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Flexible waste heat management and recovery for an electro-intensive industrial process through energy/exergy criteria

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Abstract:

The French National Laboratory for High Magnetic Fields (LNCMI) provides high magnetic fields for an international community of users. On the site of Grenoble DC electricity is used to feed dedicated high power electro-magnets to produce steady magnetic fields. The magnets electrical consumption is fully dissipated as heat at variable temperatures. An ongoing project for the LNCMI electro-intensive installation analyses the opportunities for waste heat recovery into the nearby district heating network. Recent studies have pointed out energy recoveries of the order of 20% considering waste heat at 35 °C heat pumped to 85 °C and a thermal storage. One of the main reasons for this low recovery rate is the temporal mismatch between the LNCMI's activities and the district's residential heat needs.
From 2020, the LNCMI has signed a new electricity contract that provides more flexibility to the high field experiment planning. Two strategies are explored to improve the waste heat recovery energy and exergy rates. Firstly, the rescheduling of the LNCMI planning of experiments in order to mitigate the temporal mismatch. Secondly, management of the cooling loops of the process to adjust waste heat at relevant temperatures. The energy analysis accounts for recovered heat quantity, while the exergy analysis accounts for the major sources of irreversibility within the LNCMI's processes. MILP optimisation problem formulation and solving proved these two strategies to be energy and exergy efficient for the LNCMI waste heat recovery. This work offers promising research and operational perspectives for flexible energy systems optimal management with both energy and exergy criteria.

Keywords:

Waste heat, energy system management, exergy, flexibility, optimisation.

1. Introduction

1.1. Waste heat recovery in times of climate change

Tackling climate change is a major challenge of our century and involves reducing greenhouse gas emissions caused by the energy consumption of human activities: they account for nearly 60% of carbon dioxide emissions worldwide [1]. Heat is the largest energy-end-use: it accounts for 50% of global final energy consumption in 2018, and contributes 40% of global CO_2 emissions [2]. Finding and exploiting low greenhouse gas-emitting sources of heat production to replace carbon-based sources is therefore a key to fighting climate change. While renewable means of heat production such as biomass, solar thermal or geothermal energy exist, waste heat is a source of non-carbon heat that is still under-exploited.

Waste heat, also called excess heat, can be defined as heat that is not the purpose of a given system [3]. Its recovery represents an interesting alternative to fossil fuels for the supply of heat, but is subject to some challenges such as the differences in location and temperature between the waste heat sources and heat consumption or heating networks. The durability of the waste heat source compared to recovery and networks facilities lifespan, as well as institutional and commercial issues [4] are additional challenges.

1.2. LNCMI waste heat recovery

The LNCMI is the high magnetic fields facility of the French National Centre for Scientific Research (CNRS), located in the Grenoble Presqu'île district (Figure 1). Most of its activity consists in freely providing high magnetic fields to researchers from all around the world after having been selected by a dedicated committee. As the magnetic energy produced by its electromagnets is not converted into mechanical work, all the energy injected into the magnets is dissipated as heat. A hydraulic circuit that takes its cold source from a nearby river (the Drac) extracts the calories from the primary circuit of the magnets via a heat exchanger. The heated water is then discharged into a second river (the Isère). The magnet outlet temperature of the water used for cooling purpose varies between 10°C and 40°C, depending on the electric power injected in the magnets and the temperature of the Drac in particular. The ratio between the magnet electrical consumption (i.e. heat dissipation) and the facility electrical consumption can reach 0.9. The electricity not consumed in the magnets is mainly used to power the magnets cooling system pumps, thus this ratio is not constant. For this study, an electrical to heat ratio of 0.85 is considered.



Fig. 1. (from left to right) : magnet in its housing , top view of the copper alloy active part of a high field electromagnet, location of the LNCMI in the Grenoble district of the Presqu'île. Sources: LNCMI, Grenoble Alpes Métropole.

A waste heat recovery project is under study in order to inject the electro-magnets outlet heat in the local district heating network. The aim is to recover the waste heat dissipated by the magnets while minimising the impact on the operation of the laboratory, and guaranteeing stable heat prices for the heating network users. The quantity of heat dissipated annually by the laboratory is of the same order of magnitude as the consumption on the district heating network. This latter is moreover in the process of reducing its nominal operating temperature from 120°C to 85°C, which is an opportunity for the recovery of magnets low temperature waste heat. In addition to reducing CO_2 emissions of the district heating network, actual challenges of waste heat recovery are addressed: power and time mismatches between source and consumption, and the injection of heat into an existing network from a low temperature source. The waste heat recovery system is therefore composed of a heat pump in order to increase the waste heat temperature from the magnet outlet to that of the district heating network. It also includes a thermocline storage that compensates for time and amplitude mismatches between the heat production that varies between 0 and 24 MW over the year depending on the experimental planning, and the residential season-dependant heat consumption. A first sizing of this system based on technical and economic criteria resulted in a 20 MWh storage and a 3780 kW condenser power value for the heat pump, with a COP value of 3.

The LNCMI being a public research large instrument, its data and operation can be used as a representative use case for the waste heat recovery of electro-intensive industrial processes. Various studies have been carried out for the LNCMI waste heat recovery project:

- Planning laboratory experiments under environmental, economic or social constraints [5]
- Studying the flexibility of the LNCMI consumption profiles based on the identification of typical experiments [6]
- Multi-actor optimisation applied to the LNCMI waste heat recovery project [7]
- Studying the influence of the thermo-hydraulics of the LNCMI electromagnet cooling system on the LNCMI economic and environmental balance [8]

- Optimisation based on energy and exergy criteria [9,10]
- Developing open science on the LNCMI use case [11]

These studies enabled to address various typical issues for waste heat recovery, applied to the LNCMI use case. Regarding the flexibility of the LNCMI experimental planning, and therefore of waste heat production, lessons learned point to the great difficulty in categorising the LNCMI experiments. It is then tough to model a realistic LNCMI schedule of experiments at hourly intervals: the historical data can be used instead in order to model a typical profile. Moreover, it should be noted that the actual planning of experiments of the LNCMI is realised every semester, based on the weekly experiments energy consumption among other scientific or technical considerations. Thus, using the optimisation model with weekly energy consumption from historical data on a semester basis instead of power profile on a yearly basis seems relevant for studying the flexibility of the planning of experiments in the LNCMI.

Regarding the temperature management of the LNCMI cooling system, a regulation system needs to be implemented in order to ensure a constant magnet outlet temperature for the storage and heat pump to work properly. Initial studies and tests carried out in the LNCMI have shown that a constant temperature of 35°C can be maintained without the risk of damaging the magnets, for power consumption values above 10 MW. This electrical power value corresponds to an 8.5 MW heat dissipation taking into account the electrical to heat ratio. Currently, most of the heat dissipated in the magnets has a temperature below 35°C, thus this constant magnet outlet temperature brings about high exergy destruction, as quantified in recent studies [9,10].

A recent change of context regarding the LNCMI energy management is its new electricity contract. From 2020, the electricity consumed for the high magnetic field production is bought at an almost constant price regardless of the hour of the day or the period of the year (except during exceptional peak days indicated by the French Transmission System Operator RTE). This has some consequences: the flexibility of the experimental planning that was previously fully exploited for electricity costs savings is now much less constrained. It allows researchers to work during the day rather than at night, and gives more flexibility for the objective of recovering waste heat. This calls into question the previously calculated performances of the waste heat recovery system considered for the LNCMI, and especially the storage sizing.

1.3. Objective and organisation of the paper

The objective of this paper is to offer flexibility strategies in order to improve both energy and exergy performances of waste heat recovery operations. The study focuses on the concrete use case of the LNCMI, a large and electro-intensive research instrument with specific constraints. Such work brings research in the field of waste heat recovery closer to the reality on the ground. Based on the new context of the LNCMI electricity pricing and the lessons learned from previous studies, this paper explores two flexibility strategies: first, a bi-annual planning of the experiments from weekly historical energy consumption, in order to improve energy results. Then, a temperature management strategy that adapts the magnet outlet temperature to the waste heat recovery occurrences, in order to minimise the exergy destruction. The data and open source models developed for this academic and operational work are made available. The examination of constraints and strategies in this concrete use case brings about promising perspectives for flexible energy system management with time and temperature mismatches, taking into account both energy and exergy criteria.

After introducing LNCMI waste heat recovery project main features, this paper will detail the scenarios explored in this study, based on the strategies mentioned hereinabove. The optimisation procedure will be presented before sharing and discussing the main results of the study.

2. Materials and method

2.1. Study case and input data

The LNCMI's primary objective is to provide high magnetic fields for research purposes. A by-product of this high magnetic field process is waste heat production by electromagnet Joule's heating. Within the same district, a residential network distributes heat to customers. The main objective for the district heating network operator (the CCIAG in Grenoble) is to ensure a good quality heat at a constant price for its customers.

Figure 2 displays the superposition over one year of the LNCMI energy consumption with the district heating network energy consumption. Different energy areas for the LNCMI waste heat can be identified and defined:

- Total waste heat: magnets electrical consumption, i.e. LNCMI facility consumption times the 0.85 electrical to heat ratio, fully dissipated as waste heat
- Available waste heat: waste heat for power values above the 8.5 MW threshold power value ($P_{min\ recovery}$) to ensure constant temperature

- Recoverable waste heat: available waste heat capped by the waste heat recovery system maximal power (P_{STO}+P_{HP}).

It should be noted that the storage minimal charge and discharge time is of 3 hours, that is to say the storage will be fully charged after a 3 hours charging at maximal power and will not be able to store any more energy.

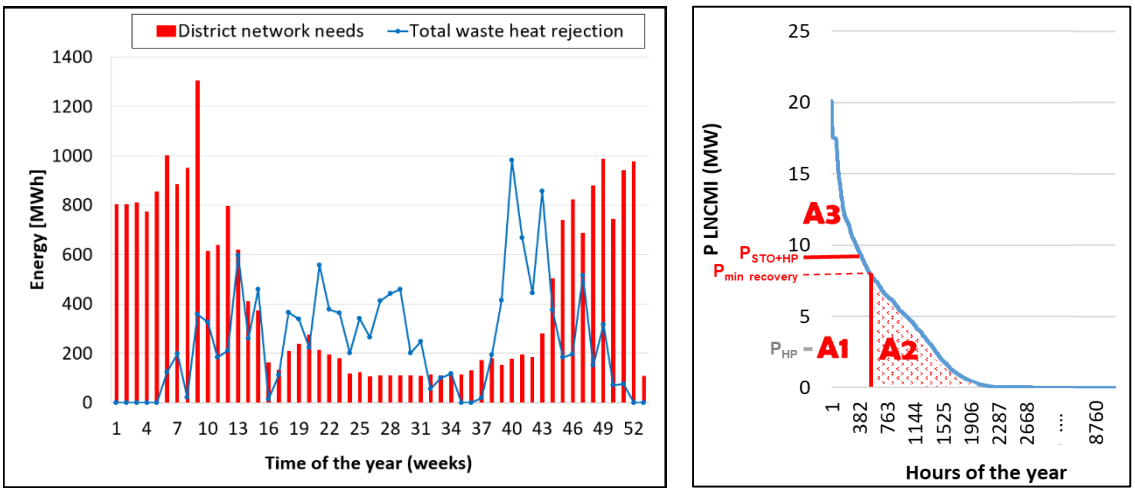


Fig. 2. Left: 7-days energy blocks of LNCMI's experiments (blue) and district heating network consumption (red). Right: LNCMI electrical consumption in descendant order, with A1 the recoverable waste heat, A1+A3 the available waste heat, and A1+A2+A3 the total waste heat.

2.2. Scenarios

The present study focuses on two strategies to increase LNCMI's flexibility. The first one consists in re-scheduling the LNCMI's yearly calendar of experiments. The second one consists in adjusting the temperature of the waste heat depending on the recovery. Table 1 shows the different scenarios conceived to analyse the influence of such strategies.

Table 1. Heat recovery scenarios modelled in this study.

Scenario	LNCMI's calendar	Waste heat's *T* management	Storage capacity
REF	Classic	Overcooling	No storage
RECO-XX	Classic	35 °C	From 0 MWh to 40 MWh
FLEXENER-XX	Rearranged (168h time step)	35 °C	From 0 MWh to 40 MWh
FLEXTEMP-XX	Classic	35 °C or Overcooling	From 0 MWh to 40 MWh
DOUBLEFLEX-XX	Rearranged (168h time step)	35 °C or Overcooling	From 0 MWh to 40 MWh

The scenario named "REF" corresponds to the reference scenario. In this scenario, there is no heat recovery at all, so no heat pump nor thermal storage. This scenario corresponds with the current situation at the Presqu'Île district. Currently, the LNCMI's waste heat is dissipated entirely, and the district heating network operator covers heat demands with production plants of their own. This scenario was modelled in order to quantify the advantages of the heat recovery approaches with respect to the current situation.

The scenario named "RECO" considers heat recovery only with the heat pump. No calendar re-scheduling or intelligent adjustment of temperature is considered here. This scenario is sort of a "second reference scenario", since the typical and unmodified consumption profile of the LNCMI is used. The effect of the new flexibility strategies was compared to this scenario in order to assess whether flexibility strategies are relevant.

The scenario named "FLEXENER" contains the first innovative strategy of this study. In this scenario, the LNCMI's yearly schedule was refined for the sake of heat recovery. The adaptation consists in placing experiments within the calendar in order to fit their energy consumption with the district's thermal needs. Sub-section 2.3 gives details on the tool used and the procedure followed.

The scenario named "FLEXTEMP" entails the second innovative strategy of this study. Unlike other scenarios, in this one the waste heat's temperature is adjusted intelligently. Whenever waste heat is to be recovered, its temperature is adjusted to 35 °C. When it is to be dissipated, its temperature is adjusted to the actual magnet outlet temperature value, magnets currently being overcooled.

In the real cooling loop, water's temperature is targeted by adjusting the magnets flowrate. An accurate modelling of this control would require dynamic simulation. The model used in this study was simplified:

whenever heat recovery is active, a constant temperature of 35 °C was assumed. The rest of the time, temperature is based on historical data.

The scenario named “DOUBLEFLEX” applies both innovative strategies at the same time. The purpose of this scenario is to check whether both effects are or are not cumulative. Synergies between both strategies may also be detected.

Each scenario was investigated with different capacities for the thermal storage unit, ranging from 0 MWh (i.e. no storage) to 40 MWh by increments of 10 MWh. This led to sub-scenarios, distinguished by the suffix “-XX” at the end of the scenario name. When analysing the influence of the strategies, each sub-scenario was compared to its counterparts with equal storage capacity.

2.3. Re-scheduling tool and procedure

The first issue with the study is the harmonization of the time steps. As explained in sub-section 1.2., a typical campaign of experiments in the LNCMI takes a full week. Accordingly, a time step of 168 hours was used for re-scheduling the calendar. However, the LNCMI’s yearly profile of power consumption is defined at a time step of 1 hour. Thus, re-scheduling the calendar implies re-building the energy profile. Dictionaries were constructed in order to switch between energy, power, and temperature profiles.

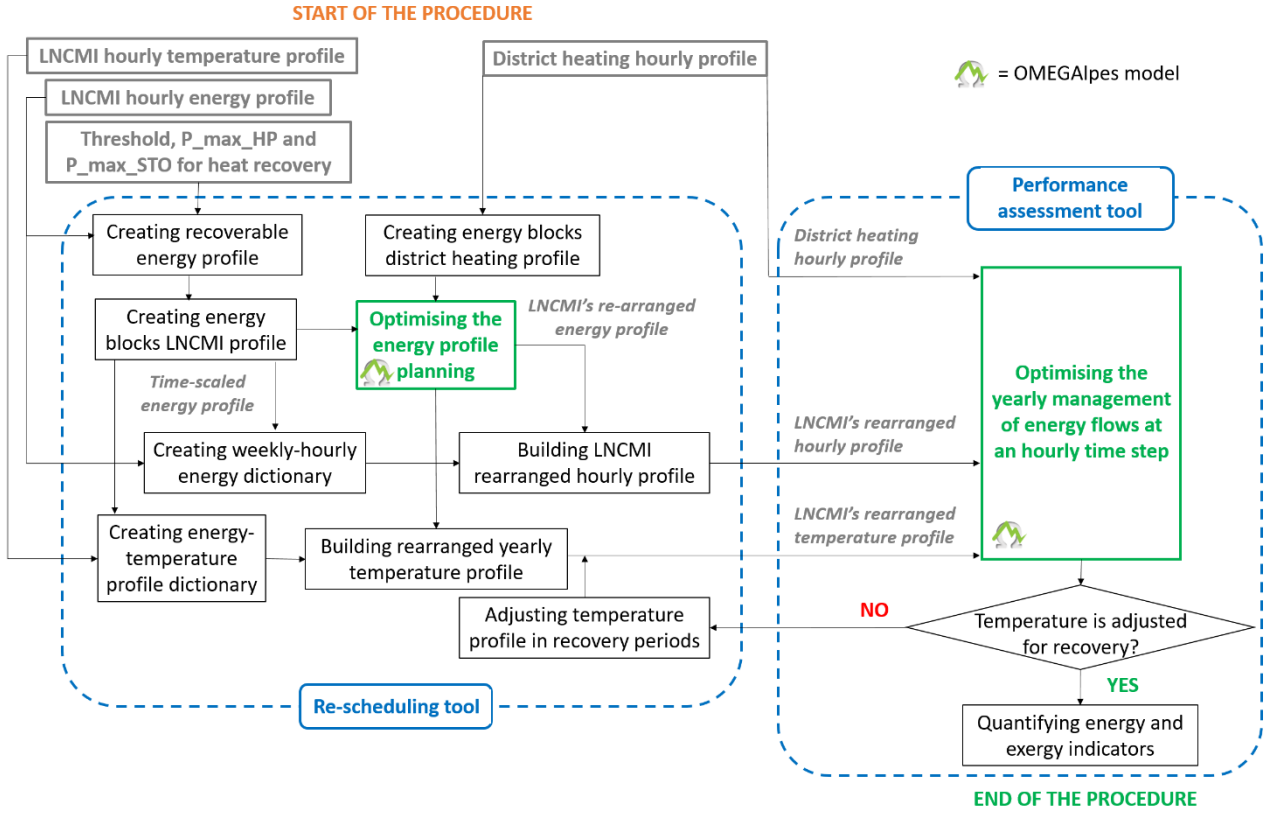


Figure 3: Procedure for rearranging LNCMI annual hourly temperature and power profiles and assessing the energy and exergy performances of the obtained profiles.

In order to redistribute the 7-days energy blocks of the LNCMI, the open source tool OMEGAlpes is used. OMEGAlpes is a decision support tool for the dimensioning and operation of multi-energy systems. It is an optimisation problem modeler for energy systems using the Mixed Integer Linear Programming (MILP) method [12], which is of great interest for processing numerous optimisation variables on a large time horizon, and adding technical or actors’ constraints. In particular, OMEGAlpes facilitates the design time phase, i.e. the preliminary stages of the energy system design process [13], and accumulates knowledge from the projects thanks to a model-based formulation capitalised in the tool library. It has been developed in an open source approach: OMEGAlpes is coded in the Python language and made available under the Apache License 2.0 [14]. It is freely downloadable via the Python Package Index (PyPI) and is available online in an open, versioned and documented project of the Gitlab platform [15] in order to foster its collaborative development. It also allows the different scientific articles where OMEGAlpes is used to be linked to the source code of the associated models in a reproducible research approach. The constitution of OMEGAlpes models thus makes it possible to define and discuss objectives and constraints and can give rise to different technical systems, practical organisation or system operation. The estimation of potential according to the objectives and

constraints also allows a better understanding and therefore a better dialogue with the experts, by identifying degrees of freedom, locks, and the search for preliminary solutions.

Two OMEGAlpes models [16] have been developed and used for this study, with specific objectives and constraints. First, a simplified model of the LNCMI waste heat recovery project in order to rearrange the LNCMI 7-days energy blocks depending on the district heating consumption profile. The storage is not explicitly considered since the time step is of 168 hours. The threshold power value for waste heat recovery as well as maximal power capabilities of the storage and the heat pump (Figure 2) are taken into account in the input data management, in order to determine the recoverable waste heat (Figure 3). In addition to the LNCMI energy blocks, energy units with free profile are considered: electricity supplier, river dissipation, heat pump and heating network production. Finally, the fixed district heat consumption is taken into account. The energy balance between the units is ensured through energy nodes, and two objectives are formulated:

- maximising the recovered waste heat, i.e. minimising the heat production from the district heating network
- minimising the difference between the district heat load energy ($E_{DH\ load}$) and the injection from the heat pump (E_{HP}) at every 7-days time step in order for supply and needs to be as consistent as possible. To do so, the formulated objective (*fitting_objective*) weights every difference with the district heat load power. This enables a fitting of recoverable and consumed energies with a scalar MILP objective:

$$fitting_objective = \sum_{t=1}^{52}(E_{DH\ load}[t] - E_{HP}[t]) * E_{DH\ load}[t] \quad (1)$$

Finally, the main constraints of this simplified model include:

- The LNCMI energy blocks are modelled as Variable Energy Units with fixed energy value (E_{block}) and equivalent power ($P_{eq\ LNCMI}$) over the 168 hours of an energy block:

$$P_{eq\ LNCMI}[t] = \frac{E_{block}}{168}\ for\ t\ in\ [1,52] \quad (2)$$

- The energy blocks can only occur on single time. This constraint uses the u_{block} binary variable that is equal to one when the unit is operating, and 0 when it is not:

$$\sum_{t=1}^{52} u_{block}[nb][t] = 1\ for\ t\ in\ [1,52] \quad (3)$$

Once the LNCMI's energy blocks are rearranged, the hereinabove mentioned dictionaries (Figure 3) enable to reconstruct the power profiles that will be the input of the complete OMEGAlpes model. The temperature profiles are also reconstructed with their original profile or constant 35°C values depending on the recovery occurrence, following the 'FLEXTEMP' strategy.

Second, an exhaustive model of the LNCMI waste heat recovery project (Figure 4) was used to determine the optimal storage management and calculating annual performances of given LNCMI power profiles.

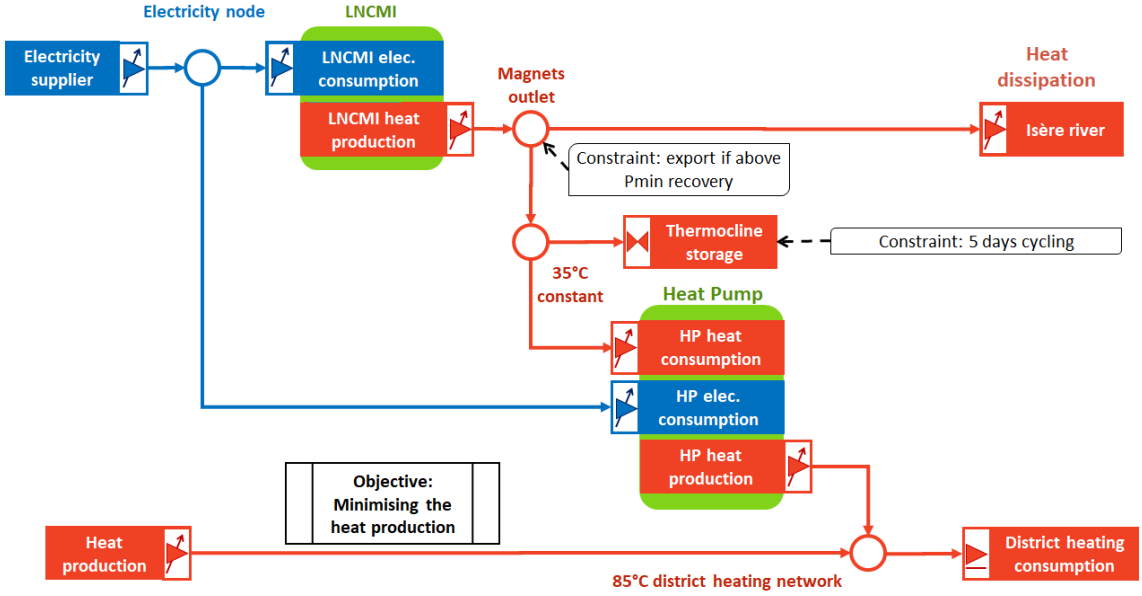


Fig. 4. LNCMI diagram of OMEGAlpes model for the waste heat recovery project, with OMEGAlpes formalism

This model include the following elements:

- An **electricity supplier** powering both the LNCMI and the Heat Pump. During the optimizations, OMEGAlpes can manage this *Variable Production Unit* freely in order to reach the objective.
- A unit representing the **LNCMI's experiments**. It was modelled as an *"Electricity-to-heat Conversion Unit"*. This type of unit converts electrical power into thermal power at a specified ratio. The LNCMI's activities

are much more complex, but this modelling suffices for this study. It takes a given electrical power profile as input and the electricity to heat ratio of 0.85 is used.

- A unit of the LNCMI's **heat dissipation in the Isère river**. It represents the overall heat exchange process between the LNCMI's primary and secondary cooling loops that ends up in the Isère river. The primary loop cools down the magnets by the mean of liquid water in physical contact with them.
- A **thermocline energy storage unit**. It represents a thermocline unit, with a minimal 3-hour total charge or discharge time. The storage must reach its maximal state of charge at least once every 5 days in order to evacuate the gradient zone when it gets too large.
- A **heat pump unit**. It represents a conventional, electrically driven water/water heat pump of industrial size. Technical specifications for this heat pump were obtained from a commercial model injecting at 85°C from heat at 35°C with a COP value of 3. Storage and heat pump power calculations are the same as the ones used in previous studies [9].
- A **district heating network**. It was modelled by the mean of an *"Energy Node"*. In OMEGAlpes, an *energy node* is a power balance between at least two interconnected units.
- A **heat production unit**. It represents the CCIAG's own heat production plants, which currently cover the heating network's needs. They were modelled as a unique *Variable Production Unit*, with enough peak power to cover the whole district's demands at any moment of the year.
- A **district heating consumption unit**. It represents the injection of heat to the network's substations, for the end-users. It was modelled as a *"Fixed Consumption Unit"*, meaning that its power profile is predetermined. The power profile is an input to the model and was provided by CCIAG's representatives.
- Several **energy nodes between the units**. OMEGAlpes optimizes the scenario by managing energy flows within those nodes. A constraint stops the export between the magnet outlet node and the recovery system node when the LNCMI power is below the threshold power value of 10 MW, to ensure constant temperature.

Objective: maximising the recovered waste heat, i.e. minimising the heat production from the district heating network

2.4. Performance analysis

Performance of the different strategies was evaluated through both energy and exergy analyses. Both the energy and exergy models are based on balances applied unit by unit and node by node. Such balances were applied with a time step of 1 hour, with the following hypotheses:

- Pseudo-steady state is assumed at every time step.
- Pressure and heat losses are neglected across all pipelines and equipment.

The energy balance and exergy balance were applied on the main units:

$$\sum \dot{Q}^{in} + \sum \dot{W}^{in} = \sum \dot{Q}^{out} + \sum \dot{W}^{out} + \Delta U \quad (4)$$

$$\sum \dot{E}x^{in} = \sum \dot{E}x^{out} + \Delta Ex^{U} + \dot{E}x^{D}. \quad (5)$$

As a reminder, with work or electric power the exergy flow equals the energy flow. The exergy factor of heat is assessed as the efficiency of a Carnot engine operating between the heat temperature and the temperature of the dead state [17]:

$$\theta^{heat}_{T=T_{wh}} = \left(1 - \frac{T_0}{T}\right). \quad (6)$$

The value chosen for the dead state temperature (T_0) was -11 °C. It is the standard design temperature suggested by the French RT2012 legislation for building energetics in the H1 climatic zone of France [18]. In order to keep thermodynamic consistency of calculations and results, the dead state temperature was attributed a constant value throughout the annual simulation [19].

The exergy analysis was a bit more detailed on the LNCMI's process. Exergy consumption for the experiments ($\dot{E}x^{in}_{exp}$) was dissociated into 3 terms: exergy destruction from generating the electro-magnetic fields ($\dot{E}^{D}_{magnets}$), exergy destruction from cooling down of the magnets ($\dot{E}x^{D}_{cd}$), and exergy outlet in the form of waste heat ($\dot{E}x^{out}_{wh}$):

$$\dot{E}x^{in}_{exp} = \dot{E}x^{D}_{em} + \dot{E}x^{D}_{cd} + \dot{E}x^{out}_{wh}. \quad (7)$$

Exergy destruction of the experiments ($\dot{E}^{D}_{exp}$) comes from transforming electricity into heat at the magnets temperature. This is a collateral effect from generating the electro-magnetic fields. Such transformation degrades the quality of electrical energy consumed by the magnets. That degradation is quantifiable through the exergy factor of heat at the magnets temperature:

$$\dot{E}x^{D}_{exp} = \dot{W}^{in}_{exp} - \dot{Q}^{out}_{wh} \cdot \theta^{heat}_{magn}. \quad (8)$$

However, that degradation is related with a useful effect: production of experimental data. Therefore, it was understood as a “useful exergy destruction” and not accounted as inefficiency. As a reminder, all electricity consumed by the experiments ($\dot{W}_{exp}^{in}$) is rejected as waste heat ($\dot{Q}_{wh}^{out}$).

Exergy destruction from cooling down the magnets ($\dot{E}_{cd}^{D}$) occurs within the transfer of waste heat ($\dot{Q}_{wh}^{out}$) from the magnets to the cooling loop. Such exchanges degrade further the quality of heat, this time from the magnets temperature to the cooling loop temperature. Again, the degradation is quantifiable through the difference in exergy factors:

$$\dot{E}x_{cd}^{D} = \dot{Q}_{wh}^{out} \cdot \left(\theta_{T=T_{magnets}}^{heat} - \theta_{T=T_{wh}}^{heat}\right). \quad (9)$$

Based on previous studies on the LNCMI’s processes [8], it was assumed that magnets temperature is 60 °C above that of the cooling loop. After the overall process, the remaining exergy is contained in the cooling loop as waste heat ($\dot{E}x_{wh}^{out}$, refer to eq. 7). More precisely, it is in the form of a water stream at a temperature between 10 °C and 40 °C depending on the magnets temperature:

$$\dot{E}x_{wh}^{out} = \dot{Q}_{wh}^{out} \cdot \left(\theta_{T=T_{wh}}^{heat}\right). \quad (10)$$

That is the recoverable exergy. Despite its low temperature and quality, the flowrate is abundant and totals for large amounts of exergy.

3. Results and analysis

3.1. Calendar re-scheduling

Figure 5 presents the LNCMI’s annual schedule of experiments, after rearrangement. The rearrangement was applied with a weekly time step (168 hours), in step with the experiments duration. The rearranged schedule is better-fitted with the district network’s needs. Refer to Figure 2 for comparison with the reference case.

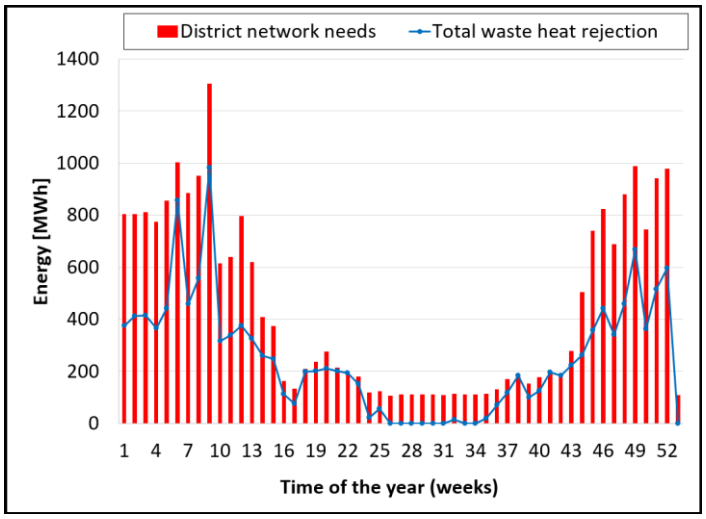


Fig. 5. Annual rearranged energy profile for the LNCMI, with a weekly time step.

3.2. Energy analysis

Figure 6 presents the main energy indicators for each strategy and storage capacity. The strategies were introduced in Table 1. The total amounts of waste heat recovered are shown on the left y-axis. The right y-axis show the relative share that those amounts represent with respect to the available waste heat. The outer-right y-axis, displayed in grey, indicates the relative share with respect to the total amount of waste heat rejected by the LNCMI. The inner-right y-axis, displayed in blue, indicates the relative share with respect to the amount of waste heat that is actually recoverable. As explained in Fig. 2, waste heat from LNCMI’s experiments can only be recovered when at least 8.5 MW of heat are being rejected.

As shown in the figure, one third of total waste heat can be recovered in the best cases. Nevertheless, it represents up to 70% of recoverable waste heat. The influence of thermal storage is quite visible, too. For any strategy, annual recovery increases by around 2-fold if applying a 10-MWh thermal storage, or by around 3-fold if applying a 20-MWh thermal storage. The effects of storage are more or less beneficial depending on the strategy. Furthermore, marginal heat recovery is greater when switching from 0 MWh to 10 MWh than when switching from 10 MWh to 20 MWh, in all scenarios. This is quite typical of energy profiles under heavy temporal mismatch, where the benefits of further storage capacity tend to be asymptotic.

Classic recovery without any flexibility approach (labelled “RECOVERY”) ranges from 5% to 28% total heat recovery when switching from no storage to a 40-MWh storage. Given the same storage capacity, all other strategies perform at least as well as this one. The strategy of re-scheduling the experiments (labelled “FLEXENER”) seems to have the greatest impact. With respect to the “RECOVERY” scenario, it recovers between 30% and 100% more waste heat depending on storage capacity.

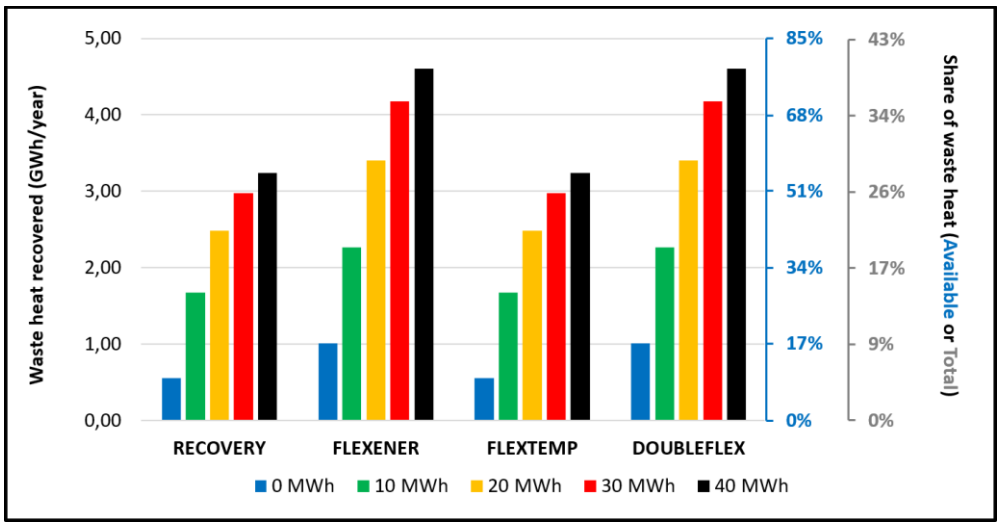


Fig. 6. Absolute and relative recovery of waste heat with various strategies and thermal storage capacity.

As expected, the “FLEXTEMP” and “DOUBLEFLEX” approaches have no impact on the energy indicator in comparison respectively with the “RECOVERY” and “FLEXENER” approaches. This is no surprise, since the approach chosen here for temperature adjustment does not change the heat pump’s performance nor the amount of heat recovered. However, it does change the quality of dissipated heat: a strong impact of this strategy is expected on the exergy indicator.

3.2. Exergy analysis

Figure 7 presents the main exergy indicator for each strategy and storage capacity. The indicator is the total amount of exergy destruction (in GWh/year) due to waste heat dissipation. The same strategies from Fig. 6 are presented, with the same storage capacities. In addition, exergy destruction in the “REFERENCE” scenario is also displayed. For the sake of analysis, a discontinuous line going from the reference to all other scenarios indicates the threshold for improvement. In the previous figure, the reference scenario was not displayed, because its energy indicator was equal to 0.

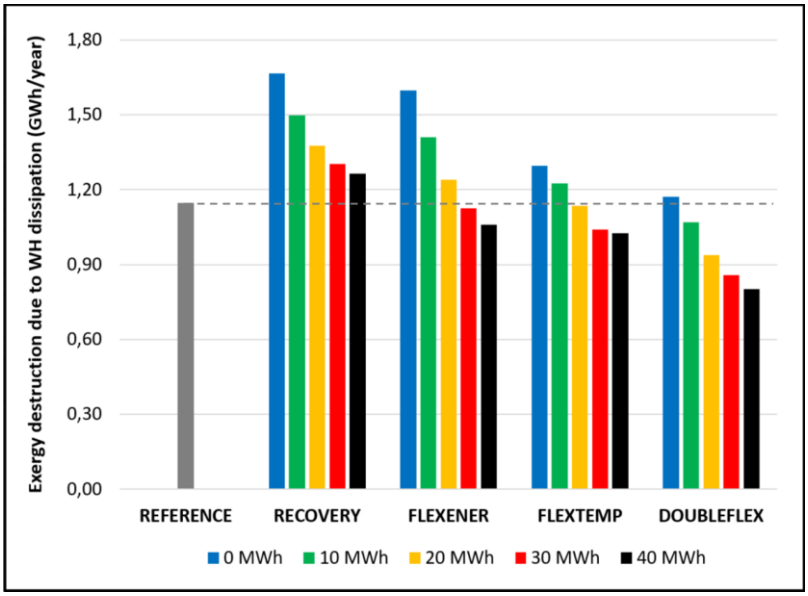


Fig. 7. Exergy destruction by waste heat dissipation in each scenario, with varying storage capacity.

As expected, the exergy analysis gives additional information with respect to the energy analysis. The most noticeable result comes from comparing the flexibility strategies with the reference scenario. In contrast to energy analysis where every strategy was an improvement, less than half the strategies improve the exergy indicator.

The “RECOVERY” approach is the least-performing one. This scenario suffers from two issues. The first one is waste heat being permanently at 35 °C. This is a major disadvantage with respect to the reference, where waste heat is usually between 10 °C and 20 °C, with some sporadic fluctuations up to 30-40 °C. Adjusting to a constant 35 °C may not be worth exergy-wise, if not enough heat is recovered. As the bar chart shows, such is the case in this scenario. Not even a 40-MWh storage leads to sufficient heat recovery for this scenario to be exergy-worthy. This leads to the second issue of this scenario: the lack of energy flexibility, which only worsen the issue related to temperature.

The “FLEXENER” approach may outperform the “RECOVERY” approach, but it needs a storage capacity of at least 30 MWh in order to be exergy-worthy. A storage unit of this size may render the project too costly. The answer to this question can only be given by a techno-economic analysis, which was not covered in this study. Thus, it is still unclear whether this approach is recommendable.

The “FLEXTEMP” approach shows its interest in this indicator. Whereas it led to no improvement energy-wise (refer to Fig. 6), it is more promising exergy-wise. Note how at “FLEXTEMP-20”, exergy destruction is already less than at “REFERENCE”. The “FLEXTEMP-0” and “FLEXTEMP-10” cases do not reduce exergy destruction with respect to the reference case, because not enough heat is recovered when rejection takes place at 35 °C. However, they still outperform their “FLEXENER” counterparts by a great margin. Thus, exergy-wise it would appear that temperature management is more promising than calendar re-scheduling.

The “DOUBLEFLEX” approach combines well the advantages of the two previous approaches. Furthermore, there appear to be synergies between the two. For instance, switching from “RECOVERY-10” to “FLEXENER-10” reduces exergy destruction from 1.498 GWh/year to 1.409 GWh/year (i.e. a reduction of 0.089 GWh/year). Meanwhile, the “FLEXTEMP-10” approach reduces exergy destruction to 1.225 GWh/year (i.e. 0.272 GWh/year reduction with respect to “RECOVERY-10”). A simple addition of both effects suggests a reduction of 0.361 GWh/year (i.e. 1.137 GWh/year of exergy destruction). However, “DOUBLEFLEX-10” entails 1.068 GWh/year, i.e. a further reduction of 0.069 GWh/year with respect to the estimation. This further reduction is 0.056 GWh/year for “DOUBLEFLEX-0”, and 0.060 GWh/year for “DOUBLEFLEX-20”. This means that not only there are synergies between calendar re-scheduling and temperature management, but those synergies reach a maximum somewhere between no storage and a 20-MWh storage. Further investigating those synergies is one of the authors’ perspectives.

The main conclusions from this figure are: 1) From an exergy standpoint, temperature management seems to be a must, since it minimises exergy destruction caused by waste heat dissipation; 2) Combining it with calendar re-scheduling can yield more promising results, since calendar re-scheduling maximises exergy recovery in the form of waste heat recovery; 3) There appear to be optimal synergies between the two methods, that require further investigation.

3.3. Discussion

The analysis and conclusions presented hereinabove are subject to several hypotheses that could be further examined and refined. First, a constant temperature is considered for the heat injection from the heat pump to the district heating network. But the district heating network actual temperature depends on the district consumption: its value will be time dependant and superior or equal to 85 °C. A modelled water logic of the district heating network can be considered in the exhaustive OMEGAlpes LNCMI model but was not presented here. Then, the planning does not take into account specific operation constraints of the laboratory such as holidays or maintenance, but the MILP formulation makes it possible to include them easily. The OMEGAlpes open source model then serve as an intermediary object to collaborate and exchange around the use case. Finally, the yearly optimisation assume an a priori known district heating network consumption: knowing this profile will depend on the consumption predictability.

4. Conclusion and perspectives

This study investigated the influence of some flexibility approaches for a waste heat recovery project in Grenoble, France. Two fundamental approaches were considered. The first one is rearranging the LNCMI’s annual calendar of experiments, in order to better fit them with periods of heating demands. The second one is adjusting the temperature of waste heat intelligently, depending on heat recovery. Then, both approaches were combined in order to evaluate the aggregated advantages and possible synergies. Performance of the waste heat recovery process was analysed energy-wise and exergy-wise, for each flexibility approach. The energy indicator was the total amount of waste heat recovered. The exergy indicator was exergy destruction by dissipation of waste heat.

The following conclusions were obtained. Calendar rearrangement effectively increases annual waste heat recovery, and intelligent adjustment of waste heat temperature effectively reduces exergy destruction. Energy wise, calendar rearrangement seems very promising: all flexibility scenarios outperform the reference scenario. In comparison with no-rearrangement, it increases the amount of heat recovered by 35% - 42%, depending on the thermal storage capacity used. If no thermal storage is implemented, it increases heat recovery by 83%. Exergy wise, not all flexibility scenarios outperform the reference scenario: heat recovery without flexibility is discouraged, it increases exergy destruction by dissipation of waste heat by 10% - 45% with respect to the reference scenario. Heat recovery with calendar rearrangement only outperforms the reference scenario if a thermal storage of 30 MWh or more capacity is used. Below that capacity, exergy destruction by waste heat dissipation increases. The strategy of temperature adjustment reduces exergy destruction by around 20% with respect to the reference case, for all storage capacities. There appear to be synergies between calendar rearrangement and temperature adjustment. Further, it seems that those synergies could be optimised.

The study carried out in this article also lead to several encouraging perspectives. First, indicators different from energy and exergy could be explored. For instance, an environmental indicator such as a calculation of the project greenhouse gases emissions depending on the district heating network and power system dynamic emissions, as well as the recovery system embedded emissions with life cycle analysis approaches. Economic indicators could also be considered taking into account both capital and operational expenditures, including energy costs. A technical and economic balance is necessary to ensure the project viability. The complex problem of annual rescheduling has been simplified in bi-annual 7-days energy blocks rearrangement with respects to the LNCMI planning procedure. A sequential intra-week optimisation could then be conducted in order to rearrange the weekly planning of experiments of researchers: the work carried out as well as this perspective makes the proposed experiments rearrangement strategy realistic and practical.

The work presented in this paper will be a valuable input for the energy management part of the new “ISABEL” Horizon 2020 European project which aims at improving the long term sustainability of the European Magnetic Field Laboratory.

CReDiT authorship statement

S. Hodencq: Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing - Original Draft. **J. Fitó:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - Original Draft. **F. Debray:** Data curation, Funding acquisition, Resources. **B. Vincent:** Data curation, Funding acquisition, Resources. **J. Ramousse:** Funding acquisition, Project administration, Supervision. **B. Delinchant:** Funding acquisition, Software, Supervision. **F. Wurtz:** Funding acquisition, Project administration, Supervision.

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Nomenclature

CCIAG	Grenoble district heating network operator
COP	Coefficient Of Performance
E	energy, GWh_{en}
$\dot{E}x$	exergy flow, GWh_{ex}
MILP	Mixed Integer Linear Programming

$P_{STO} + P_{HP}$	maximal power values for the thermocline storage and the heat pump
$P_{min\ recovery}$	Threshold LNCMI power value above which constant waste heat temperature can be ensured
$\dot{Q}$	thermal flow, GWh
T	temperature, °C
T_0	dead state temperature (for exergy analysis), °C
U	internal energy, GWh
$\dot{W}$	electric flow, GWh
θ	exergy factor, GWh_{ex}/GWh_{en}

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