Final report

1.1 Project details

Project title	PowerUp
Project identification (program abbrev. and file)	EUDP J.nr. 64018.0556
Name of the programme which has funded the project	EUDP Energieffektivitet
Project managing company/institution (name and address)	Weel & Sandvig – Energy and Process Innovation Diplomvej 377 DK-2800 Kgs. Lyngby
Project partners	Equinor Refining Denmark Nordic Sugar Nykøbing Dansk Salt (Nouryon) Arla Foods
CVR (central business register)	27255817
Date for submission	30.06.2020

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1.2 Short description of project objective and results

Formålet er at undersøge potentialet for elektrificering af industrien ved hjælp af mekaniske eldrevne højtemperatur-varmepumper med henblik på at reducere anvendelsen af brændsler og den lokale udledning af CO2. Det teknologiske stade for industrielle højtemperatur-varmepumper er undersøgt og potentialet for at indføre teknologien i industrien er undersøgt gennem nærmere analyser hos fire danske procesvirksomheder. På basis heraf er der lavet en opskalering af potentialet i industrien. Endelig er der en kort beskrivelse af mulige virkemidler for at få teknologien udbredt i større omfang samt risici i forbindelse med at investere i teknologien.

The purpose is to investigate the potential for electrification of the industry by means of electro-mechanical high-temperature heat pumps in order to reduce the use of fuels and local CO2 emissions. The technological state of industrial high-temperature heat pumps is described and the potential for introducing the technology into the industry has been investigated through detailed analyses at four Danish process companies. On this basis, the industrial potential has been scaled-up. Finally, there is a brief description of possible means of increasing the technology widespread use and the risks associated with investing in the technology.

1.3 Executive summary

In the PowerUp project the potential for high temperature electro-mechanical heat pumping in the industrial sector is investigated. There is a political agenda that the industry should be further electrified in order to reduce its CO2 emissions. With this investigation we conclude that substantial and cost efficient reduction of CO2 emission can be achieved by high-temperature heat pumping among others based on turbo-compressor technology. However, we also claim that heat pumping with high temperature lift will not be applied to a wide extent before there is a clear and predictable long-term economic incentive to apply this technology. A possible way to establish such economic incentive is steady rising taxation on all CO2 emission fossil as well as biogenic (biogenic with lower taxation). Compared to traditional heat supply by boiler or furnace, high temperature heat pumping is a more advanced technology, can be more complicated to operate (but not in all applications) and can limit the operational range of the process supplied.

Case studies

The project is based on four case studies, all of which have industrial processes where high temperature heat pumping is relevant. Studies of opportunities taking into account the individual companies' requirements and eventual reservations are applied. Budget economy based among others of price quotations of compressors etc. are established. From these results and experiences, we have up-scaled the techno-economic potential on European level.

The general results indicate that cost of electricity in Danish industry is roughly twice the cost of heat or steam meaning that the required heat pump performance factor (COP) is roughly two to balance the variable cost for upgrading excess heat with the present heat cost. Rising cost associated with all CO2 emission, will lower the required COP factor.

The specific cost for heat pump installations varies a lot and can be expressed in terms of e.g. cost per power consumption or cost per heat delivered. The cost depends on many parameters like compressor technology, producer, refrigerant, temperature of heat source and sink (temperature lift), direct or indirect integration, requirement of process modifications, standardized modular system in large numbers or tailor made single application etc.
Besides the cost for the heat pump installation itself, the economics in heat pumping depends on a number of parameters. Some important parameters are; price difference be-

tween electricity and cost related to combustion of fuel, the COP of the heat pump installation, annual operating hours, and whether or not the investment cost for the heat pump installation is considered as an add-on investment or as a substitution of an alternative investment e.g. in a new heating system (furnace or boiler).

Among others, insufficient economic incentive means that heat pumps at very high temperatures and temperature lifts are still quite limited in numbers. Consequently, equipment is typically tailored for specific applications and implies besides considerable engineering costs also high production cost due to small production series of equipment.

For high heating rates and high levels of pressure and temperature compressor technology designed for oil & gas industry can be attractive (e.g. for large steam dryers). High-pressure turbo-blowers is more common and according to our investigation more cost effective for MVC at lower temperature and pressure levels.
Untraditional heat pump technology like reverse Stirling engine is best suited for moderate heat demands with high temperature lifts but consequently the COP is rather low and as the Stirling engine is still relatively costly, at present the business cases seems rather limited.
Traditional heat pump technology, derived from the cooling industry, still has limited applications delivering heat above 100 °C.

Up-scaling of potential
Up-scaling of heat pumping potential is difficult as many factors are involved in the successful installation both with respect to economics and operation.
Based on an inventory (by P. Nellissen and S. Wolf, Ref. 1) of sector wise process heat demands in the temperature range from 60°C to 200°C, we have roughly estimated the potential for industrial heat pumping in 33 European countries to be 81 GW, assuming that 65% of the involved heat demand will be supplied by heat pumping.
We consider the target achievable by installation of approximately 103000 heat pump units corresponding to an average heat pump capacity size of approximately 800 kW of delivered heat. The remaining heat demand is assumed supplied by improved heat integration or considered economic non-feasible in the short term. The potential for reduction in CO2 emission is estimated to 100 Mill. tons annually.
The estimated target for high temperature lift heat-pumping is considered economic feasible in a “carbon neutral economy”, where the cost associated with emission of CO2 into the ecosphere is balanced with the marginal cost for removing it somewhere else. Heat demands above 200 °C is not considered in this up-scaling, but will also have a high potential in a scenario with balanced cost of CO2 emission and CO2 removal.

1.4 Project objectives

This project is proposed in conjunction with a political agenda that the industry should be further electrified in order to reduce its CO2 emissions. Substantial and economically efficient reduction of CO2 emissions can be achieved by electrically powered high-temperature heat pumping among others based on turbo-compressor technology.
Weel & Sandvig saw this opportunity and development trend in the smaller size technology years ago. Meanwhile we have achieved a lot of experience in projects that relate to the maturing and use of high-speed turbo-compressor technology. This high-speed technology is now entering the commercial market among other high-temperature technologies and therefore, it is relevant to elucidate opportunities and potentials in a detailed study and distribute results and knowledge to relevant decision makers.

1.5 Project results and dissemination of results

It is widely anticipated that heat pump technology delivering heat above 120 °C is not yet commercially available. However, turbo-compressor technology, suitable for large heat pumps and capable of pumping heat beyond 250 °C, has been commercially available for a long time (among others in gas and chemical process industry). However, it is important to emphasize that technology or equipment, ready to use for an application, cannot be expected on the market before there is some degree of certainty for a minimum market potential for such equipment.

One important reason for the rather limited installations, so far, is that historically in most places cost for electricity has been too high to make heat pumping competitive to heat generated in fuel-fired boilers or in combined heat and power plants. Especially when pumping heat with high temperature lifts and at high temperature levels, so far this has not been competitive to heat supplied by combustion of fuels eventually in combined heat and power. Low CO2 emissions related to grid electricity and requirement of substantial reduction in CO2 emissions driven by high cost penalties associated with emission of CO2 can make electric heat pumping the most competitive heat supplier for many industrial processes.

When it comes to smaller high temperature heat pumps based on turbo-compressor technology, the requirement of very high rotational impeller speed has hitherto been a barrier for such applications. However, during the recent decades the technological developments in high-speed electric motors and high-speed bearing solutions now seem to make it possible and commercially interesting for usage with turbo-compressor technology also on much smaller industrial heat pump solutions at high temperatures.

Displacement compressors (e.g. reciprocating, screw, scroll or roots) traditionally used in the cooling industry are also gradually able to operate with a higher condensing temperature level (more manufactures can supply up to about 90 C) and is in some cases relevant to use as a first temperature lift in high temperature heat pumping (here considered as beyond 100 C). At least one manufacturer (Ochsner) can operate up to 130 C.
Traditional compressors can pump heat to a higher temperature level (currently 120 C) when used in a hybrid heat pump bases on an absorption compression cycle (HAC-HP) of water and ammonia as a mixed refrigerant. However, in this application the heat is released with a temperature glide.
The reverse Stirling cycle is also in the market capable of pumping heat with a high temperature lift in one stage. One manufacturer (Olvondo) can supply heat to a temperature level of up to 180 C. The specific cost of equipment is high and the COP often not much higher than 2, making it very difficult to achieve an attractive economy without subsidy.

Heat pumping for evaporation
Heat pump in terms of mechanical vapour compression (MVC) is in many cases a more profitable solution than fuel based heat generation combined with a multistage evaporation plant. However, retrofit of a multi-stage evaporation plant with an existing heat supply system to MVC has longer payback time and may not be economical attractive. The efficient integration of an MVC may require rearrangement of steam extraction and preheating system in order to have sufficient and stable steam flow to the steam compressor suction side.

Heat pumping for drying or heat demands having a long temperature glide
MVC in drying processes often requires considerably higher temperature lift than in evaporation systems. If the heat demand of the drying process comes with a temperature glide (e.g. drying in hot air) and the heating is applied pressure stage wise by a number of condensers in series, the mass flow in the upper stages will decrease considerably. Stage wise extraction of working medium will reduce the volume flow dramatically in the upper stages and may imply that no turbo-compressors are available or appropriate for the upper stages.
At the same time the marginal COP is rather low, which means that the marginal savings is low as well and consequently the economic incentive is decreasing rapidly for high temperature lifts.
Efficient heat pumping can be achieved in such applications by dynamic oil-free compression of a refrigerant that do not tend to superheat during compression. Heat can be released with

a suitable temperature glide during cooling of the super-critical hot gas, by optimizing compressor discharge pressure and suction superheat. We call it "hot gas temperature profile shaping" to fit the temperature profile tightly with that of the heat sink. We consider the solution a promising application also for high-speed turbo-compressors in the rather low heat load range.

Variable cost of heat

In general, the higher the total temperature lift required of heat pumping the more work (electricity) is required and more costly is the heat pump equipment. Economics in terms of investment and operating cost limits the feasible temperature lift.

Cost of electricity is approximately twice the cost of heat from fuels in the Danish industry. This means that heat pumping, for upgrading excess heat at a lower variable cost than present heat cost, is feasible when the COP is higher than approximately 2.

The efficiency of a heat pumping process can be evaluated against the temperature lift relatively to the absolute temperature level. In Figure 1 (left), the possible temperature lifts of excess heat (heat source) in order to balance the variable cost for heat pumping for two values (0.55 and 0.65) of process efficiency (Carnot for constant temperature level and Lorenz for temperature glide) are shown as function of the evaporation temperature (temperature of excess heat).

The possible condenser temperature with Eta_Carnot = 0.65 is shown (to the right) together with the highest temperature of the heat sink (heated from heat source temperature) with Eta_Lorenz = 0.55. E.g. a process can with a COP = 2 be heated up from 30 °C to 285 °C with a heat pump having a Lorenz efficiency of 0.55 upgrading excess heat at 30 C. MVC as single- or multistage compression often can achieve Eta_Carnot between 0.65 and 0.75.

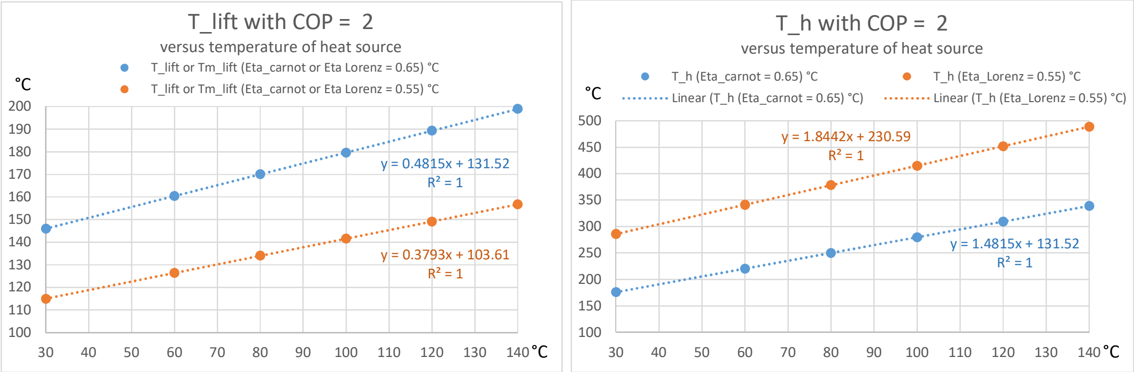


Figure 1. Possible temperature lift and heat sink temperatures of heat pumping with COP=2. "Carnot" for constant heat sink temperature and "Lorenz" assumes in this case temperature glide from T_h to temperature of heat source.

Potentials in case studies

Diary industry: MVC assisted evaporation is often the most economic solution today concerning new plants all depending on cost of electricity versus fuel of course. In the longer term we expect almost all evaporation to be supplied by heat pumping.
The cost for retrofitting existing multistage evaporation plants to heat pumping is evaluated to be economical feasible in most cases. The achievable COP of a MVC heat pump compared to multistage evaporation is rather limited and often below four. If retrofit and installation is costly, the economy might be unattractive.

High temperature heat demands such as UHT heat treatment (e.g. by steam infusion and flash-cooling for minimizing the residence time at elevated temperature) and spray drying implies heat pumping with high temperature lifts. In addition, the individual process heat demands are in many cases not that large meaning that supplying the heat demand in UHT processes and the last part of spray drying requires relatively expensive heat pump equipment not being on-the-shelf. Consequently, the installations will be relatively expensive. In addition, the COP will be rather low as the temperature lift is considerable. Installation cost is also considered rather costly, unless heat pumping is integrated as part of a new turn-key plant installation.

New standardized heat pumping technology (e.g. based on small sized high-speed directly driven turbo-compressors) is considered necessary in order to make such installations economically attractive.

Salt industry: Almost all (small part for drying) heat demand relates to evaporation having a considerable boiling point rise in the salt solution. Nevertheless, the evaporation plant can be cost efficiently supplied with heat from MVC. Especially this is the case in new plant installations, where the design is optimized for integrated MVC.

In existing multistage evaporation plants with low condenser temperature, the required temperature lift (pressure ratio) will be very high requiring multi-stage steam compression or rearrangement of evaporation stages. Consequently, the cost for integration of MVC will be rather high implying a rather long payback time.

In case of evaporation in six stages heat pump may not be applied with a COP much higher than 2.5 compared to present heat demand. Electricity price is essential in the economy of such high-lift heat pump application. No financial support can be expected from present Danish energy saving program due to the low COP (no support to heat pumping with a COP lower than 2.5).

The present case can supply steam from three sources (CHP-CC, steam boiler fired by natural gas or steam boiler fired by wood chips). At present levels of cost of commodities and cost for emission of CO2 the heat supplied from combustion of natural gas in the steam boiler seems to be economically feasible to substitute with heat pumping. The CHP plant is normally not in operation due to low own consumption of electricity and low electricity price for export.

Full heat pumping also substituting the steam generated in the wood chips fired boiler is economical feasible if some cost penalty is applied to CO2 emission from combustion of biomass. E.g. in case the penalty of CO2 emission from biomass combustion is half the cost penalty of CO2 emission originated from fossil fuels the situation is opposite. Now the biomass fired boiler is the first boiler to be outperformed by heat pumping in terms of variable cost associated with steam generation.

Sugar industry: Sugar industry has traditionally operated with high levels of heat integration in the evaporation and crystallization processes. Nevertheless, all heat demand for evaporation and crystallization can be supplied energy efficiently and cost effectively by implementation of heat pumps. Drying of beet pulp can be supplied as well by MVC heat pumping using superheated steam dryer technology.

In the present sugar factory case study we have estimated that total heat pumping on the sugar process (not including need for pulp drying) can be implemented with a COP as high as 4.5. The payback time is estimated roughly to be 4.3 years (excluding any financial support) and 3.1 years including financial support from “Energy savings program” using a specific price of 350 kr/MWh energy saving during first year.

Oil refinery: High cost associated with installation and retrofit of equipment is often seen or claimed in this sector. Large organizations, high security and risk levels in processes involved are probably major reasons. High heat integration level and many cross-linked processes may be other reasons. In addition, the complex process plants most likely requires a lot of engineering in advance of retrofitting a process in order to document savings and investigate operational performance before physical operation. Finally, short time slots for installation (during plant inspection, cleaning and overhaul) and high cost associated with processes not operating properly after retrofit are also possible reasons.

Traditionally refineries have used low cost byproducts as fuels for the process heating. This together with the high cost associated with retrofitting and installation of equipment means that heat in existing plants often is transferred in heat exchangers with rather large temperature differences.

The consequences of the above is that heat pumping most likely requires very high temperature lifts in order to significantly substitute combustion of fuels for the heat supply or at the same time requires retrofit of the existing heat exchanger system.

Heat integration, as a policy, may be restricted keeping process blocks completely separated. Thereby missing the potential for tight heat integration utilizing excess heat from one block in another one.

Taking into consideration all of the above we find that considering large scale heat pumping in the oil refining sector at least at the same time one should consider a more tight heat integration.

Extensive heat pumping with very high temperature lifts might be possible using a reverse Brayton cycle. As the required mean temperature lift will be high so will the required power (COP can be expected between 1.5 and 2). We consider such implementation will require high cost associated with CO2 emission to be economical feasible, but for sure so do e.g. joule heating or use of electro-fuels.

Examples of heat pump applications on processes and potential share of heat supply

In Table 1 examples of heat pumping proposals or theoretical solutions to processes relevant in the case studies are briefly presented.

Case	Process to be supplied by heat pumping	T_source °C	T_sink °C	T_lift mean °C	Heat pump COP	Share of heat demand		Cost balance CO2* DKK/tons CO2	TR level
1	New evap. plant: 1-effect MVR, 2-effect TVR vs 5-effect TVR	(not considered as high-temp. heat pumping)			6.2	75%	Steam (MVC)	Negative	9
	Heat treatment by steam injection	94	155.2	61.2	4.1	100%	Steam (MVC)	Low	6-7
	Drying	41 - 26	210 - 6	93	3.0	100%	CO2 and R600	Moderate	9 & 5-9
	Drying	41 - 26	220-13	105	2.0	100%	Rev. Brayton	Moderate	5-7
2	Evaporation 6-stage	35	165	130	2.5	100%	Steam (MVC)	Low	9
3	Heating with temperature glides	210 - 85	550 - 275	259	1.6	100%	Rev. Brayton	High	5 - 8
	Heat integration and heat pumps	110 - 87	117 - 165	65	4.1	10% & 6%	H.recov. & HP	Moderate	9
4	Heat integrated evaporation	95	142	47	6.2	80%	Steam (MVC)	Low	9
	and crystallization	67	110	43	6.1	80%	Steam (MVC)	Low	9
	Ratio of reduced firing rate in boilers to heat pump gridpower				5.3		Steam (MVC)		

*) Compared to traditional systems. Low (0-300 DKK/tons). Moderate (300-700). High (700-1500)

Table 1. Examples of heat pump performances in relevant processes in the case studies.

Risk assesment

High-temperature heat pumping is a more specialized and advanced technology than fuel fired boiler or furnace. Some of the service may require skilled experts from the compressor manufacturer and equipment failure may require that vital unique spare parts are already in stock or otherwise longer down time can be the consequence.

The operation of heat pumps based on dynamic compressors has a limited operating window as capacity (flow) and available temperature lift (pressure ratio) are interrelated. This means that in some applications the range of process operation can be more tightly restricted than in cases with steam supply from a high-pressure steam boiler. Normally, turbo compressors will have extensive control and warning systems and fully automatic shutdown procedures in case the operation exceeds allowable limits.

If heat pumping is installed as an alternative heat source in parallel with an existing heat source (e.g. fuel fired steam boiler), naturally the heat supply system will be more redundant and heat production cost can be minimized using the the cheapest production facility.

Economic risk

The higher temperature lifts the lower achievable COP by heat pumping. Additional investment in a heat pump can be paid by savings in heat generation compared to an alternative heat source (e.g. combustion of fuel). The savings is the difference between cost of heat subtracted the cost of electricity divided by the COP factor of the heat pumping process. The lower the COP for a given economically feasible heat pump (same payback) the more sensitive will the economics be to the variation in cost of electricity and heat.

The political unawareness of the strengths of using this technology in a climate act plan and the unpredictable future economic support programs related to climate act plans is probably the largest economic risk for investment in high temperature-lift heat pumping. E.g. if a large support (lets say 50% subsidy of heat pump investment) suddenly is initiated there is a large economic risk associated with being "early bird" and investing before such program is initiated.

As we see it, historically being progressive in energy efficiency, has typically not been awarded concerning potential for achieving financial support for further improvements of energy efficiency (e.g. ETS system for CO2 quotes or the Danish market for energy savings). Therefore, to reduce the economic risk of high-temperature heat pumping pushing the limits, long-term predictable incentives are essential, to facilitate investments with rather long payback time for the enterprise (investor).

1.6 Utilization of project results

We expect more installations of industrial heat pumps in the traditional area of evaporation. At least one of the project partners (provider of industrial cases) is planning significant investment in heat pump technology related to a new evaporation line for increased capacity. The existing evaporation lines are multi-effect evaporators. This indicates that even in evaporation with rather high boiling point rise MVC is more cost effective than multi-effect evaporation lines supplied by an external heat source.

Obscure outlook and biased subsidies is a barrier to utilize project results

The future outlook and consequences related to the political agenda and its implementation in terms of e.g. subsidies and possible restrictions is not clear at all.

In addition, the future penalty cost for process industry related to emission of CO2 is rather unpredictable even in short terms and depends among others on politics both on EU and on national level. Additional investment in heat pumps will usually take more years (usually several years in high temperature-lift applications) to payback from savings in variable heat cost.

In that context the above obscure outlook on future cost of and definition on CO2 emission and possible subsidies most likely will result in rejecting or postponing (if possible) investment in a heat pump. Alternative sources achieving high subsidy (e.g. at present biogas) for heat supply may be selected instead with much lower CO2 reduction potential on national as well as global level.

High-temperature heat pumping applied with the purpose of cost-effective (in macro economy) reduction of CO2 emission is highly competitive to alternatives even in applications requiring very high temperature-lifts implying low COP.

This claim is based on the fact that all emission of CO2 into the atmosphere (no matter if it is from biomass or fossil sources) reduces the potential for further reduction of CO2 emission and thereby increases the need for reduction in other (more costly) places in order to reduce the atmospheric CO2 level. In that sense, biomass fired boilers or furnaces (with or without CO2 capture) is in most cases not at all competitive in a progressive climate act plan that balances the real cost. Nor is firing with electro-fuels, which typically will require between five (5) and fifteen (15) times as much installed power capacity from renewables as electrical heat pumping and will be dramatically more costly. We have investigated potentials to suggest the most promising and cost effective solutions for reduction of CO2 emissions related to process industry in such perspective.

Most unfortunately, however, we cannot see that these important facts and strengths of heat pumping, driven by low CO2 emission electricity, has so far been taken into account in the climate act policy.

Market needs and potential

The investigation has confirmed that still there is a lack of suitable and commercially available industrial high-temperature heat pumps in the heat load range up to a few MW. In that sense, indeed there is a strong need for a predictable long-term driver or incentive for applying extensive heat pumping as in many cases, extensive heat pumping is much more economically attractive in the macro economy than possible alternatives.

The market potential is expected to open up if long-term outlook on heat pump economics becomes more transparent (e.g. stable and predictable rising cost for CO2 emission).

New small-scale turbo-compressor technology

During recent years, among others Weel & Sandvig has in cooperation with other partners developed and tested untraditional high-speed high-temperature heat pumps based on relatively cheap compressor technology and design derived from the automotive industry.

The present study has clarified that indeed there is strong need for and lack of cheap and suitable compressor technology to be used in heat pumps pumping heat above 100 °C for supplying heat rate demands below approximately 2-5 MW (size limit depends on application).

In cooperation with Swedish Ecergy and the Technical University of Denmark, Weel & Sandvig is (in writing moment) awaiting final approval for financial support granted from EUDP for designing and testing a high-speed direct-drive turbo-compressor. The technology is considered most suitable for industrial heat pumping in heat ranges from 300 kW up to a few MW. In case the testing shows god results and high reliability the next step is to test the compressor in an industrial heat pump application.

Experiences achieved in this project have further confirmed our confident belief that high-speed turbo compressors is a cost effective solution to this segment of industrial heat pumping and in many cases the most cost effective solution for reduction of CO2 emission.

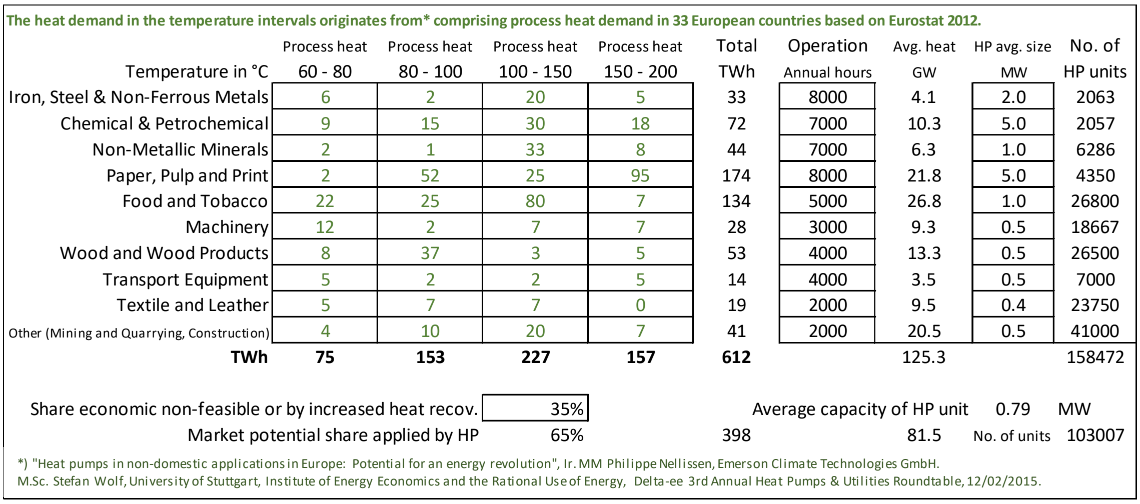
Scale-up potentials

High-temperature heat pumping is in many cases a cost-efficient solution for CO2 reduction more than a shortcut for achieving a cheap heat supply. Otherwise, in most cases and most likely, the heat pumping solution and suitable technology would already have been developed and applied.

In case the real cost for removal of CO2 from the atmosphere is balanced with a cost penalty for emission of CO2, the market potential is huge. In other terms, if cost for future CO2 emission is predictable in long-term horizon and in the range from 200 to 1000 DKK per tons CO2, the electrically driven heat pump has a huge market potential.

P. Nellissen and S. Wolf (Ref. 1) has allocated process heat demands sector wise (data from Eurostat 2012 comprising 33 countries in Europe) to certain temperature intervals. Considering the heat demands allocated to the temperature intervals from 60 °C to 200 °C to be highly relevant and applicable for heat pumping we have estimated the potential for heat pumping in these countries to be approximately 398 TWh annually corresponding to an installed capacity of 81 GW heat. We have estimated a potential of 103,000 units with an average capacity of 0.8 MW heat rate delivery. Some data are presented in Table 2.

The estimation is based on the assumption that 65% of process heat demand (between 60 °C and 200 °C) can be supplied by heat pumping, while the remaining heat demand is assumed covered by enhanced heat recovery or considered economic non feasible for heat pumping.



The heat demand in the temperature intervals originates from* comprising process heat demand in 33 European countries based on Eurostat 2012.

Temperature in °C	Process heat 60 - 80	Process heat 80 - 100	Process heat 100 - 150	Process heat 150 - 200	Total TWh	Operation Annual hours	Avg. heat GW	HP avg. size MW	No. of HP units
Iron, Steel & Non-Ferrous Metals	6	2	20	5	33	8000	4.1	2.0	2063
Chemical & Petrochemical	9	15	30	18	72	7000	10.3	5.0	2057
Non-Metallic Minerals	2	1	33	8	44	7000	6.3	1.0	6286
Paper, Pulp and Print	2	52	25	95	174	8000	21.8	5.0	4350
Food and Tobacco	22	25	80	7	134	5000	26.8	1.0	26800
Machinery	12	2	7	7	28	3000	9.3	0.5	18667
Wood and Wood Products	8	37	3	5	53	4000	13.3	0.5	26500
Transport Equipment	5	2	2	5	14	4000	3.5	0.5	7000
Textile and Leather	5	7	7	0	19	2000	9.5	0.4	23750
Other (Mining and Quarrying, Construction)	4	10	20	7	41	2000	20.5	0.5	41000
TWh	**75**	**153**	**227**	**157**	**612**		125.3		158472
Share economic non-feasible or by increased heat recov.			35%			Average capacity of HP unit		0.79	MW
Market potential share applied by HP			65%		398		81.5	No. of units	103007

*) "Heat pumps in non-domestic applications in Europe: Potential for an energy revolution", Ir. MM Philippe Nellissen, Emerson Climate Technologies GmbH.
M.Sc. Stefan Wolf, University of Stuttgart, Institute of Energy Economics and the Rational Use of Energy, Delta-ee 3rd Annual Heat Pumps & Utilities Roundtable, 12/02/2015.

Table 2.. Estimation on market potential in Europe (33 countries) assuming high penalty cost for CO2 emission associated with supplying process heat demands.

1.7 Project conclusion and perspective

The project has identified a huge low-cost CO2 reduction potential in typical energy intensive processes like evaporation, heat treatment and drying. Even in processes requiring heat pumping with high temperature-lifts (> 60 °C) such as many drying processes, some distillation, some multistage evaporation processes or heat treatment, still the overall cost for reduction of CO2 emission is considerably lower than most solutions considered in national climate action plans.

Especially when the process heat demand is sufficiently large, suitable turbo-compressor sizes are available and can give cost effective solutions.

In the smaller range of heat demands (<2 MW) cheap high-temperature heat pump technology is still missing in the market.

We claim that heat pumping with COP as low as 1.5 can be cost effective solutions for CO2 reduction compared to alternative so called "carbon neutral" heat sources.

Alternative fuels considered CO2 neutral (like carbon neutral power-to-fuels) or "zero emission" fuels like power-to-ammonia can be produced from carbon zero sources like wind or solar power. E.g. assuming an energy efficiency (lower heating value) from power-to-methanol of 60% as stated in Ref. 4 (seems high though), the total efficiency from power to heat (as steam) is 54% assuming a steam boiler fired with methanol with an efficiency of 90%. This energy chain corresponds to a COP = 0.54 from power-to-heat.

In baseload, assuming that grid electricity is not partly supplied from electro fuels, such energy chain requires four times more renewable power installation than a heat pump operating with a COP of 2.16, and three times more renewable power installation than a heat pump operating with a COP as low as 1.62.

Off-shore wind power has typically higher capacity factor than land based wind power and comes according to Ørsted[1] (mainly project developer and seller/operator of windfarms) at an installation cost down to approximately 2 Euro/W without cost for transformer and electrical transmission infrastructure. Another source (see Figure 2, Ref. 2) reports installed cost around 4-5 USD/W. Additional investment is required for electrolysers and fuel synthesis plant.

Obviously, the installation cost associated with heat pump can be very high and still be a much more economic solution than a power-to-fuel based heating solution.

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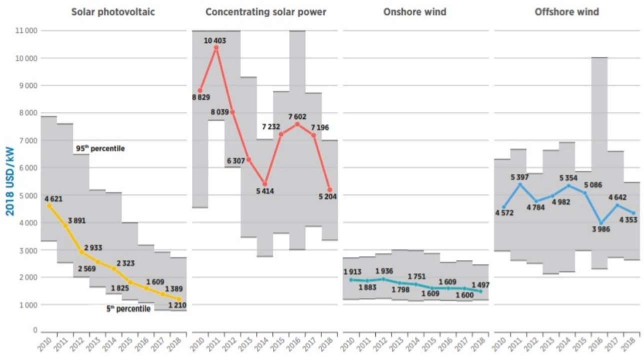
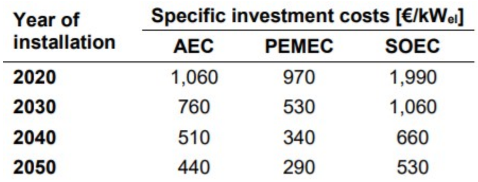
[1] https://orsted.com/-/media/WWW/Docs/Corp/COM/Investor/CMD2018/CMD-Presentation-2018.pdf





Year of installation	Specific investment costs [€/kW_{el}]		
	AEC	PEMEC	SOEC
2020	1,060	970	1,990
2030	760	530	1,060
2040	510	340	660
2050	440	290	530

Figure 2. Left: Investment cost of renewable power systems (Source: Ref. 2) and (right) predicted cost of electrolysers (Source: Ref. 3).

Investment cost for electrolysers is considerably lower than off-shore wind turbines and we expect that cost for electrolysers when large upscaling apply will decrease more rapidly than wind power where large upscaling has occurred for years.
Large scale relatively cheap hydrogen storage facility (e.g. in cavernes) in combination with electrolysers can be used for balancing the grid power demand, while the fuel synthesis is running continuously (only modest turn down ratio on load) supplied with hydrogen from the caverne storage facility.
In such energy system, in order to achieve energy and cost efficient operation, we claim that electrolysers should switch-off before electrically driven heat pumps in order to balance grid demand. This is explained above where the overall energy supply chain efficiency is much higher for the direct-power-to-pumped-heat solution (typically in the range 2 to 7) than the power-to-fuel-to-steam supply chain (as low as around 0.5). In other words, the direct heat pump solution is typically about four to fifteen times as energy efficient as process heat generated by combustion of electro-fuels.

Even in periods where direct power (e.g. from wind or solar) is insufficient for supplying the grid demand, grid power can be generated with electro-fuel fired power plants (e.g. CC or single cycle GT) for supplying industrial heat pumps with power and eventually in combination with industrial CHP. Assuming an electric efficiency of 50% for the thermal power plant (no additional heat utilisation) and a boiler efficiency of 90%, the required COP for the heat pump in such periods (with lack of grid power) just needs to be above 0.9/0.5 = 1.8 in order to be more efficient in those limited periods than electro-fuel fired boilers.
Existing CHP at industrial sites can favour heat pump integration in the overall energy system.

Ref. 1 "Heat pumps in non-domestic applications in Europe: Potential for an energy revolution", Ir. MM Philippe Nellissen, Emerson Climate Technologies GmbH and M.Sc. Stefan Wolf, University of Stuttgart, Institute of Energy Economics and the Rational Use of Energy, Delta-ee 3rd Annual Heat Pumps & Utilities Roundtable, 12/02/2015.

Ref. 2 *IRENA (2019), Renewable Power Generation Costs in 2018. ISBN 978-92-9260-126-3.*

Ref. 3 *Store&Go - Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization, 2019*

Ref. 4 *Technology Data – Renewable fuels. First published 2017 by the Danish Energy Agency and Energinet. Vers. 3.*
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