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Original Article

Initial estimates of the economical attractiveness of a nuclear closed Brayton combined cycle operating with firebrick resistance-heated energy storage

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ABSTRACT

The Firebrick Resistance-Heated Energy Storage (FIRES) concept developed by the Massachusetts Institute of Technology aims to enhance profitability of the nuclear power industry in the next decades. Studies carried out at Massachusetts Institute of Technology already provide estimates of the potential revenue from FIRES system when it is applied to industrial heat supply, the likely first application. Here, we investigate the possibility of operating a power plant (PP) with a fluoride-salt-cooled high-temperature reactor and a closed Brayton cycle. This variant offers features such as enhanced nuclear safety as well as flexibility in design of the PP but also radically changes the way of operating the PP. This exploratory study provides estimates of the revenue generated by FIRES in addition to the nominal revenue of the stand-alone fluoride-salt-cooled high-temperature reactor, which are useful for defining an initial design. The electricity price data is based on the day-ahead markets of Germany/Austria and the United States (Iowa). The proposed method derives from the equation of revenue introduced in this study and involves simple computations using MatLab to compute the estimates. Results show variable economic potential depending on the host grid but stress a high profitability in both regions.

1. Introduction

The electricity market in the Western countries is facing changes engendered by market deregulation as well as new environmentally friendly energy policies. Studies show that large penetration of nondispatchable generators, mainly solar and wind generators, in an energy mix induces market volatility and that this is amplified in a deregulated market [1,2]. The variability in electricity price is expected to threaten the profitability of future nuclear power plants (PPs), while most current ones are currently operating in base-load to lower the impact of the investment cost on the electricity price.

Led by Massachusetts Institute of Technology, the project of the fluoride-salt-cooled high-temperature reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES) aims to develop a PP that is able to generate profit from a variable electricity price [1,3,4]. This is achieved by operating a nuclear reactor at constant thermal power and using additional heat sources to provide a variable electric power output: natural gas burned with the air used as coolant of the power conversion cycle and the FIRES system in which heat can be charged, stored, and discharged. Both heat sources are added in addition to the nuclear heat when the market prices are sufficiently high. The additional heat from the heat storage system or the combustion of natural gas increases the highest temperature of the conversion cycle and is converted to electricity using the plant turbines. The system is able to convert the additional heat sources to electricity with an efficiency up to 66%, which is above efficiencies of most current PPs [1]. Moreover heat at high temperature can be sold directly to industry, offering an additional option to maximize profit. A supplemental revenue source from ancillary services, using the flexible capacity of such PPs, can also be valuable to a lesser extent [5].

Economically this system generates profit from variable electricity prices as well as from the difference in electricity and natural gas prices. Estimates for such a PP show a high profitability when the PP is implanted in markets in which natural gas price is slightly higher than the average variable electricity price. The case of the Iowa market (US) was studied when the system was applied to industrial heat supply (IHS) [6].

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Nomenclature

Abbreviations

FIRES	Firebrick Resistance Heated Energy Storage
FHR	Fluoride-salt-cooled High temperature Reactor
NACC	Nuclear Air-Brayton Combined Cycle
IHS	Industrial Heat Supply
NCCC	Nuclear Closed Combined Cycle
PP	Power plant

Variables

R_X	Additional revenue generated by FIRES during X hours [€ or \$]
Δt	Cycle duration [h]
$p^{DA}(t)$	Electricity price on the day-ahead market at time t [$€/MWh_e$ or $\$/MWh_e$] (simply noted p^{DA})
P_{in}	Electrical power to charge FIRES [MW_e]
$\dot{Q}_{out}$	Thermal discharging power of FIRES [MW_{th}]
$\dot{Q}_{nuclear}$	Thermal nuclear power [MW_{th}]
S_k	State of charge of FIRES after the k^{th} event (charge or discharge) [MWh_{th}]
η^{eh}	Electricity-to-heat efficiency of FIRES′ electrical resistances
K	Incremental heat-to-electricity efficiency related to FIRES
$t_{c,ini}^{i,k}$	Starting time of the i^{th} FIRES charge (k^{th} event, not displayed if unnecessary) [h]
$t_{c,fin}^{i,k}$	Ending time of the i^{th} FIRES charge (k^{th} event, not displayed if unnecessary) [h]
$t_{c,ini}^{j,k'}$	Starting time of the j^{th} FIRES discharge (k'^{th} event, not displayed if unnecessary) [h]
$t_{c,fin}^{j,k'}$	Ending time of the j^{th} FIRES discharge (k'^{th} event, not displayed if unnecessary) [h]
m	Number of FIRES charges during the current cycle
n	Number of FIRES discharges during the current cycle
μ	Yearly average of the amount of heat discharged from FIRES between two charges [MWh_{th}]
σ	Yearly standard deviation of the amount of heat discharged from FIRES between two charges [MWh_{th}]
H	Heat storage capacity of FIRES [MWh_{th}]

However closing the Brayton cycle can be of some interests; this is detailed in the first subsection. Instead of focusing on the revenue of the PP from both natural gas price and the electricity price, here the PP makes a profit only on the variable electricity price. This study aims to provide estimates of PP revenue when FIRES operates with FHR and a closed Brayton combined cycle.

First, we introduce the main points of interest of using the nuclear closed Brayton combined cycle with FIRES and describe how it operates. Second, we discuss a methodology to estimate the revenue expected from operating FIRES. Finally, results are given and discussed.

1.1. Main points of interest

The main motivation of using a closed Brayton cycle is a more robust containment against accidents releasing radioactive elements from the nuclear reactor. The closed Brayton cycle acts as an additional containment barrier.

Besides this advantage, the closed Brayton cycle gives more choices for the design of the PP, such as the Brayton cycle working fluid (use of inert gas, noncorrosive fluid, and fluid with high specific heat), the operating pressures (increase of the compactness), etc. The choice of the working fluid is a key factor to enlarge the range of nuclear reactors able to operate with FIRES. This is especially the case for some sodium fast reactors, e.g. the ASTRID project in France. The closed Brayton cycle involved in nuclear PPs is not new and experience already exists, in particular on helium-operated turbomachinery [7]. Table 1 presents some of the concepts of nuclear plants involving a closed Brayton cycle.

Table 1
Nonexhaustive list of nuclear plant concepts involving a closed Brayton cycle.

Reactor	Brayton cycle coolant	Projects and references
HTGR (High Temperature Gas-cooled Reactor)	*He*, $He-N_2$	GT-MHR (Gas Turbine Modular Helium Reactor) [8], HTGR-GT (High Temperature Gas-cooled Reactor - Gas Turbine) [9], PBMR (Pebble bed modular reactor) [10]
SFR (Sodium Fast Reactor)	N_2	ASTRID Project [11]
GFR (Gas-cooled Fast Reactor)	*He*, $He-N_2$	EM2, ALLEGRO Project [12]

Finally, in countries where natural gas is mostly imported and its access is costly compared to the average wholesale electricity market price, the ability to use natural gas for supplemental power production can be less valuable. This has to be tempered by the high economical sustainability of NACC PPs, even in case of high break-even natural gas prices [13]. Hence the advantages of closing the Brayton cycle could surpass the benefits of keeping the cycle opened. The choice is made to perform estimates of revenue on the European market in Germany/Austria. To ensure comparison with estimates done in the previous study in the case of IHS, additional estimates are provided for the Iowa wholesale market [6].

1.2. Operating modes

The PP is built with a high-temperature nuclear reactor, using a combined cycle in which the Brayton cycle is closed and a FIRES-like heat storage unit is installed. A flow-sheet of the simplified

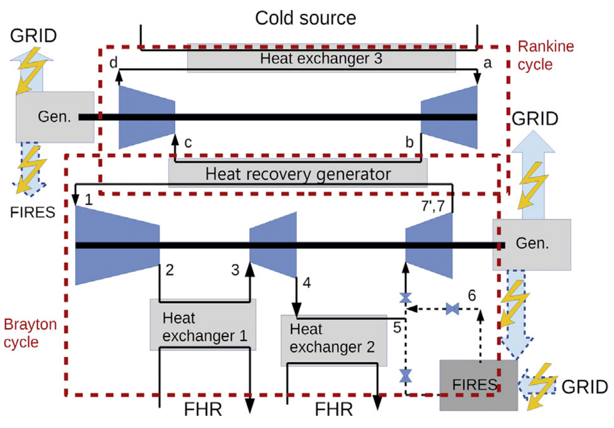

Fig. 1. Flow-sheet of the PP conversion cycle.
FIRES, Firebrick Resistance-Heated Energy Storage; FHR, fluoride-salt-cooled high-temperature reactor; PP, power plant.

power conversion cycle is shown in Fig. 1. More complex nuclear closed Brayton combined cycles have been studied by North-West University (South Africa) [14]. Further studies will have to answer the design issues raised by the need to keep the nuclear reactor in nominal operating conditions of temperature and pressure while varying the thermal output power of FIRES.

The PP can operate in three modes:

- in base-load mode, the FIRES unit is bypassed and the Brayton cycle coolant goes through the second turbine (from *pt.*5 to *pt.*$7'$ in Fig. 1) after being heated by the primary loop (from *pt.*4 to *pt.*5). The maximum coolant temperature is mainly defined by the FHR. Then, only the FHR and its auxiliaries operate to provide electricity through the combined cycle;
- in storage mode, starting from the base-load mode, the PP operators redirect the electrical power from the generators to electrically heat FIRES. Additional electrical power is also provided from the grid to charge FIRES. At that step, the PP is a net buyer of electricity from the grid;
- in peak-load mode, the Brayton cycle coolant goes through the FIRES unit (*pt.*5 to *pt.*6 in Fig. 1). The heat from FIRES raises compressed gas temperatures after addition of the nuclear heat from the FHR. The combined cycle integrating FIRES enables a topping cycle with an incremental heat to electricity efficiency significantly above the base-load PP efficiency. It also implies that the steam cycle operates at higher temperature. Then, the PP output power increases and is able to meet the peak demand.

We consider in this study a business based only on the purchasing and the selling of electricity. This study does not consider neither the possibility of selling process-heat to industry nor the provision of ancillary services. In practice, a hybrid business for a FIRES-like system which involves selling both valuable heat and electricity is expected.

2. Materials and methods

The method developed in this study is to provide estimates of added revenue by using FIRES within the nuclear PP. We assume that installing the PP does not impact the electricity market. One study currently being conducted at Massachusetts Institute of Technology details the impact on the market of operating a large FIRES capacity [15].

2.1. Equations

The first step consists of writing the equation that gives the revenue generated by FIRES over a cycle Δt. We define a cycle as a period of time in which the amount of heat discharged from FIRES is equal to the amount of heat charged into FIRES and in which the operator knows the electricity price for each hour in that period. Two aspects limit the value of Δt are as follows:

1. economical constraint: operating long cycles has a value only if we can maintain a certain amount of heat for a long period. This means a certain allocated part of the FIRES′ storage capacity becomes unavailable for other transactions, and hence requires an over-sized storage unit. Contrary to the open Brayton cycle case, operating in a closed Brayton cycle requires a pressurized FIRES vessel. Although FIRES is compatible with a high pressure Brayton cycle, there are currently no estimates of the incremental cost of a pressurized FIRES unit. However, we expect that this cost will increase with the pressure requirement leading to a limit of the vessel size, i.e. a heat storage capacity that is proportional to the mass of firebrick in the unit;
2. technical constraint: charging and discharging FIRES are planned when the profitability is known or expected, i.e. when the electricity price is forecast. This depends on the forecasts of the electricity consumption and supply. Current mathematical methods and models provide hourly estimates of the electricity consumption, e.g. the French distribution network operator publishes workable estimates up to 9 days ahead [16]. The supply, modeled by a curve giving the electricity price against the production capacity, is less predictable due to the major impact of the weather (wind speed, cloudiness, etc.) on wind and solar energy production and the possibility of unplanned thermal plant outages. In global production, the difficulty of accurately forecasting the electricity supply is expected to increase based on the wind and solar production capacities. Market deregulation could also be a factor increasing the difficulty in forecasting the supply curve as there is no authority to fix minimum thresholds for the electricity price from these nondispatchable sources. According to the US National Renewable Energy Laboratory, forecasts of wind and solar productions are made up to 6 days ahead to schedule required fossil-fuel production [17].

Considering these two aspects, we assume that Δt can take values from 24*h* since the PP sells electricity on the day-ahead market up to 168*h* (a week).

The equation of revenue generated by operating FIRES, denoted $R_{\Delta t}$ [€ or $], is written below for a cycle Δt with *m* heat charges and *n* discharges. It derives from the business model described in Section 1. The state of charge [MWh] after each event, i.e. a charge or a discharge, is denoted S_{kf} with k_f the index of the last event. Each charge is identified by the index *j* and each discharge by the index *i*.

$$R_{\Delta t} = \sum_{i=1}^{n} \overbrace{\int_{t^i_{s,ini}}^{t^i_{s,fin}} K\dot{Q}_{out} p^{DA} dt}^{\text{gain on the electricity sale during the } i^{th} \text{ FIRES discharge}} - \sum_{j=1}^{m} \overbrace{\int_{t^j_{p,ini}}^{t^j_{p,fin}} P_{in} p^{DA} dt}^{\text{electricity cost of the } j^{th} \text{ FIRES charge}} \tag{1}$$

with $t^i_{s,ini}$ and $t^j_{p,ini}$, the starting time of the i^{th} discharge and j^{th} charge, respectively and $t^i_{s,fin}$ and $t^j_{p,fin}$, the ending time associated. The constraints are

$\mathcal{G}_1$	$\max_{kf\in[1,n+m]}(S)\leq H$	Limit storage capacity of FIRES
$\mathcal{G}_2$	$\min_{kf\in[1,n+m]}(S)\geq 0$	
$\mathcal{G}_3$	$\max(t^n_{s,fin}, t^m_{p,fin}) \leq \Delta t$	Duration limit
$\mathcal{G}_4$	$S_{n+m}=0$	Cycle constraint

such as,

$$S_{k_f} = \overbrace{\int_{t_{p,ini}^{1,1}}^{t_{p,fin}^{1,1}} \eta^{eh} P_{in} dt}^{\text{heat added to FIRES at the } 1^{st} \text{ charge, } 1^{st} \text{ event}} + \ldots - \overbrace{\int_{t_{s,ini}^{i,k}}^{t_{s,fin}^{i,k}} \dot{Q}_{out} dt}^{\text{heat removed from FIRES at the } i^{th} \text{ discharge, } k^{th} \text{ event}} + \ldots - \overbrace{\int_{t_{s,ini}^{i',k_f}}^{t_{s,fin}^{i',k_f}} \dot{Q}_{out} dt}^{\text{heat removed from FIRES at the } i'^{th} \text{ discharge, } k_f^{th} \text{ event}} \tag{2}$$

and $\forall k_f \in [1,n+m]$, $t_{p,ini}^{1,1} < t_{p,fin}^{1,1} \ldots < t_{s,ini}^{i,k} < t_{s,fin}^{i,k} < \ldots < t_{s,fin}^{j',k_f}$ [chronology of events (charge or discharge)] with k as the event index, $k \in [1,k_f]$, $i \in [1,n]$ as the discharge index, and $j \in [1,m]$ as the charge index.

The index k is introduced here to take into account the sequence of events.

Three main types of variables impact the revenue $R_{\Delta t}$:

- variables linked to the operating schedule n, m, $t_{s,ini}^{i}$, $t_{s,fin}^{i}$, $t_{p,ini}^{j}$, and $t_{p,fin}^{j}$;
- PP characteristics H, P_{in}, $\dot{Q}_{out}$, K, and η^{eh};
- electricity price p^{DA}.

2.2. Input data and assumptions

Power plant reference characteristics: These characteristics are either computed using thermodynamic equations or taken from the literature. Though a closed Brayton cycle is used, most characteristics are close to those of the original project involving the NACC. We assume that the transition times when the operators switch the PP operating modes are sufficiently short compared to the time spent in each mode. Moreover we assume that the temperatures of the coolants in the combined cycle remain constant during the discharge of FIRES. This last statement is made in case of the first approach but needs to be verified to obtain more accurate estimates of $R_{\Delta t}$. Admitting those two assumptions is tantamount to making all the PP characteristics just functions of the PP operating mode. Table 2 gives the values of each PP characteristic.

The storage capacity of FIRES, denoted H, is not set. The storage capacity of FIRES is easily changeable since it is proportional to the mass of firebricks in the storage unit. H needs to be chosen based on the nature of the grid in which the PP is built and the incremental investment cost of FIRES, which is expected to increase with the working pressure. The revenue is computed for various values of H from 500MWh to 2500MWh.

2.3. Computations

Every variable involved in the equation of $R_{\Delta t}$ is known except those related to the operating schedule, i.e. when each PP operating mode is used during Δt. This schedule is modeled by the variables t, n, and m. Finding these variables presents three major issues:

1. there are $2^*(n+m)-1$ unknown variables t, plus, n and m are also unknown for each cycle;
2. these variables need to be optimized to obtain good estimates of the revenue $R_{\Delta t}$;
3. in practice, other constraints need to be considered before defining these variables, e.g. the time-lapses required between a charge and a discharge of FIRES or the maximal duration the PP is able to operate in peak-load.

Note that the term -1 in the first issue is due to the definition of a cycle given previously, i.e. there is an equality between the heat charged into FIRES and the heat discharged from FIRES during a cycle (constraint $\mathcal{G}_4$). All those points make defining the operating schedule a complex task, one that is not useful for obtaining first estimates of $R_{\Delta t}$. The method used in this study to circumvent a complex optimization process is to bound the optimized value of $R_{\Delta t}$ from below and above.

Lower bound of $R_{\Delta t}$: Since we cannot optimize the operating schedule, we constrain it to reduce the complexity of defining an optimized operating schedule. The cycle duration Δt is fixed at 24 h and only one charge and one discharge of FIRES are planned for each cycle, then n and m are equal to 1. Hence, the number of independent and unknown variables is reduced to three: $t_{p,ini}^{1}$, $t_{p,fin}^{1}$ and $t_{s,ini}^{1}$. $t_{s,fin}^{1}$ is determined from these three variables. Afterward an optimization is made to find the three remaining unknown variables. The target of the optimization is to maximize $R_{\Delta t}$. Note that the heat stored in FIRES is included in these variables and is equal to $\eta^{eh} P_{in}(t_{p,fin}^{1} - t_{p,ini}^{1})$. This leads us to constrain the optimization to take into account the constraint $\mathcal{G}_1$. We also constrain the maximum value of $t_{p,fin}^{1}$ to be smaller than $t_{s,ini}^{1}$ (constraint $\mathcal{G}_2$) and $t_{s,fin}^{1}$ to be smaller than Δt (constraint $\mathcal{G}_3$).

After finding the value of each variable, $R_{\Delta t}$ is computed using numerical integrations. All constraints (from $\mathcal{G}_1$ to $\mathcal{G}_4$) are fulfilled and the operating schedule is severely constrained. It is expected that a such PP will operate with a more flexible operating schedule to maximize the revenue. Hence the value $R_{\Delta t}$ computed by this method is used as a lower bound of what can be easily expected from the PP and especially from operating FIRES.

Upper bound of $R_{\Delta t}$: The next step is to obtain an upper bound to frame the realistic additional revenue of FIRES. One way to obtain this limit is to remove some constraints related to $R_{\Delta t}$. We propose here to remove the constraints $\mathcal{G}_1$ and $\mathcal{G}_2$, i.e. that the FIRES unit is considered full and with an infinite storage capacity. Without these two constraints, obtaining the values of all t, n, and m that optimize $R_{\Delta t}$ can be done by the following these steps:

1. discretize the hourly electricity price $p^{DA}(t)$, noted p_u^{DA} with u an integer, and sort from the lower to the higher price to

Table 2
Reference power plant characteristics.

Characteristics	Values
$\dot{Q}^*_{nuclear}$ [a]	250 MW_{th}
$\dot{Q}^*_{out}$ [a]	215 MW_{th}
P_{in} [b]	332.5 MW_{th}
η^{eh} [a]	1
K [b]	0.56

[a] Pre-conceptual design characteristics [1,4].
[b] Computed characteristics.

Table 3
Estimates of the economical potential of FIRES operating with FHR and NCCC.

Data set	Germany/Austria 2015	Iowa (United States) 2014
Source	EPEXSPOT (PHELIX) [18]	MISO [19]
Period	January 1st,2015–December 30th, 2015	January 1st,2014–December 30th 2014
Revenue of stand-alone FHR[a]	28.33 M€	21.51 M$
Electricity volume sold of stand-alone FHR[a]	895.4 GWh	
H[b]	1698 MWh	1958 MWh
μ+1.5σ (Δt=24h)	977 MWh + 1015 MWh	863 MWh + 1185 MWh
μ+1.5σ (Δt=168h)	3187 MWh + 5745 MWh	3738 MWh + 4990 MWh
$\Sigma_{year}R_{\Delta t=24h}$—lower bound	2.25 M€	5.36 M$
$\Sigma_{year}R_{\Delta t=24h}$—upper bound	2.49 M€	5.75 M$
$\Sigma_{year}R_{\Delta t=168h}$—upper bound	4.99 M€	9.37 M$
Additional elec. volume sold$_{\Delta t=24h}$—lower bound	110.4 GWh	208.2 GWh
Additional elec. volume sold$_{\Delta t=24h}$ – upper bound	134.7 GWh	244.4 GWh
Additional elec. volume sold$_{\Delta t=168h}$—upper bound	185.9 GWh	279.2 GWh
Investment FIRES cost[c]	7.98 M€	9.89 M$

FIRES, Firebrick Resistance-Heated Energy Storage; FHR, fluoride-salt-cooled high-temperature reactor; NCCC, Nuclear Closed Combined Cycle.

[a] Computed for 364 effective full-power days.

[b] Heat storage capacity to get 95% of the lower bound estimate when H tends toward infinity.

[c] Indicative investment costs based on the heat capacity H provided and on an incremental cost of an unpressurized FIRES around 5$/kWh [1]. We assume the incremental cost in Europe equal to 5€/kWh.

have $p^{DA}_{u'}$ increase with u'. Each value of u' is associated to a value u;

2 find u'_1 and u'_2 such as $|u'_1 - u'_2|$ is minimum while keeping $Kp^{DA}_{u'_2} > \frac{1}{\eta^{eh}} p^{DA}_{u'_1}$. This inequality is made to maintain a positive revenue. The constraint $\mathcal{G}_4$ gives the following relationship: $\frac{u'_1}{\Delta t - u'_2} \approx \frac{\eta^{eh} P_{in}}{\dot{Q}_{out}}$. The equality is not strict because the time variable has been discretized. Finally the problem consists of finding just one value, e.g. u'_1;

3. recover all the discrete times of purchase u by inverting the process done in step one for all u' in between 0 and u'_1. The selling times are given for all u' in between u'_2 and Δt;
4. compute $R_{\Delta t}$ and the FIRES state of charge S using numerical integrations.

The main consequence of this method and the assumptions related to it is that the revenue $R_{\Delta t}$ is necessarily above the revenue expected in practice. The information on the storage capacity is not considered in this method, but analysis of S provides the orders of magnitude of heat storage capacity H required. Since we do not keep the constraints $\mathcal{G}_1$ and $\mathcal{G}_2$, studying the absolute value of S is meaningless. We study its variations to obtain the required order of magnitude of heat storage.

3. Results

The method described above was implemented with two electricity price data sets. Table 3 sums up the output of the estimation. All computations were done for 364 days by summing all cyclic revenues, i.e. 364 daily cycles or 52 weekly cycles if Δt is equal to 24 h or 168 h, respectively. We introduce μ and σ to estimate the heat storage capacity required to obtain revenue close to the upper bound estimate. These variables correspond to the average and the standard deviation of the amount of heat discharged from FIRES between two charges. The choice of focusing on the heat discharged and not charged is arbitrary, but both values indicate the range of heat storage capacity required. Analyzing the distributions of the amount of heat discharged between two charges shows that

- 99% of this amount is between 0 and μ+1.5σ in the case of a weekly cycle;
- 89% of this amount is between 0 and μ+1.5σ in the case of a daily cycle.

We need to consider that μ and σ do not take into account the effect of heat accumulation in FIRES, e.g. when several charges and discharges are done alternately but with larger charges than discharges.

The maintenance costs of FIRES and all systems associated in the PP are not considered in this study. They are expected to be low compared to the investment cost. The incremental cost of FIRES has been computed in the case of the study related to the FHR with NACC and FIRES. This cost might change if FIRES is designed to meet the requirements of a closed Brayton cycle, e.g, a higher operating pressure or a coolant gas other than atmospheric air. For these reasons, the investment costs given in Table 3 are only estimates and show the ratio between the yearly revenue and the investment cost of the storage unit.

4. Discussion

This exploratory study stresses the potential profitability of the FIRES system. The results might indicate that FIRES is able to benefit from variable electricity prices in both investigated markets. The ratio between the revenue expected from operating FIRES and its capital cost suggests a pay-back from the system after several years.

The forecast capability of the suppliers appears as a key factor to increase the operating revenue generated by FIRES. In both case-studies, forecasting the electricity in the week-ahead instead of the day-ahead could double the additional revenue, with the consequence of multiplying the required heat storage capacity by three.

As mentioned in Section 1, closing the Brayton cycle is advantageous if the natural gas price is significantly higher than the average electricity prices, such as can be in Western Europe because natural gas is mostly imported. Questions of dependency on suppliers might be argued for limiting importations of gas. The German/Austrian case shows interesting financial results despite the German renewable energy policy. This factor tends to smooth the electricity prices in the wholesale market by guaranteeing the purchasing price of electricity produced from these energy sources. This energy policy of supporting and developing wind and solar PPs could open an important market for this FIRES system in Europe.

The size of the German/Austrian market also tends to smooth the electricity price since the day-ahead electricity price is made for the entire region. Moreover the integration of the German/Austrian electrical grid within the European grid enables numerous commercial exchanges with the surrounding countries such as France, limiting the occurrence of dramatic price peaks or gaps in the wholesale markets.

The Iowa case-study, in which the profitability of selling process-heat has been shown in the case of a PP applied as an IHS, still demonstrates high revenue estimates in this configuration with a closed Brayton cycle.

Further investigations would give more accurate estimates of the financial potential of setting a PP with NCCC and FIRES, notably in Europe. This means taking into account the commercialization of process-heat and ancillary services together with electricity production as well as estimating of the investment and maintenance costs related to setting up pressurized FIRES units in NCCCs.

Conflict of interest

The authors declare that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2017.11.011.

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