Evaluation of Flexibility Potential of Cold supply Systems by the Example of a Generic Cold Warehouse

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Abstract:

In this conference paper, the flexibility potential of a generic cold warehouse is investigated. The purpose of the work is to estimate and take advantage of the flexibility potential of cold supply systems to apply Demand Side Management (DSM) measures for different goals. The fulfilled goals in this work include minimization of electricity purchase costs, minimization of $\mathrm{CO_2}$ emissions, maximization of the integrated renewable energy sources (RES) into the electricity grid, maximization of integration of a photovoltaic plant on location, and peak load shaving. To this aim, an optimization model of the generic warehouse is developed in OEMOF, which is a tool to carry out mathematical optimization using mixed-integer linear programming. An objective function is defined for each goal to be minimized. Different criteria such as electricity costs, maximum peak load, $\mathrm{CO_2}$ emissions, electrical energy consumption and load change are employed to analyze the optimization results. A flexibility factor is used to enable a comparison of the flexibility potential of the generic cold house for different goals. The results show that a generic cold warehouse shows a high flexibility potential that can be taken advantage of for economic, technical, and ecological purposes.

Keywords: flexibility potential, cold warehouse, cold supply systems, Demand Side Management, renewable energy sources, OEMOF

1 Introduction

In line with Energiewende [1], renewable energy sources (RES) are being increasingly harnessed in Germany to reduce the $\mathrm{CO_2}$ emissions by decreasing the share of generated electricity via conventional fossil fuel power plants and to overcome the future shortages in the electricity grid due to the phase-out of nuclear power plants [2]. Consequently, the proportion of fluctuating energy input into the electricity grid in Germany has increased dramatically. This makes the efficient use of the electricity from the RES difficult as a lot of energy may be wasted when the electricity generation exceeds the demand and there is not enough energy storage capacity. Besides, bottlenecks may occur at locations in the grid where the input electricity from RES is more than the electrical energy transmission capacity of those parts of the grid [3]. Therefore, a pressing need for new technologies has arisen to harness this volatility and deal with its resulting dilemmas.

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One of the plausible solutions to such problems is taking advantage of the flexibility potential of energy systems or adding flexibility to them using different types of electric and non-electric energy storages. This flexibility potential can be then used to store the electrical energy in the same or other forms of energy for a certain period. This enables an energy system to adjust its operation based on the electricity input to the grid from different sources to maintain stability between the power supply and energy demand by storing the electrical energy in times of high supply and low demand and vice versa [4] for different purposes. Cold supply systems have can be used as non-electric energy storages to store electricity in the form of cold thermal energy and therefore can play a substantial role in dealing with the problems arising from the increasing share of RES in the electricity grid. This is firstly because of their high electricity consumption, which amounts to 14% of the total electricity consumption in Germany [5], and secondly due to their high flexibility potential, which makes them a suitable option for DSM measurements.

The flexibility potential of cold supply systems roots mainly in their inherent thermal capacity, which allows them to remain within a safe temperature range for a certain period while uncoupled from the grid without causing damage to the quality of the refrigerated goods or a substantial reduction of the comfort level. However, it must be noted that certain temperature ranges must be maintained for some products [6]. Low costs of availability and implementation can be named as other advantages of the application of cold supply systems as non-electric energy storages [7]. In many cases, the refrigerated goods or the mass of the air-conditioned area can be used as the cold energy storage. Otherwise, a separate cold energy storage, for example latent cold energy storages (PCM) or ice storages [8], must be used, which will incur investment costs.

A cold warehouse (also known as refrigerated warehouse) is one of the most interesting candidates for DSM measures. This is mainly because the stored goods in these warehouses can be used as the cold energy storage. This can be done by lowering the temperature of the refrigerated good to a certain point below the nominal minimum temperature of the cold warehouse, for example -24 °C instead of -20 °C [9]. In this process, the heat is removed from the refrigerated goods and the temperature of the cold warehouse remains in a safe range for a longer period than in the normal operation (also known as reference operation), which makes a flexible operation of the refrigeration system of the cold warehouse possible. In case of a vapor-compression refrigeration system (VCRS), for instance, the compressors can remain out of service during the peak load hours to help to maintain the electrical energy balance in the grid by lowering the demand [10]. However, the refrigerated goods cannot be used as a cold energy storage when they are quickly replaced or relocated in large quantities. Similarly, the use of the refrigerated goods as cold energy storage is impossible if their quality is affected negatively by lower temperatures, especially in case of fresh food, fruits, and vegetables. Thus, a separate cold energy storage such as a cold-water storage or an ice storage must be used in such cases. Additionally, a separate cold energy storage may be needed when the thermal capacity of the refrigerated goods is not enough for flexible operation.

This paper investigates the flexibility potential of a generic cold warehouse as an exemplary system for analyzing the flexibility potential of cold supply systems. In Section 2, it is explained how the generic cold warehouse is modelled, which DSM goals are set to achieve by taking advantage of its flexibility potential, and which methodology is used to evaluate this potential. The results of the flexibility potential of the generic cold warehouse for the selected goals are shown and discussed in Section 3. Finally, the conclusion is made in Section 4.

2 Methodology

In this section, it is explained how the generic cold warehouse studied in this work is modelled and characterized and finally which approaches are used to estimate its flexibility potential.

2.1 Characteristics of the generic cold warehouse

The main elements of a cold warehouse are the configuration and size of the cold warehouse, the refrigeration demand of each section, the cold supply system, the cold energy storage, and the energy supply. These elements need to be characterized properly for a generic cold warehouse for a valid analysis. It is explained here how the generic cold warehouse modelled in this work is characterized.

2.1.1 Cold warehouse

In order to conduct a more comprehensive analysis, the generic cold warehouse studied in this work consists of two sections, namely a normal refrigeration section and a deep refrigeration section. Based on [11], the volume of the deep refrigeration section is considered to be 72000 m^3, which is three times as big as the normal refrigeration section with a volume of 24000 m^3.

2.1.2 Refrigeration demand

The maximum refrigeration demands of the deep and normal refrigeration sections, $\dot{Q}_{0,max}$ are calculated based on [12] and amount to 720 MW and 320 MW, respectively. However, the exact value of the refrigeration demand of the cold warehouse differs for different hours of the day and for each month. Therefore, hourly normalized refrigeration demand (HNRD) and monthly normalized refrigeration demand (MNRD), which include values between 0 and 1, are considered for the cold warehouse according to [13] (see Figure 2.1). The refrigeration demand for each time step $\dot{Q}_{0,t}$ can be therefore calculated by Equation 2.1.

$$\dot{\boldsymbol{Q}}_{\boldsymbol{0,t}} = \dot{\boldsymbol{Q}}_{\boldsymbol{0,max}} \times \mathbf{HNRD} \times \mathbf{MNRD} \tag{2.1}$$

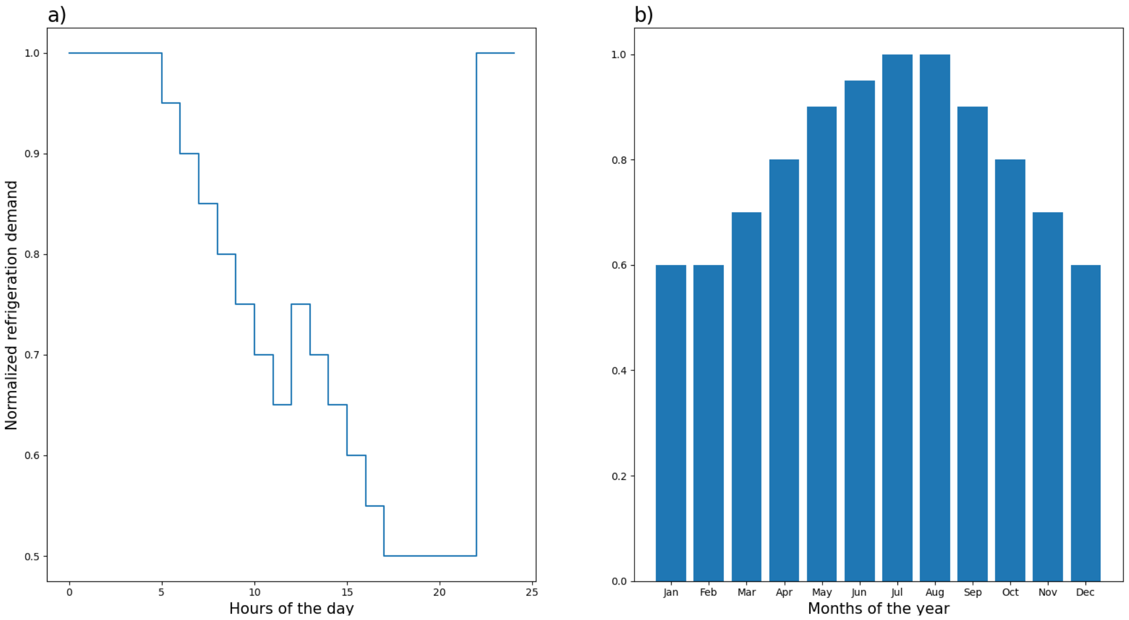

Figure 2.1 *a) Hourly normalized refrigeration demand of the cold warehouse for a single day. b) Monthly normalized refrigeration demand of a cold warehouse for a year.*

It is assumed that HNRD and MNRD apply to both deep and normal refrigeration sections and the values of HNRD remain the same for every day of the year.

2.1.3 Cold supply system

Eight VCRSs are used to meet the refrigeration demand of the two sections of the cold warehouse, four for each section. Each VCRS consists of a reciprocating compressor selected based on [12]. The refrigeration load that needs to be covered by the compressors $\dot{Q}_C$ should be around 10% - 20% more than the maximum refrigeration demand $\dot{Q}_{0,max}$ of each section [14]. In addition, a duration factor f_z with a value between 0.67 and 0.75 is used to include the downtime effect of the compressors according to Equation 2.2 [14]. The calculated mean value of $\dot{Q}_C$ must be therefore equal to or bigger than 1172 kW and 647 kW for the deep and normal refrigeration sections, respectively.

$$\boldsymbol{\dot{Q}_C \geq \frac{\dot{Q}_{0,max}}{f_z} \times 1.1\ or\ 1.2} \tag{2.2}$$

The required electric power of the compressors P_C can be calculated based on a parameter called energy efficiency ratio (EER), which is the ratio of $\dot{Q}_C$ to the electric power of compressors P_C as in Equation 2.3 [15].

$$\boldsymbol{EER = \frac{\dot{Q}_C}{P_C}} \tag{2.3}$$

The higher the value of EER, the lower is the required electric power to meet the refrigerated demand. The values of EER in this work for deep and normal refrigeration systems are 1.41 and 2.40, respectively [16]. Therefore, the total required electric power for the deep and normal refrigeration sections are 831.76 kW and 269.59 kW. By rounding these values to 800 kW and 260 kW and dividing them to the number of compressors, each compressor of the deep refrigeration and normal refrigeration section has a maximum power of 200 kW and 65 kW, respectively. A minimum electric power of 25% is set for each compressor as well, below which the compressor is turned off. The effect of the ambient temperature and the partial load behavior of the compressor on the EER are implemented in this work as well.

2.1.4 Cold energy storage

For the deep refrigeration section, the mass of the refrigerated goods is considered as an inherent cold energy storage. It is also assumed that the temperature of the refrigerated goods can be reduced from -18 °C to -24 °C without negatively affecting their quality and only 90% of the refrigerated goods is considered for storing the cold energy as the other 10% are relocated on a daily basis. Therefore, the inherent thermal capacity of the deep refrigeration section amounts to approximately 70000 kWh.

The temperature of the cold warehouse is considered to increase 3 °C on a daily basis when no refrigeration load is supplied, which means it takes the fully-loaded cold energy storage two days to be fully discharged. This thermal energy loss amounts to a storage efficiency of 0.9. The charge and discharge efficiencies of the storage are set to 0.9 and 1, respectively. The discharge efficiency of the storage is set to 1 because the temperature loss itself is the main source of cold energy supply in an inherent cold energy storage. There is no maximum charge or discharge rate as the refrigerated goods can intake or lose any amount of thermal energy at once.

On the other hand, it is assumed that fruits are stored in the normal refrigeration section. As the temperature of fruit cannot be lowered more than 1 K [9], an ice cold energy storage with a thermal capacity of 2000 kWh is considered instead of an inherent cold thermal storage for this section. Ice storages are suitable for temperatures above 0 °C [12]. The efficiency of the ice storage is set to 0.96. Additionally, charge and discharge efficiencies of 0.94 are applied based on [17]. A maximum discharge rate of 220 kW is considered for the ice storage as well [17].

2.1.5 Energy source

The required energy for the cold supply system of the cold warehouse is supplied via the electricity grid. The electricity is bought from the EPEX spot market based on Day-ahead, Intraday auction and Intraday continuous markets [18]. The changing price of electricity in the EPEX spot market opens room for operational optimization to achieve the minimum electricity purchase costs.

2.2 Modeling approach

Different approaches can be used to analyze an energy system. Static approaches have been widely used to estimate the DSM potential of energy systems, where mathematical calculations are used without considering time resolutions and the dynamic changes in the load curve, electricity supply etc. Examples of static approaches can be seen in [7] and [19]. In contrast, dynamic methods are used, for example in [20], to analyze the behavior of an energy system by considering the changes that happen in the system over time. As a result, the smaller the time resolution, the more accurate are the results. In this work, a dynamic method with a fifteen-minute time resolution is applied.

Two of the most common dynamic approaches to analyze an energy system are optimization models and simulation models [21]. In this work, an optimization model is used to develop the energy system. Since the flexibility potential of cold supply systems can be used to optimize their operation mode, an optimization model can be used to find out the optimized operation of a refrigeration system to achieve a certain goal.

The energy system of the generic cold warehouse considered for this study was implemented in OEMOF (Open Energy Modelling Framework), which is a modelling tool for optimizing energy systems developed in the programming language Python [22]. The optimization conducted in OEMOF is based on mixed integer linear programming (MILP). In brief, the implemented solver in OEMOF tries to figure out the minimum value for a cost-based objective function by trying out different operation modes for each 15-minute interval over a certain optimization period. The optimized solution normally consists of a different plant operation than its normal operation, where the cold supply system is simply used to cover the demand at any given time without further considerations such as the amount of peak load or $\mathrm{CO2}$ emissions.

Different features such as minimum run time, maximum number of starts per hour, ramp-up and ramp-down time can be implemented in the compressor model to make the optimization model more accurate. However, these limitations do not apply to reciprocating compressors for a 15-minute time resolution. For example, the maximum possible number of starts per hour in a model with a 15-minute time resolution is 2, which means a compressor is not affected by this limitation if it has the capability to be turned on/off at least two times per hour. On the contrary, if a compressor can be turned on/off only once per hour, the minimum number of starts must be applied. Reciprocating compressors have the ability to be turned on between 3 to 5 times per hour [15], which means these compressors can be modelled in a 15-minute time resolution frame without implementing the maximum number of starts. Similarly, reciprocating compressors can be turned off soon after they are turned on and their operating power can be increased or decreased without any time limits [15]. Therefore, no minimum run time, ramp-up or ramp-down time are necessary.

Figure 2.2 depicts the generic cold warehouse, which has been modelled in OEMOF in this work. The arrows show the direction of the energy flow, with colors orange light blue, and blue representing electricity, cold energy for the normal and the deep refrigeration sections, respectively. The refrigeration demand must be always fully met. Depending on the goal, the VCRSs shall be turned on or off independent of the refrigeration demand. The cold energy storage is used to store the cold energy generated using the excess/cheap available electricity in times of high proportion of electricity from RES in the grid or low electricity prices. The stored cold energy is discharged to meet the refrigeration demand in times of high electricity price or low proportion of electricity from RES in the grid.

2.3 Goal-based evaluation of flexibility

There seems to be no consensus on the definition of flexibility in the context of energy systems [23]. In this work, the flexibility of an energy system is defined as its ability to react to an external signal without jeopardizing the quality of the refrigerated goods [23, 24]. In case of a generic cold storage, this reaction is realized by a change in the operation mode from on to off or from a high power consumption to a low power consumption and vice versa. According to [23], the amount of the available flexibility of a generic cold warehouse depends largely on the capacity of its cold energy storage and how fast this storage can be charged and discharged. The flexibility of an energy system is, therefore, not a fixed value as the external signals and the way the energy system reacts to them are dynamic [23].

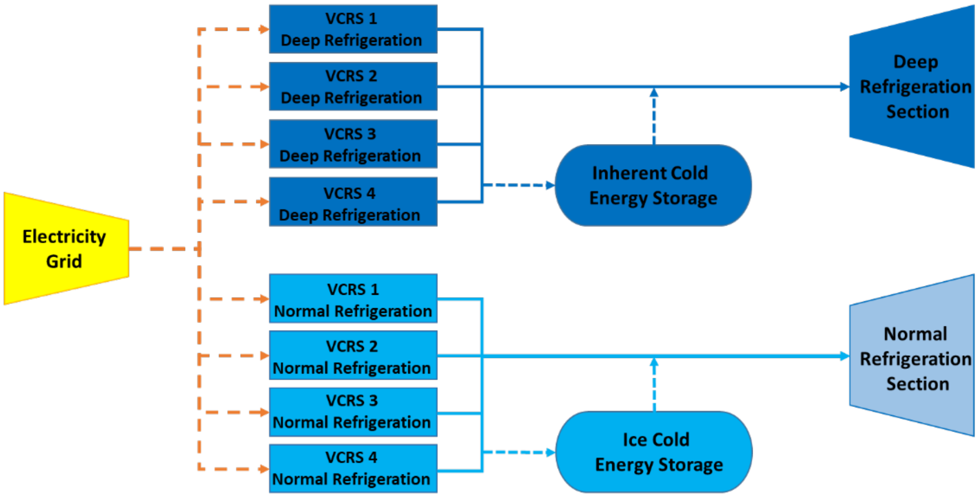

Figure 2.2 Generic cold warehouse modelled in OEMOF

Static approaches normally use a set of metrics or key performance indicators (KPI) to define the flexibility potential of an energy system [23]. The most important KPI are, among others, the maximum shiftable power or energy and the maximum duration over which power or energy consumption can be shifted [23]. In this work, however, the flexibility potential of an energy system is evaluated based on the reaction of the energy system to an external signal. Unlike the static approach, the method used in this work helps us understand how the flexibility potential of an energy system can be used to achieve certain goals and how flexible such systems can be operated in reality.

In this work, the optimization model is used to achieve three types of goals, namely technical, economic, and ecological. Technical goals aim at optimizing the energy system operation by changing a technical aspect of the energy system. Peak load shaving, for example, aims to reduce the maximum power consumption of the system as a technical characteristic of the energy system. Economic goals, such as minimization of electricity purchase costs, try to reduce operation costs or make a profit by optimizing the operation of the energy system. Minimization of the $\mathrm{CO_2}$ emissions and maximization of the integration of the RES in the grid and on location are examples of ecological goals, which move towards environmentally friendly energy systems.

A general objective function Z is defined to achieve these goals (see Equation 2.4). In Equation 2.4, t_0 and $t_n$are the first and last intervals of the optimization period, Δt is the length of each interval than amounts to 15 minutes in this work, $P(t)$ as the amount consumed power is a decision parameter whose values are defined by the solver, and $variabl\_costs$ which is an input parameter is imported to the model as a time series.

$$\boldsymbol{min\, Z = min\,\{\textstyle\sum_{t_0}^{t_n} (variabl\_costs(t) \cdot P(t) \cdot \Delta t)\}} \tag{2.4}$$

Although the same objective function is used for different goals, the optimization results for each goal is unique as the values of $\boldsymbol{variabl\_costs}$ are different for different goals.

2.3.1 Minimization of electricity purchase costs

To minimize the electricity purchase costs, time series of the electricity purchase prices from EPEX Spot Market are imported to the optimization model as $variabl\_costs$ in Equation 2.4. Accordingly, the solver tries to buy as much electricity as possible in times of low electricity prices by turning on the cold supply systems and storing the electrical energy in the form of cold thermal energy in the cold energy storage. In times of high electricity prices, the cold supply systems are turned off or operated at a lower power rate and the cold energy storages are discharged to meet the refrigeration demand.

2.3.2 Minimization of $\mathrm{CO_2}$ emissions

In order to realize this goal, penalty costs are imported for the $\mathrm{CO_2}$ factor (g_{co2}/kWh_{el}) as $variabl\_costs$ in the objective function in Equation 2.4. The values of the $\mathrm{CO_2}$ factor are taken from [25] as in the German electricity grid. In this case, the solver tries to minimize to the objective function by purchasing electricity from the grid when the $\mathrm{CO_2}$ factor is lower. The penalty costs do not affect the real operation costs of the energy system, but help the solver to find an optimized solution for the corresponding goal.

2.3.3 Maximization of the integration of RES in the grid

It is challenging to harness RES efficiently because of their volatile nature. If no DSM strategy is applied, it is possible that a fair amount of the generated electricity from these sources is wasted, especially when the supply is far more than the demand. Therefore, there is a pressing need to adopt a strategy to use the energy from these sources more effectively, which is of [26] ecological and economic benefits as it helps to further reduce the $\mathrm{CO_2}$ emissions from electricity generation and electricity purchase costs.

For this goal, the share of the electricity from photovoltaic and wind plants [27] in the grid is used as input parameter. As a higher share of electricity from photovoltaic and wind sources leads to a smaller amount of $\mathrm{CO_2}$, the solver buys electricity from the grid when this share is high and therefore less $\mathrm{CO_2}$ is generated. This also helps to harness as much electricity from wind and photovoltaic plants as possible by storing the excess electricity from these sources in the form of cold energy. In this case, penalty costs are used as $variabl\_costs$ in Equation 2.4 for other electricity sources such as fossil power plants. Consequently, the solver tries to minimize the operation costs by maximizing the electricity purchase from photovoltaic and wind sources in the grid.

2.3.4 Maximization of the integration of a photovoltaic plant on location

Maximization of the integration of decentral RES is of crucial importance as well. In this work, it is investigated how an on-location photovoltaic plant can be maximally integrated into the electricity network of the cold warehouse by converting the generated electricity from the photovoltaic plant to cold energy and storing it in cold energy storages for later use.

For this goal, a photovoltaic plant is exclusively implemented as an additional electricity source next to the grid with a maximum power of 750 kW. The values of $variabl\_costs$ in Equation 2.4 can be set to zero or smaller than the values of $variabl\_costs$ for the electricity purchase prices from the spot market so that the solver gives priority to the electricity generated by the photovoltaic plant.

2.3.5 Peak shaving

Peak shaving, as a technical goal, can be achieved by establishing especial tariffs for higher power consumptions. Electricity purchase costs consists of two terms (see Equation 2.5). The first term is calculated by multiplying the amount of consumed energy $E(t)$ [kWh] by the work price C_{WP} [€/kWh]. The second term is calculated by multiplying the maximum power consumption by a special tariff called power price C_{PP} [€/kW].

$$\boldsymbol{min\, Z = min\, \{ \sum_{t_0}^{t_n} (E(t) \cdot C_{WP} + P_{el,max} \cdot C_{PP})\}} \tag{2.5}$$

Given the right objective function, the solver can take advantage of the flexibility of the system to keep the maximum consumed electric power of the cold supply system as low as possible and therefore minimize the operation costs. However, real or penalty costs can not be used as $variabl\_costs$ in Equation 2.4 as ,unlike other case, the value of $P_{peak}(t)$ is not known beforehand and must be decided by the solver. Consequently, a different approach must be used. To this aim, a so-called OEMOF transformer, named Peak Transformer, is created with two input parameters, namely $P_{parameter}$ and $penalty_{costs}$ and three variables, namely $P_{el,in}(t)$, $P_{el,out}(t)$ and $P_{peak}(t)$. The Peak Transformer is placed between the electricity source and the cold supply systems and aims at minimizing the value of $P_{el,out}(t)$. $P_{el,in}(t)$ and $P_{el,out}(t)$ must be equal all the time. $P_{parameter}$ is defined by the user. $P_{peak}(t)$ is defined as a non-negative parameter and is calculated according to Equation 2.6, which means the $P_{el,out}(t) \geq P_{parameter}$. The objective function is defined as in Equation 2.7.

$$\boldsymbol{P_{peak}(t) = P_{el,out}(t) - P_{parameter}} \tag{2.6}$$

$$\min \boldsymbol{Z} = \min\ (\boldsymbol{P_{peak}(t).penalty\_costs}) \tag{2.7}$$

The input variable $penalty\_costs$ is a positive constant value and is defined by the user. The solver minimizes the value of $\boldsymbol{P_{el,out}(t)}$ [€/kW] indirectly by minimizing the objective function. Mathematically, the value of $P_{parameter}$ can be initially set to zero to achieve the best results for $\boldsymbol{P_{el,out}(t)}$. However, the refrigeration demand cannot be met if $\boldsymbol{P_{el,out}(t)}$ tends towards zero. Therefore, a more realistic value shall be selected for $P_{parameter}$ by trial and error.

2.4 Quantification of Flexibility

A set of criteria are used to compare the optimization results for different goals based on a comparison to the normal operation, where the normal operation is given the value 1 and the optimized results are compared to it accordingly. The selected criteria are as follows:

- Maximum peak load
- Load change
- CO2 emissions
- Electricity purchase costs
- Electrical energy consumption.

Load change shows how many times the compressor power consumption has changed in optimized operation compared to the normal operation.

However, none of these criteria can be used to directly quantify the flexibility of the energy system. In the literature, different approaches are introduced to quantify flexibility (see [28-30]). In this work, the approach proposed by [29] is used to evaluate the flexibility of the generic cold warehouse. To this aim, a flexibility factor called shifted flexible loads (S_{flex}) is introduced to compare the deviation between the load in the optimized operation and the load in the normal operation for the intervals in which the load of the optimized operation is smaller than the load of the normal operation. Equation 2.8 is used to calculate S_{flex} as follows

$$S_{flex} = \frac{\sum_{i=1}^{n} \max\{\boldsymbol{L_{ref,i} - L_{opt,i}}, \boldsymbol{0}\}}{\sum_{i=1}^{n} \boldsymbol{L_{ref,i}}} \tag{2.8}$$

where n is the number of intervals in the optimization period, and $L_{ref,i}$ and $L_{opt,i}$ show the required load in the optimized and in the normal operation, respectively. The average daily flexibility is calculated based on Equation 2.8 and used to compare the flexibility of the cold warehouse for different goals. The advantage of this approach is that it can be used to compare the optimization results for all the goals with different external signals.

3 Results and discussions

In total, the optimization results were produced for eight different cases. Figure 3.1 depicts the comparison between the values of the criteria introduced in Section 2.4 in optimized operation and in normal (reference) operation. Load change has been demonstrated separately for easier visual comparison, as its values were much bigger than those of the other criteria. As it can be seen, all the criteria have been given the value 1 for the reference and the optimization results have been scaled accordingly.

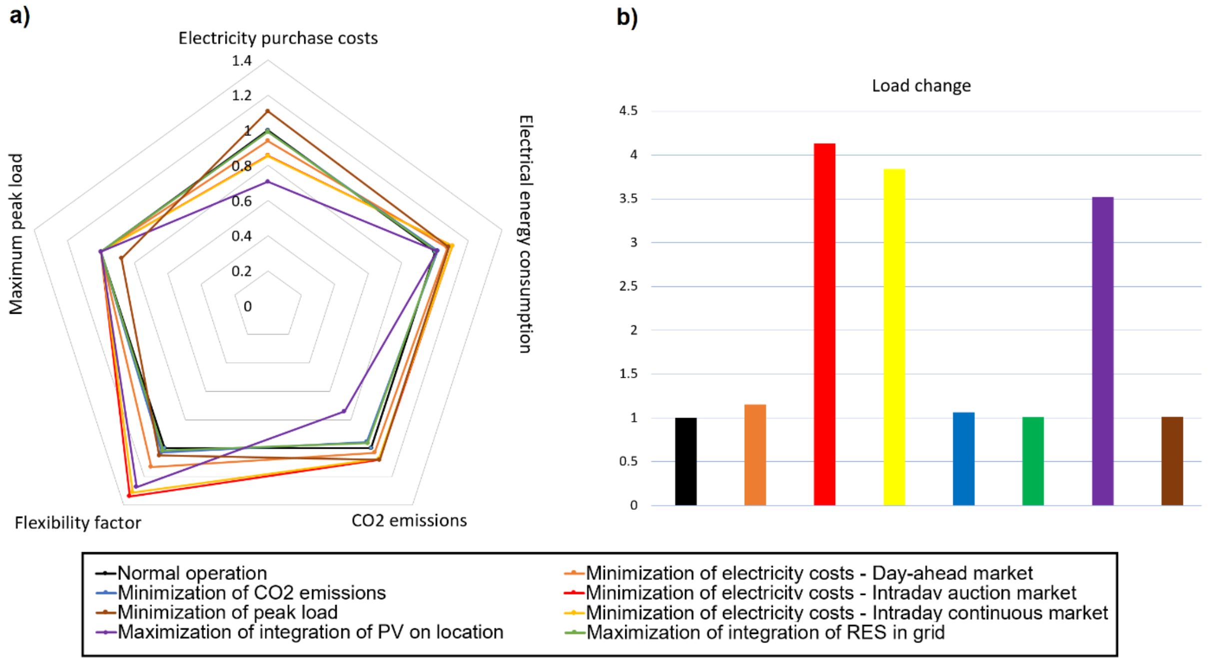

Figure 3.1 Optimization results for different goals compared to the normal operation as reference. a) The resulting values for electricity purchase costs, maximum peak load, flexibility factor, co2 emissions, and electrical energy consumption. b) Load change

Maximization of the integration of a photovoltaic plant on location resulted in the minimum electricity purchase costs and CO_2 emissions, both approximately 30% less than the normal operation. However, the comparison for this goal must be excluded from the comparison between other goals, as they did not include the 750 kW photovoltaic plant. In terms of electrical energy consumption and maximum peak load, no considerable deviation between the normal operation and the optimized operation can be seen in this case. However, the amount of electricity drawn from the grid has decreased by 29%. Load change increased approximately 3.5 times compared to the normal operation.

Excluding the integration of a photovoltaic on location, the minimum electricity purchase costs was achieved by the goal “minimization of the electricity purchase costs” by using the electricity prices from intraday continuous market followed narrowly be intraday auction market and then the Day-ahead market. The lower electricity purchase costs from goals like minimization of CO2 emissions and maximization of integration of RES in the grid can be justified by lower electricity prices at EPEX Spot market in times of higher RES input in the grid due to the so-called Merit Order effect [31]. Peak load shaving was the only goal that resulted in higher electricity purchase costs than the normal operation. This is because the solver did not consider any penalty costs for the electricity from the grid and only tried to minimize the maximum peak power throughout the optimization period. It must be noted that only the work price has been considered in this case to calculate the electricity purchase costs for different goals. Therefore, the total electricity purchase costs including the power price can be different, which means the difference between the electricity purchase costs in case of peak shaving and other goals can decrease as peak shaving leads to lower power cost due to lower maximum power consumption.

Maximum peak load did not change for any of the goals except for peak shaving. This is mainly because no penalty costs were considered for the maximum load in other cases. Consequently, the solver simply tried to minimize the objective function based on other costs, no matter how high the peak load was. The amount of peak load reduction was, however, different throughout the year. Lower peak load values were achieved in colder months of the year, reaching a minimum in January, and vice versa, reaching a maximum in July.

Minimization of the CO2 emissions and maximization of the integration of RES in the grid resulted in the lowest values of CO2 emissions by a reduction of 0.88% and 0.34%, respectively. However, their contribution to this goal was negligible to that of a photovoltaic plant on location. The amount of CO2 emission increased for all the other goals reaching a peak in the case of peak shaving.

Compared to the normal operation, electrical energy consumption changed around 1% for four goals, namely minimization of CO2 emissions, maximization of integration of RES in grid, maximization of integration of a photovoltaic plant on location and peak shaving. However, a more considerable increase of around 10% was observed for minimizing electricity purchases costs using the Intraday auction market and Intraday continuous market. Minimization of the electricity purchase costs using the Day-ahead market cause in increase of around 7% in electrical energy consumption as well.

Load change occurred maximally in the case of minimization of energy purchase costs through intraday auction market, intraday continuous market, and in the case of maximization of the integration of a photovoltaic plant on location. For these three goals, the compressors of the VCRS must have the capability to be frequently turned off/on or operated at a different power rate throughout the year.

Flexibility factor showed higher values for all the goals compared to the normal operation, which was expected as any deviation from the normal operation need a certain degree of flexibility. The cold supply system of the generic cold warehouse had to function more flexibility to achieve the DSM objectives by participating in the intraday auction and continuous market. The maximization of the integration of a photovoltaic plant on location requires high amounts of flexibility as well. On the contrary, minimization of CO2 emissions, maximization of the integration of RES in the grid, and peak shaving did not require much flexibility of the energy system.

The results show that higher amounts of energy are shifted for higher values of S_{flex}. The values of the evaluation criteria for minimization of CO2 emissions and maximization of the integration of RES in the grid were very similar in most of the cases except for electricity purchase costs, where the maximization of the integration of RES in the grid resulted in higher financial saving.

The inherent cold energy storage was never fully charged due its very high capacity, which means the temperature of the refrigerated goods never reached -24 °C. From one point of view, it could be argued that the deep refrigeration section of a cold warehouse can be used as a cold energy storage without causing damage to the quality of the refrigerated good. On the other hand, it means the deep refrigeration section of the cold house can be used to store more electricity in the form of cold energy when necessary as long as the refrigerated goods are safe.

4 Conclusion

The study shows that a generic cold warehouse has a high flexibility potential, which can be used to fulfill certain goals. For example, this flexibility enables a substantial economic benefit by reducing the electricity purchase costs through participation in the EPEX Spot market. However, conflicts between different goals may occur. By taking part in the EPEX Spot market, for example, more electrical energy shall be used to reduce electricity purchase costs, which results in higher CO2 emissions. In addition, the fulfillment of certain goals such as maximization of the integration of a photovoltaic plant on location requires high flexibility potentials, which may negatively affect the technical characteristics of the energy system. Investment cost may arise as well if a cold energy storage needs to be installed to add flexibility to the energy system. Additionally, external factors shall be investigated more extensively such as the effect of the ambient temperate on peak shaving.

In future work, it can be investigated which goals can be achieved more effectively under different economic, technical, ecological, and even environmental conditions. In addition, the effects of different types of cold supply technologies, compressor types, different types of cold energy storages and their capacity, electricity market etc. on the flexibility potential of cold supply systems for different goals can be studied.

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