SunHorizon advanced control system and proactive maintenance tool: Case study in Latvia

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Abstract. Currently, buildings represent a large percentage of the energy consumption in the European Union. Increasing the introduction of renewable energy sources is becoming necessary to achieve an effective reduction of greenhouse gas emissions. SunHorizon project demonstrates the potential of combining solar appliances and heat pumps in buildings for meeting heating and cooling (H&C) demands in Europe. The energy systems are managed by an advanced Python-based control system. Using the forecast of the demand and occupancy of the building, a predictive controller calculates the optimal exploitation of resources and storage use in order to maximize the renewable energy use and cost performance. Furthermore, the control system operates in combination with a proactive maintenance tool that includes fault detection and maintenance surveillance capabilities. This tool is based on the Reliability-Centred Maintenance (RCM) strategy, which focuses on understanding the equipment failure modes, applying all the different possible maintenance strategies and considering consequences and cost of failures. To achieve this goal, several key performance indicators (KPIs) are defined, calculated in real-time operation and compared with simulation data to detect faults. When any failure is obtained, the system triggers specific alarms via web and email, hence notifying house operators or final users. KPIs are also evaluated to calculate their remaining useful life (RUL) and therefore predict future faults. The solution is applied in a building in Riga (Latvia) and the methodology beneath these tools is explained in this paper. The use of prediction for control and maintenance will allow the system to avoid wasting energy, increase self-consumption as well as to save costs on the energy bills.

Keywords. SunHorizon, Heat pumps, Advanced control, Proactive maintenance tool, Latvia.
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1. Introduction

In the following years, both residential and tertiary buildings are expected to increase their use of renewable energy, leaving aside conventional technologies and avoiding CO_2 emissions to the environment. Furthermore, in the European Union, the energy associated to heating and domestic hot water (DHW) represents the 79% of total final energy use in households (192.5 Mtoe), and the cooling demand, although smaller, increases significantly in summer months [1]. In addition, climate change threats to increase the cooling energy demand, which may further aggravate electricity peaks in summer [2].

SunHorizon project aims to demonstrate that the proper combination of up-to-date technologies, such as solar panels, heat pumps and storage systems, managed by a controller along with proactive maintenance, can avoid wasting energy, identifying malfunctioning of equipment, maximizing energy coming from renewable energy sources (RES), increasing self-consumption, reducing local energy bills and cutting off greenhouse gases emissions.

In this paper, an advanced control methodology is presented for a case study in Riga. Based on a model of the energy system and using building demand prediction profiles, day-ahead control strategies are calculated optimizing the operation for different criteria, such as maximum self-consumption or minimum operation cost. This predictive optimization uses a combination of the Extended Ant Colony Optimization and Improved Harmony Search algorithms. In addition, a proactive maintenance tool based on the Reliability-Centred Maintenance (RCM) technique is exposed. This tool processes measured and forecast data in order to calculate KPIs and performance indicators (PIs), which describe the actual health of the system, and trigger alarms in case any problem is detected. Besides, the maintenance tool is able to calculate the RUL of the technologies and their auxiliary elements. All measured and calculated data are stored in a cloud database.

To verify their correct operation, both the advanced control system and the proactive maintenance tool will be tested in the eight demo sites included in SunHorizon project, where several of the H&C devices and management tools designed in the project will be also installed and tested. In this article, the Riga Sunisi house demo intervention and operation are explained.

At the time this article was written, the installation of all devices was in progress, so testing the control system and the proactive maintenance tool with real data was not possible. Instead, simulation tests using historical data were performed.

The remainder of this paper is organized as follows. In Section 2, the Riga Sunisi demo site is described. The advanced control system technique and its implementation are exposed in Section 3. Section 4 shows the proactive maintenance tool developed and adapted to Riga Sunisi. In Section 5, the validation of both tools is included. The conclusion is given in Section 6. Section 7 gathers the acknowledgements. The list of all KPIs and PIs used by the proactive maintenance tool in Sunisi is presented in Section 8 (Appendix A). Finally, Section 9 includes the references.

2. Riga Sunisi demo site description

Riga Sunisi demo site (Fig. 1) consists of a residential house situated in Riga. It was built in 2015 and is composed by a two-floor house and a garage building. The intervention that is been performed in SunHorizon is mainly focused on the heating system, which includes space heating (SH) and DHW systems of the house.

Fig. 1 - Riga Sunisi demo site.

In Fig. 2, a diagram with the technologies which are being installed in Sunisi and their connections is shown.

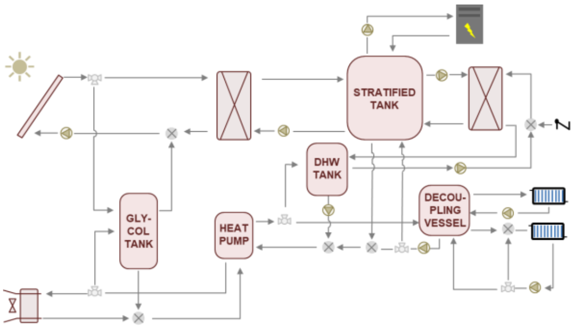

Fig. 2 - Sunisi technologies diagram.

Specifically, the technologies that will be implemented in Sunisi are: hybrid photovoltaic-thermal solar panels (PVT, a natural gas-driven heat pump (HP, a stratified water tank (ST and a glycol tank (GT. The heat output of the PVT is prioritized to store energy in the ST, and, when the outlet temperature of the PVT is not high enough, the heat output of the PVT is stored in the GT. The GT is used to drive the HP when the outdoor temperature is colder than the water stored in the GT, which improves the operation of the DHW and SH loops. The ST pre-heats the DHW and (SH) loops, and the HP supplies the rest of the energy needed. When there is an excess of electrical output from the PVT, a smart electric heater is used to heat up the water inside the ST. The thermal needs of the house include DHW and SH, which is covered using radiators and a radiating floor. The electricity consumption of the house and the technical room are also considered. In order to monitor the SunHorizon system operation, a high number of sensors are being installed at building and room levels.

The energy system is controlled at local level using a rule-based strategy that defines the energy flows to cover the demand, based on temperatures and operation conditions. An advanced controller is used to also consider the prices of gas and electricity to optimize the system's operation (see Section 3). The controller has predictive capabilities to calculate operation strategies that the local controller applies as part of the programmed rules.

The proactive maintenance tool aims to study all the available information in order to provide insights about the current and future status of the previously described system, raising alarms if needed. In the case of Sunisi, both the advanced control and the proactive maintenance tools are executed in a Microsoft Azure server (Fig. 3. This cloud-based virtual machine has been selected because of its advantages, which includes scalability, security and computing power.

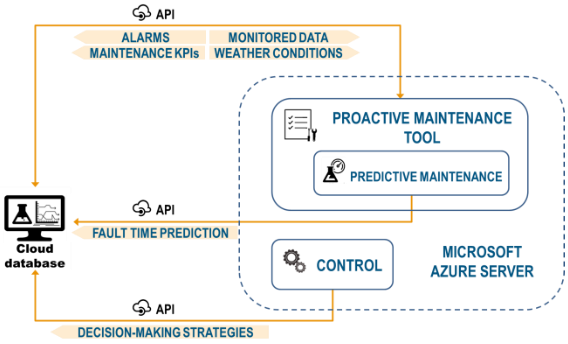

Fig. 3 - Communication flowchart, including Microsoft Azure server.

3. Advanced control system

The heating system of Riga Sunisi incorporates an advanced control system with predictive capabilities, which allows to achieve the optimization of the system in a 24-hours time horizon, to avoid wasting energy, maximize the use of RES and reduce the energy bills.

The advanced controller has been developed in a generic way to be easily adaptable to other cases. Thus, the hybrid controller is implemented on Azure server to avoid the need of any additional architecture at the demo sites (e.g. computer on site). In the particular case of Riga Sunisi, weather forecast data and the predicted demand is provided by IESVE by means of the cloud database [3], and read by the advanced controller through a Python API. Those data are processed and used as an input in a TRNSYS-based model [4]. The model is then co-simulated in TRNSYS and Python and optimized to obtain the predicted optimal status of the system in the next 24 hours to reduce the energy consumption and bills. The general workflow of the advanced controller is shown in Fig. 4.

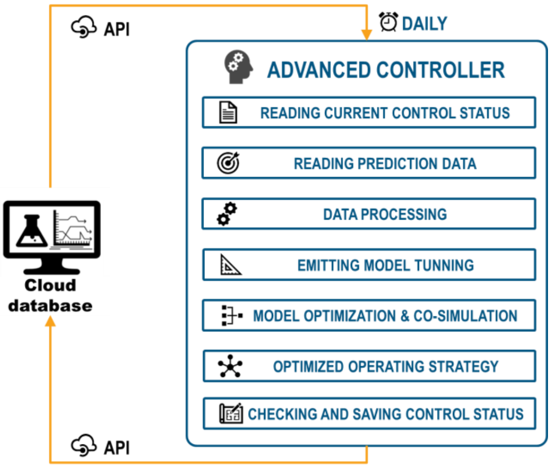

Fig. 4 - Advanced controller flowchart.

In Riga Sunisi, two control decision variables are considered for optimization: the status of the three-way valve that decides whether the PVT stores the thermal output in the ST or the GT, and the amount of power inyected into the smart heater connected to the ST. Costs of gas and electricity are considered to drive the optimization.

For this optimization, the heuristic algorithms Extended Ant Colony Optimization (GACO), Improved Harmony Search (IHS) and Simple Genetic Algorithm (SGA) were used due to their time-efficient computation of integer decision variables, although they do not reach an exact solution, but approximate. The three algorithms were obtained from the pygmo library [5], based on Python, and are compared in Section 5. After testing all of them, IHS was the chosen algorithm to operate the optimization, given that the best results were achieved. In Section 5, the validation results of the advanced controller using IHS are also shown.

4. Proactive maintenance tool

The proactive maintenance methodology in SunHorizon project is based in the Reliability-Centred Maintenance (RCM) strategy, which is a reliability technique used to ensure the inherent designed reliability of a process or piece of equipment through the understanding and discovery of equipment functions, functional failures, failure modes and failure effects. RCM evaluates and applies the different possible maintenance strategies based on consequences and cost of failures, with a strong focus on the proactive maintenance. In this way, RCM integrates traditional preventive, corrective, predictive and condition-based maintenance practices, trying to minimize maintenance and improve reliability throughout the life-cycle. Nowadays, there exist several standards that define the RCM approach, such as [6] and [7].

Following the RCM methodology, the proactive maintenance tool developed in SunHorizon project is focused on the automatic detection and prediction of faults that triggers the maintenance actions defined in the Failure Modes, Effects and Criticality Analysis (FMECA). The tool, which has been developed in Python, includes several steps that are executed once a day (see Fig. 5).

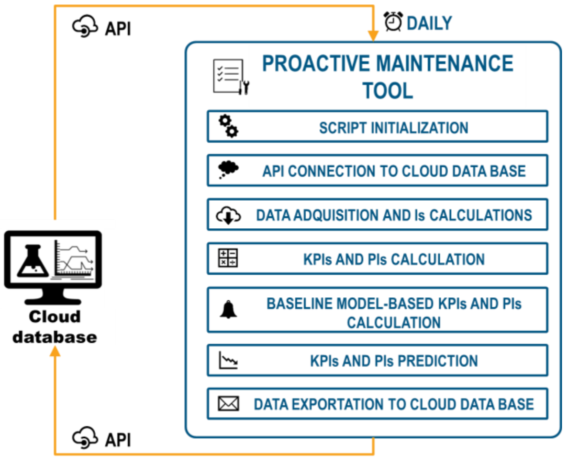

Fig. 5 - Proactive maintenance tool flowchart.

Firstly, the tool gets the monitoring data from a cloud database using an API. Then, KPIs, PIs and other useful indicators (Is) are calculated using their respective formulas (obtained from [8]) and with a different time resolution depending on their characteristics (e.g. 15 minutes, hourly, daily). The complete list of KPIs and PIs calculated in Riga Sunisi can be found in Section 8 (Appendix A). The difference between KPIs and PIs is that the first ones refer to the SunHorizon system as a whole, while the second ones focus on the performance of each of the installed technology. In a third step, the expected KPIs and PIs are estimated using a set of baseline TRNSYS models of the technologies and the real measured data as inputs. The objective of this estimation is performing a comparison between the real and the expected KPIs and PIs, which will help to detect possible faults in the installed devices. Next step is the RUL calculation of the different systems. The KPIs and PIs time series are fit to the predefined fault evolution models, and their prediction is used for the RUL calculation. The RUL value will be very useful for the scheduling of the maintenance tasks. The last step consists of sending to the cloud database all the Is, PIs and KPIs calculated by the proactive maintenance tool and check if any alarm has to be raised comparing real and the expected KPIs and PIs, as previously explained. If any alarm is triggered using the approach in Tab. 1, a notification is sent by web and email. Thresholds from Tab. 1 will be fine-tuned throughout the progress of the project, as well as the evolution of each KPI and PI.

Tab. 1 - Alarms definition.

Alarm level	Formula
Warning	$50\% \leq \frac{Indicator_{actual} - Indicator_{estimated}}{Indicator_{estimated}} \leq 80\%$
Danger	$\frac{Indicator_{actual} - Indicator_{estimated}}{Indicator_{estimated}} \geq 80\%$

5. Validation

In order to validate the operation of the advanced controller and the proactive maintenance tool, simulated data of the building demand have been generated using the models from [4] and uploaded to the cloud database.

Firstly, the three heuristic optimization algorithms selected were studied. The daily costs obtained during one week of February are compared in Fig. 6. Tab 2. shows the average daily cost calculated for that week. IHS is the algorithm that achieves the best performance.

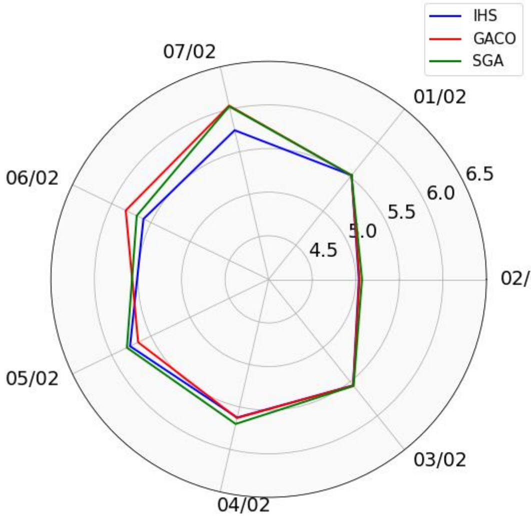

Fig. 6 - Cost comparison between IHS, GACO and SGA algorithms for one week.

Tab. 2 - Average daily cost reached by IHS, GACO and SGA algorithms.

Algorithm	Average daily cost (€)
Improved Harmony Search (IHS)	5.55
Generalize Ant Colony Optimizer (GACO)	5.61
Simple Genetic Algorithm (SGA)	5.63

After choosing the IHS optimization algorithm, the operation of the controller has been validated. One year of simulated data has been used. The results are compared with the "baseline" conditions, i.e. how the system would operate if only rule-based control strategies were applied. As can be seen in Tab. 3, the optimization allows primary energy savings of 4.72%, and a reduction of 9.34% of green-house emissions and 2.88% of operational costs per year.

Tab. 3 - Comparison between baseline and optimized results

Variable	Baseline	Optimized results
Gas consumption (MWh/year)	17.90	14.94
Electricity self-consumption from PVT (MWh/year)	2.92	3.94
Electricity exported (MWh/year)	5.04	4.03
Non-renewable primary energy consumption (MWh/year)	24.52	23.22
Renewable energy ratio (%)	19.11	24.23
Operation costs (€)	1478.66	1436.10

In the case of the proactive maintenance tool, the validation was performed at the functional level. Malfunctioning situations were simulated to ensure the correct alarms calculation and notification.

6. Conclusion

In this paper, a novel advanced control methodology has been presented, along with a proactive maintenance tool. Both developments have been applied to the Riga Sunisi demo site, within SunHorizon project, and have been validated with simulated data. Their combined operation ensures a smart management of innovative H&C devices, resulting in energy, economic and environmental benefits.

Our future work will be focused on the fine-tuning of the advanced controller and the proactive maintenance tool. Once all the devices are installed in the house, real data will be collected, and the operation of all equipment will be analysed and improved.

7. Acknowledgement

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8. Appendix A

Tab. 3 and Tab. 4 include all the KPIs and PIs used in Sunisi by the proactive maintenance tool.

Tab. 3 - KPIs of Riga Sunisi demo site.

Name	Unit
Capital expenditure	€
Costumer's bills reduction	€
Customer's satisfaction rate	%
Greenhouse gases emissions reduction	gCO_2
Heating comfort index	°C·h
Levelized cost of heat	€/kWh
Operational expenditure	€
Non-renewable primary energy savings	kWh
Renewable energy ratio	%
Electricity self-consumption fraction	%
Simple pay back	years

Tab. 4 - PIs of Riga Sunisi demo site.

Name	Unit
Dual panels solar electric efficiency	%
Dual panels solar thermal efficiency	%
Dual panels solar thermal fraction	%
Dual panels thermal-electricity ratio	%
Heat pump seasonal gas utilization efficiency	%
Heat pump seasonal performance factor	%
Water tank stratification efficiency	°C
Glycol tank stratification efficiency	°C

9. References

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Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.