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INTEGRATED HEATING AND COOLING CO_2 HEAT PUMP SYSTEM IN A MODERN DISTRIBUTION CENTRE

Karoline Husevåg Kvalsvik[(a)], Armin Hafner[(b)]

[(a)] SINTEF Energy Research

Trondheim, 7034, Norway, KarolineHusevag.Kvalsvik@sintef.no

[(b)] Norwegian University of Science and Technology (NTNU),

Trondheim, 7491, Norway, armin.hafner@ntnu.no

ABSTRACT

Industry is responsible for about 25-30 % of the global primary energy demand (Elmegaard, Zühlsdorf et al. 2017), and around two thirds of this is used for heating and cooling (Elmegaard, Zühlsdorf et al. 2017). Several recent innovations can improve the thermal energy efficiency and enable smart utilization of sun and/or surplus heat in several plants, yet they are not well-known and therefore rarely used. Novel approaches for supplying heating and cooling by integrated CO_2 heat pump systems are presented; including: direct heat exchange with CO_2, multiejectors, solutions to avoid implosion in CO_2 refrigeration systems at low ambient temperature, integration with high temperature heat pumps (above 100°C), ground condensers and optimal insulation. Some of these technologies are implemented, some are under construction and others still remain at concept level.

Keywords: Integrated systems, Flooded evaporation, Thermal storage, Peak shaving

1. INTRODUCTION

This article is an attempt to present and summarize the most recent, yet possible, ways to build an efficient refrigeration plant with CO_2. Most plants built do not utilize the potential improvements, which are many in number and reduce the total energy consumption of the building significantly. Heating and cooling are often made as separate units, and AC as a third unit, independent of one another. This means all surplus heat from cooling is lost to ambient at the same time as heat is purchased from another source. Until recently, this way of doing it made sense because:

- Energy is inexpensive, wasting it was not a big cost.
- Surplus heat often has a too low temperature level to cover heat demands and could not be utilized anyway.
- Means to increase the temperature relied on non-existing, emerging, unknown and/or very expensive technologies.
- Integrated systems are more complex. The simple, independent operation of separate units is easier to maintain and understand.

However, as the focus on environmental impact, climate changes and energy prices increases (especially handling of peak demands), and as a strong enhancement in energy efficiency is required to reach the climate goals, integration of all these functions into one unit is a good way to achieve a significant reduction in primary energy usage. However, there are a few challenges in doing so:

1. Surplus heat does not always occur at the same time as the heat demand and the amount of surplus heat might be too high or too low to cover the heating demand.
2. Many processes have special demands which require heating or cooling by water or steam, and equipment for alternatives do not exist.
3. If bad choices related to equipment are made, integrated systems can be more expensive and less efficient than they could have been if they were well-designed and -controlled.
4. Scepticism to new technology and profitability of the green solutions.
5. Complexity of integrated systems make them more challenging to understand/control/maintain; in addition, processes become more dependent on each another.

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Applying natural working fluids like ammonia and CO_2 has the great advantage that the substances belong in nature. Synthetic fluids might have unknown detrimental effects, like those that have been detected and found to be a major problem twice already (depletion of the ozone layer and global warming). Developing new synthetic fluids involves the risk of more such unpleasant surprises in the future. Therefor are natural refrigerants good and safe alternatives in most cases.

CO_2 is a very good and efficient heat transfer fluid, and can be used directly and efficiently both in the refrigeration unit and for direct distribution, achieving high COPs and low pressure losses. A transcritical CO_2 cycle is also excellent for heating of hot water, due to the heat rejection at gliding temperatures, as utilised in millions of domestic heat pumps in Japan (SHECCO 2016). The energy efficiency of CO_2 systems can be strongly improved by ejectors, enabling an efficient recovery of expansion work (Hafner 2014, Gullo, Hafner et al. 2017). CO_2 is safe (nontoxic, non-flammable, A1 classified), has no ODP and a GWP of 0 or 1[1], requires small pipes and is used for direct cooling in many applications (e.g. grocery stores). Thus, if a system in contact with people or food articles is to be built, CO_2 can be used directly for cooling, AC and ideally also for heating, and for production of hot tap water. There might be challenges related to high ambient temperature operation, and large capacity compressor packs are still more expensive than for ammonia units.

2. THERMODYNAMIC IMPROVEMENTS

The largest savings one can achieve is normally found through integration (30-80% in drying systems (Colak 2009a, Colak and Hepbasli 2009b)). This means that surplus heat from one process is used to heat another, instead of throwing the surplus heat (for example surplus heat from a refrigeration system) away and purchase new energy to cover the heat demand. As the surplus heat is often at a too low temperature to be used directly, heat pumps are often necessary to achieve integration. The result is that the heat demand is reduced/removed entirely, and in addition, the COP of the refrigeration equipment will be much more stable, and, if properly designed, it will always be high and predictable. Extreme temperature lifts for the refrigeration unit are avoided when it is cooled by the heat pump rather than ambient. However, the heat surplus and the heat demand will not always match or occur simultaneously, and thus the process may require back-up systems and storages, and can be more challenging to control.

To avoid exergy losses and also lower costs and complexity, direct refrigerant expansion systems should be used as much as possible. The fewer circuits with temperature exchange, the fewer pumps, circuits, and energy losses there will be, while higher system COPs are achievable. For a specific case study (Kvalsvik 2017), the yearly saving in lifting the evaporation temperature from -10 to -1.5°C was 33% (the effect of lifted condensation pressure is removed). In the study, the possibility of applying direct heating with CO_2 was also investigated. This gave savings of 3%. Thus, exact saving potential is very process specific and also depends on the heat sink. Calculations should thus be performed before the system is built, however, these measures will reduce both investment and operation costs. Indirect systems will however sometimes be necessary because equipment is made for one specific fluid or a specific set of fluids only (typically steam/water).

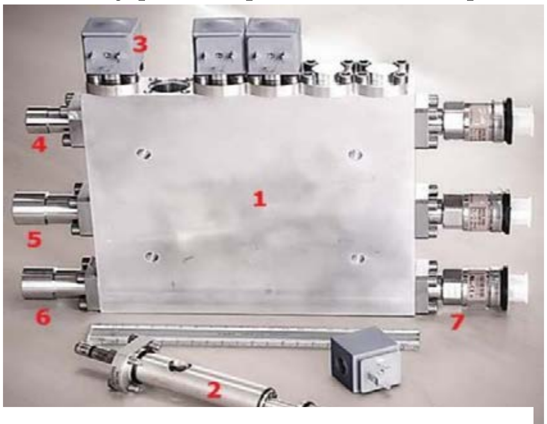

Figure 1: Multiejector, taken from (Gullo and Hafner 2017)

For some working fluids (CO_2, propane, butane), the use of an ejector can enhance system efficiency. For CO_2, the improvement can be up to 40% (Hafner 2014), even though the normal range is 15-27% (Gullo, Hafner et al. 2017) depending on the conditions. An ejector recovers some of the energy which is lost upon throttling the fluid from high pressure to low pressure, reducing the need for compression power. However,

[1] Depending on where it is taken from and how one calculates it. If one burns oil to produce it, the number should clearly be 1, but if it is taken from a process which would otherwise have emitted it to the environment, one can argue for that the net effect of harvesting it and using it in another process is 0 additional net effect of the CO_2, or even less than zero, as it spends time in a refrigeration system rather than in the atmosphere. However, CO_2 is CO_2, and one could say that it should be 1.

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it is important to consider how large savings the ejector will offer at given conditions, and how it effects other process parameters. When the pressure ratio for the compressor is changed, so is the compressor efficiency. If this is to the worse, the total COP might not improve (Drexler-Schmid, Lauermann et al. 2017). Therefore, experts in the field should be consulted when a dedicated design and proper control of ejector is needed to achieve energy savings.

Existing systems should be simulated with the new ejector and realistic compressor efficiency profile to investigate potential savings before installing them. For CO_2 refrigeration systems, an ejector is normally only economically justified in warmer climates (30°C and higher ambient temperatures). At such high ambient temperatures, the highest working pressure of the system must be above 100 bar to achieve good performance.

Working fluids in refrigeration units and heat pumps are normally superheated at the end of the evaporator. This has two drawbacks: the evaporation temperature must be lower than if superheat was not used (lower COP) and, as liquid and phase changing fluids have much higher heat transfer than gas, superheating the fluid in evaporators also requires a larger heat exchanger. Normally, 10-30% of the heat exchanger is used solely for superheat (Swep 2017). Using the same heat exchanger, controlling the system to exit at 90-100% vapour quality the evaporation pressure and COP will increase (Ericsson 2011). When applying ejectors in a system with a low-pressure receiver, downstream of the evaporators, overfed liquid leaving the heat exchangers is pumped to the liquid storage device upstream of the evaporators.

When several rooms or areas should be kept at various temperatures, they should therefore be placed in such a way that the heat flow is minimized. This means that lower temperature zones should be kept together, the highest and lowest temperature zones should be as far from each other as possible and the coldest rooms would normally take advantage of being placed on the south side of the building on the southern hemisphere, and north side of the building on the northern hemisphere.

Insulation should follow the following guidelines to reduce energy demand, based on results in (Kvalsvik and Hafner 2017):

- Insulation between temperature zones with different temperature should be as high as possible, this saved 69-228 kWh/year/m^2 wall/ 0.01 decrease U-value in a study, depending on the differences in room temperature (ranging from 8-26°C).
- Insulation between ambient and rooms *for which* the setpoint temperature is *lower* than the yearly average ambient temperature should be as high as possible. For a case study (Kvalsvik and Hafner 2017), results for the two coldest storages were (average ambient temperature was 4.7°C):
  - freezer room (T=-25°C): saved 251 kWh/year/m^2 wall/0.01 decrease in U-value
  - cold storage room (T=2°C): saved 23 kWh/year/m^2 wall/0.01 decrease in U-value
- Insulation between ambient and rooms *for which* the setpoint temperature is *higher* than the yearly average ambient temperature should be as low as possible. For the mentioned case study, results for a room to be kept at 18-25°C was that one saved 49 kWh/year/m^2 wall/0.01 *increase* in U-value.

Similar values can be found for roof and floor. What limits how much insulation one can have is of course the costs, and one should thus calculate the yearly energy savings for each room, multiply by approximate energy price divided by COP and compare to the cost of increasing the insulation. Some rooms will use less energy if they have less insulation. The limitation for how little insulation one can use is determined by the peak demands and the cost of these. Less insulation will increase peak demands and perhaps both heating and cooling will be necessary.

It has been stated that the main economics in the energy business of tomorrow lies not in how the energy is provided, but in the ability to store it. Good control for systems with imbalanced heating and cooling demands should involve storage possibilities, both to balance demands and to produce heat and cold when prices are low and/or system COPs are high. From an energy perspective, they should be large enough to store all excess heat and cold for later usage, and well insulated to minimize losses. However, their size and cost limits the economics in saving energy. Too small storage tanks will however prevent some saving that would have been economic. Thus, detailed planning (see also 3.4.2) and simulation to find the most cost-efficient storage sizes and insulation should be performed.

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For an industrial case (Kvalsvik and Hafner 2017), it was suggested to use the fire distinguishing water tanks as a thermal storage, to prevent additional costs. The tanks should be cooled to low temperature and could be be placed underneath the ceiling in the cold storage. Note that many tanks in series is a much better choice than one large, due to stratification and significant reduction in mixing losses. Phase changing materials (PCM) are very space effective storage materials, however, until now demonstrates poor heat transfer. A PCM storage unit has been installed at the University college in Bergen, Norway (Høgskulen på Vestlandet) (Hanne Kauko, Jokiel et al. 2016, Jokiel 2016), but work to improve the heat transfer is still ongoing.

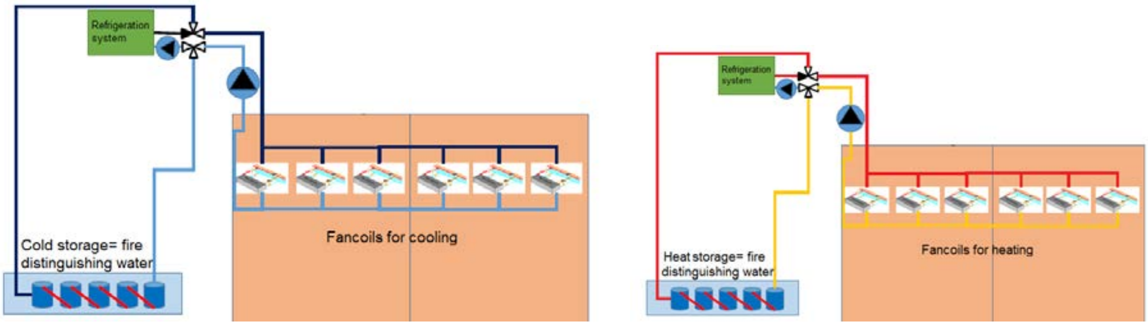

Figure 2: The system using fire distinguishing water as thermal storage, figure taken from (Kvalsvik and Hafner 2017)

It is also an option to store electricity in batteries. Producing batteries causes substantial amounts of emissions, both GHG and other substances which harm the environment in different ways. A comparison of cars concluded that today's most energy efficient fossil fuelled cars are more environmentally friendly than electric cars if the size/battery is large (Ellingsen, Singh et al. 2016). Small battery vehicles were better. Likewise, it might and might not be beneficial to invest in solar power and batteries to store electricity to the night or winter. This depends on the battery's cost, size and energy loss. Charging the batteries will also require a higher installed solar power effect than if batteries were not used, as the installed capacity of solar panels must exceed the demand for electricity during the day. Installing enough solar panels to cover both the peak electricity demand and also charge the batteries makes this solution even more costly. Much of the available sunlight cannot be economically used because it occurs in large amounts during relatively short time. An evaluation will most likely turn out to determine that it is economic to buy a medium sized battery in combination with thermal storage to reduce the peak electricity demand.

3. IMPROVEMENTS FROM BEST PRACTICE

Most energy systems only operate efficiently (in terms of both energy usage and cost) if they are controlled in a good way. Optimal control should include changing temperature setpoints in order to reduce both costs and energy. For cold storage rooms rejecting heat to ambient, the COP will be higher, and electricity prices lower during the night. Hence, one could reduce the temperature setpoint (not in freezer rooms) during the night. As the demand during night is normally low, the load can be increased without requiring higher installed capacity. The room will then have a lower temperature when the daylight comes, for example 2°C instead of the normal 4°C, and less cooling will be necessary during the day as a temperature increase can be allowed. If one can also allow a slight temperature increase, say up to +5 °C, it will be even better. The amount of cold that can be stored depends on the room's thermal mass. If this thermal mass is high, the refrigeration system can be switched off entirely during the peak load hours, or at least operate at reduced capacity, so the peak power limit is not exceeded. This solution is simple, but one should simulate the process first to determine when the system should be switched off or operated at reduced capacities, and how long it will take before cooling at full capacity is again necessary.

Charging at night could also be done by cooling down water/other fluids like PCMs in tanks during the night when there is excess cooling capacity, and then use the cold water to reduce the return temperature of the working fluid after condensation during the day at high ambient temperatures. This will improve the COP during the day, and can reduce the installed cooling capacity. A sufficient number of storage tanks is required,

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as explained at the end of the previous section. Another alternative is to apply a ground condenser (Kvalsvik and Hafner 2018).

For systems with solar PV panels, the task is more complex. The highest cooling demand will normally occur a short time after the solar peak. Now, one can of course use solar panels and get free electricity in this period and accept that the system COP is slightly lower while the electricity is free, but the peak solar power will occur before the peak heating load. Thus, when the available solar power is reduced, the heat demand will still be high and the investment in solar panels and refrigeration equipment follows the required capacity installed. If the equipment shall cover the peak cooling demand with bad COP, it is a larger investment than if system control could be used for peak shaving. Thus, such a system can easily become costly and inefficient. Therefore, the situation should be simulated and weather forecasts used to predict the demands for changing the set-points. Roughly, the strategy should be as follows, also visualized in Figure 3:

1. Cool down building and equipment to the lowest temperature acceptable during the night hours.
2. Switch off/reduce cooling (in the morning) when electricity prices increase.
3. Turn on again when costs drop or own solar power is available; keep a low temperature set-point during the day as long as free solar power is available.
4. When available solar power is less than the required power, use the available solar power, and reduce cooling along with this until the highest permittable temperature is reached. The system should be designed so that this occurs in the evening when it is again chilly.
5. If prices are higher than they are expected to be later in the night, keep the high setpoint until they drop.
6. Start over.

Similar strategies could be obtained for other installations, depending on the situation. Storing electricity should also be considered.

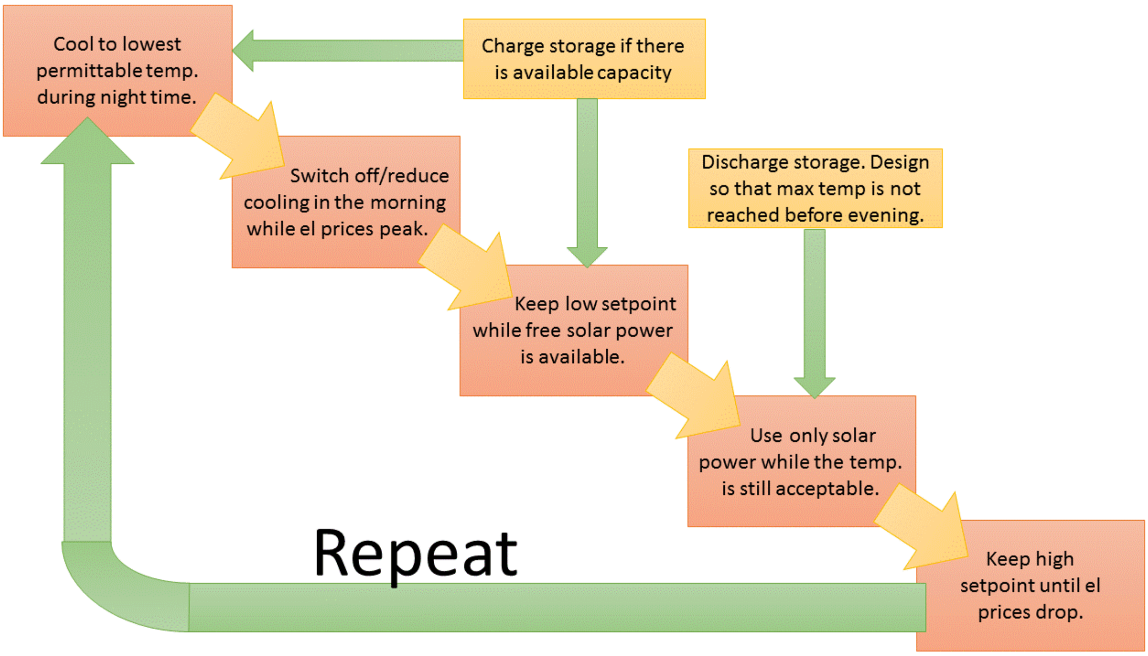

Figure 3: Suggested cooling strategy for energy efficient systems with access to solar power and eventually thermal storage

Due to imbalances between heating and cooling demands, many processes need to get rid of surplus energy or purchase some auxiliary heat. However, other processes/industries have opposite demands, and might have a net demand for what other industries have a surplus of. The mutual benefit of coupling many different industries together in a larger cluster can reduce the primary energy demand for the cluster and also the need for storage in each industry. Companies in Mo Industripark (Mo Industry cluster) for example, are annually saving 400 GWh (Mo Industripark 2017). In such clusters, surplus heat can be sold from one firm to another, which results in zero emission heating for the other firm. Heat should be provided at a lower cost than the

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alternative heat, so that both firms earn money on the solution compared to the alternative (dumping the heat without getting paid for it and purchasing energy at a higher price).

Free cooling can be available some parts of the year. For a cold storage, several weeks every year, the ambient temperature is lower than inside the cold storage, and one could simply circulate the working fluid between the evaporator and condenser without compressing it. In a study of a drying facility in Norway (Michael, Inna et al. 2015), 21% of cooling demand could be covered by free cooling. However, if heat is required by another process, which could be delivered by running the refrigeration system, running the refrigeration system will be a better overall solution.

Changing temperature setpoints and other small and costless changes can be made to reduce energy demand or investment costs. For temperature, this is straight forward. The question is simply: Is the present temperature setpoint really necessary? Could it be changed to another value, which would enable a higher COP or in other ways result in a reduction of the annual primary energy demand?

If situated close to water, or if much water is freely available, using water as a heat source for heat pumps rather than ambient air will be better at cold ambient conditions, and also require smaller heat exchangers. For processes with excess heat and no other place to get rid of it, water cooled condensers will increase COP, either by spraying water into cooling air or onto the surfaces of air-cooled condensers, or even directly into air which is to be cooled. For all cases, the availability of water, permitted temperature change, frost and salt issues must be discussed with authorities/producers, but the techniques have been successfully implemented in several plants where water availability is not an issue.

During the warm summer period, there is normally a surplus of district heat. For companies with cooling demand in the summer, or with very even cooling loads, it is possible to apply heat driven refrigeration by use of absorption heat pumps or by means of adsorption systems. A large unit of the last type is installed at the St. Olavs hospital in Trondheim, Norway, and the district heat supplier delivers cold to the hospital (Åmund Utne and supplier 2016).

It is also possible to apply an absorption chiller. It can reach very low temperatures, and unlike adsorption systems, it applies not only to cooling of air. Its advantage is that it can manage very high temperature lifts (120°C is reported (Ziegler F. and G. 1991)), and it receives and rejects heat at gliding temperature. The COP is normally low (example values for COP are 0.57 and 0.68 for one-stage cooling and 1.2 for two-stage (ASHRAE 2009)), but if the heat source is free or cheap, this is not a problem. It can be used in two ways: cooling at a low temperature level by means of heat from a high one and rejecting heat at an intermediate level or receiving heat at an intermediate level and deliver to a high and a low level.

4. SUMMARY AND CONCLUSIONS

Innovative technologies, like high temperature heat pumps, CO_2 ejectors, evaporative condensers can enhance energy efficiency, reduce greenhouse gas emissions and/or reduce investment and operational costs. Some of these technologies are implemented, some are under development and others still remain at concept level. Table 1 gives a summary of the discussed solutions and an indication of their energy saving potential and costs. Integration of functions is an important step to achieve systems with a lower total cost of ownership. A key point is that no solution fits all plants and industries. Every plant has a unique setting (demands, surroundings, possibilities for integration, free cooling or district heating connection, etc.) and must be considered especially, thus there is not one good solution for all cases.

To utilise most of the current resources and to achieve primary energy savings within acceptable cost and risk frames the following steps have to be made: first reconsidering processes to minimize demand, then collection of data, modelling/simulation, analyses of expected costs/savings for various choices and smart control of processes when in operation. Consulting experts able to perform a thorough planning and simulation of new solutions should be involved to evaluate the different solutions in terms of energy usage, peak demand, costs and GHG emissions. Efficient, integrated systems require smart control and a holistic planning approach. The importance of storage and/or share resources and the ability to use energy when it is available, becomes very important in the future due to the rapid phase-in of highly varying renewable energy sources and prosumers,

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while stable loads and sources are being phased out. An energy storage unit can also remove the need to purchase power when the power prices peak. A highly efficient energy system with low demand will also contribute to the same. These are both the key and the challenges in future energy systems.

Table 1: Summary of energy saving measures and their expected cost and savings compared to today's normal solutions

Suggested action	Investment costs [2]	Estimated savings in energy unless otherwise stated[3]	Comments
Integration	Higher	30-80%	Reported range for drying systems in review articles (Colak 2009a, Colak and Hepbasli 2009b).
Direct systems	Lower	3-33%	Savings are numbers form a study in HighEFF (Kvalsvik 2017).
Temperature zones	Unchanged	NN	Savings are presumably in the same range as for "Right amount of insulation"
Right amount of insulation	Higher/lower	20-70 or 200-250 kWh/m^2 wall/year (chilled/freezer rooms)	Savings are from (Kvalsvik and Hafner 2017).
Changing setpoints, using storages	Unchanged /slightly higher	NN	
Cluster sharing/DH connection	Higher /unchanged	NN	Change in investment costs depends on what the standard is, and there is no given standard in this case.
Free cooling	Unchanged	21% of energy	Saving is from a study of a drying plant (Michael, Inna et al. 2015).
Use of work recovery devices	Higher	15-27% improvement in COP	Given savings are the typical savings for ejectors. These really vary much more (0-50%(Hafner 2014)).
Use of flooded evaporators	Unchanged /lower	16-48% higher COP	According to the reference: *Rizzvi Z and Dr Peter Heggs 2003 Defrosting refrigerators 21th International Congress of Refrigeration, Washington, USA, IIR/IIF: paper ICR0660. "Flooded Circuit cop + 16-48 %"* in (Ericsson 2011)
Reconsider process demands	Unchanged /lower/higher	NN	
Use water to enhance the COP	Unchanged /lower	7% higher COP in a given setting (Visser 2017)	The ambient temperature was 33°C in the study, and the wet bulb temperature 28°C (Visser 2017).
Absorption cooling	A bit higher	≈100% /-200% energy	Requires a very small fraction of electricity (only for a pump) and thus saves nearly all of the electricity demand compared to the vapour compression cycle, yet, it requires much energy from a heat source.

[2] Expected compared to standard solutions
[3] NN=No number known/available

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