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Potential evaluation of Carnot battery integrating waste heat recovery in industry

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Abstract:
One of the keys to the current energy and ecological transition is the development of electrical energy storage. This demand has motivated the development of alternative technologies that overcome some of the shortcomings of the storage systems used until now. Among these, Carnot battery has experienced a rapid development in the last decade. Its principle is to store electrical energy in the form of heat and restore it with a heat engine. This technology has several advantages: a long life span, the possibility to increase easily its storage capacity, and the use of small environmental footprint materials. Current research tends to show the lack of competitiveness of classical Carnot batteries architectures compared to other technologies due to their relatively low roundtrip electric efficiency. It is therefore necessary to investigate the integration of heat streams in order to increase their attractiveness. A large part of the industrial energy consumption is used for thermal purpose. It is estimated that a large part of this energy is then lost as waste heat. The aim of this paper is to provide economic key performance indicators concerning the potential of a Carnot battery integrating waste heat recovery in a given industry. The key performance indicators provided are based on the temperature level of the waste heat, the energy rates consumed and dissipated by the industry, the type of primary energy used and the electricity pricing. This paper shows that electricity pricing is the key to this technology development. High price variability and negative purchase prices are factors leading to a potentially interesting profitability of this system. The primary energy ratio is the second most important parameter influencing the results. As an illustrative example: an industry with a recoverable waste heat at 100℃, a gas consumption three times higher than the electricity consumption, and a ratio of the minimum (positive) purchase price of electricity to the maximum sale price equal to 50% can expect a maximum reduction in its electricity bill of 25%. This maximum reduction rises to 50% if the the gas consumption is seven times higher than electricity consumption or if the electricity price ratio is 27%.

Keywords:
Waste Heat Recovery, Carnot Battery, Key Performance Indicator, Industry, Mapping.

1. Introduction

1.1. Context

The main challenge to massively develop renewable energy is the electrical storage. Among the different possible technologies, the Carnot Battery (CB) is more and more developed. This concept uses a Heat Pump (HP) to convert excess renewable electricity into thermal energy . The thermal energy is stored until there is a peak of electrical consumption, a Heat Engine (HE) can re-convert this thermal energy into electricity. In its stand-alone layout, this technology presents a low roundtrip efficiency. However, its potential to integrate heat fluxes makes it profitable in various cases (Thermally Integrated Carnot Battery). In the most common configuration, the heat pump can work with a low temperature difference between the waste heat temperature and the thermal energy storage temperature. This leads to high Coefficient Of Performance (COP) and therefore high roundtrip efficiencies [1, 2]. Waste heat represent a huge waste, especially in the industry sector. 42% of the waste heat is lost at temperatures below 100℃ and 20% between 100℃ and 299℃ [3]. The integration of Carnot batteries in the industry is promising since it makes an efficient use of waste heat and it allows to store electricity (increase of renewable energy self-consumption).

1.2. State of the art

Few papers discuss the potential of Carnot batteries based on mappings. Some papers refer to specific case studies and are listed in [4]. The first attempt to characterize the performance of such a system in a wide range of operating conditions is performed in [5] through a constant efficiency model. In this paper, the roundtrip efficiency of a Thermally Integrated Carnot Battery is plotted for different waste heat temperatures and ambient temperatures. It allows to identify which cases are interesting (high waste heat temperature, low

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glide of the sensible storage and low ambient temperatures). Also, it was shown that the efficiency is improved in zones where the compactness (and the use of the waste heat) of the system is low. This conclusion has been discussed in several papers [1, 4, 6]. [4] proposed an enlarged mapping with a larger range of working temperatures. A zone where the three Key Performance Indicators (waste heat use, roundtrip efficiency and compactness) are not competing has been found. To the best authors' knowledge, no literature focus on the waste heat constraints in the industrial sector which can significantly affect the Carnot battery potential.

1.3. Aim of this paper

The main question that an industry could ask about the installation of a Carnot battery to valorize its waste heat is the profitability. A precise calculation of the benefit can not be obtained without a detailed study of the case. The aim of this paper is to give the absolute maximum values that could be reached in terms of benefit of such a system for a given industry. The Key Performance Indicators (KPIs) provided are determined according to global parameters allowing to easily characterize an industry (primary energy ratio, electricity pricing and waste heat temperature mainly) without an in-depth study. The results provided are voluntarily very optimistic so that a mismatch between the industry's expectations and these results indicates a clear incompatibility. In this case, the installation of a Carnot battery integrating waste heat recovery is not justified and this possibility can be dismissed without further study. The case of favorable results for the industry studied will automatically lead to a further study of the solution integrating the time constraints that such a system implies to determine the real benefit that can be brought. The compatibility of the industry's expectations with the results of this study is therefore a necessary but not sufficient condition for the profitability of the system.

2. Methodology

2.1. Assumptions

2.1.1. Conservatism principle

Since the aim of this paper is to provide the necessary conditions for the further study of the potential integration of the system, it is important not to exclude any case. To this end, all the assumptions made in this study are deliberately very optimistic. In particular, the cycles studied as well as the exchangers are considered as perfect. Since this study ignores the temporality for the purpose of convenience, the coordination of the waste production with the electricity costs is considered ideal in order to favor advantageous results. The limitations in terms of electrical power exchanged with the grid is largely overestimated. No limitation are put on the thermal storage volume. Also, the investment cost of the system is neglected. This is a very conservative assumption since this cost is directly linked to the nominal power of the system and its storage volume. On the other hand, the evaluation of the benefits in terms of cost reduction of the electrical substation is not considered. In view of the previous hypothesis, it is considered that neglecting this element will not put in default the conservatism required in this study.

2.1.2. Restriction on industry studies

Since the problem is treated ignoring temporal constraints and for the clarity of the methodology, some limitations must be set on the industries studied. The studied industry is taken as a whole and a single CB is matched as appropriate as possible. This CB has only one storage whose nominal temperature is fixed and greater than the maximum waste heat temperature considered. This consideration implies that an additional cold storage is not considered. It is assumed for each process (or sub-process) a nominal waste temperature invariable over time. The ambient temperature is fixed at $20^\circ C$. The waste heat is entirely dedicated to the CB. No district heating or recovery of this heat to reintegrate it into the process is considered. The waste heat not used by the CB is lost. The waste heat rejected by the heat engine of the CB is also lost.

The availability of Renewable Energy Sources (RES) internal to the industry, whose production is not always self-consumed, is a special case that requires a specific methodology. This case is treated in Section 3.6..

2.1.3. Limit values of the studied system

Based on the literature and in order not to exclude any case according to the principle of conservatism, the following values are used as limit values of the studied system:

- The unavoidable irreversibilities of a real system lead to the consideration of an efficiency g with respect to the ideal cycles. This value is often estimated [5] between 0.4 and 0.5 so in this study, $g = 0.5$.
- According to [7], the waste heat of the industry not directly recovered on-site is below 200℃ excepted for the iron and steel industry (200-400℃, 700-900℃) and the glass industry (500-600℃). Waste heat temperature $T_w \in [T_{amb}, 200]^\circ C$ is considered for this study. This choice is justified in Section 3.5..
- The highest temperature cycle (Brayton) that can be applied to a CB is in the order of 1200℃ [1, 2]. This value (used in (22)) is considered as the limit reached in the system.

2.2. Carnot battery description

The purpose of this section is to describe the Carnot battery as it is considered in the following development. The goal is to define the most generic architecture in order not to exclude any case and to make assumptions that allow to respect the conservatism principle announced in the previous section. Two approaches are considered in the description of the cycles used: a machine working with a Carnot cycle and one working with a Lorenz cycle. This allows to cover entirely the existing and future Carnot batteries.

2.2.1. Generic architecture

Figure 1 represents the architecture of a CB as general as possible when it integrates waste heat recovery. An amount of used waste heat $Q_{w,used}$ extracted from the available waste heat Q_w such that

$$Q_{w,used} = Q_w \frac{\Delta_{T_w}}{T_{w,in} - T_{amb}} \tag{1}$$

corresponds to a quantity of heat stored according to the COP of the heat pump considered:

$$Q_{sto} = Q_{w,used} \frac{1}{1 - \frac{1}{COP\ g}} \tag{2}$$

The electrical energy W_{HP} stored by the CB is determined by

$$W_{HP} = Q_{sto} - Q_{w,used} \tag{3}$$

The stratification of the storage and its thermal insulation are considered perfect so that the amount of thermal energy recovered from this storage is equal to the stored amount Q_{sto}. This thermal energy is used to feed the heat engine and to extract the electrical energy W_{HE} according to

$$W_{HE} = Q_{sto}\ \eta\ g \tag{4}$$

Figure 1 also allows the introduction of the different temperature levels of the CB. It is necessary to add 3 temperature differences to entirely characterize this simplified machine. These parameters can be defined by:

- $\Delta_{T_w} = T_{w,in} - T_{w,out}$
- $lift_{HP} = T_{sto,h} - T_{w,in}$
- $\Delta_{T_{sto}} = T_{sto,h} - T_{sto,c}$

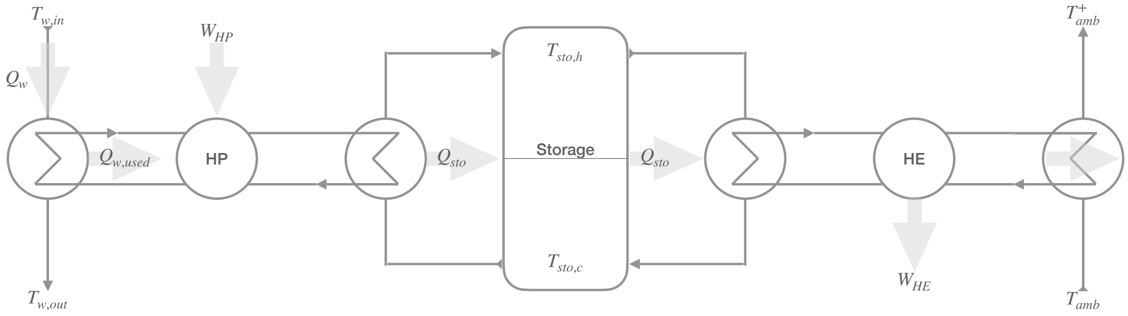

Figure 1: Generic architecture of a Carnot battery integrating waste het recovery

2.2.2. CB with Carnot cycles

Cycles based on Carnot HP and HE are mainly used in CBs. These ideal cycles are represented by their T-S diagram in Fig.2 and Fig.3 respectively. The performance of these cycles is determined by the system temperature levels also shown in the diagrams. For the HP, the COP is expressed by

$$COP_{Carnot} = \frac{T_{sto,h}}{T_{sto,h} - T_{w,out}} = \frac{T_{w,in} + lift_{HP}}{lift_{HP} + \Delta_{T_w}} \tag{5}$$

The COP can be maximized by minimizing Δ_{T_w}. However, according to (1), this will decrease $Q_{w,used}$ and thus the maximum stored energy. This value is therefore kept as a parameter in the study. Concerning the HE, its performance η is expressed by

$$\eta_{Carnot} = 1 - \frac{T^+_{amb}}{T_{sto,c}} = 1 - \frac{T^+_{amb}}{T_{w,in} + lift_{HP} - \Delta_{T_{sto}}} \tag{6}$$

To maximize this efficiency, two assumptions are made: $T^{+}_{amb} \rightarrow T_{amb}$ and $\Delta_{T_{sto}} \rightarrow 0$. With $T_{w,in}$ fixed by the characteristics of the industry, only the choice of the Δ_{T_w} lift remains. Since it intervenes in an opposite way on the performance of the two cycles, it is not possible to choose an optimum for all cases and it is kept as a parameter in the study.

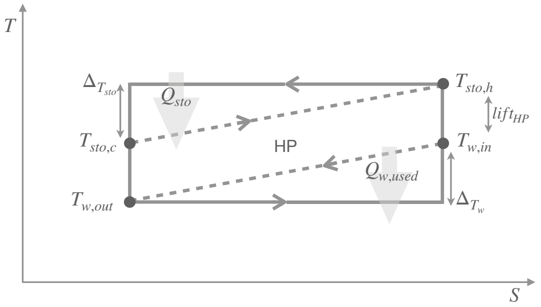

Figure 2: Ideal HP based on Carnot cycle limited by the characterizing temperatures of the CB represented in T-S diagram

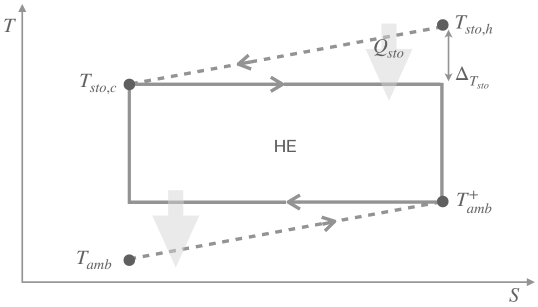

Figure 3: Ideal HE based on Carnot cycle limited by the characterizing temperatures of the CB represented in T-S diagram

2.2.3. CB with Lorenz cycles

Lorenz cycles [8] are based on heat exchanger at variable temperatures when Carnot cycles are isothermal. The implementation of these cycles requires zeotropic working fluids, super or trans-critical cycles, or a serial assembly of multiple HP and EH. This type of cycle is less implemented in CB than the Carnot cycle. However, with identical temperature glides, it theoretically gives better performance and several projects are currently developing this type of system. In order to remain conservative and to cover a maximum of possibilities, these two types of cycles will be used to obtain results according to the implementation of a CB working with Carnot or Lorenz cycles. Figures 4 and 5 represent the two Lorenz ideal cycles as well as the system temperatures in T-S diagrams. The COP and η are expressed by

$$COP_{Lorenz} = \frac{T_{sto,h}+T_{sto,c}}{T_{sto,h}+T_{sto,c}-T_{w,in}-T_{w,out}} = \frac{2T_{w,in}+2lift_{HP}-\Delta_{T_{sto}}}{2lift_{HP}+\Delta_{T_w}-\Delta_{T_{sto}}} \tag{7}$$

$$\eta_{Lorenz} = 1-\frac{T_{amb}+T^{+}_{amb}}{T_{sto,h}+T_{sto,c}} = 1-\frac{T_{amb}+T^{+}_{amb}}{2T_{w,in}+2lift_{HP}-\Delta_{T_{sto}}} \tag{8}$$

With the same approach as for the Carnot cycles, the *lift* and Δ_{T_w} are kept as parameters and T^{+}_{amb} can be fixed such that $T^{+}_{amb} \rightarrow T_{amb}$. The intervention of the storage glide $\Delta_{T_{sto}}$ in both formulations does not allow this time to conclude. It must also be kept as a parameter.

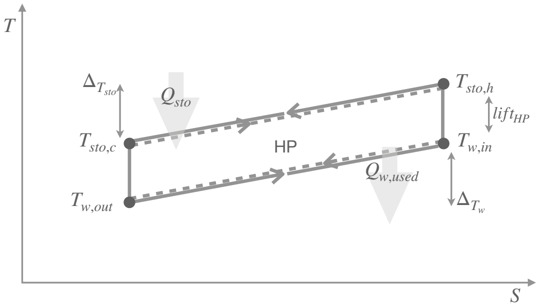

Figure 4: Ideal HP based on Lorenz cycle limited by the characterizing temperatures of the CB represented in T-S diagram

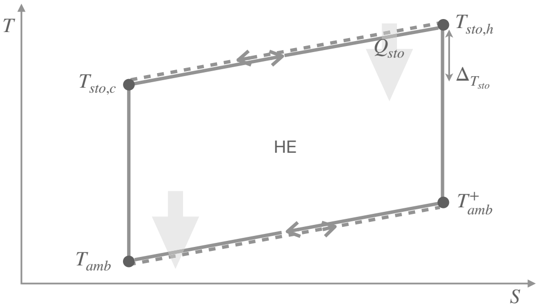

Figure 5: Ideal HE based on Lorenz cycle limited by the characterizing temperatures of the CB represented in T-S diagram

2.3. Industry description

The purpose of this section is to provide a generic description of energy flows in an industry so that it can be adapted to any industry. The characteristics of the industry allowing further development will also be identified.

2.3.1. Characteristic period

Temporal considerations of energy flows in industry would involve complex modeling to obtain results. Since the purpose of this study is to provide a first approach, these considerations are ignored. The different energy flows are integrated over a characteristic period $\Delta t(0 \rightarrow T_f)$.

This period is to be chosen on a case by case basis. Ideally, it should cover a duty cycle representative of the industry. This period also corresponds to a cycle on the storage, so it would seem judicious that it is of the order of a day. It is important that the chosen period respects the principle of conservatism (Section 2.1.1.).

2.3.2. Generic representation of energy distribution in an industry

Figure 6 represents the simplified topology of an industry as it is used in this study. This generic representation is such that it corresponds to any industry considered.

The electrical energy bought to the grid $E_{el,grid}$ is added to the electrical energy of the self-consumed RES of the industry $E_{el,RES}$. This total electrical energy E_{el} is added with the energy supplied to the industry in the form of gas E_{gas} to be redistributed between the auxiliary consumptions E_{aux} (considered with inexploitable waste heat) and the processes E_p. The energy injected in each process $E_{p,i}$ is partly converted into recoverable waste heat $Q_{w,i}$ of temperature $T_{w,i}$. The other part of this energy $Q_{amb,i}$ is lost directly to the environment.

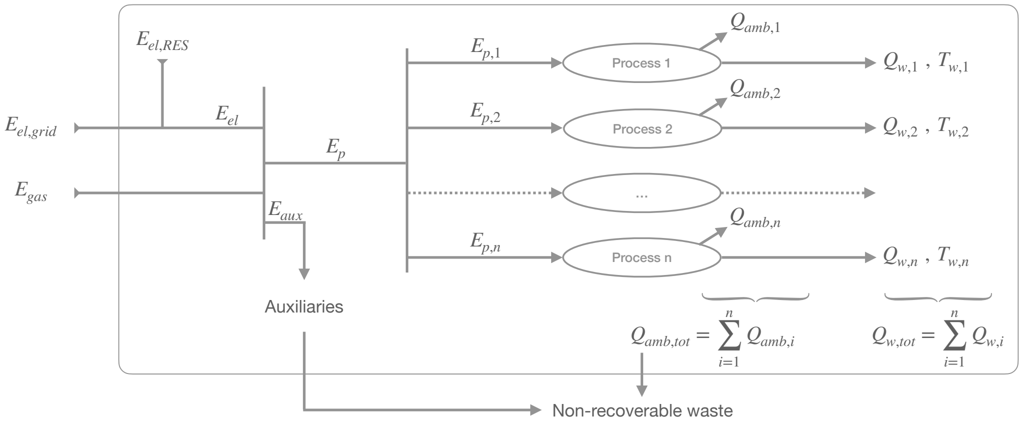

Figure 6: Generic representation of energy fluxes distribution in an industry integrated on the characteristic period Δt

2.3.3. Distribution of primary energy

A first useful characteristic of the industry is its primary energy allocation E_{gas}/E_{el}. In the case of fully self-consumed RES, E_{el} should be taken as the sum of RES electricity production and imported electricity $E_{el,grid}$ (Fig.6).

2.3.4. Waste heat temperatures

The processes are ranked from 1 to i such that $T_{w,1} > T_{w,2} > ... > T_{w,n}$. According to [7], this ranks in most cases the amount of waste heat such that $Q_{w,1} < Q_{w,2} < ... < Q_{w,n}$ but it is not a necessary condition.

2.3.5. Electricity pricing

Considering the variable cost C of electricity over the period Δt, different electricity pricing are identified:

- (A) $C_{buy} = C_{sell} = C \in \mathbb{R}_0^+ \ , \ \forall t \ \in [0, T_f]$
- (B) $C_{buy} = C_{sell} = C \in \mathbb{R}^+ \ , \ \forall t \ \in [0, T_f]$
- (C) $C_{buy} \in \mathbb{R}_0^+ \ , \ \forall t \ ; \ C_{sell} \in \mathbb{R}^+ \ , \ \forall t \ ; \ with\ C_{buy} \geq C_{sell} \ , \ \forall t \ \in [0, T_f]$
- (D) $C_{buy} \in \mathbb{R} \ , \ \forall t \ ; \ C_{sell} \in \mathbb{R}^+ \ , \ \forall t \ ; \ with\ C_{buy} < C_{sell} \ iff\ C_{sell} = 0 \ , \ \forall t \ \in [0, T_f]$

By these definitions: $(A) \subseteq (B) \subseteq (D)$ and $(A) \subseteq (C) \subseteq (D)$. An industry included in several electricity pricing as defined will be characterized by the most restrictive.

An electricity cost ratio C_{min}/C_{max} used as a parameter in the study is determined for each electricity pricing with for (A) and (B):

$$C_{min} = \min_{\forall t}(C) \text{ and } C_{max} = \max_{\forall t}(C) \tag{9}$$

By definition, the ratio is strictly greater than zero for (A) and equal to zero for (B). For (C) and (D), the ratio is determined with:

$$C_{min} = \min_{\forall t}(C_{buy}) \text{ and } C_{max} = \max_{\forall t}(C_{sell}) \tag{10}$$

By definition, the ratio is strictly greater than zero for (C) and less or equal to zero for (D).

This definition of the electricity cost ratio for (C) and (D) cannot be applied in the special case $\max_{\forall t}(C_{sell}) = 0$. It is therefore necessary to defined two sub-categories ((C*) and (D*)) of electricity pricing for which a special treatment is applied with a definition of the electricity cost ratio given by

$$\frac{C_{min}}{C_{max}} = \frac{\min_{\forall t}(C_{buy})}{\max_{\forall t}(C_{buy})} \tag{11}$$

Using strictly the limits of the electricity cost for determined C_{min} and C_{max} ensures conservatism. A more moderate choice of these values can lead to more restrictive results but closer to reality. These values are used to define the price for the entire selling and buying period. If the limits used represent only a very short period compared to Δt, the results will be so optimistic that they will no longer be useful. A good practice rule would be to choose a limit if it represents at least 5% of the period Δt.

2.4. Recoverable waste heat

The quantity of waste heat Q_w available for the HP is an important parameter to characterize the industry. With the usability factor u representing the proportion of primary energy converting in available waste heat, it is defined by

$$Q_w = u(E_{gas} + E_{el}) \tag{12}$$

In an ideal configuration, $u = 1$. This will never be the case in reality. u is bounded by a value $u_{s,max}$, with the subscript s refers to the selected $T_{w,s}$. It is defined by

$$u_{s,max} = (1 - \frac{E_{aux}}{E_{gas} + E_{el}}) \sum_{i=1}^{s} (\frac{E_{p,i}}{E_p}(1 - \frac{Q_{amb,i}}{E_{p,i}})) \tag{13}$$

The purpose of this section is to describe in more detail the expression of $u_{s,max}$.

2.4.1. Auxiliary consumptions

In the frequent case where all the incoming energy of the industry is not dedicated to the processes on which waste recovery is possible, it is necessary to deduct these auxiliary consumptions from the primary energy transformed into usable waste heat. This consumption is included in the factor $(1 - \frac{E_{aux}}{E_{gas}+E_{el}})$.

2.4.2. $T_{w,s}$ selection

Since it is assumed that there is only one CB and one storage, the temperature of the waste heat exploited $T_{w,s}$ must be unique and chosen between the $T_{w,i}$ temperatures. In the case $T_{w,s} > T_{w,n}$, part of the processes are excluded from the waste heat recovery system. This reduces the amount of energy exploitable by the factor $(\sum_{i=1}^{s} \frac{E_{p,i}}{E_p})$.

However, the choice of $T_{w,s}$ higher than $T_{w,n}$ has the advantage of increasing the performance of the system. At the time of the exploitation of the results, it is necessary to test various couples $[T_{w,s}; u_{s,max}]$ in order to select the optimum for the considered industry. The selected $T_{w,s}$ corresponds to the temperature $T_{w,in}$ of Section 2.2..

2.4.3. Processes ambient losses

In any process, not all of the primary energy $E_{p,i}$ used can be converted into usable waste heat. Unavoidable losses $Q_{amb,i}$ are rejected throughout the process ($Q_{w,i} = E_{p,i} - Q_{amb,i}$), which completes the previously developed factor:

$$\sum_{i=1}^{s} (\frac{E_{p,i}}{E_p}(1 - \frac{Q_{amb,i}}{E_{p,i}})) \tag{14}$$

In the case where $Q_{amb,i}$ is too difficult to evaluate for each process, a value $Q_{amb,tot}$ can be estimated for all the processes so that this factor is replaced by

$$(1 - \frac{Q_{amb,tot}}{E_p}) \sum_{i=1}^{s} \frac{E_{p,i}}{E_p} \tag{15}$$

2.4.4. Direct measurement of the available waste heat

The determination of the above factors can be complex. In some cases, it is easier to measure the quantity of waste heat directly after the processes. In this case, (13) becomes

$$u_{s,max} = \frac{\sum_{i=1}^{s} m_i c_{p,i}(T_{w,i} - T_{amb})}{E_{gas} + E_{el}} \tag{16}$$

with m_i the mass flow rate of the waste heat constituent for the process i integrated over Δt and the corresponding specific heat $c_{p,i}$. It is necessary to note that if waste heat constituents can condense in the considered temperatures, it is necessary to take into account the latent energy.

2.5. Calculation of the economic gains generated by the CB

Based on the assumptions, equations and values previously introduced, it is possible to calculate the maximum economic gain brought by the installation of a CB integrating waste heat recovery. The evaluation of this gain is directly linked to the considered electricity pricing and will be evaluated differently for each case. Since the aim is to determine the maximum profitability of the system, the waste heat will always be considered as available when the prices are the most favorable.

The purpose of these gain expressions is to highlight the terms characterizing an industry: C_{min}/C_{max}, u and E_{gas}/E_{el}. These latter two terms are expressed on the basis of (1-4,12) by W_{HP}/E_{el} and W_{HE}/E_{el} such as

$$\frac{W_{HP}}{E_{el}} = u(\frac{E_{gas}}{E_{el}} + 1)\frac{\Delta_{T_w}}{T_w - T_{amb}}\frac{1}{COPg - 1} \tag{17}$$

$$\frac{W_{HE}}{E_{el}} = u(\frac{E_{gas}}{E_{el}} + 1)\frac{\Delta_{T_w}}{T_w - T_{amb}}\frac{COP\eta g^2}{COPg - 1} \tag{18}$$

2.5.1. (A) and (C) electricity pricing

For electricity pricing (A) and (C), the maximum gain can be defined as the reduction in the electricity bill. The most favorable conditions are a purchase (W_{HP}) of electricity at C_{min} and a resale (W_{HE}) of electricity at C_{max}. To ensure maximum gain, the electricity consumed is hypothetically purchased at C_{min}.

$$gain_{(A,C)} = \frac{W_{HE}C_{max} - W_{HP}C_{min}}{E_{el}C_{min}} = \frac{W_{HE}}{E_{el}}(\frac{C_{min}}{C_{max}})^{-1} - \frac{W_{HP}}{E_{el}} \tag{19}$$

2.5.2. (B) and (D) electricity pricing

For electricity pricing (B) and (D), the previous gain formulation cannot be used since C_{min} is less than or equal to zero. The maximum payoff must therefore be evaluated as the maximum net profit generated by the installation of the system. Stored electricity is always bought and sold at the most favorable prices. The gain must be normalized in order to express a usable value in the results.

$$gain_{(B,D)} = W_{HE}C_{max} - W_{HP}C_{min} \quad \rightarrow \quad \frac{gain_{(B,D)}}{E_{el}C_{max}} = \frac{W_{HE}}{E_{el}} - \frac{W_{HP}}{E_{el}}\frac{C_{min}}{C_{max}} \tag{20}$$

2.5.3. (C*) and (D*) electricity pricing

For electricity pricing (C*) and (D*), it is never interesting to sell electricity back to the grid. Electricity restitution (W_{HE}) must only be used to cover the electricity consumption of the industry E_{el}. In the formula, the cost of electricity applied to W_{HE} must therefore be the same as applied to E_{el}. In order to express the maximum gain, C_{max} is used. This formula expresses the gain as the maximum reduction of the electricity bill.

$$gain_{(C^*,D^*)} = \frac{W_{HE}C_{max} - W_{HP}C_{min}}{E_{el}C_{max}} = \frac{W_{HE}}{E_{el}} - \frac{W_{HP}}{E_{el}}\frac{C_{min}}{C_{max}} \quad with\ W_{HE} \leq E_{el} \tag{21}$$

2.5.4. Choice of system parameters

In accordance with the principle of conservatism, for each point $[T_w, E_{gas}/E_{el}, C_{min}/C_{max}]$ the choice of the system parameters (Δ_{T_w}, $\Delta_{T_{sto}}$, $lift_{HP}$) as described in the Section 2.2.1. is determined by the following optimization problem:

$$\begin{aligned} & \max(gain) \\ s.t.\quad & 0 \leq \frac{W_{HP}}{E_{el}} \leq 1 \quad , \; 0 \leq \Delta_{T_w} \leq T_w - T_{amb} \\ & 0 \leq \frac{W_{HE}}{E_{el}} \leq 2 \quad , \; 0 < \Delta_{T_{sto}} \leq T_{sto,h} - T_{amb} \\ & 0 \leq \frac{Q_{sto}}{E_{el}} \qquad\quad , \; 0 < lift_{HP} \leq 1473K - T_w\ [K] \end{aligned} \tag{22}$$

It is assumed that the consumption of electricity by the CB must be in the order of the industry's electricity consumption. The value of 1 is deliberately optimistic in order to remain conservative. Considering the electricity restituted by the CB distributed between the consumption of the industry and the grid, the value of 2 is chosen with the same considerations. For the electricity pricing (C*) and (D*), the constraint $W_{HE}/E_{el} \leq 1$ is added. In the case where Carnot cycles are considered, $\Delta_{T_{sto}}$ = 0 (Section 2.2.2.).

3. Results and discussions

Results are determined with T_w=100℃ as an example and for discussions. Complementary results are shown in Appendix A, with waste heat temperatures covering the whole range considered.

Figures 7, 9 and 11 show the results for a CB based on Carnot cycles. Figures 8, 10 and 12 show the results for a CB based on Lorenz cycles. These results correspond to the gain as defined by (19), (20) and (21).

It is important to note that the results (Fig.11 and 12) for electricity pricing (B) and (D) express the maximum net benefit normalized by E_{el} and C_{max} and not the maximum reduction in electricity bill. The scale applied is therefore different.

All results are obtained with u = 1 and are expressed as a function of E_{el}. In order to apply u, it is necessary to multiply the results obtained by its value. In the case of a self-consumed RES electric production, the results must be expressed as a function of $E_{el,grid}$ and are therefore to be multiplied by $E_{el}/E_{el,grid}$ = 1+($E_{el,RES}/E_{el,grid}$).

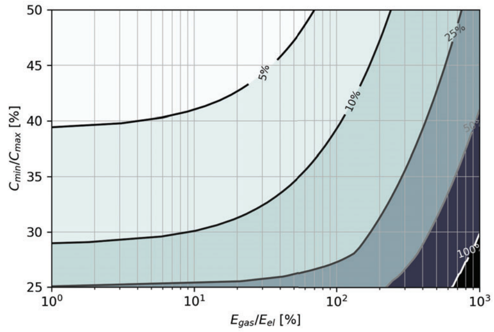

Figure 7: Maximum gain for electricity pricing (A) and (C) with CB based on Carnot cycles (T_w=100℃)

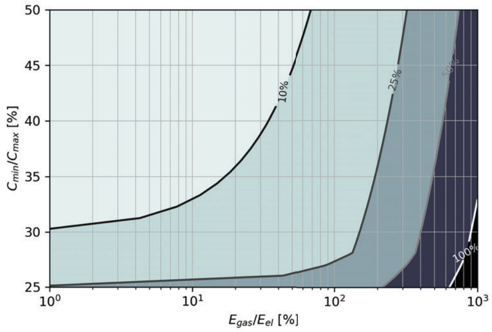

Figure 8: Maximum gain for electricity pricing (A) and (C) with CB based on Lorenz cycles (T_w=100℃)

Based on the results obtained for 100℃ (representative of the other T_w trends), some preliminary observations are made. Calculations based on the Lorenz formulations always give similar or better results than those based on the Carnot formulations. A clear superiority of the Lorenz cycles is visible from an electricity cost ratio higher than 30%. However, the differences are small compared to the assumptions. It is necessary not to jump to conclusions. Moreover, in practice, the application of Lorenz cycles is more expensive and more complex to implement. [9]. It is interesting to note that the optimum glides $\Delta_{T_{sto}}$ for Lorenz cycles are close to the maximum of the allowed values, while they are at zero for Carnot cycles. This gives an important advantage to Lorenz cycles in real considerations. Increasing waste temperatures promotes good results. Also, the results improve with the increasing of gas proportion and/or the decreasing of electricity cost ratio.

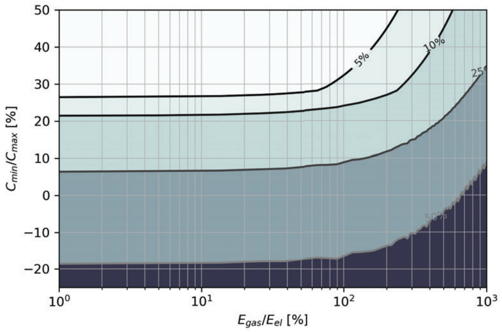

Figure 9: Maximum gain for electricity pricing (C*) and (D*) with CB based on Carnot cycles (T_w=100℃)

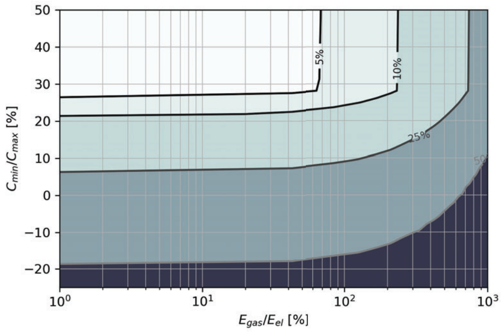

Figure 10: Maximum gain for electricity pricing (C*) and (D*) with CB based on Lorenz cycles (T_w=100℃)

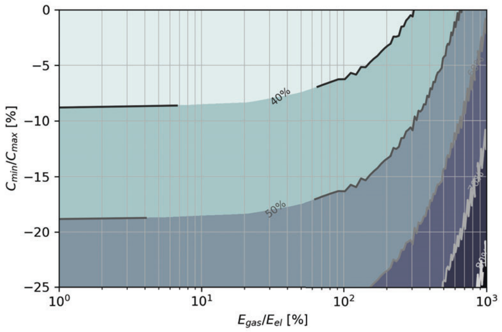

Figure 11: Maximum gain for electricity pricing (B) and (D) with CB based on Carnot cycles (T_w=100℃)

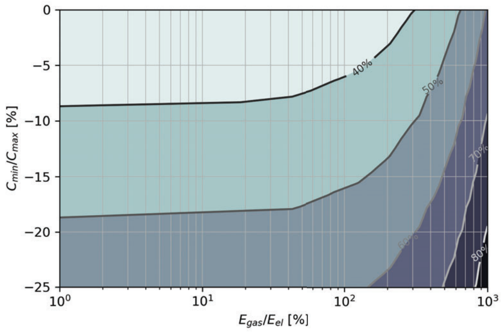

Figure 12: Maximum gain for electricity pricing (B) and (D) with CB based on Lorenz cycles (T_w=100℃)

3.1. Impact of the electricity pricing

For (A) and (C), a realistic case is an electricity cost ratios above 35%. In the case of E_{gas}/E_{el}=1, the gain is 10% for T_w=100℃. These results are weak compared to the hypotheses. Moreover, in some industries, the cost of electricity is still constant. The results for T_w at 50 and 200℃ are respectively 5% and 25%. (C*) must tend towards (D*) to be in the same order, i.e. a purchase cost less than or equal to zero.

Cases (B) and (D) seem more interesting. In general, a purchase cost less than or equal to zero seems to be a necessary condition for profitability. Considering the investment of the system, the conservative assumptions and the fact that u = 1 for these results, a gain of 10% seems to be the minimum to find interest in the system. A more variable electricity pricing will therefore be the key to this technology.

3.2. Impact of the gas consumption

Increasing gas consumption increases gains. It is obvious that the objectives in terms of reducing emissions of greenhouse gases lead to avoid this solution. It is therefore an additional argument for an adapted electricity pricing.

In the case of a gas-intensive industry, the system can be interesting. First of all, it allows to reduce the electricity bill and to use the RES more advantageously. In a second time, its decarbonization will make the system less efficient. However, since this transformation of the industry will be done over the next 30 years and that the life cycle of a CB is of the same order, it is interesting to consider that the installation of the system will already put in place heat recovery devices that will be later used for other purposes.

3.3. Discussion on the restriction of the industries studied

The industry studied is considered to be entirely operated by a single CB and storage (Section 2.1.2.). It is possible to remove this assumption by dividing the processes by groups and linking each group to a CB and a storage (so different T_w). It is necessary to adapt the corresponding i indices in 13 and repeat the methodology several times. The gains can then be summed up. This method, if not applied sparingly, has the disadvantage of further distorting the results of reality by neglecting the investment cost of several systems instead of one.

An ambient temperature different from 20℃ has a significant impact on the results (a lower T_{amb} improves the gains and vice versa). This is one of the reasons why the characteristic period must be chosen carefully. It is always possible to do once the methodology for a winter case and once the methodology for a summer case and then average the results. The results for different T_{amb} are available in the Appendix A.

Finally, [5] demonstrates that considering only batteries with hot storage remains conservative.

3.4. Waste heat used

From Fig.13 and Appendix A, it appears that the maximum recoverable waste heat fraction is below 50% in realistic cases for electricity pricing (A), (C) and (C*). For (B), (D) and (D*) this fraction can rise to between 60 and 70% for restricted areas of application. Thermal Integrated Carnot Battery is therefore not a dedicated waste heat recovery technology (it makes use of it but with constraints).

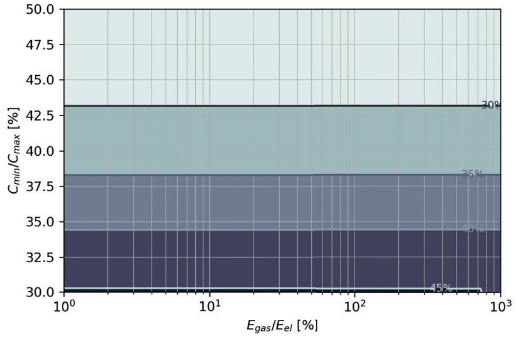

Figure 13: Waste heat used $Q_{w,used}/Q_w$ to obtain the maximum gain for electricity pricing (A) and (C) with CB based on Carnot cycles (T_w=100℃)

3.5. Optimized use of Thermal Integrated Carnot Batteries

Another application for Thermal Integrated Carnot Battery is the integration of district heating. This solution has an interesting potential of profitability [10]. It could be possible to combine the two systems to increase the potential benefits. In this case, the methodology of this paper can no longer be used as is. It is possible to include the consumption of the district heating network in the ambient losses ($Q_{amb,i}$ for (14) or $Q_{amb,tot}$ for (15)) . In this case, the results give lower gains to which must be added the economic gains due to the district heating network.

The waste heat temperatures considered in this paper are based on a study [7] considering that higher temperatures waste heat are used to feed the lower temperature processes. In most sectors, waste heat above 200℃ is used for this purpose. The iron and steel industry and the glass industry are special cases. The waste heat temperatures, although very high, are not converted because the majority of the processes require an even higher temperature. The recovery of this waste is however not considered because its quality allows a much more interesting balance with other technologies [1]. Graphs in Appendix A show the limits of the considered system, for high temperatures, in terms of energy efficiency.

3.6. Non-self-consumed RES

The case of non-self-consumed RES are directly related to time constraints. Despite the assumptions made, it is not possible to express the gain for all electricity pricing:

- (D*) is used instead of (C*) with $\frac{C_{min}}{C_{max}} = 0$
- (D*) can be used as is
- (D) is used instead of (B) with $\frac{C_{min}}{C_{max}} = 0$
- (D) can be used as is

For the transformations in (B) and (D), a strong assumption must be made: non-self-consuming production occurs only when the network is saturated and imposes $C_{sell} = 0$. In all these cases, the term $E_{el,RES}$ of the correction $1 + (E_{el,RES}/E_{el,grid})$ factor must be evaluated as the sum of the RES production (self-consumed

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or not). For (A) and (C), it is not possible to conclude. In any case, if the energy of the non-self-consumed RES is small compared to the self-consumed RES, these steps can be neglected given the advantageous assumptions on which the gain calculations are based.

4. Conclusions and perspectives

The objective of this paper was to determine Key Performance Indicators concerning the potential of Carnot battery integrating waste heat recovery in Industry. A generic definition of the Carnot Battery was determined according to Carnot and Lorenz. Industry was also described generically. The necessary assumptions were made to cover as wide a range as possible. The different parameters of the system were then determined. On the one hand for the industry with simple to define values: ratio of primary energy used, ratio of minimum and maximum electricity costs, temperatures of available waste heat, and electricity pricing type. On the other hand, the Carnot Battery parameters are optimized to give the most optimistic results. For each combination of industry parameters, a maximum gain is calculated, which is the main result of this work. Throughout, conservative assumptions are applied so that the results are as robust as possible.

Industries using at least as much electricity as gas and for which the ratio of the minimum (positive) purchase price to the maximum selling prices is over 50% cannot expect significant benefits from using Carnot batteries integrating waste heat recovery. Intermediate results are also defined and discussed leading to the following conclusions:

- Electricity pricing with high variability and negative purchase prices will be the key to this technology.
- The application of Lorenz cycles can theoretically significantly increase the benefits of the system compared to Carnot cycles in the least favorable cases.
- The system is more efficient for gas-intensive industries. It can be a gateway to low temperature waste heat recovery.
- The amount of waste heat recovered remains low in all cases. It is used for the benefit of the system, but Thermal Integrated Carnot Battery is not a dedicated waste heat recovery technology
- The introduction of other heat streams (District Heating) can contribute to the sustainability of the system.
- It is difficult to conclude in the case of a Renewable Energy Sources not entirely self-consumed without strong assumptions. Further study will often be required.

An interesting perspective will be to test several cases and to position them on the graphs. This will allow to determine more precisely which industries are unsuitable for the system and which ones would deserve a more advanced study. On the other hand, it would be interesting to realize a more complex model integrating temporal considerations, investment prices and a Carnot Battery defined according to considerations closer to reality. Describing this model on the basis of the same parameters as those of this paper will allow the second more advanced study. Finally, the confrontation of the results with other storage systems as well as with a model integrating more widely the use and the management of heat flows would be of great interest.

Appendix A Additional mappings

Although reduced to a minimum, the number of parameters in this study only allows to propose mapping for illustration purposes. In order to provide to the reader the specific KPIs adapted to his case of interest, all the results for the considered ranges can be found at: `https://hdl.handle.net/2268/302631`

Nomenclature

Latin letters

C	electricity cost, €/J
c_p	specific heat, J/kg.K
E	energy, J
g	ideal cycle efficiency, $-$
m	mass, kg
Q	thermal energy, J
S	entropy, J/K
t	time, s
T	temperature, K
u	usability factor, $-$
W	electrical energy, J

Greek symbols

η	efficiency

Abbreviations

CB	Carnot battery
COP	coefficient of performance
HE	heat engine
HP	heat pump
KPI	key performance indicator
RES	renewable energy source

Subscripts

amb	ambient
aux	auxiliary
c	cold
el	electric
h	hot
in	input
max	maximum
min	minimum
out	output
p	process
s	selected
sto	storage
tot	total
w	waste heat

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