EFFICIENT ENERGY SYSTEMS FOR THE DRY-CURED MEAT INDUSTRY

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ABSTRACT

Eight energy systems for dry-cured meat drying were modelled and simulated in Dymola and their energy consumptions compared. The systems included heat pumps, electrical heat, air compression and adsorption. All but an adsorption system were satisfactorily modelled, and a system using CO_2, with an additional heat exchanger and controlled to dehumidify as little of the air as possible, showed the best performance. A similar ammonia system was the second best if excess heat could be utilized, using 8.9 MWh against 5.3 MWh in the simulation. Drying efficiencies up to 190 % were found. Utilization of excess heat and minimizing the fraction of air for dehumidification had large impacts.
Keywords: Heat pump, drying, ham, CO_2, cost analysis

1. INTRODUCTION

To minimize production costs in the energy intensive industry of dry-cured meat, an energy effective drying process is necessary [1, 2]. Dry-cured meat is meat that is salted and dried, often for very long times, to achieve desired aromas and preservation [3]. Many techniques to lower drying time have been performed, but frequently, these either harm the product, drying the meat too hard or increase energy consumption or both [3, 4]. For high quality products, faster drying must be accompanied by faster ripening processes in the meat, which determines the flavour, but this is difficult to achieve [3]. Alternatively, the required drying conditions and time can be kept, but the system supplying them be made as efficiently as possible. Higher efficiency could be achieved by using heat pumps [2, 5], adsorbers [6], reduced fan power [7] or extra heat exchangers [8]. This work considered all these methods and a system compressing air for high-temperature condensation. As ammonia is a usual medium and CO_2 a promising one [9], both were included.

2. METHOD

Modelling and simulation of 5400 hams in a drying tunnel with six successive sections, each with uniform conditions, were performed in Dymola. To ensure satisfactory quality, real drying conditions, 13 °C and 68 % relative humidity, were used. Simulation lasted until all hams had lost 35 % of their original weight of eight kg assuming a loss of 3.5 % before drying [3]. To model the meat being dried a model developed by [10] was used. Its parameters were based on experiments by Inna Petrova and Michael Bantle with medium salted ham, described in [11]. An energy system similar to a system at an existing plant was modelled. All results were compared to this basic system, denoted BS. It used refrigeration with ammonia to condense vapour from the moist air, and electrical heating, as seen in Figure 1.

The drying involved a closed air system, because otherwise, energy is rejected to ambient, and closed systems gives higher quality [2] A glycol circuit exchanged heat between the ammonia evaporator and the air, as ammonia is toxic. Excess heat was rejected to ambient. Heat pump systems use some of this excess heat for reheating the air. These systems were abbreviated HPS (which was otherwise equal to BS) or HPSX followed by a number. All these used ammonia and required an additional glycol circuit for heating the air. See also Figure 3.

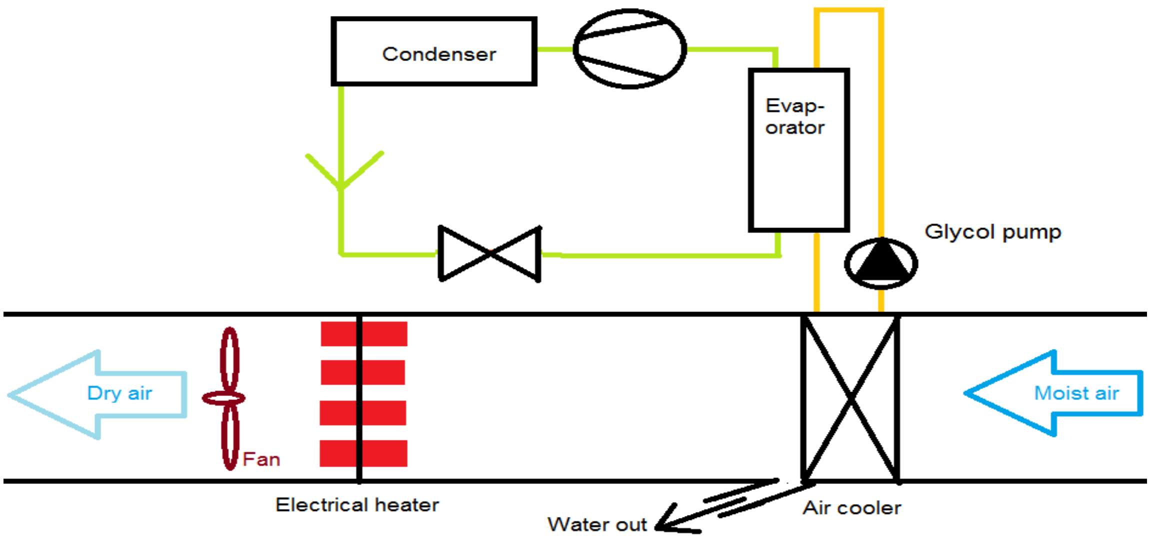

Figure 1. The basic system involved cooling by an ammonia and glycol system for condensing water, rejecting surplus heat to ambient and electrical heating.

Using an extra heat exchanger between cooled, dehumidified air and the uncooled, wet air, some free cooling and heating is obtainable [8]. Systems denoted HPSX plus a number, which are further explained in table 1, used such an extra exchanger. Some of them dewatered only a part of the drying air to save energy, but this also requires condensation at a lower temperature to remove sufficient amounts of water from this smaller stream. Studying a Mollier diagram, required cooling and heating was found for all systems. Cooling all the air, it should be cooled to 7 °C if it was saturated before cooling. Systems cooling a fraction of the air, cooled it to 1 °C if it was saturated, stay above the freezing point of water. The smallest fraction of saturated air one could dewater by cooling to 1 °C is ≈37 %, and was done in HPSX37. Less cooling is required for unsaturated air, and so the temperature for condensation rises for drier air. Eventually the same temperatures can be kept with a lower air fraction. The last principle was applied in HPSX1 and a system denoted CO2S, keeping the lowest air temperature constant by decreasing the airflow for dehumidification for drier air.

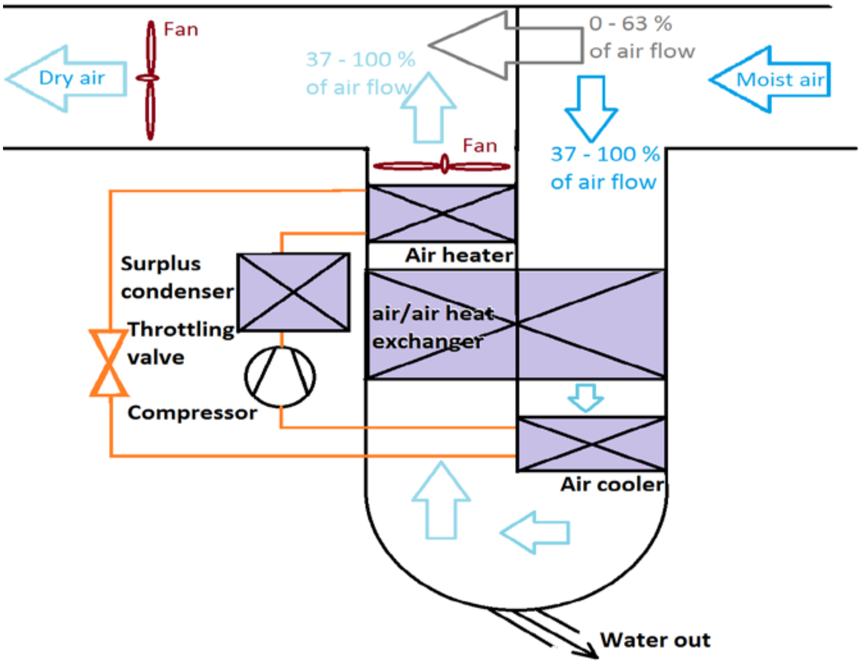

Figure 2. The CO2 system, CO2S cooled and heated the drying air at the evaporator and condenser.

CO2S was a system equal to HPSX1 except that it used CO_2 as refrigerant, and avoided the glycol circuits and extra temperature differences, see Figure 2. This should lower its power consumption. Another idea to reduce power consumption was to avoid the heat pump, see Figure 4, and simply compress the air, increasing the dew point and allowing condensation at a higher temperature. Cooling could then be achieved by heat exchange with ground water at 6 °C [12]. This compression system, CS, compressed only a fraction of the air, decreasing with drier air, to avoid excessive drying. The high pressure was then kept constant. Calculations showed that an appropriate operation point would be compressing 1.01 kg air per second to 3.0 bars at saturated inlet conditions. Pressures of 2.5 and 3.5 bars were also investigated for comparison.

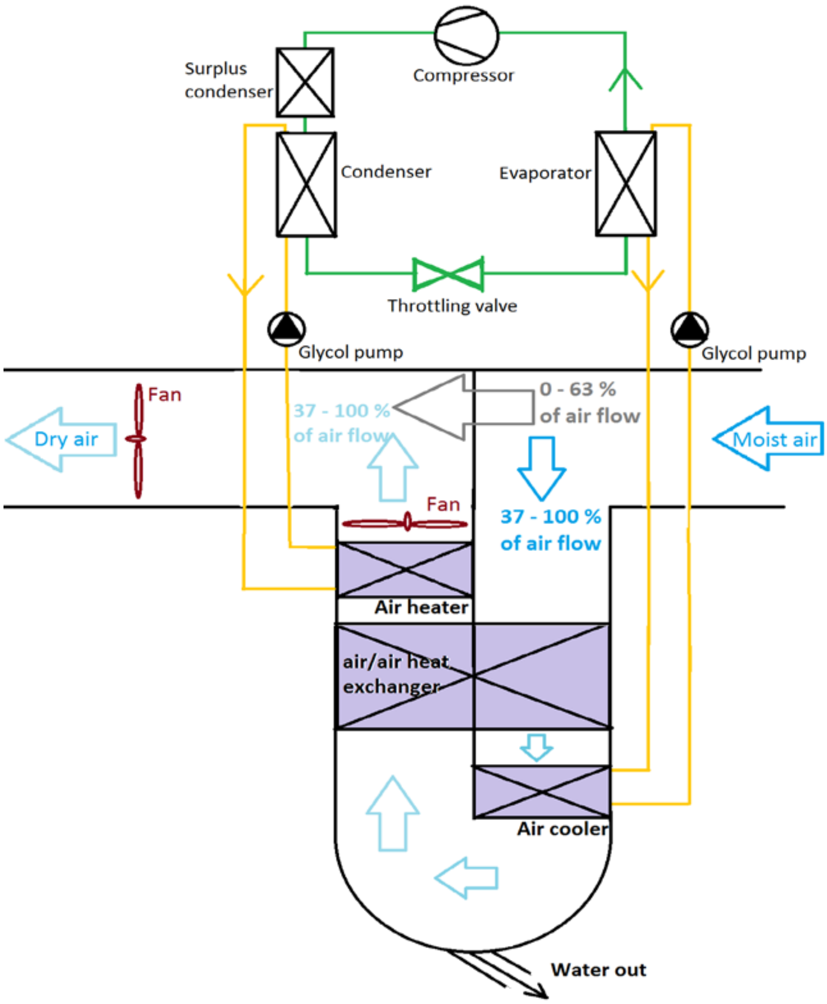

Figure 3. The HPSX systems involved cooling and heating one part of the air (blue arrows), and bypassing some of it (grey arrow). The grey arrow would have zero flow in HPSX100; 63 % in HPSX37; an increasing fraction in HPSX1 and CO2S and zero flow in HPS. In HPS the air-air heat exchanger would not be present. In CO2S, the air heater and cooler would instead be condenser and evaporator in a CO_2 heat pump.

Table 1. Overview over the energy systems considered, where the adsorber system used a CO_2 heat pump and all heat pump systems except CO2S used an ammonia heat pump and glycol circuits for heat transfer

System name	Description
BS	Basic system with refrigeration for cooling and electrical heating
HPS	Heat pump system with a heat pump for both cooling and heating
HPSX100	Heat pump system with extra heat exchanger, dehumidifying 100 % of the air
HPSX37	Heat pump system with extra heat exchanger, dehumidifying 37 % of the air
HPSX1	Heat pump system with extra heat exchanger, always cooling to 1 °C
CO2S	Best performing ammonia system made with CO_2 heat pump, without glycol
CS	Compression system where air is compressed to condense water
ADS	Adsorption system using Econosorb and recovering heat in a heat exchanger

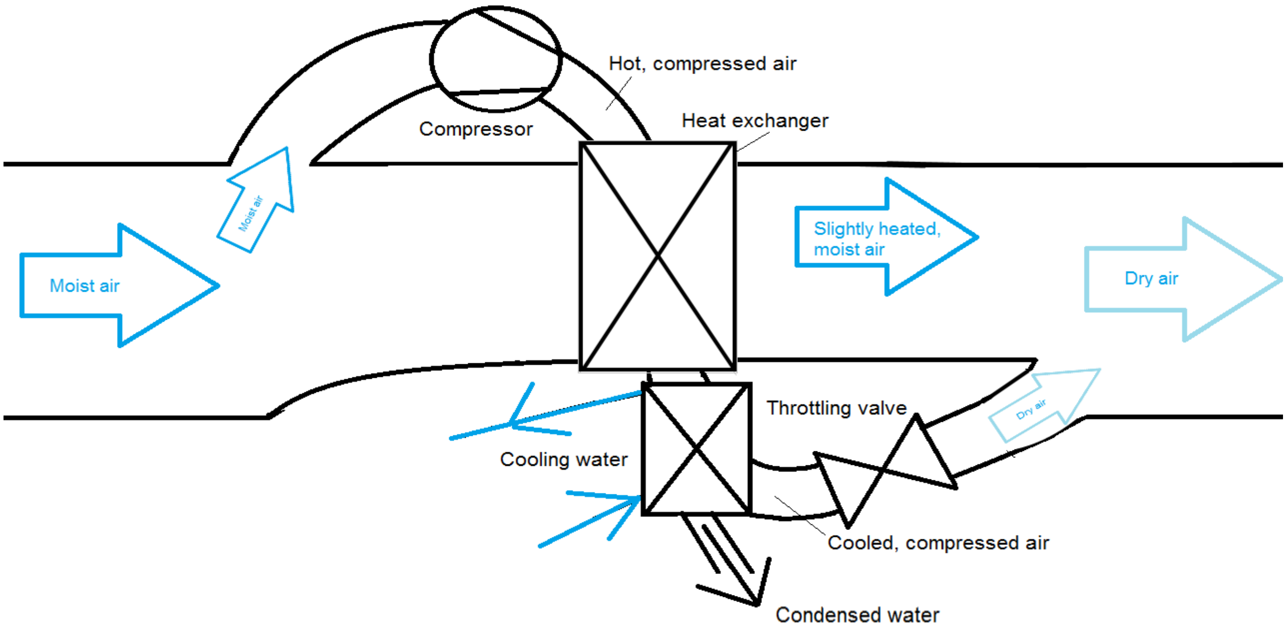

Figure 4. The principle of the air compression system, CS, where a part of the moist air is compressed, heats the uncompressed air and is cooled in an air-water heat exchanger before throttling and remixing of air

A final system used an adsorber with specifications from [13], assuming a correction factor of 0.8. It involved adsorbing the air moisture to one part of a rotating disc, comprised by an adsorbing material. The other part of this wheel was dried by an air stream at 55 °C, taken from ambient, regenerating the material. The principle is shown in Figure 5. The heat pump was a transcritical CO_2 heat pump. This system was modelled with the simplification that the adsorber worked as desired and reported, provided the regeneration air was always 28.2 °C, the initial value, after regeneration.

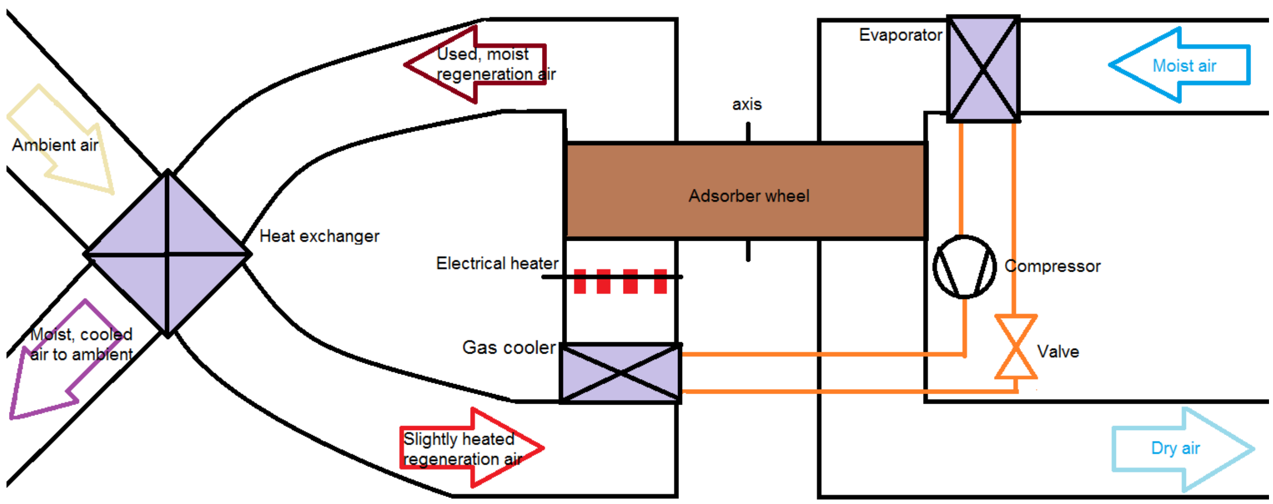

Figure 5. The modelled adsorber system, ADS, based on Econosorb from AG [6]: An additional air-air heat exchanger was added to recover heat. From the upper left corner, ambient air enters the exchanger, is partially heated and then further heated by a heat pump and eventually an electrical heater and desorbs moisture in the right part of the wheel, which rotates about the drawn axis. It preheats incoming air before it exits. The moist drying air, in the upper right corner, is cooled by the heat pump, some moisture condenses, remaining moisture is adsorbed in the wheel.

Ambient temperature was modelled from climate data [14] from Trondheim, Norway, by fitting a curve to the data, as seen in Figure 6. Heat pumps had one stage compression, internal heat exchange after condensation and before compression and varying isentropic and volumetric efficiencies, given in the subject TEP4255, taught by Prof. Eikevik, at NTNU the spring 2014. Pressure drops for refrigerants were neglected.

Pressure drops for air were modelled by the Haaf model in Dymola. For glycol and water, a quadratic expression, proportional to 0.556, fitted to values from [15] was used. Pressure drops occurred in heat exchangers and in a 2x100 m long (to and from) air distribution system with pipes 1 m in diameter. Fans and pumps had efficiencies of 0.6 and 0.4, in that order. Losses were added to the fluids' energy balance.

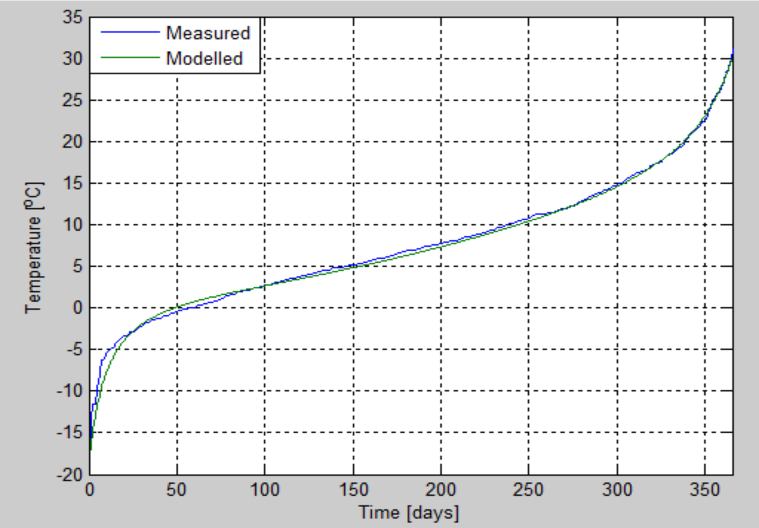

Figure 6. Measured and modelled outdoor temperature, based on daily minimum and maximum temperatures at Voll, Trondheim, Norway [14], from fourth of February 2014 to third of Feruary 2015: were used.

All heat exchangers were specially designed for each case, using the method log mean temperature method when possible, and the NTU method otherwise, both described in [16]. The methods give the same answers, so no inconsistency resulted. A temperature difference of 7 °C was used except for at the worst operational conditions, were 5 °C was allowed, mainly to avoid too high pressures, and in the air-air heat exchangers in heat pump systems. In the latter ones, a difference of 7 °C was not always obtainable due to the inlet temperatures, and 1.7 °C was used consistently instead. Details are found in [17]. A cost analysis for how large investments would be profitable was also performed, assuming a discount rent of 7 % and an energy price of 0.65 NOK kWh^{-1}. Savings in terms of energy and money per year were calculated relative to BS, and investments with payback times of one to three years found.

3. RESULTS

Table 2. Resulting energy flows and improvements compared to BS: The total energy was E_{tot}, energy for compression E_{compr}, and energy for heating and cooling the air, E_q and E_{cool}. SMER is the specific moisture extraction ratio, or kg evaporated water per kWh used. Three results are given for the compression system; CS2.5 compressed the drying air to 2.5 bars; CS3.0 compressed the air to 3.0 bars and CS3.5 to 3.5 bars.

System:	E_{tot} [MWh]	E_{compr} [MWh]	E_{cool} [MWh]	E_q [MWh]	SMER [kg water kWh^{-1}]	Efficiency	Improvement
BS	69.64	6.54	60.60	58.13	0.21	15 %	0 %
HPS	21.05	10.23	60.55	54.63	0.70	48 %	70 %
HPSX100	17.25	7.87	48.51	43.68	0.85	59 %	75 %
HPSX37	14.88	4.68	29.98	24.50	0.99	68 %	79 %
HPSX1	8.93	4.39	22.66	22.01	1.65	113 %	87 %
CO2S	5.32	3.81	25.13	23.88	2.76	190 %	92 %
CS2.5	196.19	194.92	194.71	0.00	0.07	5 %	-182 %
CS3.0	192.27	191.00	190.76	0.00	0.08	5 %	-176 %
CS3.5	192.69	191.42	191.15	0.00	0.08	5 %	-177 %
ADS***	27.60	6.63	26.54	52.12	0.53	37 %	60 %

***Preliminary result, model not entirely completed

Required energy per kg of produced ham in BS was 2.58 kWh, or ≈68 % of the average value for a real plant, 3.79 kWh kg^{-1}. The used amounts of groundwater in the compression system, listing values corresponding to from the lowest to the highest pressure were 3.01, 2.83 and 2.16 tonnes. Results were reported as required energy, drying efficiency, and SMER. Efficiency is the ratio of energy to evaporate water from a product to the total amount of energy used, typically 0.35-0.40 for hot air drying and 0.95 for heat pump drying (Jon and Kiang, 2016). SMER is specific moisture extraction ratio, kg of water evaporated divided by energy needed, typically 0.12-1.28 for hot air and 1.0-4.0 for heat pump drying.

4. DISCUSSION

Best results were obtained for CO2S, which performed 40 % better than the second best, HPSX1. Avoidance of extra temperature differences with glycol was probable the main reason for the large difference. Both these dehumidified an as small part of the airflow as possible, and HPSX37 performed better than HPSX100, thus this seemed to be important for high efficiency. The effect of changing refrigerant in itself cannot be seen from the results.

The result for BS was lower than for a real plant, probably because of the near ideal operation in simulation, and possibly wrong assumptions on efficiencies, air distribution systems and temperature differences. Upgrading from BS to HPS, required energy was reduced by 70 %, similar to a result reported by Strømmen [18] in a review by Colak and Hepbasli [5]. Most energy savings reported in this review were lower, normally 30-50 %, but they also compared heat pump drying to hot air drying, not to BS, which involves cooling as well as heating, and so a higher improvement should be expected here.

SMER and efficiency for BS was also lower than typical values for hot air drying, shown in Table 1. Inclusion of pressure drops, the low temperature, long drying time and large airflow could also be reasons for this, as most of the heat pump systems also had lower SMER and efficiency than the typical values. CO2S and HPSX1 on the other side, had high efficiencies and typical SMER values, but not as high as the highest reported by [19].

Table 4. Calculated savings or investments that can be repaid in payback times of one to three years, compared to BS, assuming the discount rent is 7 %, and the price of energy 0.65 NOK kWh^{-1}.

System	Required energy [MWh]	Saved energy [MWh $year^{-1}$]	Saved money [NOK $year^{-1}$]	Investment [NOK] that can be repaid in:		
				1 year	2 years	3 years
HPS	21.05	145.8	94 753	88 555	171 316	248 663
HPSX100	17.25	157.2	102 164	95 481	184 715	268 111
HPSX37	14.88	164.3	106 777	99 792	193 055	280 217
HPSX1	8.93	182.1	118 369	110 626	214 014	310 639
CO2S	5.32	193.0	125 418	117 213	226 758	329 137
ADS	27.60	126.1	81 971	76 608	148 205	215 117

A cost analysis resulted in Table 4, and showed that the differences in possible investments between the heat pump systems using ammonia were relatively small, but the simulation results were valid for 5400 hams of initially eight kg each. After drying the total weight of all hams were 26 987 kg. For larger production, one must scale up these numbers accordingly. Because BS used less energy than the real plant, the values shown are probably a bit low. One should perhaps multiply by a factor 3.79/2.58≈1.47. This says something about uncertainty for the results. Only results for systems requiring less energy than BS were included.

Most systems had surplus heat, which was dumped to the surroundings. An energy efficient plant would rather use it for heat demands, like heating tap water, if possible. In this case, subtracting the excess heat, all systems but ADS would have other results, shown in Table 5.

Table 5: Savings if excess heat can be utilized, equivalent with profitable investments, shown for payback times of one to three years, assuming a discount rent of 7 % and an energy price of 0.65 NOK kWh^{-1}.

System	Required energy [MWh]	Saved energy [MWh $year^{-1}$]	Saved money [NOK $year^{-1}$]	Investment [NOK] that can be repaid in:		
				1 year	2 years	3 years
HPS	4.90	194.2	126238	117980	228241	331290
HPSX100	4.55	195.3	126916	118613	229467	333068
HPSX37	4.72	194.8	126593	118311	228882	332219
HPSX1	3.90	197.2	128195	119808	231779	336424
CO2S	0.26	208.1	135281	126431	244591	355021
CS3.0	1.51	204.4	132855	124163	240203	348652

In this case, CS was actually the second best system. Only the best result is shown as the results were nearly identical. This system would also be fair simpler, probably cheaper than the others, and avoid refrigerants and their environmental concerns [9]. It also reached higher temperatures than the other systems, ≈145 °C against about 80-120 °C in other systems. The quality of the surplus heat is not shown in any of these calculations, and perhaps an exergy analysis would be more appropriate. It did however, require a low groundwater temperature, and might only be applicable in temperate or colder climates.

An efficient plant would heat tap water by a heat pump, though, not electricity, thus, only a fraction of the heat should be subtracted. Assuming heating with COP=4, then only ¼ of the energy should be subtracted, giving values for E_{tot} [MWh] of HPS: 17.0, HPSX100: 14.1, HPSX37: 12.3, HPSX1: 7.7, CO2S: 4.1 and CS: 144.6. Thus, the value for CS is again higher than that of BS, and this system is only economical if heat pumps should be avoided. However, utilize surplus heat resulted in savings of significant sizes.

The adsorption system was not entirely completed, but a preliminary result is shown. The heat demand for the regeneration air was high, and designing the system, it was assumed that much of this heat could be taken form the drying air. However, as the drying air became less moist as the process proceeded, the same amount of cooling resulted in excessive condensation of vapour before the adsorber. Too dry final conditions, and total energy needs of ≈23.9 MWh, were achieved unless more heat was supplied electrically, which increased the energy demand to 27.60 MWh. As simplifications were made, the obtained results probably differ somewhat from the true value, but using the rated total power, 10.3 kW, and assuming that it was run 60 % of the time due to the normally applied on-off operation, total energy should be 10.3 kW · 0.6 · 1.4e7 s ≈24 MWh. Hence, the obtained results seemed to be in the right range. If excess heat could be utilized, the energy required should be 85-99 % lower to be equally good as CO2S, depending on whether one fourth or all of the heat was subtracted.

Whether a new plant should be built or an existing upgraded determines which investments would be good. Plants using ammonia cannot use the same equipment with CO_2 in it instead, due to its much higher pressure. The higher density of CO_2 means that its equipment would be smaller, and avoiding the glycol, new plants should be built with CO_2, as this would be more efficient and perhaps cheaper to buy. Existing plants using ammonia should rather upgrade stepwise to better ammonia systems. Both solutions should utilize surplus heat if possible. One efficient but simple and inexpensive change that any system could implement is to dehumidify as little of the air as possible. However, one should also evaluate the adsorber more properly than managed here before making any decision.

5. CONCLUSIONS

The highest efficiency was obtained for CO2S. Avoiding extra temperature differences decreased energy needs by 40 %. Utilization of excess heat and dewatering as little air as possible were also important ways to decrease energy needs. Heat pump drying is efficient, as latent heat can be recovered, and efficiencies up to 190 % were achieved. To compete with this, an adsorber must also use a heat pump. A preliminary result indicated it was no better than heat pump systems at the applied conditions, but this system was not completed. The advantages of heat pump drying would increase even more if surplus heat could be used. Compressing the air showed poor results unless surplus heat could replace electrical heating, which would rarely be relevant.

6. FURTHER WORK

Realization of the systems must be further investigated. Ice formation and use of CO_2 close its critical point could bid on challenges. Because utilization of excess heat had a great impact, an exergy analysis should be carried out. Modelling of the adsorption system should be completed, and data on real adsorbers collected.

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