Study on the efficiency of large shallow GSHP Systems. ELI-NP after one year operation

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Abstract. This paper is an overview of the performances of the Shallow Ground Source Heat Pump HVAC system from ELI-NP after one year of operation. It approaches the system performances in terms of energy consumption, stability of the indoor comfort parameters and prospective of optimal control. The use of a research facility is different from a classic non-residential building. The large equipment and the large built area of the clean rooms, the high stability of the required comfort parameters imply a high consumption of energy for heating, ventilation and air conditioning. The final goal is to achieve a viable model with replication potential for general use applications (air conditioning of non-residential objectives or district centralized air conditioning). Databases resulting from the continuous real-time monitoring of the system, during 2020, have been analyzed. Deviations of data from the reference values have been interpreted to find solutions for the long-term keeping of indoor microclimate parameters at the required values. The data analysis shows that the system covers the building load / the building energy needs at a high parameters stability. The Energy Intensity Use of the ELI-NP facility (436.13 kWh/ m^2/yr) is less than half of the median EUI for Technology/Science laboratories in the US (1004 kWh/ m^2/yr), as published on the platform Energy Star. The use of the shallow Ground Source Heat Pump HVAC system instead of a traditional fossil fuel one, comes with estimated savings of 60% in the cost of energy consumption of buildings. The next step to follow is a higher accuracy separation of the Ground Source Heat Pump HVAC system electricity consumption. Then an optimization strategy to supply the indoor comfort parameters at the lowest possible energy consumption follows.

Keywords. Heat pumps, buildings, energy efficiency, shallow GSHP
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1. Introduction

The Extreme Light Infrastructure – Nuclear Physics Research Infrastructure (ELI-NP) is a European and international center for high-level research on ultra-high intensity laser, laser-matter interaction and secondary sources with unparalleled possibilities. ELI-NP is a very complex facility, which hosts the most powerful LASER in the world.

The main objective the ELI-NP buildings concept design was to create an optimal environment capable of hosting state-of-the-art research equipment and technologically advanced experimental configurations.

Features, such as a clean room of 2400 m^2, large working spaces (i.e. laboratories) without natural lighting, research equipment that require a large cooling capacity, and demands of the environmental parameters, come with significant energy consumption.

The interest of the US authorities to benchmark buildings in terms of energy efficiency generated studies and surveys regarding the energy efficiency of the research laboratories in the US. Based on the available data, the ELI-NP facility was assessed by comparison, in terms of the core activity, to similar facilities as defined on the Energy Star platform, run by the US Environmental Protection Energy.

ELI-NP has been operating for 5 years, of which two years at 70% capacity. After having continuously monitored the buildings in real time, it turns out that the energy consumption rates are lower than expected, the systems providing high parameters stability.

One of the key factors leading to low energy consumption is the HVAC geothermal system the research infrastructure was provided with. The system doesn't use fossil fuels as energy source, the main energy source for both heating and cooling (including technological cooling) is geothermal energy, equipment being powered by electricity.

After observing the performance of buildings and systems, as well as the consumption behavior during the last two years, it came out that there is room for optimization both in terms of control and in terms of energy efficiency. The aim is to optimize both the geothermal HVAC system and the other systems so to get the optimal ratio between consumption and technological requirements.

Currently, optimization strategies applied for smaller geothermal HVAC systems are being studied to determine the one that is best suited to be adapted to the ELI-NP case. Also, additional ways to reduce electricity consumption for lighting and related activities are being investigated.

2. Shallow geothermal HVAC system at ELI-NP

The running of the scientific equipment requires accurate specific conditions, therefore the shallow geothermal system with heat pump units is one of the core systems of the buildings. Its efficiency and proper working are vital for the good functioning of scientific equipment.

The configuration of the site and the breakdown of the total gross area of 33.000 sqm served by the system is shown in Table 1.

Tab.1 - Breakdown of the facility area.

Building / Space	Destination	Gross Built Area (m^2)
Laser Building	research	11.543
Gamma Building	research	13.452
Office Building	support	5.237
Guests House	support	2.568
Other buildings	support	212

The shallow geothermal system, installed on a plot of 27.000 sqm, provides the buildings with all the energy necessary for heating, ventilation, air conditioning, hot water, and technological cooling water.

It has a length of 135 km, and 1080 drills deep of 120 m each. The total installed thermal capacity is approximately 6.2 MW.

Due to the large thermal capacity provided by the shallow geothermal system, the operation of the buildings does not require fossil fuel systems. Thus, the impact of the ELI-NP buildings on the CO_2 emissions is low.

The energy source of the Shallow Geothermal System designed for the ELI-NP facility is the geothermal energy, provided by a closed geoexchange circuit, transferred to the buildings by heat pump units.

The system is a closed-loop made of 1080 boreholes with a depth of 120 m each. Each group of 60 holes is connected to 2 of the 18 existing manifolds. From the existing distributor and collector in each of the 18 manifolds, a pair of geothermal pipe-lines go to the pumping station that performs the management of the extracted energy from the earth throughout the cold season, respectively the injected energy to the earth throughout the warm season.

The required primary thermal agent (water) is pumped from the manifolds to 9 thermal plants equipped with water to water heat pumps that carry out the heating and cooling of the buildings. The secondary thermal agent (water) for cooling and heating prepared with the water-water heat pumps is delivered to the HVAC equipment (air handling units, fan coils units).

The required thermal load of 6,0 MW for heating and 4.2 MW for cooling is provided by 129 water-water heat pumps. On top, 46 water-air heat pumps directly carry out the cooling or heating of the indoor air of some rooms. The heating, ventilation, and conditioning of the buildings is performed by air handling units. Energy recovery is used wherever possible. For the LASER building, a total of 8 handling units are used, out of which 3 are fresh air units that supply a mixed flow rate 85.000 mc/h.

Their major endpoint is to carry out the heating and ventilation of the LASER clean room and of the other existing clean rooms ISO 6 and ISO 7, providing for this purpose 20 air changes per hour with a vertical air flow of 435,000 m^3/h. The required humidity load for the LASER building is provided by steam humidifiers attached to the air handling units.

For the GAMMA building, 2 fresh air handling units are used to supply a flow rate of 80,000 m^3/h each in the experiments rooms.

The shallow geothermal system is digitally controlled by the DDC system. Thus, the temperature and humidity are continuously monitored, recorded and, adjusted, the information being transmitted to the BMS system.

The major endpoint of the SHALLOW GEOTHERMAL SYSTEM is to deliver high stability of the operating parameters.

Some parameters required in the reserch laboratories are presented in Table 2.

Tab.2 – Operating parameters of the Laboratory Buildings

Parameter	Unit	Value	Building
Temperature	^oC	22±0.5	Laser
Temperature	^oC	20±0.5	Gamma
Relative humidity	%	35-50	Laser
Relative humidity	%	30±0.5	Laser
Overpressure	Pa	40	Laser
Negative pressure	Pa	14	Gamma
Cleanliness class	ISO	6, 7	Laser

3. Breakdown of the energy consumption at ELI-NP. Energy Use Intensity

At the same time with the parameters, the total electricity consumption of the research facility was monitored, as the only energy consumption with a precise cost, known based on the supplier's metering and bills.

Figure 1. shows the total consumption during June 2016, when the testing and commissioning of the facility took place, up to December 2021. This period of time covers different stages of occupancy, but years 2020 and 2021 can be considered years of fully operation, meaning full occupancy of the office building, the research equipment and experimental building installed. Only the installation of one equipment is in progress at the moment.

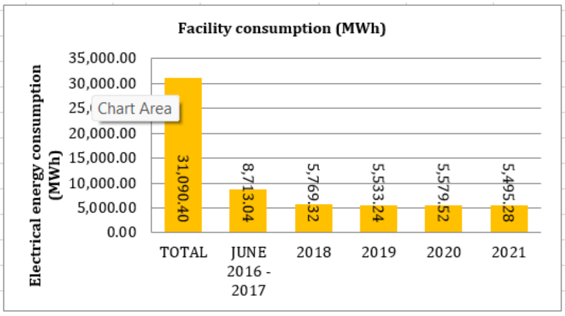

Fig.1 - Total facility consumption begining of the commisioning.

The total electricity consumption from commissioning to the end of 2021 was around 31,100 MWh. The diagram shows that in the last four years of the monitoring period the consumption was relatively constant, with small variations due to environmental factors or the volume of works and tests carried out in the buildings.

The consumption mentioned above means a cost of around 1,3 euro/gross built area m^2, computed considering to the supplier's bills, based on the cost of the electricity on the Romanian free market. This amount includes all the consumptions, meaning: heating, cooling and ventilation of the laboratories and of all the support buildings, hot water, electricity for lighting and office equipment, electricity for the data rooms, electricity consumed to running and cooling the research equipment, exterior lighting of the entire side and the adjacent road.

We found that two-thirds of the electricity consumed comes from the HVAC system together with the technological cooling, both needs being covered by the shallow ground source heat pump system (Figure 2).

For the operating years 2020 and 2021, which we considered as the basis for a future optimization of the energy consumption, the pattern shows, as expected, that the maximum consumption is recorded in the summer months and in the winter months, when the need of cooling or heating is high (Figure 3).

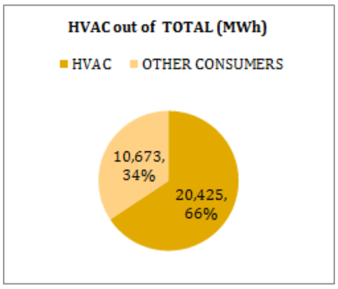

Fig.2 - HVAC consumption out of total begining of the comissioning

Figures 3 and 4 represent the breakdown on months of the total facility consumption for years 2020 and 2021.

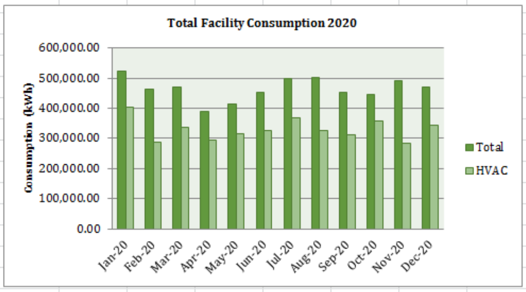

Fig.3 - Breakdown on months 2020

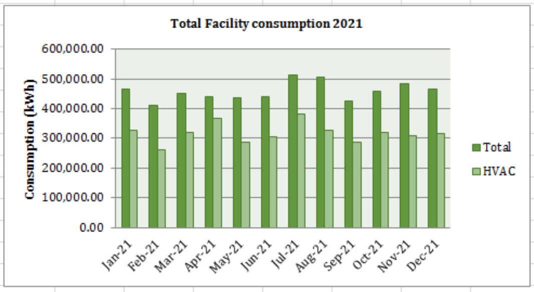

Fig.4 - Breakdown on months 2021

Figures 5 and 6 represent the breakdown on months of the total facility consumtion for years 2020 and 2021.

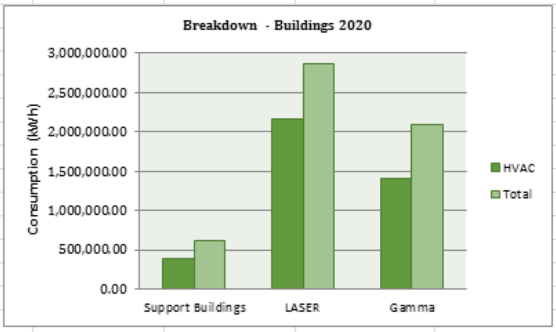

Fig.5 - Breakdown – Buildings 2020

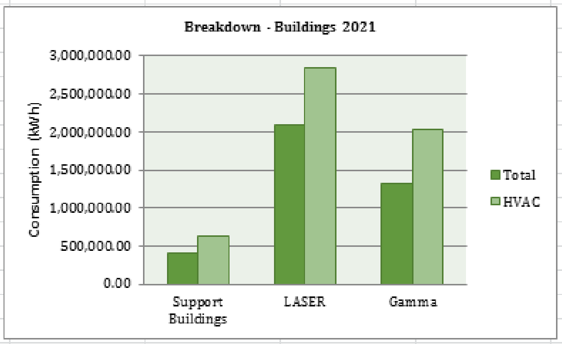

Fig.6 - Breakdown – Buildings 2021

To improve the use of energy, one of the directions followed by authorities was to develop regulations for assessing the energy performance of buildings. Both the existing stock of buildings and the design of new buildings were taken into account.

Rules to rank and evaluate different categories of buildings have been drafted both in the EU and in the US.

The most used key metrics to benchmark buldings in terms of energy performance are:
a. According to EPA (US Environmental Protection Energy) Energy Use Intensity (EUI) is expressed as energy per square foot per year and calculated by dividing the total energy consumed by the building in one year (measured in kBtu or GJ) by the total gross floor area of the building (measured in square feet or square meters) [1].
b. Specific Energy Consumption (SEC) expressed as energy per square meter per year and calculated by dividing the total energy consumed by the building in one year (measured in kWh) by the useful area of the building (measured in square meters).

The calculation of SEC may differ from a country to another or from an author to another [2].

The calculation of SEC explained above is the one used in the Romanian Calculation Methodology of Buildings Energy Performance [3].

Studies indicate that science is more energy intensive than other disciplines.

Therefore the interest in benchmarking the research laboratories in terms of energy performance has grown in recent years to improve the metrics or key performance indicators that score the research facilities [4].

The lack of data on similar infrastructures makes difficult the assessment of the ELI-NP energy performance.

Healthcare facilities, more intensely benchmarked are to some extent similar to ELI-NP in terms of the share of the HVAC system consumption from the total consumption.

The rooms that host the main research equipment are single volume halls, having large areas and considerable heights (maximum height around 16 m), being similar in this respect to event halls and sports facilities.

Therefore, comparison with similar size infrastructures is not relevant due to the fact that research activity comes with high-energy consumption. Comparison with other geothermal systems is also of small relevance due to the fact that there are few geothermal systems of this size.

To achieve our purpose of an assessment in terms of energy consumption, we considered a comparison of the energy performance of the ELI-NP facility with research facilities in the United States.

The EUI of ELI-NP is compared:
a) to the results of a three-year benchmarking study conducted by kW Engineering for the Boston Green Ribbon Commission's Higher Education Working Group [5], [6], [7]and
b) to the median EUI in the United States US for Technology/Science laboratories, published by EPA on the platform Energy Star (programme run by EPA) [1].

Values of source EUI have been compared.

According to EPA the site energy is the annual amount of all the energy the building consumes on-site, regardless of the source and source energy is the total amount of all the raw fuel required to operate your building, including losses that take place during generation, transmission, and distribution of the energy [8].

The conversion factor for electricity (grid purchase) of the site energy to source energy according to the Romanian regulations is 2,62 [3].

According to the glossary of Portofolio Manager application, LABORATORY refers to buildings that provide controlled conditions in which scientific research, measurement, and experiments are performed or practical science is taught [8].

Gross Floor Area should include all space within the building(s) including workstations/hoods, offices, conference rooms, restrooms, storage areas, decontamination rooms, mechanical rooms, elevator shafts, and stairwells [8].

At the time of kW Engineering study the EPA had not provided an ENERGY STAR® rating for lab buildings, and widely used national energy usage datasets contained very limited lab building data. The goal of the study was to construct a new lab building benchmarking dataset comprised of Boston-area higher-education labs, with data quality exceeding that of any other sample.

The data requested from the respondents for each building:

a. Whole-building annual energy usage, meaning energy consumed (from all sources) in one year calendar
b. Building functional requirements: these are the metrics on which buildings are compared, and include total building area, total lab area, number of fume hoods, and predominant lab type (biology/biochem, chemistry, physics/engineering, and other).
c. Building design and operational parameters: these include properties of the buildings that are expected to influence energy consumption but which are not necessarily needed to meet functional requirements. Examples include HVAC system type (e.g. variable air volume with reheat), HVAC control type (e.g. pneumatic), and the use of night airflow setback in labs.
d. Perceived energy efficiency: respondents were asked to rank the buildings in terms of efficiency of original design and efficiency of current operation [5].

The data about the Energy Intensity Use for the studied laboratories have been published in the final report on June 2018 and are presented in Table 3 [7].

Tab.3 - Energy intensity use summary. kW Engineering Study.

LAB TYPE Total area 17k ft^2	No. B.	Average SOURCE EUI (kWh/ m^2/yr)	Average SITE EUI (kWh/ m^2/yr)	Median SOURCE EUI (kWh/ m^2/yr)
Bio/ Biochem	46	1.725	921	1.728
Chemistry	13	1.996	1.120	1.908
Physich/ Eng	43	1.363	770	1.217
Other	7	1.709	902	1.741
TOTAL	109	1.615	883	1.599

Later on, EPA updated the Portfolio Manager application on its Energy Star platform with more buildings categories and published the median value of the source EUI for Technology/Science laboratories, based on Commercial Buildings Energy Consumption Survey (CBECS) conducted by the U.S. Department of Energy's Energy Information Administration. The survey considered 11k laboratories totalising an area of 705m ft^2 [9].

The published median value of EUI for Technology/Science laboratories is 318,2 kBTU/f^2/y, meaning 1004 kWh/ m^2/y [6].

Regardless of the study considered, it comes out that the ELI-NP research facility has a EUI below the median value of the EUI for research laboratories assessed and scored in the United States. To be noted that the consumption of the technological cooling is not separated from the HVAC, both needs being covered by the shallow ground source heat pump system. Values of the EUI for the entire facility are presented in Table 4 and Figure 7. In Table 5 the value of the EUI for the research purpose building are presented.

Tab.4 - Energy intensity use ELI-NP for the entire Facility

ELI-NP	Cons (MWh)	SOURCE EUI (kWh/m^2/yr)	SITE EUI (kWh/m^2/yr)
2020	5.579	442.81	169.01
2021	5.503	436.13	166.46

Fig.7 - Source EUI ELI-NP compared to EUI for research laboratories in USA

Tab.5 - Energy intensity use ELI-NP for the Research Purpose Buildings

ELI-NP	Cons (MWh)	SOURCE EUI (kWh/m^2/yr)	SITE EUI (kWh/m^2/yr)
2020	4.965	518.60	197.94
2021	4.875	509.16	194.34

We consider that an assessment of the ELI-NP facility based on SEC has a high degree of uncertainty due to a) high rate area/volume of the main laboratories (approx. 8.000 m^2), b) very large area of the main clean room (approx 2.400 m^2).

4. Strategies considered for the HVAC System Optimisation

Two of the optimisation strategies that we investigated have drawn our attention as matching for the shallow Ground Source Heat Pump System ELI-NP.

The first one is a model based strategy proposed by Zenjun Ma and Lei Xia, tested on the geothermal system that serves the Sustainable Buildings Research Centre at the University of Wollongong, Australia and summarized by the authors in Figure 8.

The developed strategy is suitable for systems equipped with variable speed pump(s) in the ground loop system to modulate the water flow rate and we considered it due to the fact that all hydraulic circuits in the ground loop of the ELI-NP system contain at least one variable speed circulation pump [10].

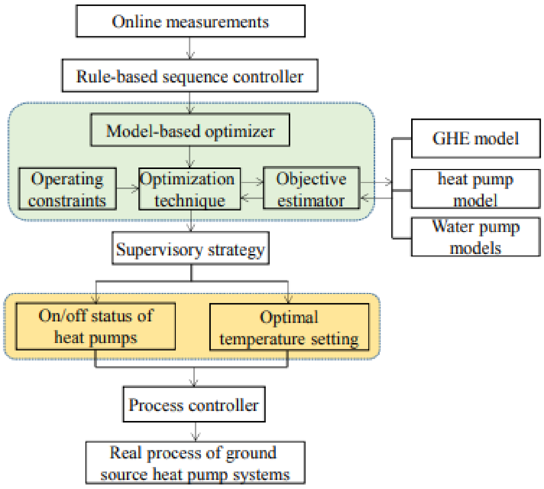

Fig. 8 - Outline of the proposed optimization strategy.

The variable optimized is the outlet water temperature from the ground heat exchanger, which can be used as a set-point to control the operation of the variable speed pumps in the ground loop system. The objective of the optimization is to minimize the system power consumption while providing required building heating and cooling demand.

To estimate the system performance under various trial setting three component models were used: the variable speed circulation pumps in the ground loop, the ground heat exchange and the water to water heat pumps.

The process consists of two steps:
The first step is to use a rule-based sequence controller to determine the operating number of the heat pumps based on the building heating/cooling demand and the capacity of each heat pump as well as the operating constraints of practical applications. The second step is to determine the optimal combination of the outlet water temperature from the GHEs and the water flow rate circulating through the GHEs to minimize the total power consumption of the water pumps in the ground loop and the water-to-water heat pumps.

The exhaustive search method used in this study is not a good search method for real-time control applications due to the nature of its exhaustive search, thereby relatively high computational cost requirement. However, the results obtained using this method can be potentially useful to generate a performance map, which can then be used for real-time control applications.

Although this method comes with only 4.2% energy savings compared to a rule-based control strategy, we considered it due to the fact that we can easily implement it. Also, an extra control is expected over the baseline control strategy we use

The second strategy that we considered is an “in situ” optimisation methodology for ground source het pump system propose by Javier Cervera-Vázquez Carla Montagud José Miguel Corberán Antonio Cazorla-Marín.

The authors previously developed an experimental in situ optimization methodology for the water circulation pumps frequency and then they upgraded it to ensure user comfort. The methodology has been implemented and tested in heating and cooling mode in a real GSHP installation located at the Universitat Politècnica de València in Valencia, Spain [11], [12].

5. Conclusions

The total energy consumption of ELI-NP during operation has been monitored and registered.
Also the consumption for buildings and systems has been registered given that the systems are 85% metered and the HVAC system is fully metered but the consumption of the technological cooling is not separated by the HVAC. To be noted that both needs are covered by the shallow Ground Source Heat Pump System.
A comparison with similar buildings is not an easy task due to the fact that the assessment of the energy performance of research laboratories is recent and the key performance indicators used do not take into account all the characteristics of the research facility with an impact on energy performance.
Beginning of 2021, the EPA included the Technology /Science laboratories in the portfolio of the benchmarked buildings in the United States, publishing their median EUI. The ELI-NP EUI value is 436.13 kWh/ m^2/yr and the median value of EUI for Technology/Science laboratories published on the Energy Star platform is 1004 kWh/ m^2/yr.

After having studied the behavior of ELI-NP in terms of energy consumption, we came to the conclusion that there is room for improving the energy performance of the facility. To be noted that stability of the operating parameters of the systems is of major importance.

We have studied several optimal control strategies proposed by specialists for similar but smaller systems. Our goal is to extend one of these strategies for the ELI-NP geothermal system and eventually to estimate the long-term variation the coefficient of performance of the system.

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