THEORETICAL APPLICABILITY EVALUATION OF CARNOT BATTERIES FOR AGRICULTURAL ENERGY DEMANDS IN FARMS

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Abstract. With the rapid growth of variable renewable energy (VRE) technologies, their high dependence on weather conditions results in significant intermittency. Carnot battery (CB) is considered a promising energy storage technology to enhance their resilience and be applied in residential buildings, communities, and power plants. The potential of CBs applied for agricultural activities in farms is investigated, and their demands differ from those of the above sectors. Two generic systems are studied with a heat pump (HP) to cover power/cooling demands or an electrical heater (EH) to only cover power demands. The indicator *gain* is proposed to evaluate their economic gain with various hot storage temperatures (T_h), grid reliability, the ratio of the diesel and grid price, the proportion of the solar energy after curtailment (e), the proportion used for load directly (u), and specific investment cost of VRE and CBs (c_{PV}, c_{CB}). The *gain* value in the system with an HP is higher, and the condition to get positive *gain* for the system only supplying power is harder. In the system with an HP, when e = 1, c_{PV} = 0.15 € / kWh, c_{CB} = 0.40 € / kWh, and T_h = 373 K, the *gain* is with 1.5 ~ 5.8 with u from 0.1 to 0.9. The gain is only within 0.15 ~ 2.5 for another system with c_{CB} = 0.25 € / kWh and T_h = 1473 K. The results can be a reference for determining and designing a proper energy solution for farms.

Keywords. Pumped thermal energy storage, Techno-economic evaluation, Heat pump, Heat engine, Electrical heater.

Nomenclature

C	Cost (€)
c	Specific cost (€/kWh)
COP	Coefficient of performance (-)
g	Efficiency with respect to ideal cycles
gain	Economic gain ratio (-)
PV	Photovoltaic
P2P	Power-to-power efficiency (-)
Q	Thermal/cooling energy (kWh)
R	Reliability of grid (-)
RTE	Round-trip-efficiency (-)
r	Ratio (-)
T	Temperature (K)
W	Work (kWh)

Special characters

η	Efficiency (-)
Δ	Difference of temperature (K)

Subscripts

a	Annual, air
c	Cold, cooling
Carnot	Carnot efficiency
diesel	Diesel generator
EH	Electrical heater
grid	National grid
h	Hot
HP	Heat pump
HE	Heat engine
inv	Investment
PV2l	From PV to loads
req	Required by demands
1	Generic systems with an HP
2	Generic systems with an EH

1 Introduction

It is a challenge to keep on track to meet either 1.5℃ or 2℃ climate targets [1] and some urgent actions must be undertaken to reduce global CO_2 emissions [2], with solar and wind energy playing a key role. Pumped thermal energy storage (Carnot battery, CB) is a technology that stores electricity as thermal energy by heat pump (HP) or electrical heater (EH) and transforms it back to power by heat engines (HE) when it is needed [2, 3]. CBs have been developed sharply, acting as a supplement to renewable energy resources [4], and they are mainly focused on those sectors: residential buildings, power plants, and industry [3-8], neglecting the agricultural sector. However, there are about 570 million farms in the world at present [9], illustrating the importance of farms and agricultural activities in energy research and CO_2 emission targets. Farms are facing plenty of energy problems, for instance, many farms are off-grid, or the national grid is intermittent, thus they use diesel/petrol generators for power generation when the grid is not available [10, 11]. This is neither economical nor environment-friendly, meaning those farms need a new energy solution. Hence, CBs combined with renewable energy are ideal energy solutions for farms, especially if the power demand peaks mismatch the power production peaks, for instance, the irrigation activity is conducted during the night when photovoltaic (PV) does not work.

Farms have electricity demand for irrigation pumps and cooling demand for food preservation, and they might also have electricity demand for the desalination process as the irrigation water is too salty in many farms, which is not good for the growth of crops. If there is a cooling demand for food preservation, the required temperature range is about 0-5 ℃, which is lower than the cooling requirement of residential buildings [10]. As a result, whether there is some techno-economic potential to apply CBs in farms should be studied.

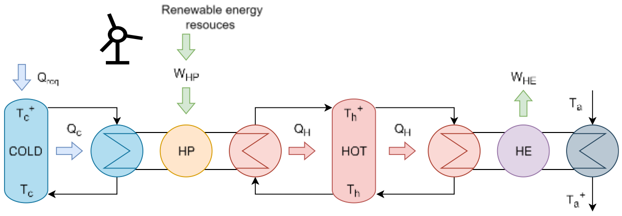
This study investigates the potential of two generic CB configurations, replacing the national grid and diesel generators to cover power/cooling demands in farms. The variety of grid reliability, grid/diesel price, specific cost of PV and CB, and effective percentage of renewable energy used for loads are considered. The second section is the description of the studied systems, and the third section is the techno-economic evaluation model for generic systems. In Section 4, the economic potential in generic systems is presented under various e, u, c_{PV}, c_{CB} and R and r_c, and the techno-economic comparison of the two proposed systems is also given.

2 Carnot battery description

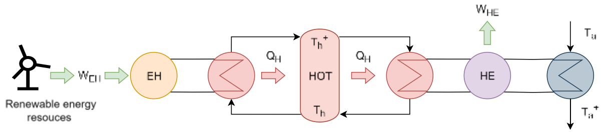
This study assumes that there is power demand for agricultural activities (irrigation or desalination), and cooling demands for food preservation, whose temperature range is 0-5 °C [10]. The ambient air is 27 °C. Renewable energy resources are represented by solar energy, which is PV here. The maximum temperature of the hot storage and HE is 1200 °C [12-15].

2.1 Generic system without EH

This configuration shown in Figure 1(a) is proposed by Guo and Lemort [10] and modified to be more generic here. The HP is charged by PV, and it charges hot/cold storage, and the HP/cold storage can supply cooling capacity to the farm's cooling demands. On the other hand, the HE discharges hot storage and produces power.



(a). Generic system with HP



(b). Generic system with an EH

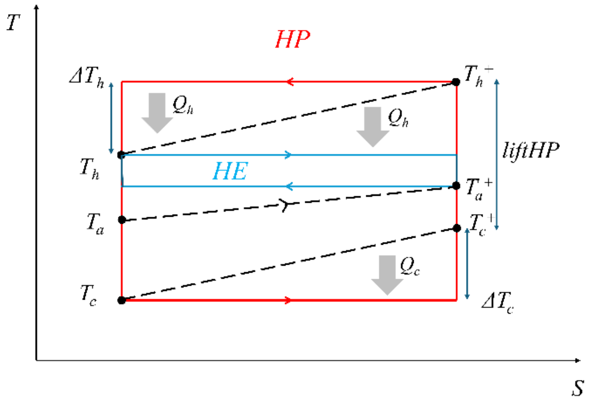
Figure 1. Configurations of generic systems

2.2 Generic system with an EH

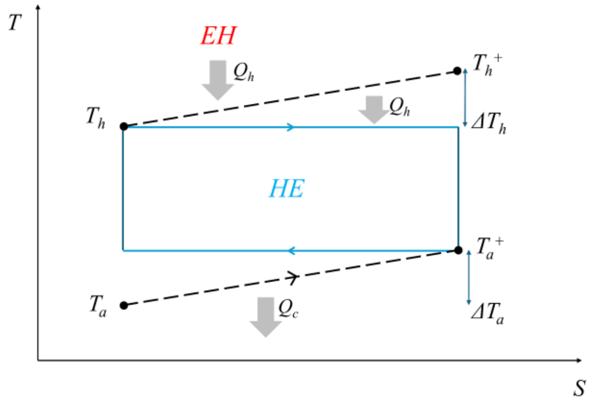
This configuration is also investigated because it can reach a higher hot storage temperature, and it is shown in Figure 1(b). An EH is used to replace HP for charging the hot storage, and the farm's cooling demands are still covered by the existing cold rooms or refrigerators. Hence, the hot storage can reach higher temperatures without the limitations of HP ability and the CB here only supplies power for the farms. More technical details of these two generic systems can be found in Section 3.

2.3 Carnot cycles in HP/HE

The HP and HE are both working in an ideal Carnot cycle [14] in the two above systems, but an efficiency g is introduced with respect to the ideal cycles, considering the inevitable irreversibility. The detail of their efficiency is described in section 3.1. Their ideal Carnot cycles are shown in Figure 2.



(a). Carnot cycle with an HP



(b). Carnot cycle with an EH

Figure 2. Ideal Carnot cycles of generic systems

3 Methodology

3.1 *Generic system without EH*

These parameters are introduced to evaluate HP/HE performance:

$$\Delta T_c = T_c^+ - T_c \tag{1}$$

$$liftHP = T_h^+ - T_c^+ \tag{2}$$

$$\Delta T_h = T_h^+ - T_h \tag{3}$$

The maximum *liftHP* is set as 120 K [16], so the maximum T_h^+ is 398 K. Thus, Carnot efficiency of HP / HE (*COP*, η) can be expressed as:

$$COP_{Carnot} = \frac{T_h^+}{T_h^+ - T_c} = \frac{T_c^+ + liftHP}{liftHP + \Delta T_c} \tag{4}$$

$$\eta_{Carnot} = 1 - \frac{T_a^+}{T_h} = 1 - \frac{T_a^+}{T_c^+ + liftHP - \Delta T_h} \tag{5}$$

Considering the actual cycles are not ideal, the real *COP*, η and *P2P* are:

$$COP = COP_{Carnot} \times g \tag{6}$$

$$\eta = \eta_{Carnot} \times g \tag{7}$$

$$P2P = COP \times \eta \tag{8}$$

The efficiency of the hot storage is assumed to be 100 %, and thus the energy connection of HP/ HE is:

$$Q_h = COP \times W_{HP} = \frac{W_{HE}}{\eta} \tag{9}$$

For maximum efficiency, $\Delta T_h = 0$, $\Delta T_c = 0$, yielding max.$P2P = g^2$. For PV, *e* represents the percentage of effective energy for HP charging and loads [17, 18] after the curtailment (1 - *e*), and *u* is the effective energy percentage only for loads:

$$e \times W_{PV} = W_{HP} + W_{PV2l} \tag{10}$$

$$u = \frac{W_{PV2l}}{e \times W_{PV}} \tag{11}$$

Thus, the relationship of W_{HP}, W_{HE} and W_{PV} is:

$$W_{HP} = (1-u) \times e \times W_{PV} \tag{12}$$

$$\frac{W_{PV}}{W_{HE}} = \frac{1}{COP \times \eta \times e \times (1-u)} \tag{13}$$

Regarding the cold storage side, it supplies cooling capacity for cooling demands:

$$Q_c = W_{HP} \times (COP - 1) \tag{14}$$

$$\frac{Q_{req}}{Q_c} = k \leq 1 \tag{15}$$

Regarding the power demand, the relationship of W_{HE} and W_{PV2l} is:

$$W_{req} = W_{HE} + W_{PV2l} \tag{16}$$

As the electricity demand is covered by HE and PV in the generic system, an evaluation criterion is proposed in equation (17), where if *gain* > 0, the Carnot battery makes profits:

$$gain = \frac{C_{a,grid} + C_{a,diesel} - C_{a,inv}}{C_{a,inv}} \tag{17}$$

The annual cost of the system is simplified as the sum of PV annual cost and CB annual cost:

$$C_{a,inv} = c_{PV} \times W_{PV} + c_{CB} \times \left(W_{HE} + \frac{Q_c}{EER}\right) \tag{18}$$

As the discount rate is not considered here for simple evaluation, the above parameter c_{CB} is higher than the levelized cost of energy of the corresponding type of Carnot battery and it is assumed to be within the range of 0.1 ~ 0.7 € / kWh [4, 19]. The c_{PV} is assumed as 0.15 € / kWh [20]. The grid reliability (*R*) is the proportion of hours in one year when the grid is available. The total electricity of the grid and diesel generators includes the required electricity demand and electricity consumption of the refrigerators used at present in the farm, which is Q_{req} divided by *EER*, so the annual costs of the grid and diesel are:

$$C_{a,grid} = c_{grid} \times R \times (W_{req} + \frac{Q_{req}}{EER}) \qquad (19)$$

$$C_{a,diesel} = c_{diesel} \times (1 - R) \times (W_{req} + \frac{Q_{req}}{EER}) \qquad (20)$$

EER represents the energy efficiency ratio of the refrigerators in farms. As the fluctuation of the diesel price is larger than the grid price [21-23], c_{grid} is assumed constant and a ratio of diesel to grid price is defined:

$$r_c = \frac{c_{diesel}}{c_{grid}} \qquad (21)$$

Substitute the above formula into the definition formula of *gain*, it can also be expressed as:

$$gain = c_{grid} \times [R + r_c \times (1 - R)] \times \frac{1+e\times u+k\times e/EER\times(1-u)\times(COP-1)}{c_{PV}+c_{CB}\times[P2P\times e\times(1-u)+e/EER\times(1-u)\times(COP-1)]} - 1 \qquad (22)$$

The *gain* will be impacted by R, r_c, and u, c_{PV} and c_{CB} if the CB performance is fixed. When the parameter $k = 1$ (the HP cooling capacity has no loss), the *gain* can reach the maximum value, so k is set as 1.

The CB round-trip-efficiency is defined [10] as:

$$RTE = \frac{W_{HE}+\frac{Q_{req}}{EER}}{W_{HP}} = P2P + \frac{k\times(COP-1)}{EER} \qquad (23)$$

The electricity saved by the HP cooling capacity that replaces the existing refrigerators for food preservation is also included in the definition of the *RTE*, as the energy output of the system.

3.2 Generic system with an EH

For this system, the Carnot efficiency of HE can be expressed as:

$$\eta_{Carnot} = 1 - \frac{T_a^+}{T_h} \qquad (24)$$

The real η are also defined as the ideal value multiplied by g. As the EH replaces HP for charging the hot storage, assuming the heating efficiency of the EH is also 100%, the energy relationship between EH and HE is:

$$Q_h = W_{EH} = \frac{W_{HE}}{\eta} \qquad (25)$$

Regarding the PV, as the EH is also charged by renewable energy, the relationship among them is:

$$e \times W_{PV} = W_{EH} + W_{PV2l} \qquad (26)$$

According to equations (16) (26), the W_{req} / W_{HE} and W_{PV} / W_{HE} can be gained:

$$\frac{W_{req}}{W_{HE}} = 1 + \frac{u}{(1-u)\times\eta} \qquad (27)$$

$$\frac{W_{PV}}{W_{HE}} = \frac{1}{e\times(1-u)\times\eta} \qquad (28)$$

The annual cost of this system:

$$C_{a,inv} = c_{PV} \times W_{PV} + c_{CB} \times W_{HE} \qquad (29)$$

For the CB layout of an EH and HE, its specific cost is lower than that with an HP [3, 24, 25], so the c_{CB} in this system is assumed within 0.10 ~ 0.40 € / kWh. In this system, only the solution for power demands is replaced, and the cost for cooling demands is not changed, so the annual costs of grid and diesel are:

$$C_{a,grid} = c_{grid} \times R \times W_{req} \qquad (30)$$

$$C_{a,diesel} = c_{diesel} \times (1 - R) \times W_{req} \qquad (31)$$

At last, in this system, the *gain* can be expressed as:

$$gain = \frac{c_{grid}\times[R+r_c\times(1-R)]\times[\mathrm{e}\times(1-u)\times\eta+e\times u]}{c_{PV}+c_{CB}\times e\times(1-u)\times\eta} - 1 \qquad (32)$$

Regarding the studied application, ambient air temperature (T_a) is assumed to be 300 K. For η, T_h should be as high as possible until reaching its maximum limit (1473 K), when max $\eta = 0.8147 \times g$ is achieved. Hence, the *gain* will be also impacted by R, r_c, and u, c_{PV} and c_{CB} with the constant η.

The round-trip-efficiency in this system is defined as:

$$RTE = \frac{W_{HE}}{W_{EH}} = \eta \qquad (33)$$

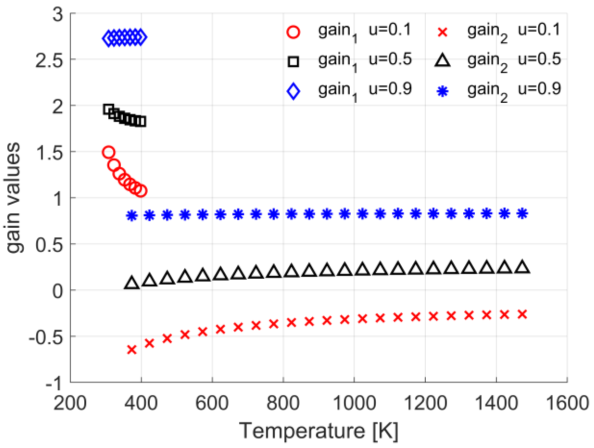
In both systems, the value of g is assumed to be 0.5 [14]. The value of the *EER* is set to be 2.73 [10, 11]. Only the grid purchase is considered without selling electricity to the grid. Grid price is assumed to be fixed to be 0.20 € / kWh [26].

4 Results

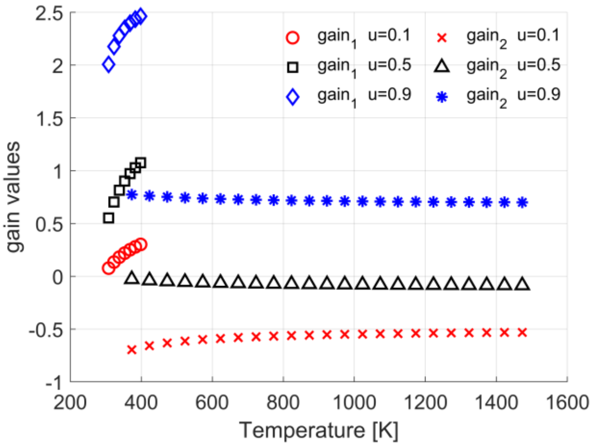
4.1 Impact of hot storage temperature

Figure 3 presents the variation of $gain_1$ and $gian_2$ values with T_h, under different conditions (a. c_{PV} / $c_{CB} > 1$; b. c_{PV} / $c_{CB} < 1$). For $gain_1$, the $T_{h,1}$ will influence the *COP* and η simultaneously, and the trending of the $gain_1$ is impacted by the trade-off of the W_{PV}, W_{HE}, and Q_c in equation (22). When c_{PV} / $c_{CB} > 1$, $gain_1$ decreases with the rising of $T_{h,1}$, and when c_{PV} / $c_{CB} < 1$, $gain_1$ increases with the rising of $T_{h,1}$. In equation (32), when c_{PV} / $c_{CB} \geq 1$, $gain_2$ always increases with the rising of η and $T_{h,2}$. When c_{PV} / $c_{CB} < 1$, if $u < e \times c_{PV}$ / c_{CB}, $gain_2$ will increase with η, and if $u > e \times c_{PV}$

/ c_{CB}, $gain_2$ will decrease with η. This is the trade-off result of the costs of PV and CB, because W_{PV} and W_{HE} will decrease and increase with η, respectively, under two above conditions. Hence, the value of c_{PV} / c_{CB} will affect the trending of $gain_2$ at various u.



(a). $c_{CB,1} = c_{CB,2} = 0.1$ € / kWh



(b). $c_{CB,1} = c_{CB,2} = 0.4$ € / kWh

Figure 3. *gain* values against T_h

Regarding the *RTE* values of both systems, the utilization of HP increases the RTE_1 in the system with an HP, compared to another one, as shown in Figure 4. With the T_h increasing, RTE_1 is reduced because the *COP* of HP drops significantly, from 4.40 to 1.59, and RTE_2 is lifted by the enhanced η. In conclusion, a lower $T_{h,1}$ is good for the technical performance but reduces the economic gain when $c_{CB,1}$ is high, and a higher $T_{h,2}$ contributes to better technical performance and economic gain as it varies little with $T_{h,2}$. The value of RTE_1 can exceed 1 as the electricity saved by the cooling of HP is included.

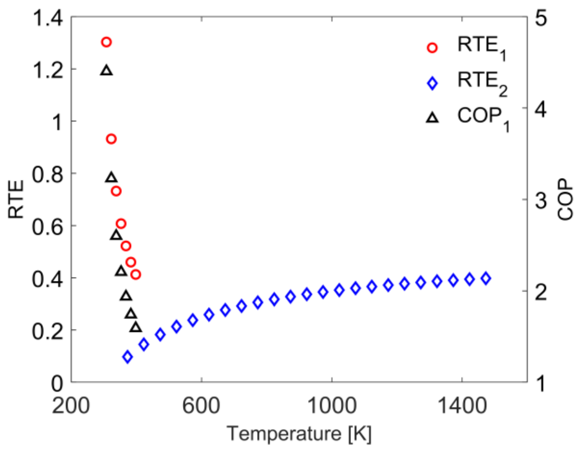


Figure 4. *RTE* values against T_h

4.2 Impact of cooling loss

The $T_{h,1}$ is set to be 373 K with $COP_1 = 1.87$ and $\eta_1 = 10$ %, and $T_{h,2}$ is set to be 1473 K with $\eta_2 = 40$ % in the following calculation. Figure 5 presents the $gain_1$ variation with parameter k when $R = 0.5$ and $r_c = 2$, which can represent the effective proportion of the cooling capacity, and $(1 - k)$ means the percentage of the colling energy loss. The $gain_1$ is increased slightly with the growth of k, and the incline is larger at $c_{CB,1} = 0.1$ € / kWh than that at $c_{CB,1} = 0.7$ € / kWh when c_{PV} is fixed at 0.15 € / kWh.

When k is low, the required cooling demand is relatively low and HP cooling capacity has a lot of overage, because the HP is sized large to get a huge Q_h and W_{HE} for high power demands. Compared to the existing energy solution, where the $C_{a,grid}$ and $C_{a,diesel}$ is expensed for high power and low cooling demands, the proposed system with an HP needs a high investment and annualized cost for high power demands and by-produced high cooling capacity, leading to a low $gain_1$ value. When k is higher, higher cooling demands make full use of the by-produced cooling capacity in the system with an HP, but in the present energy solution, the consumption of the grid/diesel should be increased, resulting in a higher $gain_1$ by the proposed system. As the HP cooling capacity is related to the $c_{CB,1}$, if $c_{CB,1}$ is lower, the difference between the grid/diesel annualized cost and PV/CB annualized cost is enlarged when k is growing, so the $gain_1$ rises more significantly. What's more, the incline of the $gain_1$ is becoming smaller from $u = 0.1$ to $u = 0.9$, because the proportion of the cooling demands in all the power/cooling demands drops. As the variation of $gain_1$ is not significant as shown in Figure 5, the value of k is set as 1 in the following calculation.

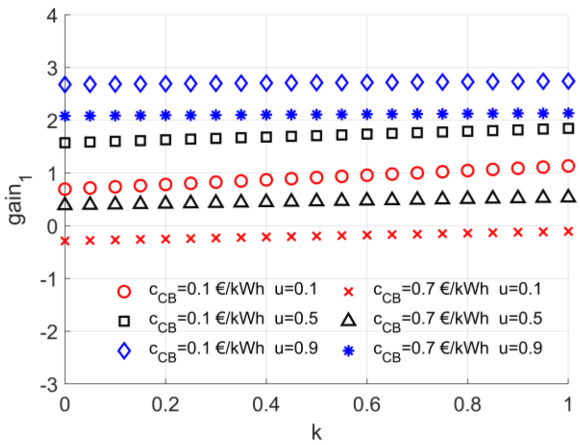


Figure 5. $gain_1$ values against k

4.3 Impact of R and r_c

Figure 6 presents the variation of the criterion $gain_1$ in the generic system with HP for various R, u, r_c, and $c_{CB,1}$. The lower R and higher r_c lead to better $gain_1$ values, as the total cost of grid and diesel is high. When r_c is about 1, the impact of R is less compared to r_c, and when R is about 1, the impact of r_c is less. In the system with an EH, Figure 7 illustrates the impact of R and r_c on the criterion $gain_2$ at various $c_{CB,2}$. The overall trending of $gain_2$ value with R and r_c is the same as in the system with an HP. If $c_{CB,2}$ is above 0.25 € / kWh and u = 0.1, it is hard to get a positive $gain_2$, because of high values of both W_{HE} and $c_{CB,2}$.

Even $c_{CB,1} > c_{CB,2}$, the system with an HP performs better in economic gain, illustrating the advantage of the integration of power and cooling solution by CB with HP/HE.

4.4 Impact of specific cost of PV/CB

Figure 8 presents the variation of $gain_1$ and $gain_2$ with c_{PV} and c_{CB}, when $R = 0.5$, and $r_c = 2$ and the T_h values keep the same as in Section 4.2. Lower PV and CB costs contribute to higher $gain$ values in both systems. For the system with an EH and without cooling capacity, lower c_{PV} and c_{CB} are needed to get a positive $gain_2$ value than those in the system with an HP. With the u increasing, the c_{PV} has more effect than c_{CB}, due to the smaller value of W_{HE}. This is more obvious in the system with an EH because it cannot supply cooling capacity and more sensitive to the change of W_{HE}.

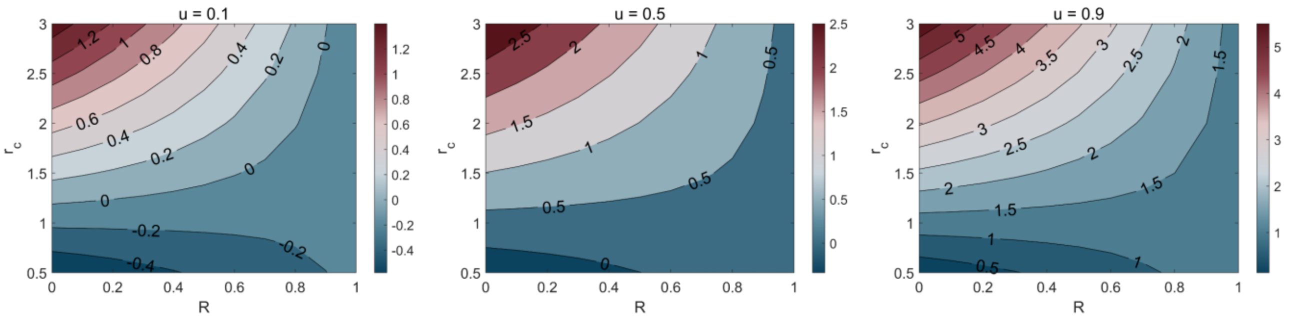


Figure 6. Relative $gain$ with HP (c_{CB} = 0.40 € / kWh)

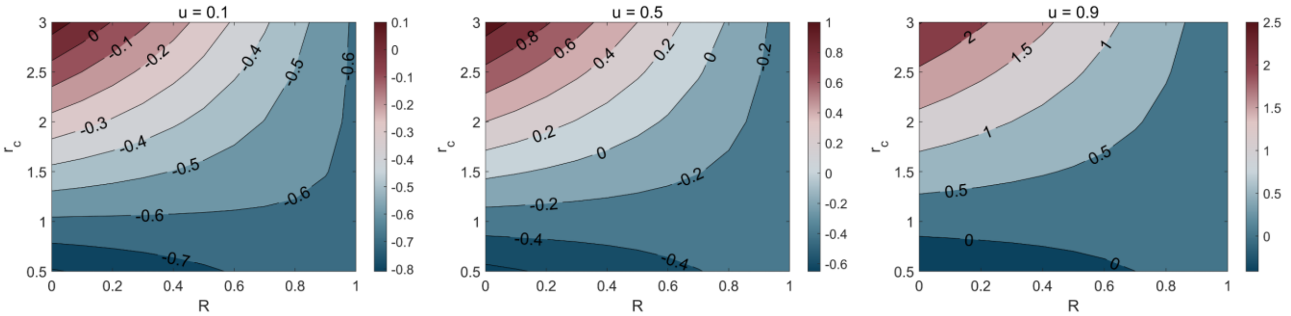


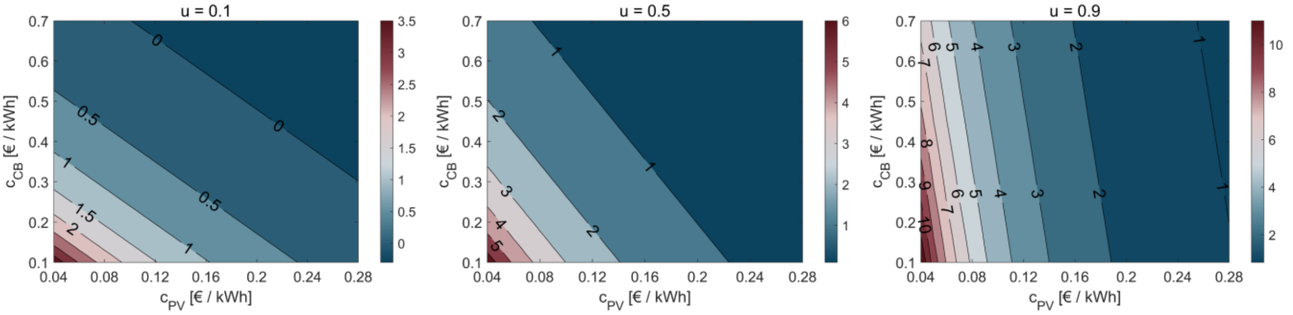
Figure 7. Relative $gain$ with an EH (c_{CB} = 0.25 € / kWh)

4.5 Impact of PV curtailment and parameter u

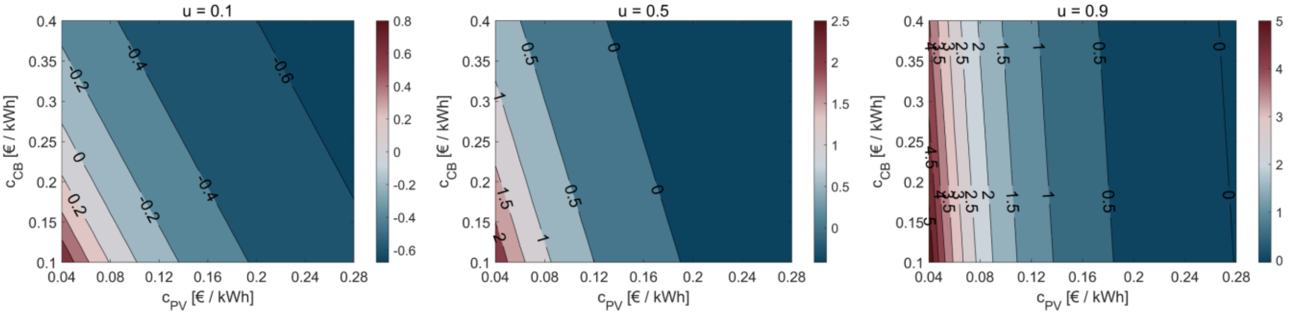
In the above sections, e is fixed as 1 in the assumption that there is no curtailment of PV output, but it is ideal, so the effect of e is studied in Figure 9 ($c_{CB,1}$ = 0.40 € / kWh, $c_{CB,2}$ = 0.25 € / kWh).

In the system with an HP, when u < 0.5, more PV output is used for HP consumption than that for the power load directly, illustrating the ratio of W_{HE} and

W_{PV2l} is high, and thus the lifted CB cost is higher than the reduced PV cost with the growth of e, so higher e leads to lower $gain_1$. If $c_{CB,1} < 0.15$ € / kWh, this situation will not happen. In the system with an EH, increasing the e value means more W_{PV2l} and less W_{HE}, so the $gain_2$ grows with e. When $u < 0.5$, it is impossible to get positive $gain_2$ until $e = 1$ (no PV curtailment) at $c_{CB,2} = 0.25$ € / kWh.



Generic system with HP



Generic system with EH

Figure 8. *gain* values with c_{PV} and c_{CB}

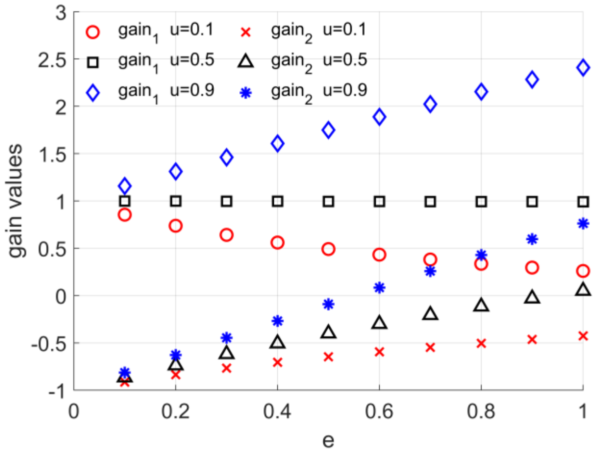


Figure 9. *gain* with e and u

The *gain* improves with the u increasing. In the system with an HP, a higher u means a higher value of W_{PV} / W_{HE} according to equation (13), and regarding the variation of the W_{PV}, there are 2 cases. If W_{PV} is decreasing or constant, W_{HE} cannot be rising because of their increasing ratio above. In the second case, if W_{PV} is rising, and u is also rising, W_{PV2l} will increase more, and thus W_{HE} will decrease a lot, because of their relationship in equation (17). In conclusion, in any case, W_{HE} and Q_c will decrease with u, and when the grid and diesel prices (c_{grid}, c_{diesel}) are fixed, the $gain_1$ is higher. In the system with an EH, the impact of u is weaker than that with a HP, because the value of W_{PV} / W_{HE} is smaller.

5 Conclusions

Two generic Carnot battery systems for the energy demands in farms are proposed and their techno-economic potential evaluation is conducted. A new evaluation criteria *gain* is proposed and its values in two systems are presented and analysed with various grid reliability (R), the effective percentage of solar energy (e), the proportion of the solar energy used for load directly after its curtailment (u), the ratio of the diesel price to grid price (r_c), and the specific investment cost of the Carnot battery (c_{inv}). The main conclusion is listed here:

- In the system with a HE for power demands and HP for cooling demands ($T_{h,1}$ = 373 K), the defined $gain_1$ value can reach 1.5 to 5.8 with u from 0.1 to 0.9 at various R and r_c values, when $c_{CB,1}$ = 0.4 € / kWh.
- For the generic systems with an EH ($T_{h,2}$ = 1473 K), it only supplies power, and the farm's cooling demands is covered by existing refrigerators. Its $gain_2$ value can reach 0.15 to 2.5 when $c_{CB,2}$ = 0.25 € / kWh, and u ranges from 0.1 to 0.9.
- The hot storage temperature has more effect in the system with an HP than in that with an EH, and $gain_2$ is not sensitive to $T_{h,2}$. The system with an HP can get a higher *gain* value than another system, illustrating the advantage of the solution with integrated HP and HE for power and cooling demands, respectively.
- The $gain_1$ in the system with an HP varies slightly with the proportion of the cold energy loss. When $c_{CB,1}$ is lower, the $gain_1$ growth is more significant.
- Lower R and higher r_c contribute to higher *gain* values in both systems. In the system with an EH, $gain_2$ is more sensitive to c_{PV} than $c_{CB,2}$ at each u, and $gain_1$ is more sensitive to $c_{CB,1}$ than c_{PV} at u = 0.1.
- The system with an HP is more sensitive to u than another system without cooling capacity. The $gain_2$ grows with e, but when $c_{CB,1}$ > 0.15 € / kWh, $gain_1$ decreases at a low level of u (u < 0.5) with the growth of e.

In this study, the HP/HE cycles are based on the Carnot cycle as limited by pages, so in future studies, the Lorenz-cycle-based potential evaluation will be investigated to provide a more comprehensive reference for energy solution design in agriculture. The impact of parameter g is not presented in this study due to the page limitation, which should be studied in future work.

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