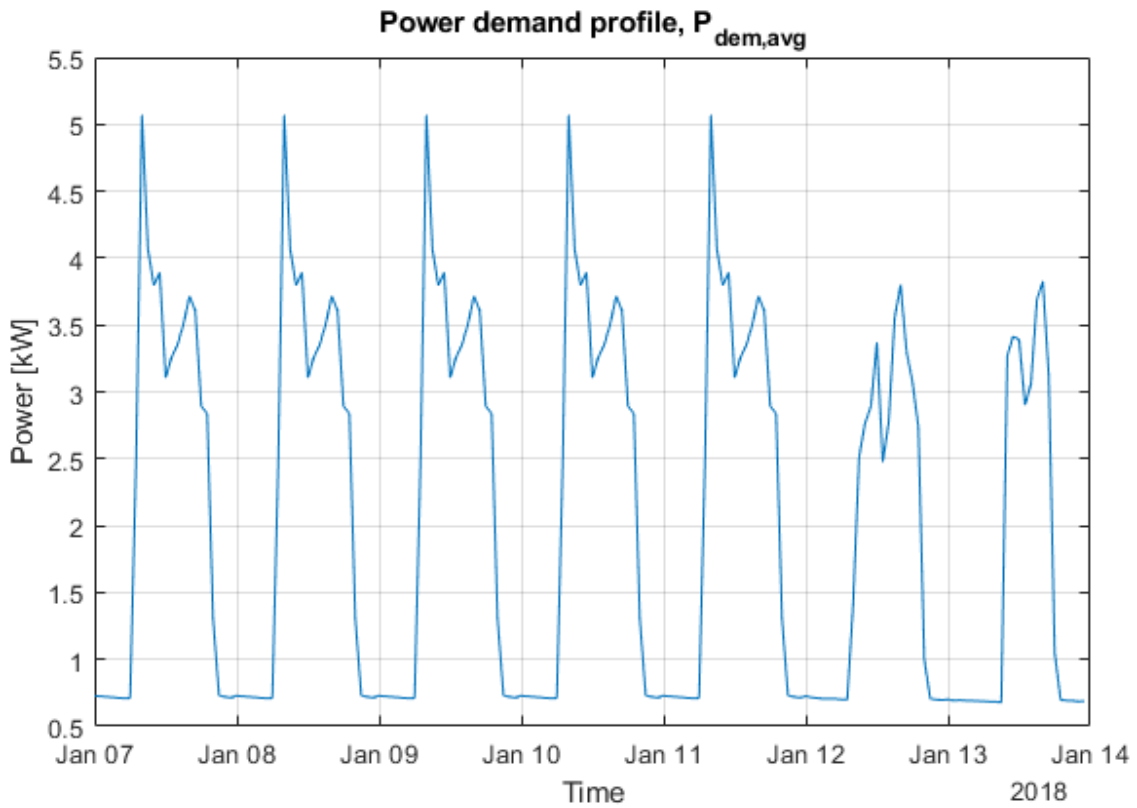**Figure 13. A full year electrical power demand profile of the Cuneo pilot site.**

Figure 14. A weekly electrical power demand profile of the Cuneo pilot site.
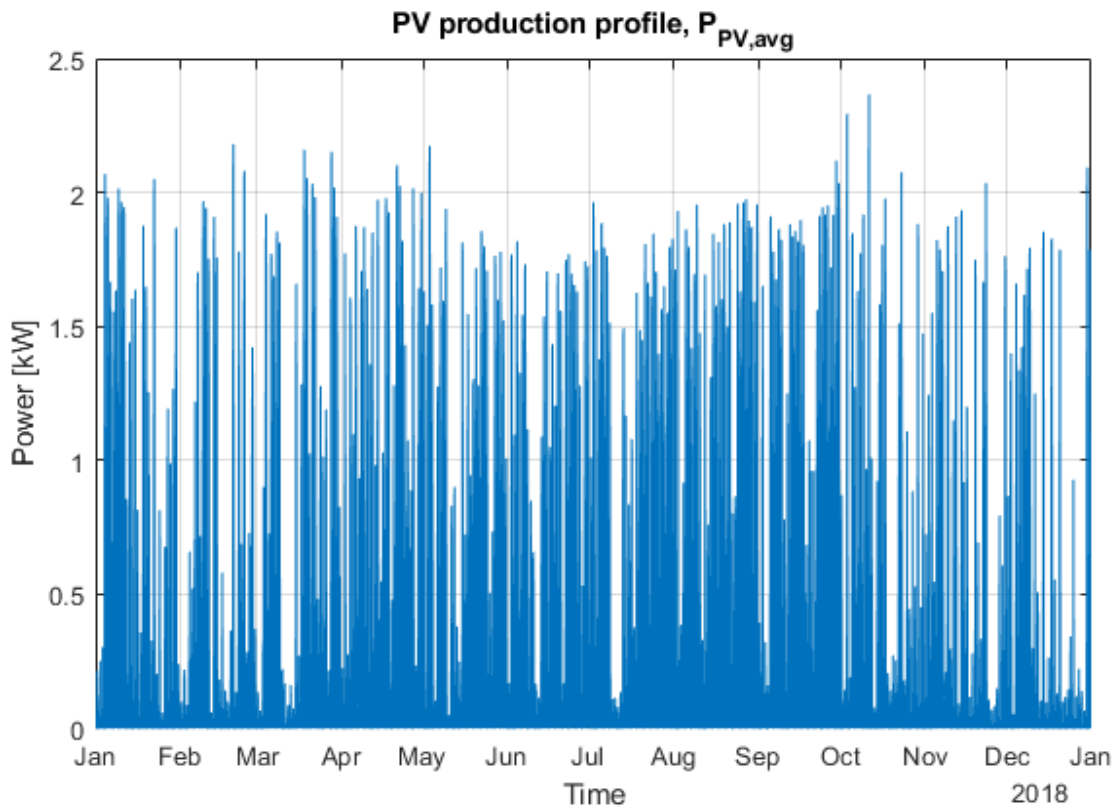
Figure 15. Possible PV production profile according to orientation and inclination angles of the Cuneo pilot site.

Chosen BESS parameters are the default ones from the Optimal sizing calculator:

- Number of cycles (n_{cyc}): 2000

- Depth of discharge (DoD): 0.8 (80%)

- Discharging efficiency (η_{dch}): 0.9 (90%)

- Charging efficiency (η_{ch}): 0.9 (90%)

- Lifetime of power converter (n_{PC}): 25 years

- Price of the new battery pack (c_{bat}): 770 €/kWh

- Price of the new power converter (c_{PC}): 660 €/kW

The results are obtained for different duration of payoff period and for different optimality criterions. The results are presented in Table 4, Table 5, and Table 6.

Table 4. Optimal PV + BESS sizes for the Cuneo pilot site, using yearly amount of energy taken from the grid (KPI1) as the optimality criterion.

Investment payoff period [years]	10	15	20
Battery capacity (SoC_{max}) [kWh]	0.00	0.00	2.57
Power converter power ($P_{pc,max}$) [kW]	0.00	0.00	2.02
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	10.00	10.00

Table 5. Optimal PV + BESS sizes for the Cuneo pilot site, using yearly cost of energy exchanged with the grid (KPI2) as the optimality criterion.

Investment payoff period [years]	10	15	20
Battery capacity (SoC_{max}) [kWh]	0.00	1.18	3.49
Power converter power ($P_{pc,max}$) [kW]	0.00	0.85	2.51
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	10.00	10.00

Table 6. Optimal PV + BESS sizes for the Cuneo pilot site, total yearly cost (energy cost + yearly scaled investment + yearly maintenance) (KPI3) as the optimality criterion.

Investment payoff period [years]	10	15	20
Battery capacity (SoC_{max}) [kWh]	0.00	0.00	0.00
Power converter power ($P_{pc,max}$) [kW]	0.00	0.00	0.00
PV system peak power ($P_{pv,peak}$) [kWp]	0.00	10.00	10.00

3.3. Austrian pilot site in Weizberg

The pilot site in Weizberg undertook the installation of a heat energy storage system to enable more efficient operation of the central biomass-based heating station and to be able to supply the buildings of the parish complex with heat while considering the limited capacity of the heat distribution infrastructure.

Task of the EMS tool for the case of Weizberg is to plan the optimal daily operation of the storage system in different heat demand conditions in the parish complex – it takes into account the heat dissipation in the storage, minimum required starting temperature to ensure heat supply for the required comfort conditions, required temperature conditions in the storage for efficient and long-life operation of the biomass-based boilers.

Based on the computed optimal daily behaviours for different demand conditions it will be possible to program the behaviour of the system accordingly.

The following functionalities of the Store4HUC EMS are envisioned on the Weizberg site.

Off-line:

1) planning the optimal operation of the storage by taking into account daily heat demands of the existing HUC set-up with respected HUC-induced constraints as well as heat biomass-based heat generation costs, if applicable;

Thus module (2) is applied on the Weizberg site.

3.3.1. Module (2) results for the Weizberg pilot site

The pilot site in Weizberg uses 2 woodchip boilers to heat the water inside a storage tank, which is then used to heat 12 consumers of the district heating system. Both of the boilers are KÖB Pyrot, one with rated power of 300 kW and one with rated power of 540 kW. However, as stated in their technical guide [6], they should not be operated at their maximal power for longer period of time. Therefore, their maximal powers used in the tool are 270 kW and 480 kW. Since the tool uses a single heat source for heating, these boilers can be aggregated into a single heat source. Its minimal power is then the minimal power of the smaller boiler, $P_{min} = 80$ kW, while its maximal power is the sum of the maximal powers of both boilers, $P_{max} = 270 + 480 = 750$ kW. The efficiency of two boilers is the same, so it can be easily used as such in the tool: $\eta_{min} = 92$ % and $\eta_{max} = 90$ %. Also, because the two boilers are the same (except for the size), their warm-up time is the same, $T_{hs} = 30$ min.

The storage tank installed at the Weizberg pilot site has the volume of 38 m³, it is 7 m tall, and it is insulated with 40 cm of polyurethane foam. Maximal allowed temperature in the tank is 95 °C. The typical temperature difference between the top and the bottom of the tank can be found in the data collected at the site. The data was collected from January to May of 2021. By averaging the temperature difference by months, it can be seen that it does not vary a lot: from minimal value of $T_{dif} = 32$ °C in April to maximal value of $T_{dif} = 37$ °C in January. Therefore, the overall average value is used, $T_{dif} = 35$ °C.

Results of this this module are shown for two different scenarios, one for a colder day and one for a warmer day. The power demand profile of the colder day, on January 5th 2021, is shown in Figure 16, while the power demand of the warmer day, on April 5th 2021, is shown in Figure 17. On the colder day the required supply temperature was $T_{sup} = 85$ °C and the outside air temperature was around $T_{env} = 0$ °C, while on the warmer day the required supply temperature was $T_{sup} = 80$ °C and the outside air temperature was around $T_{env} = 10$ °C. Results for both scenarios were obtained for two values of power changing intervals, one with power change every 1 h, and one with power change every 4 h.
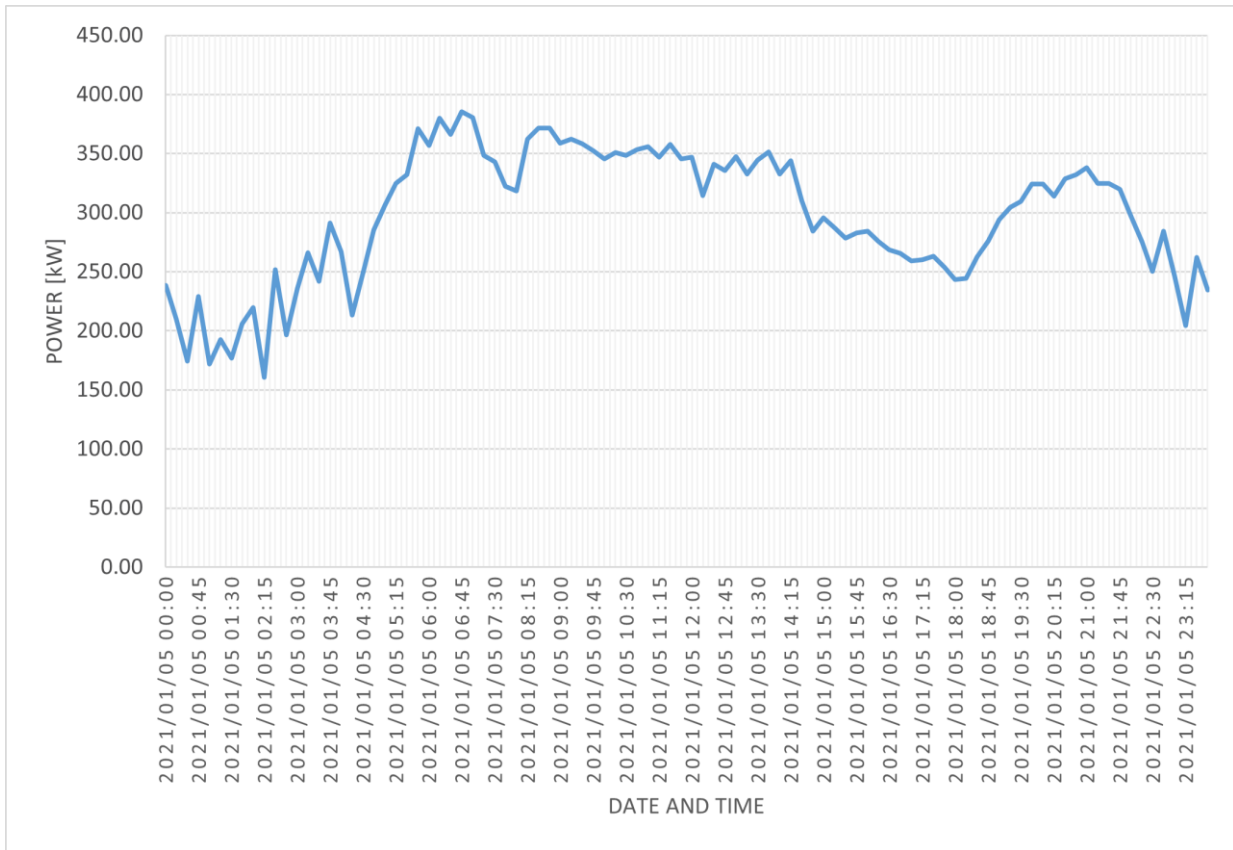
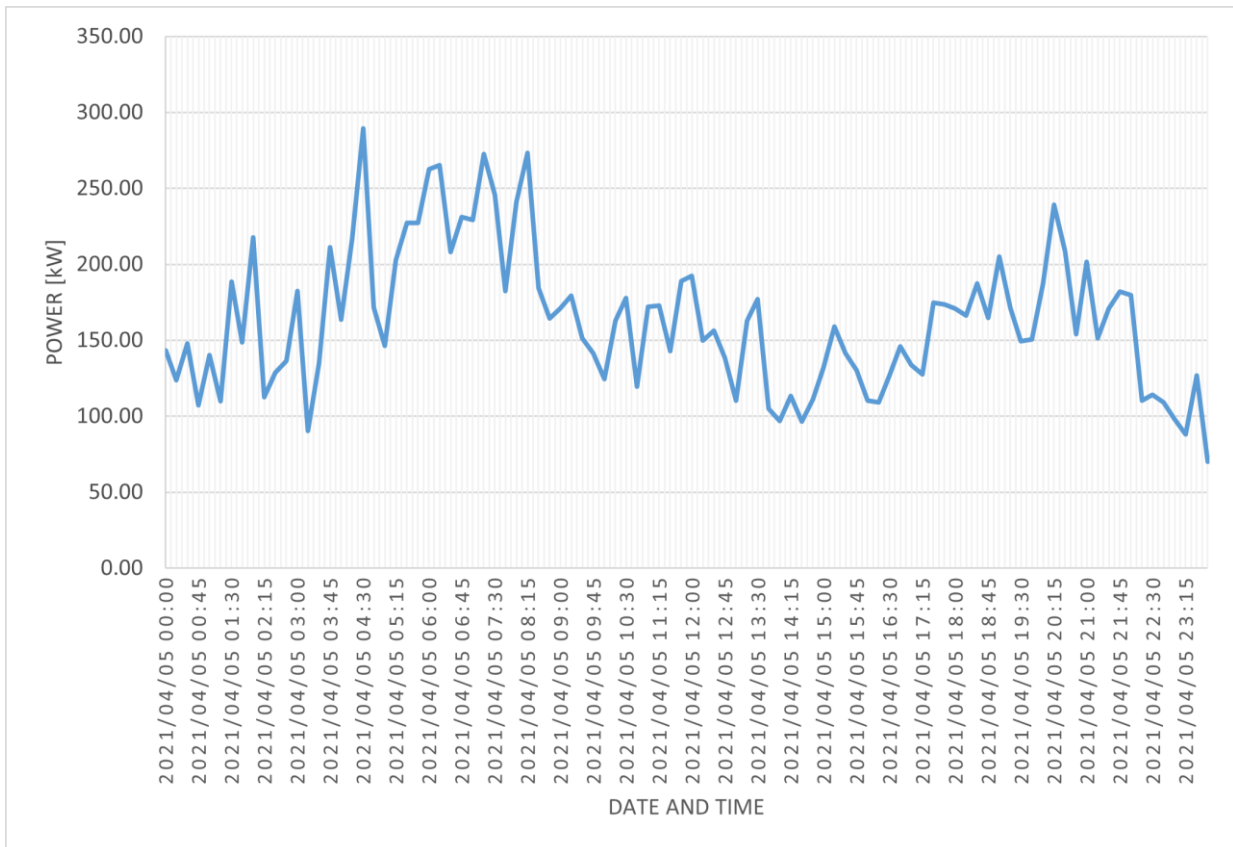**Figure 16. Power demand profile of the Weizberg pilot site on January 5th 2021.**

Figure 17. Power demand profile of the Weizberg pilot site on April 5th 2021.

Results of the tool for the scenario of the colder day, January 5th 2021, with power change every 1 h, is shown in Figure 18 (energy analysis), Figure 19 (power schedules), and Figure 20 (simulated temperatures).

ANALYSIS				
	Optimal schedule	Classical control	Difference	Without storage
Total energy demand [kWh]	7133.27	7133.27	N/A	7133.27
Total primary energy consumption [kWh]	7818.43	7820.05	1.62	7811.24
Total energy loss [kWh]	685.16	686.78	1.62	677.97
└ Due to storage [kWh]	6.77	6.73	0.04	N/A
└ Due to efficiency [kWh]	678.39	680.05	1.66	677.97

Figure 18. Energy analysis for the colder day scenario of the optimal schedule with power change every 1 h, and the classical control schedule.
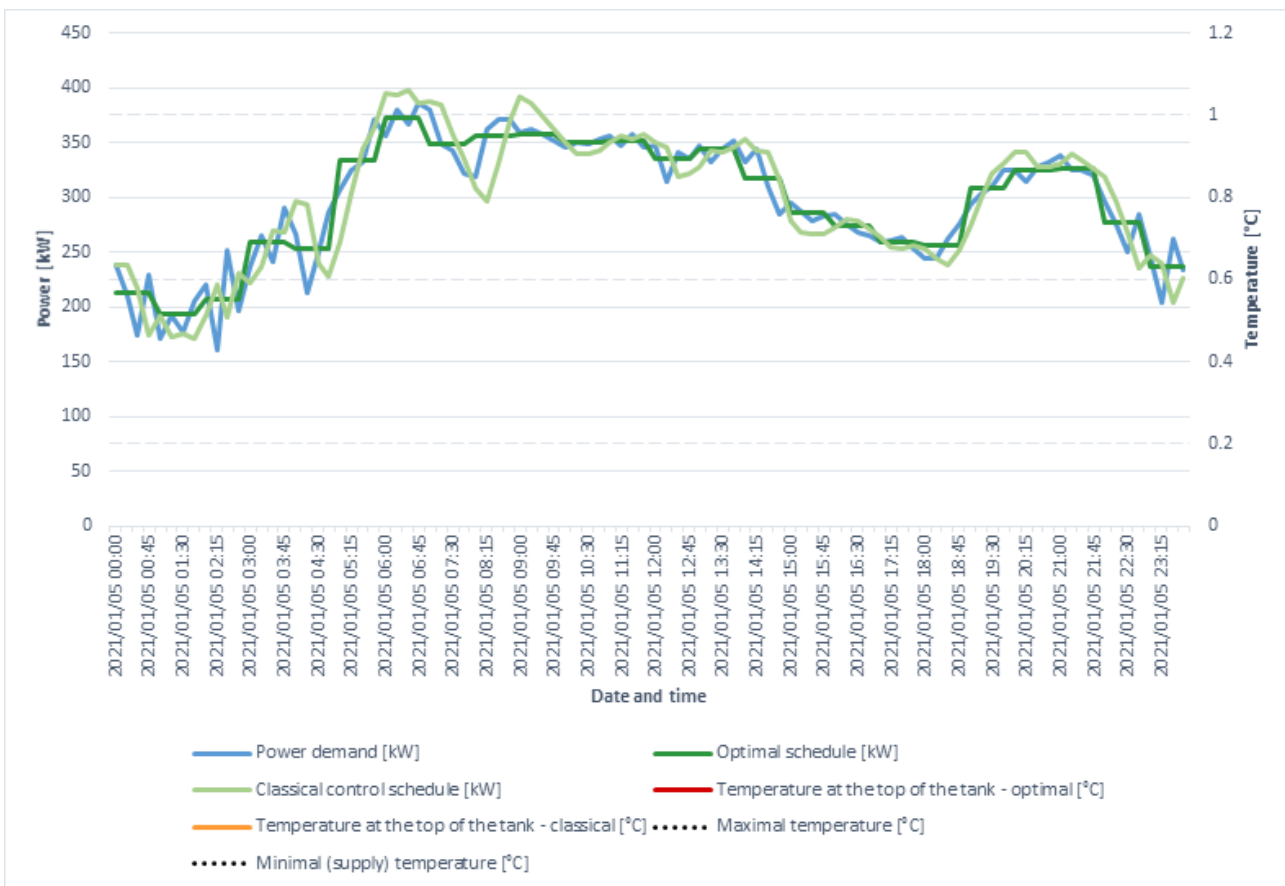

Figure 19. Power demand (blue), the optimal schedule with power change every 1 h (darker green), and the classical control schedule (lighter green) for the colder day scenario.
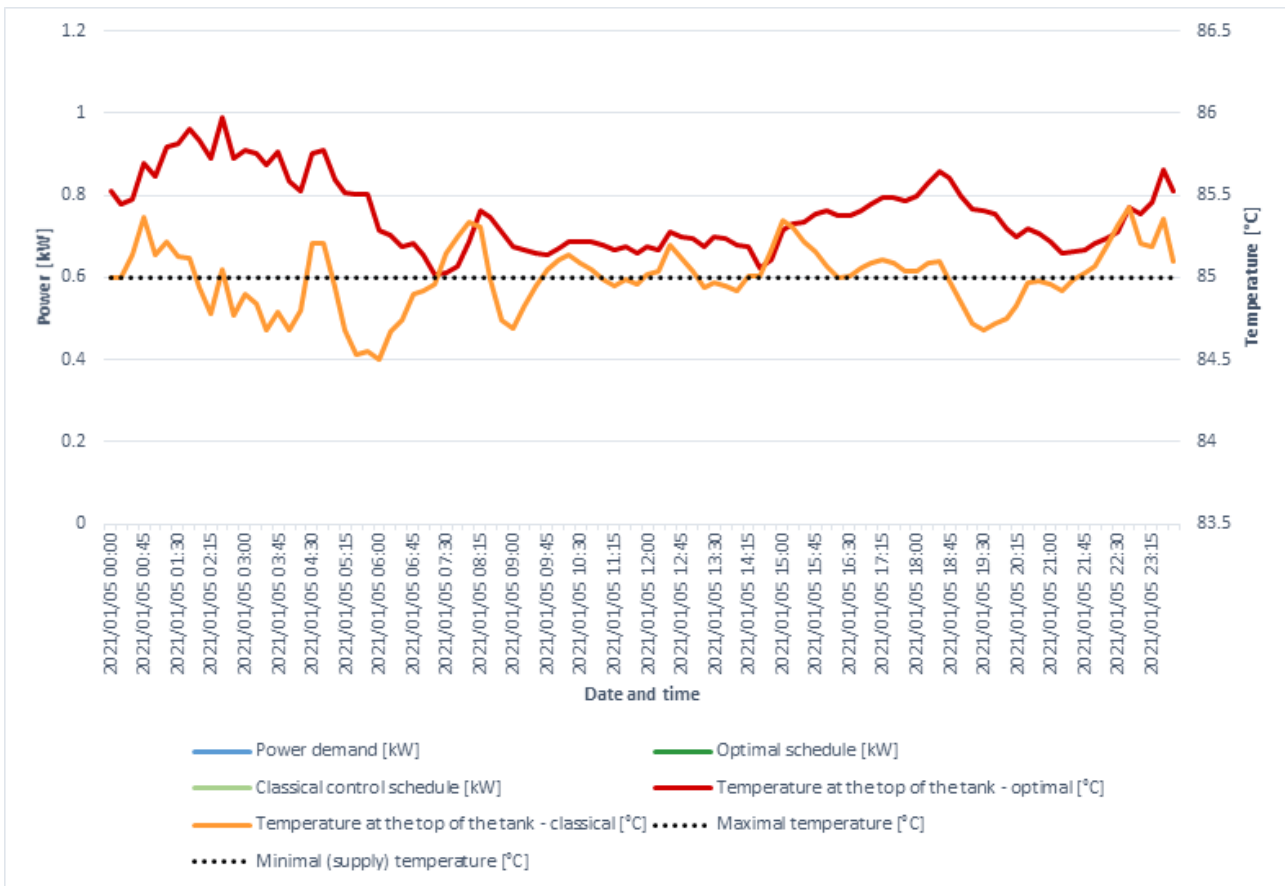
Figure 20. Simulated water temperatures in the top of the storage tank for the colder day scenario: optimal schedule with power change every 1 h (red), classical control (orange), and required supply temperature (black dots).

Results of the tool for the scenario of the colder day, January 5th 2021, with power change every 4 h, is shown in Figure 21 (energy analysis), Figure 22 (power schedules), and Figure 23 (simulated temperatures).

ANALYSIS				
	Optimal schedule	**Classical control**	**Difference**	**Without storage**
Total energy demand [kWh]	7133.27	7133.27	N/A	7133.27
Total primary energy consumption [kWh]	7817.87	7811.33	6.54	7811.24
Total energy loss [kWh]	684.60	678.06	6.54	677.97
ᒪ Due to storage [kWh]	6.90	6.73	0.17	N/A
ᒪ Due to efficiency [kWh]	677.70	671.33	6.37	677.97

Figure 21. Energy analysis for the colder day scenario of the optimal schedule with power change every 4 h, and the classical control schedule.
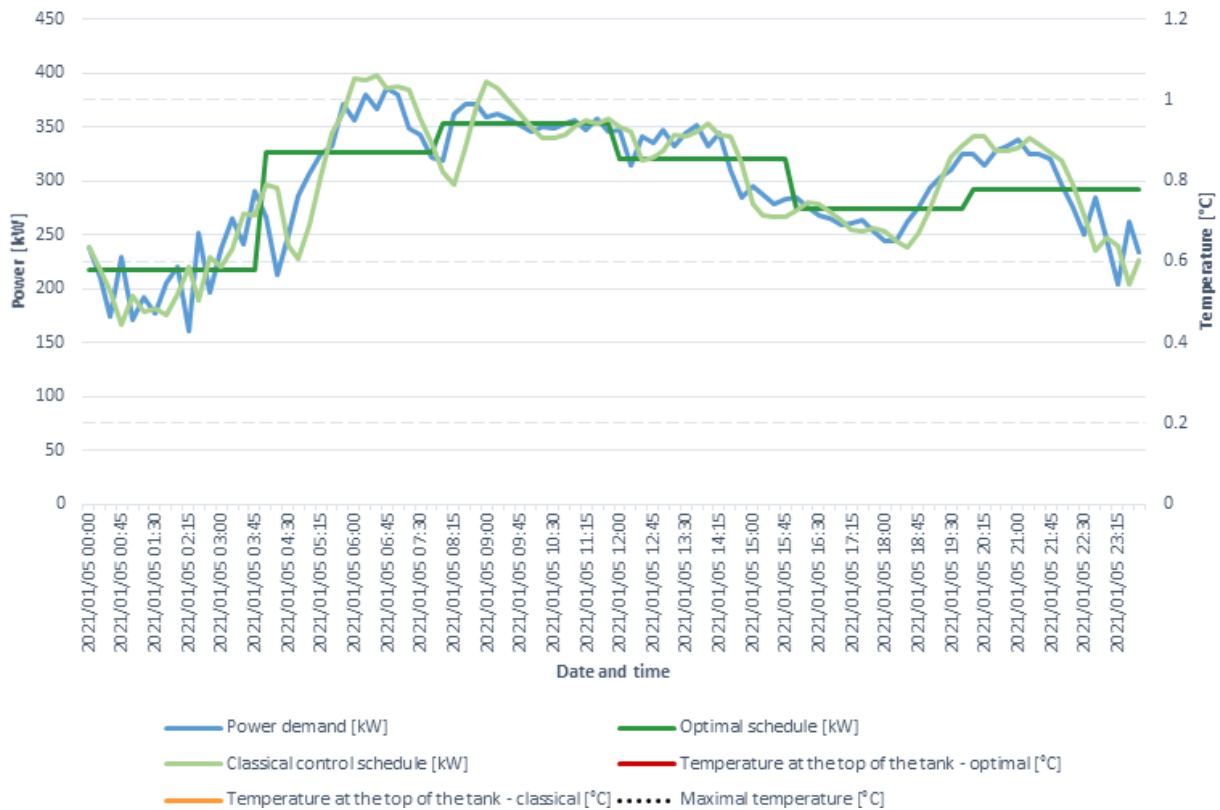
Figure 22. Power demand (blue), the optimal schedule with power change every 4 h (darker green), and the classical control schedule (lighter green) for the colder day scenario.
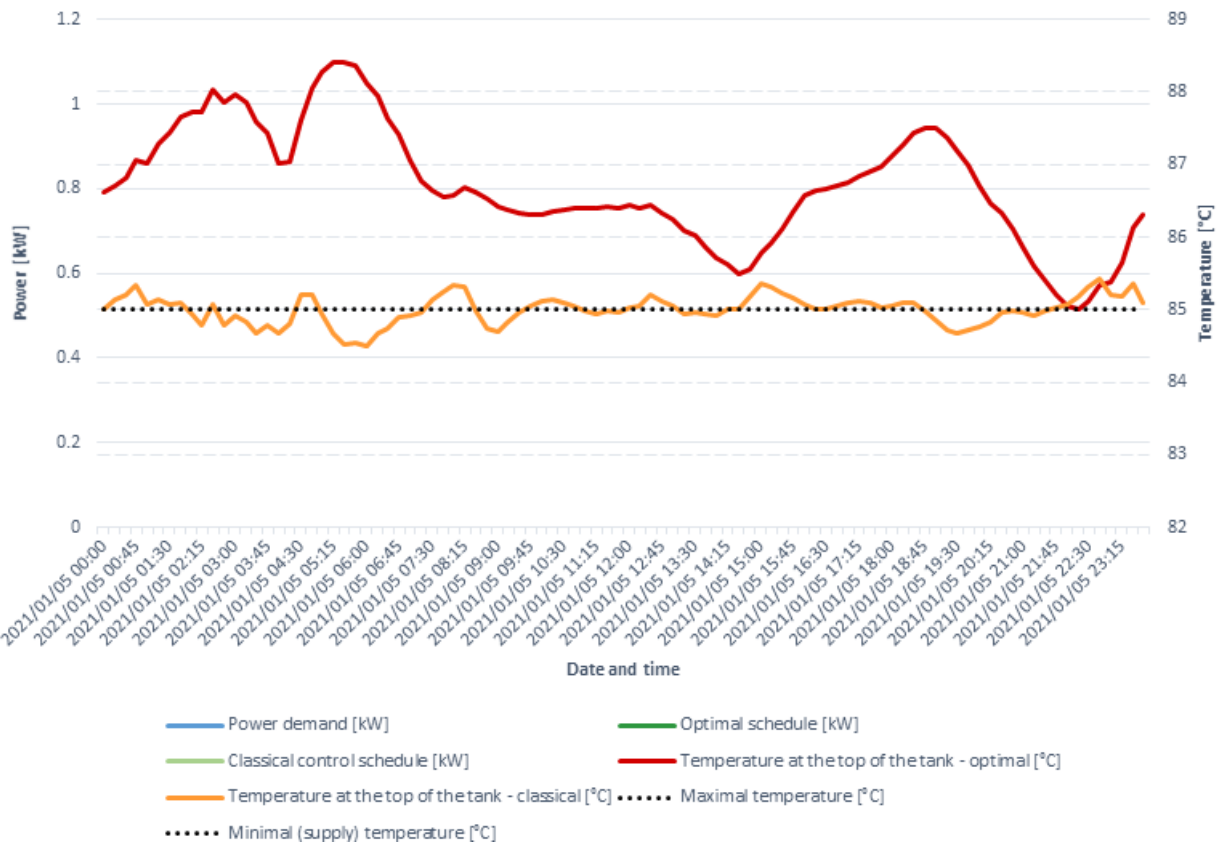

Figure 23. Simulated water temperatures in the top of the storage tank for the colder day scenario: optimal schedule with power change every 4 h (red), classical control (orange), and required supply temperature (black dots).

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Results of the tool for the scenario of the warmer day, April 5th 2021, with power change every 1 h, is shown in Figure 24 (energy analysis), Figure 25 (power schedules), and Figure 26 (simulated temperatures).

ANALYSIS				
	Optimal schedule	Classical control	Difference	Without storage
Total energy demand [kWh]	3915.28	3915.28	N/A	3915.28
Total primary energy consumption [kWh]	4275.29	4292.70	17.41	4269.09
Total energy loss [kWh]	360.01	377.42	17.41	353.80
└ Due to storage [kWh]	6.29	6.23	0.06	N/A
└ Due to efficiency [kWh]	353.72	371.18	17.47	353.80

Figure 24. Energy analysis for the warmer day scenario of the optimal schedule with power change every 1 h, and the classical control schedule.
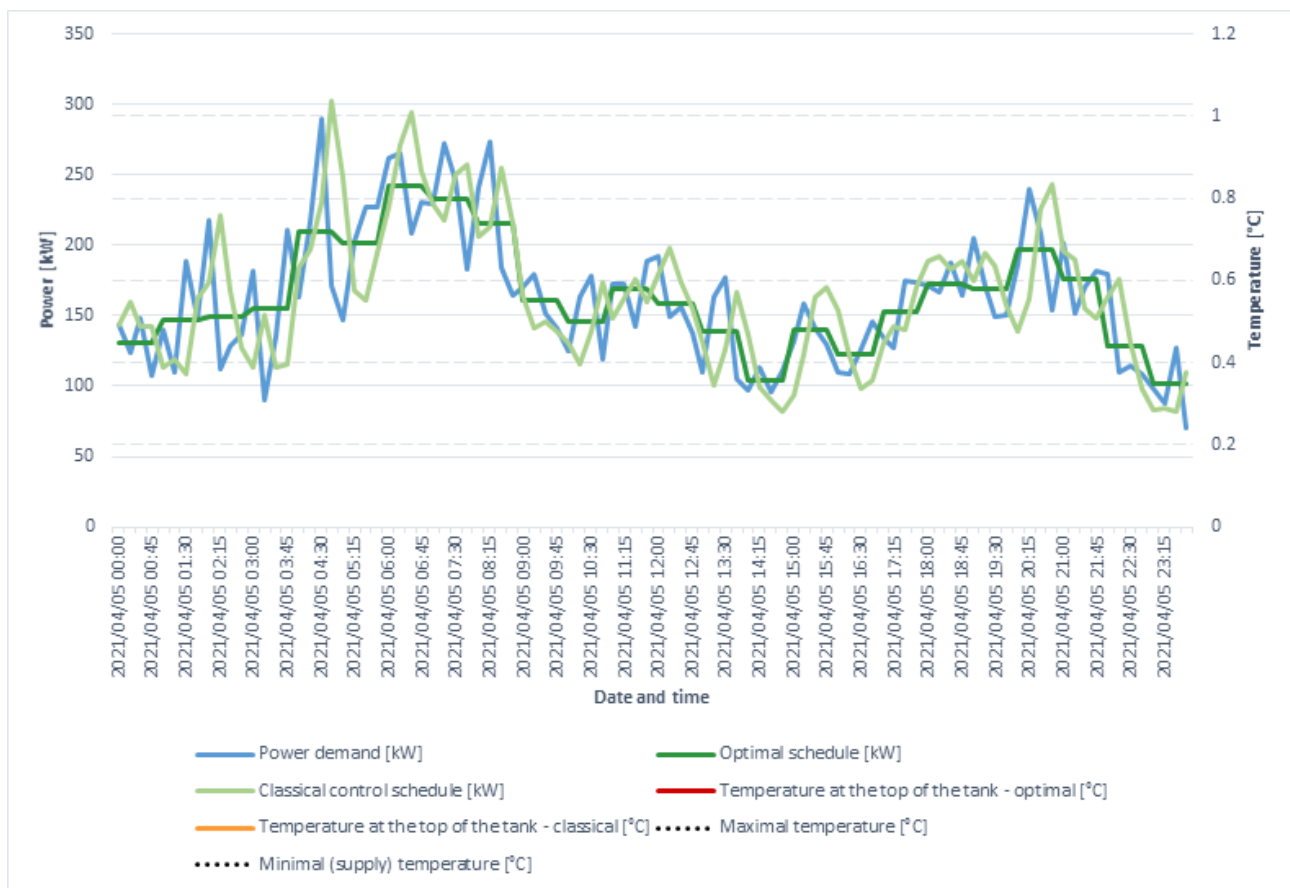

Figure 25. Power demand (blue), the optimal schedule with power change every 1 h (darker green), and the classical control schedule (lighter green) for the warmer day scenario.
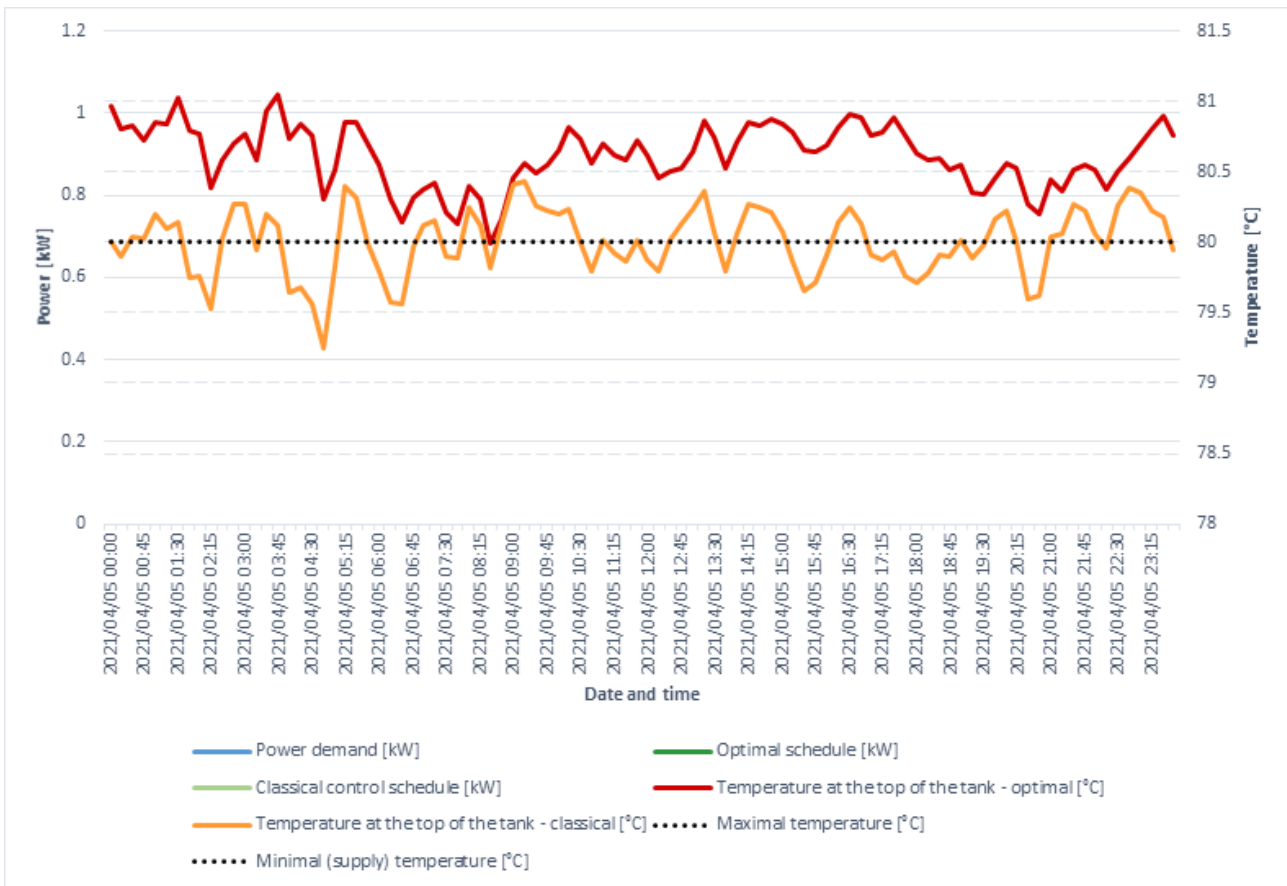
Figure 26. Simulated water temperatures in the top of the storage tank for the warmer day scenario: optimal schedule with power change every 1 h (red), classical control (orange), and required supply temperature (black dots).

Results of the tool for the scenario of the warmer day, April 5th 2021, with power change every 4 h, is shown in Figure 27 (energy analysis), Figure 28 (power schedules), and Figure 29 (simulated temperatures).

ANALYSIS				
	Optimal schedule	Classical control	Difference	Without storage
Total energy demand [kWh]	3915.28	3915.28	N/A	3915.28
Total primary energy consumption [kWh]	4274.94	4284.92	9.98	4269.09
Total energy loss [kWh]	359.66	369.64	9.98	353.80
└ Due to storage [kWh]	6.40	6.23	0.17	N/A
└ Due to efficiency [kWh]	353.26	363.40	10.14	353.80

Figure 27. Energy analysis for the warmer day scenario of the optimal schedule with power change every 4 h, and the classical control schedule.
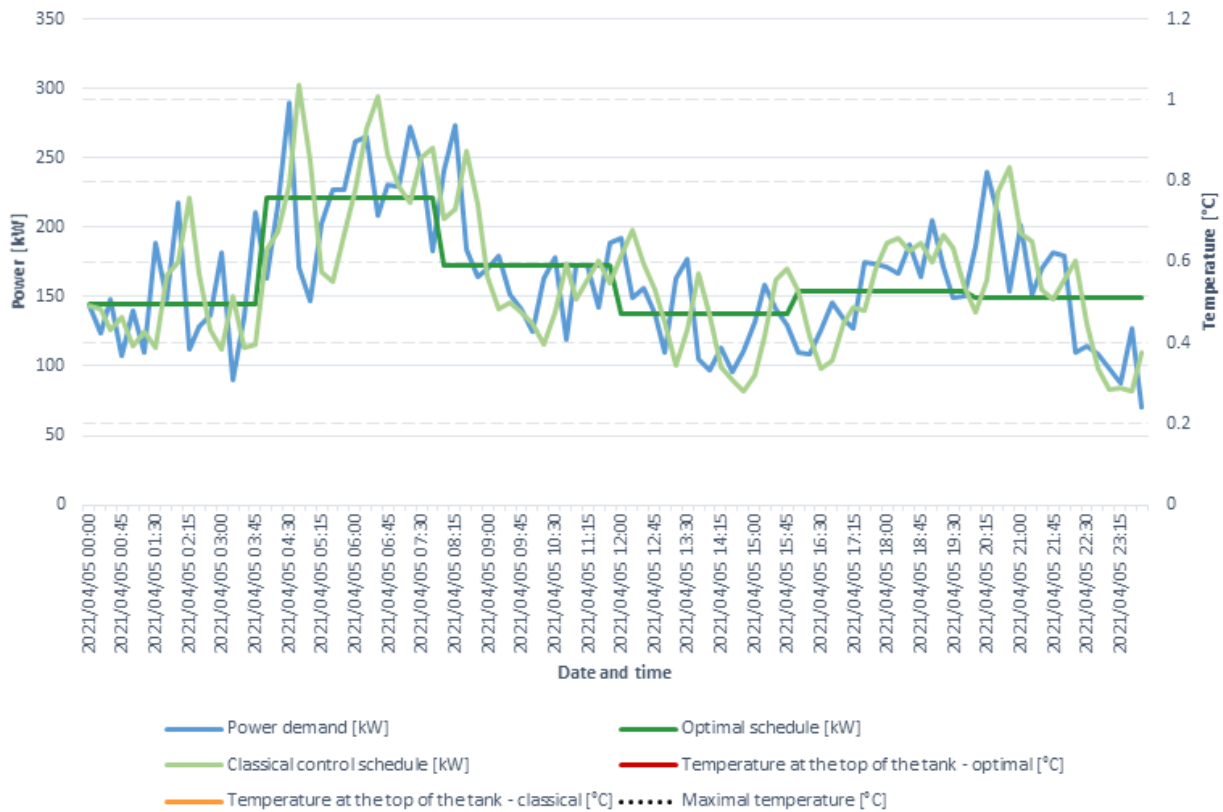
Figure 28. Power demand (blue), the optimal schedule with power change every 4 h (darker green), and the classical control schedule (lighter green) for the warmer day scenario.
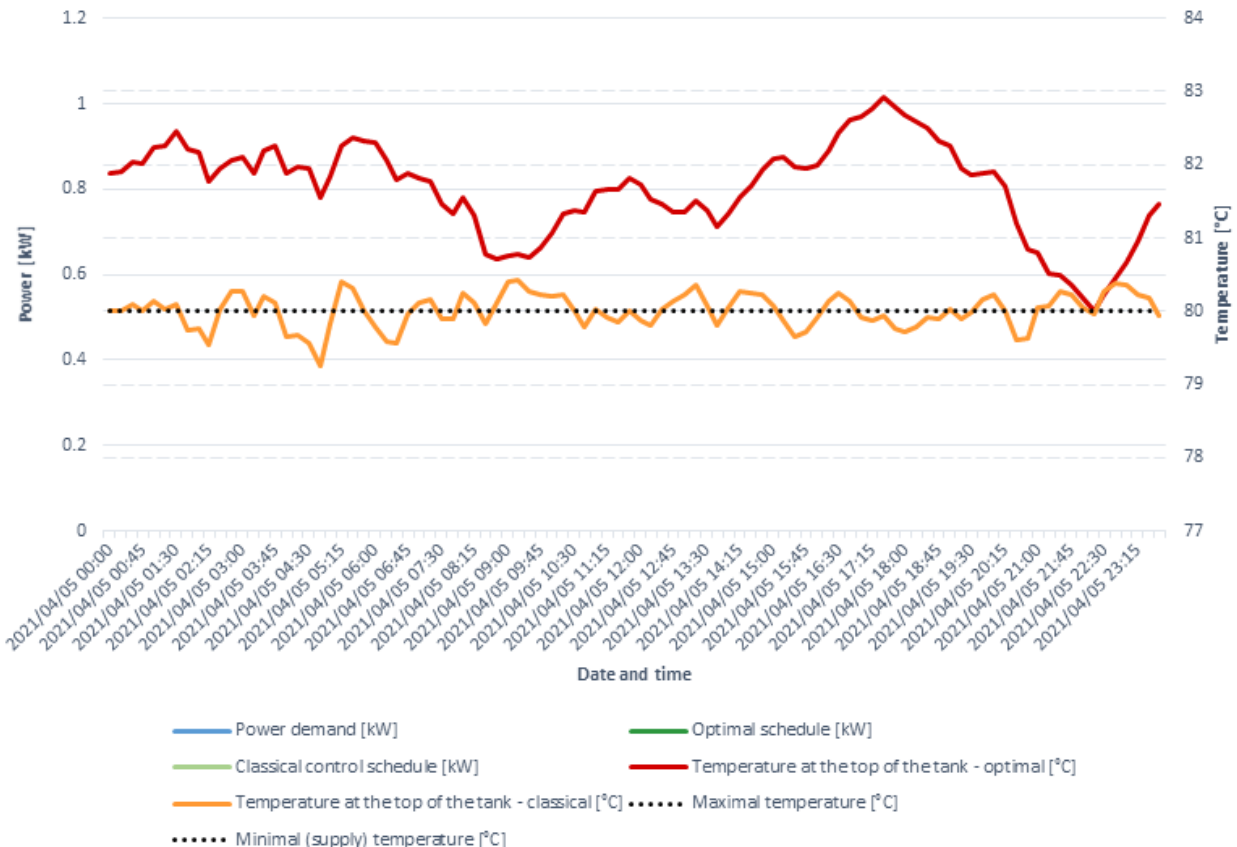

Figure 29. Simulated water temperatures in the top of the storage tank for the warmer day scenario: optimal schedule with power change every 4 h (red), classical control (orange), and required supply temperature (black dots).

4. Conclusions

This deliverable shows the design and implementation of the two modules of the Store4HUC energy management tool, as well as examples of their usage applied to the pilot sites. One concerns the optimal parametrization of PV and battery storage system for a site. The other concerns the computation of the optimal daily operation of heat sources connected to a heat storage tank with known demand, in order to be able to suggest its optimal way of operation.

The modules reside on predictive control and mathematical optimizations, and the underlying mathematical programs are shown for them.

The modules are applied on Store4HUC pilot sites, and the obtained results are shown. They give an insight how the historical pilot site can be parametrized (just for the case of PV + BESS) and then operated to gain optimal performance in accordance with the set KPIs.

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