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Techno-Economic Analysis of Adsorption-Based DH Driven Cooling System

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Abstract. This study has examined the economic feasibility of adsorption-based district heat driven cooling system compared with convention air compression unit through a techno-economic model built in GAMS. The article describes the model settings, equations and input data as well as the result and discussions. The sensitivity analysis of adsorption investment cost, heat price, electricity price and the discount rate and two other scenarios of other locations and of constant outdoor temperature profile are also included. Overall, the results indicate that this type of system is not competitive, mainly because of its technological constrains by temperature. Only when a fixed outdoor temperature profile is assumed plus free heat, adsorption systems would be preferable. This implies that the potential of its application at other climate and free heat source is still worth investigating.

1. Introduction

With the arising environmental awareness against greenhouse gas emissions, a significant amount of investment has been put to district heating (DH) systems and cogeneration and/or trigeneration in the last decades [1]. DH systems are particularly well developed in Central and Eastern European Countries as well as in Scandinavia. For instance, in Poland about 12 million Polish citizens are supplied by district heating networks and ca. 20% of electricity is produced in cogeneration [2].

However, it also implies a more competitive DH supply market in addition to the growing improvements of building energy efficiencies which decreases the heat demand per customer and the clear seasonal demand division cause DH providers to re-plan their business strategies to maintain the profit level. Meanwhile, the demand for air conditioning increases due to more frequent heat waves in summer and it corresponds to the increasing electricity demand. A solution of DH-driven cooling will not only increase the heat demand market but also allow higher production and sell of both heat and electricity for cogeneration plants during non-heating seasons to maintain/increase the profits.

The more promising heat-driven cooling processes are sorption cycles and they can be further divided into absorption and adsorption (ADS). On one hand, absorption chillers are more mature and have better performance compared to adsorption chillers but they require minimum temperature 75°C for regenerating sorbents [3, 4]. The common heat source for absorption chillers are boilers, solar or waste heat from internal combustion engines. To utilize the waste heat at this temperature level, it is required to install absorption chillers close to cogeneration plants and thus, the extra distribution networks must be built to deliver cool from the production to the end-user, which is not realistic. On

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the other hand, although adsorption chillers have higher investment costs and lower performance dependent on temperatures, they can be operated with driving temperature as low as 60°C which is possible supplied by DH. As the adsorption chillers can be installed at the end-user side with a heat exchanger with DH, the addition cool distribution networks will not be required. It is foreseen that temperatures of DH systems are to be reduced in the future as a solution to adapt increasing amounts of renewable energy [5]. Therefore, this study focuses on the adsorption systems.

Many researches have been done regarding different designs and performance of adsorption chillers under different conditions. [6] have found the possibility of using DH driven adsorption chiller instead of electricity driven air conditioners is economically unfeasible through an experimental setup for 10 kW cooling capacity. They have analysed different compressor and adsorption hybrid system configurations. TRNSYS environment was used by [7] to create a model for a novel solar-geothermal district heating, cooling and domestic hot water system. The developed model was then used in a case study in the council housing district area of Monterusciello in Southern Italy. One of the main elements of this system was an adsorption chiller activated in summer to provide district cooling. The generator side of the adsorption chiller was supplied with hot water from renewable energy sources with the minimum temperature requirement of 60ºC. The results of the economic analysis showed that the system is scarcely profitable in absence of public funding policies. Three cases of energy supply for building complex were analysed by [8]. First two considered cooling only with electric air conditioners. The third case considered additionally an adsorption chiller with 30MW cooling capacity sufficient to cover about 60% of peak cooling load in summer by using the waste heat from CHP system. The chiller was operated with the hot water supply temperature ranging from 65ºC to 75ºC and the corresponding COP from 0.58 to 0.62. The calculations showed that in the third case the primary energy savings in summer over case 1 and 2 were around 35% and 30%, respectively. However, no economic analysis accompanied these technical calculations.

In this study, we emphasis on the commercially already available options for both compressors and adsorption systems. Our techno-economic model chooses the installed capacity of air conditioners and/or adsorption systems on given ambient conditions and parameters of commercialized cooling technology modules to meet the cooling demand of a building with maximum cooling load of 100 kW at outside temperature of 35°C. It is helpful for common consumers to make the decision on whether to switch their cooling technologies. Some factors are considered in the sensitivity analysis including the ADS investment cost, the interest rate and the energy price. Moreover, the model is tested in other scenarios of different location and of constant outdoor temperature profiles in order to fully examine the potential of this technology.

2. System and mathematic model

2.1. System definition

The model is built for cooling solution decision-making of a building. The system boundary as illustrated in figure 1 includes a conventional air conditioner and adsorption system as cooling technologies and a building to be cooled. The environment provides electricity from the power grids and heat from a heat exchanger connected with district heat distribution systems. Moreover, the outdoor temperatures affect both the cooling technologies and the cooling demand.

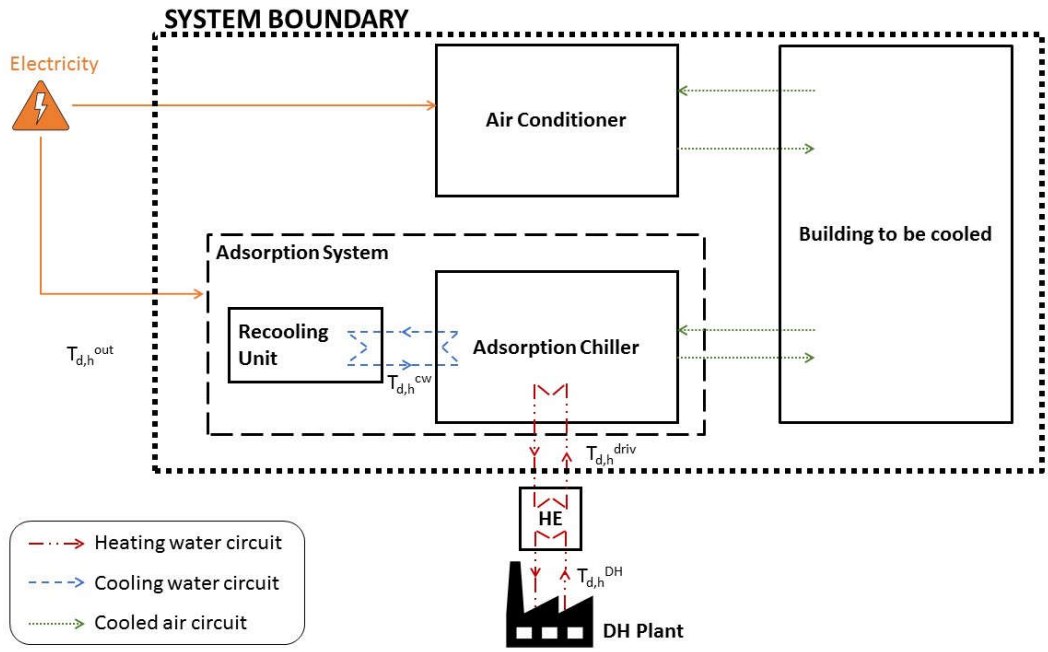


Figure 1. Illustration of system boundary of the model.

In the model, the air conditioner is treated as a black box because of its commercial maturity. The parameters are assumed as a common available air conditioner consuming electricity to produce cooled air. Its physical constraints on performance caused by high ambient temperatures are taken into considerations. The adsorption system consists of two main parts: the adsorption chiller itself and a recooling unit. The cool is produced by evaporating moistures which are absorbed by the adsorbents in the chiller. The adsorbents are later regenerated by the heating water and then the recooling unit condenses the vapor and evacuates the heat from the system. Although the adsorption system is also modelled as a black box, impacts on cooling water by outdoor temperature and heating water by diving temperatures are taken into considerations. The cooling demand of the building is simplified as being proportional to the outdoor temperature at each hour.

2.2. Model setting

The model is built within General Algebraic Modelling System (GAMS). The goal is to minimize the total net present cost by mixed integer programming using CPLEX solver. The model includes the following sets, parameters and variables.

- Sets
  - t: cooling technology ($t \in$ T), including subsets:
    - AC
    - ADS
  - h: given hour in a year ($h \in$ H)
  - d: given day in a year ($d \in$ D)
- Parameters
  - Cap_t^u: unit capacity of technology t, desecrate value provided by the user, assumed 1 kW
  - C_t^{Inv}: investment cost of technology t, paid in starting year, [EUR/kW]
  - $C_t^{O\&M_FIX}$: annual fixed operation and maintenance costs of technology t[EUR/kW/y]
  - $C_t^{O\&M_VAR}$: variable operation and maintenance costs of technology t, excluding fuels, [EUR/kWh]
  - C_t^{Rep}: replacement cost of technology t, [EUR/kW]

- $Cap^{max}_{t,d,h}$: maximum cooling capacity of technology *t*, adjusted to the conditions in hour *h* of day *d*, [kW]
- $D^{Cool}_{d,h}$: cool demand in hour *h* of day *d,* [kWh]
- $COP^{th}_{t,d,h}$: thermal coefficient of performance of technology *t* in hour *h* of day *d*
- $COP^{el}_{t,d,h}$: electric coefficient of performance of technology *t* in hour *h* of day *d*
- H^{price}: heat price per kWh, [EUR/kWh]
- E^{price}: electricity price per kWh, [EUR/kWh]
- CRF: capital recovery factor of the project
- L_t: lifetime of cooling technology *t*, [y]
- L^R_t:remaining lifetime of cooling technology *t* (after replacement), [y]
- i: discount rate, [%]
- N: project lifespan, [y]
- $T^{DH}_{d,h}$: outdoor temperature in hour *h* of day *d*, [K]
- $T^{cw}_{d,h}$: outdoor temperature in hour *h* of day *d*, [K]
- $T^{driv}_{d,h}$: outdoor temperature in hour *h* of day *d*, [K]
- $T^{out}_{d,h}$: outdoor temperature in hour *h* of day *d*, [K]

- Variables
  - *NPC*: net present cost of the project, free variable [EUR]
  - R_t: replacement cost of technology *t*[EUR]
  - S_t: an estimated resale value of technology *t* at the end of its lifetime i.e. *a salvage value*[EUR]
  - C_{ann}: annualized cost [EUR/y]
  - *LCOC*: levelized cost of cool[EUR/kWh]
  - $P^{Cool}_{t,d,h}$: cool production by technology *t* in hour *h* of day *d*[kWh]
  - $E^{In}_{t,d,h}$: electricity consumption by technology *t* in hour *h* of day *d*[kWh]
  - $H^{In}_{t,d,h}$: heat consumption by technology *t* in hour *h* of day *d*[kWh]
  - x_t: number of installed unit capacity of technology *t*, integer variable

2.3. Equations

2.3.1. Objective function. The objective function is to minimize the net present cost (NPC) which expresses the costs throughout the project span with present values. It consists of the following components:

- Initial investments

$$\sum_{t\in T}\left(x_t \times Cap^u_t \times C^{Inv}_t\right)$$

- Net present total fixed O&M costs

$$\sum_{t\in T}\left(x_t \times Cap^u_t \times C^{O\&M_FIX}_t \times CRF^{-1}\right)$$

- Net present total variable O&M costs

$$\sum_{t\in T}\sum_{d\in D}\sum_{h\in H}\left(P^{Cool}_{t,d,h} \times C^{O\&M_VAR}_t \times CRF^{-1}\right)$$

- Net present total electricity purchase costs

$$\sum_{t\in T}\sum_{d\in D}\sum_{h\in H}(E_{t,d,h}^{In}\times E^{price}\times CRF^{-1})$$

- Net present total heat purchase costs

$$\sum_{t\in T}\sum_{d\in D}\sum_{h\in H}(H_{t,d,h}^{In}\times H^{price}\times CRF^{-1})$$

- Net present replacement cost
(maximum one replacement in the project span, $N \leq 2*L_t$)

$$\sum_{t\in T}\left(\frac{R_t}{(1+i)^{L_t}}\right)$$

- Net present salvage value, expressed as a negative cost

$$-\sum_{t\in T}\left(\frac{S_t}{(1+i)^{N}}\right)$$

The CRF, replacement cost R_t, salvage value S_t and the remaining lifetime L_t^R are expressed as:

$$CRF=\frac{i\times(1+i)^N}{(1+i)^N-1}$$

$$R_t=x_t\times Cap_t^u\times C_t^{Rep}\times\left[\,ceiling\left(\frac{N}{L_t}\right)-1\,\right]$$

$$S_t=R_t\times\frac{L_t^R}{L_t}$$

$$L_t^R=L_t-\left[N-L_t\times floor\left(\frac{N}{L_t}\right)\right]$$

2.3.2. Constraints and other equations. Equations of constraints and other economic variables are listed below:

- Hourly cool production meets the demand

$$\sum_{t\in T}P_{t,d,h}^{Cool}=D_{d,h}^{Cool}$$

- Electricity consumption

$$P_{t,d,h}^{Cool}\times COP_{t,d,h}^{el}=E_{t,d,h}^{In}$$

- Heat consumption

$$P_{ADS,d,h}^{Cool}\times COP_{ADS,d,h}^{th}=H_{ADS,d,h}^{In}$$

- Cool production constraint, cool production does not exceed the maximum capacity under the temperature constraints

$$P_{t,d,h}^{Cool}\leq x_t\times Cap_{t,d,h}^{max}$$

- Annualized cost

$$C_{\text{ann}} = NPC \times \text{CRF}$$

- Levelized cost of cool LCOC, which expresses the cost by unit production, are also calculated in the model for economic analysis.

$$LCOC = \frac{C_{ann}}{\sum_{t\in T}\sum_{d\in D}\sum_{h\in H} P_{t,d,h}^{Cool}}$$

2.4. Sensitivity Analysis

The parameters presented in table 1 are discussed to see the impact to cooling technology selection and the NPC.

Table 1. Parameters and scenarios considered in the sensitivity analysis.

Parameter	Description
Investment costs of ADS	Cost reduction of a technology happens naturally through the learning curve or artificially by policy design or strategy planning. In addition, the investment cost can be (partially) covered by heat producer in other business models. The motivation is to increase the heat market during summer in order to maintain the plant operation and revenue. The investment cost reductions of adsorption chillers of 20%, 50%, 80% and 100% are considered
Heat price	District heat price consists of heat itself plus the transmission costs and the composition depends on strategies. By lowering the heat price, the heat provider can expect more sells. For CHPs, it also implies higher electricity production. The reduction of 40%, 60% and 100% of heat price is considered.
Electricity price	The results of 2, 5 and 10 times higher of electricity price are compared, although such dramatic changes of electricity price are not expected.
Discount rate	Discount rate is used to analyze the present value and the future cash flow. It reflects the confidence of the investors to the project. In generally, the newer or uncertain the project is, the higher the discount rate is. The effects of 4%, 8% and 10% of discount rates are analyzed in additionally.
Scenario - *Location*	Different locations have various weather profile and heat demand and the performance of cooling technologies depend heavily on it. The typical hourly temperature profiles of other three European cities, Hamburg, Rome and Stockholm, are examined.
Scenario - *Constant temperature profile*	The ambient temperatures have wide impact on demand and performance. In this scenario, the temperature profile is assumed to be constant throughout the year from 20 to 35°C and other parameters are kept the same. Under this assumption, there are four cases discussed: constant outdoor temperature (T-0), constant outdoor temperature with free district heat (T-a), constant outdoor temperature with free adsorption units (T-b), constant outdoor temperature with free district heat and free adsorption units (T-c),

3. Input parameters

3.1. Hourly cool demand

The study is performed for a reference building with the hourly cool demand as a function of outdoor temperature. It is assumed that the cool demand was proportional to the outdoor temperature from 0 kW below 17°C to 100 kW at 35°C and higher [9].

$$D_{d,h}^{\text{Cool}} = 0, \text{for} T_{d,h}^{\text{out}} \leq 17$$

$$D_{d,h}^{Cool} = 100 \times \frac{T_{d,h}^{out} - 17}{35 - 17}, \text{ for } T_{d,h}^{out} > 17$$

3.2. *Outdoor temperature* and DH temperature profiles

The outdoor temperature profiles are extracted from the International Weather for Energy Calculations (IWEC).The IWEC database contain hourly typical weather data derived from several years. EDF Polska provides the daily output water temperature of their CHP plant in Krakow. Same temperature is used for 24 hours in the same day.

3.3. Technology characteristics

The main input parameters of air conditioner unit (AC) and adsorption system (ADS) are listed in table 2 and table 3.

Table 2. Main input parameters of AC and their sources.

Rated characteristics	Value	Source
Unit capital cost [EUR/kW]	440	IEA ETSAP
Fixed O&M cost [EUR/kW/y]	15	IEA ETSAP
Variable O&M cost [EUR/kWh]	0	Own assumption
Replacement cost [EUR/kW]	440	Own assumption
Lifetime [y]	14	IEA ETSAP
$COP^{el,r}$[-]	3.5	IEA ETSAP

Table 3. Main input parameters of ADS and their sources.

Rated characteristics	Value	Source
Unit capital cost [EUR/kW]	1327	InvenSor LTC30 e plus
Fixed O&M cost [EUR/kW/y]	5.3	Own assumption (0.4% of capital cost)
Variable O&M cost [EUR/kWh]	0	Own assumption
Replacement cost [EUR/kW]	1327	Own assumption
Lifetime [y]	20	Own assumption
$COP^{el,r}$ [-]	33.52	InvenSor LTC30 e plus
$COP^{th,r}$ [-]	0.72	InvenSor LTC30 e plus

However, high outdoor temperatures cause performance drop of both types of cooling technologies. For AC. it is assumed that if the outdoor temperature is above 30°C, the maximum unit capacity has a 0.9% drop and the electric coefficient of performance has a 3.33% drop every 1°C increase of outdoor temperature.

$$Cap_{AC,d,h}^{max} = Cap_{AC}^{u} \times \left[1 - 0.009 \times \left(T_{d,h}^{out} - 30\right)\right], \text{ for } T_{d,h}^{out} > 30$$

$$COP_{AC,d,h}^{el} = COP_{AC}^{el,r} \times \left[1 - \frac{1}{30} \times \left(T_{d,h}^{out} - 30\right)\right], \text{ for } T_{d,h}^{out} > 30$$

The performance of adsorption systems is affected significantly by the cooling water from the re-cooler in the system and the driving temperature. It is assumed that the cooling water temperatures are 2°C above outdoor temperature.

$$T_{d,h}^{cw} = T_{d,h}^{out} + 2$$

Due to the energy loss of the distribution through the DH networks and the heat exchangers for adsorptions at the user-side, the driving temperatures for the adsorption system are estimated with a 5°C-drop compared to the output from the CHP plant.

$$T_{d,h}^{driv} = T_{d,h}^{DH} - 5$$

In this study, a regression of dual variable cubic equation is estimated from the datasheets of three types of adsorption models from InvenSor with chilled water at 15°C. The regression models are applied during the cooling water temperature higher than 17°C and the lowest possible values are 0. Nevertheless, the impact on electric coefficient of performance is neglected.

$$\begin{aligned} \mathrm{Cap}_{\mathrm{ADS},h,d}^{\max} = \mathrm{Cap}_{\mathrm{ADS}}^{u} * \Big[& \alpha_{00} + (\alpha_{10} * \mathrm{T}_{d,h}^{\mathrm{driv}}) + (\alpha_{01} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\alpha_{11} * \mathrm{T}_{d,h}^{\mathrm{driv}} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\alpha_{20} * \mathrm{T}_{d,h}^{\mathrm{driv}\,2}) \\ & + (\alpha_{02} * \mathrm{T}_{d,h}^{\mathrm{cw}\,2}) + (\alpha_{21} * \mathrm{T}_{d,h}^{\mathrm{driv}\,2} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\alpha_{12} * \mathrm{T}_{d,h}^{\mathrm{driv}} * \mathrm{T}_{d,h}^{\mathrm{cw}\,2}) + (\alpha_{30} * \mathrm{T}_{d,h}^{\mathrm{driv}\,3}) \\ & + (\alpha_{03} * \mathrm{T}_{d,h}^{\mathrm{cw}\,3}) \Big], \text{ for } \mathrm{T}_{d,h}^{\mathrm{cw}} > 17 \end{aligned}$$

$$\begin{aligned} \mathrm{COP}_{\mathrm{ADS}d,h}^{th} = \mathrm{COP}_{\mathrm{ADS}}^{th,r} * \Big[& \beta_{00} + (\beta_{10} * \mathrm{T}_{d,h}^{\mathrm{driv}}) + (\beta_{01} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\beta_{11} * \mathrm{T}_{d,h}^{\mathrm{driv}} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\beta_{20} * \mathrm{T}_{d,h}^{\mathrm{driv}\,2}) \\ & + (\beta_{02} * \mathrm{T}_{d,h}^{\mathrm{cw}\,2}) + (\beta_{21} * \mathrm{T}_{d,h}^{\mathrm{driv}\,2} * \mathrm{T}_{d,h}^{\mathrm{cw}}) + (\beta_{12} * \mathrm{T}_{d,h}^{\mathrm{driv}} * \mathrm{T}_{d,h}^{\mathrm{cw}\,2}) + (\beta_{30} * \mathrm{T}_{d,h}^{\mathrm{driv}\,3}) \\ & + (\beta_{03} * \mathrm{T}_{d,h}^{\mathrm{cw}\,3}) \Big], \text{ for } \mathrm{T}_{d,h}^{\mathrm{cw}} > 17 \end{aligned}$$

The regression results are illustrated in figure 2 and figure 3 and the coefficients are listed in table 4.

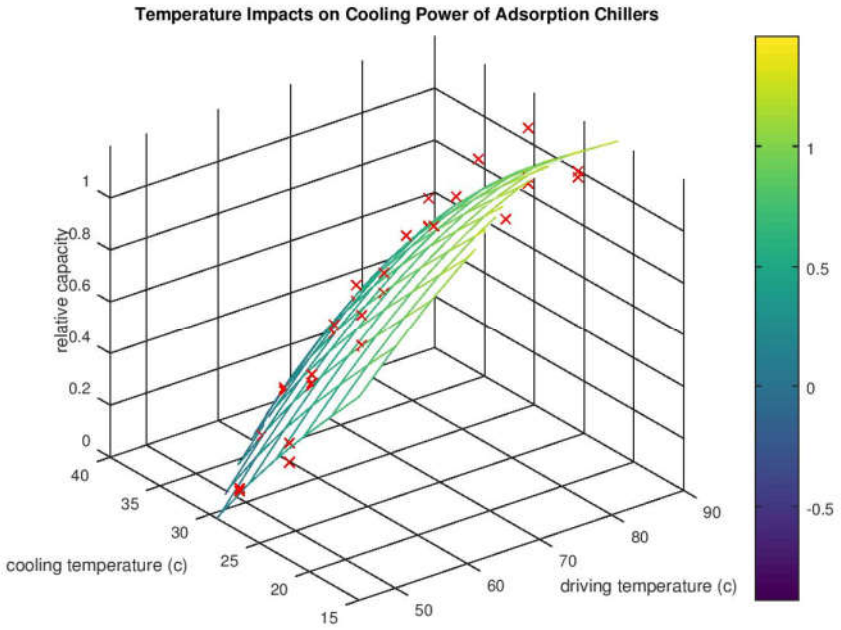


Figure 2. Regression of temperature impacts on cooling power of ADS, based on data sheet from Invensor.

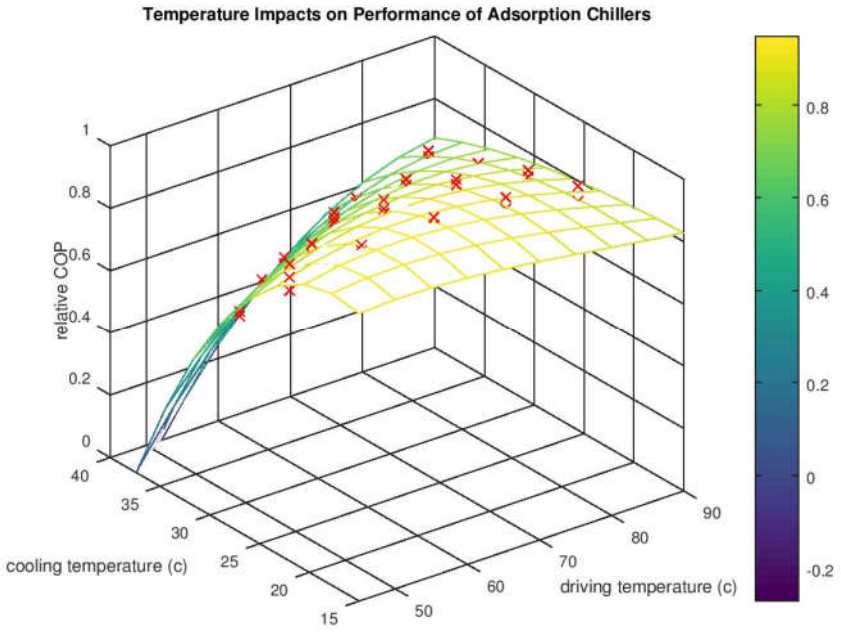


Figure 3. Regression of temperature impacts on cooling performance of ADS, based on data sheet from Invensor.

Table 4. Regression results of parameters of ADS.

Cap^{max}_{ADS} regression parameters		COP^{th}_{ADS} regression parameters	
α_{00}	- 4.08270E-03	β_{00}	7.76010E-03
α_{10}	3.35790E-02	β_{10}	9.42150E-03
α_{01}	- 4.92380E-02	β_{01}	8.72720E-02
α_{11}	- 5.07210E-04	β_{11}	3.55200E-04
α_{20}	1.96440E-04	β_{20}	- 1.41670E-04
α_{02}	5.63440E-04	β_{02}	- 4.07420E-03
α_{21}	1.48130E-06	β_{21}	- 1.53500E-05
α_{12}	1.72610E-05	β_{12}	4.79890E-05
α_{30}	- 3.16700E-06	β_{30}	1.59400E-06
α_{03}	- 2.94910E-05	β_{03}	- 5.99460E-06
R^2	0.95401	R^2	0.95857
RMSE	0.067084	RMSE	0.020606

3.4. Other economical characteristics

The assumed price of electricity was equal to 0.13 EUR (0.56 PLN) [10] whereasthe price of district heat equalled to 0.035 EUR (0.1465 PLN) [11] . Discount rate reflects the level of risks. Higher risks result in higher discount rate. A 6% discount rate is used in the reference scenario. Lifespan of the whole project is assumed to be 20 years.

4. Results and discussion

4.1. Base case

The results as shown in table 5, indicate the installation of 85 kW AC units with NPC of 75.7 k EUR and LCOC of 0.2039 EUR per kWh. The adsorption units, however, will not be installed.

Table 5. Results of base case.

	AC	ADS
Installed [kW]	85	0
NPC [EUR]	75727.51	
Annualized cost [EUR/y]	6602.27	
LCOC [EUR/kWh]	0.2039	
Cool production [MWh]	32.378	-
Electricity consumption [MWh]	9.27	-
Heat consumption [MWh]	-	-

Figure 4 shows the composition of the annualized cost. The investment and replacement take up to 65% and the O&M and electricity cost 18% and 17%. The annual cool production is 32.4 MWh and the electricity consumption is 9.27 MWh.

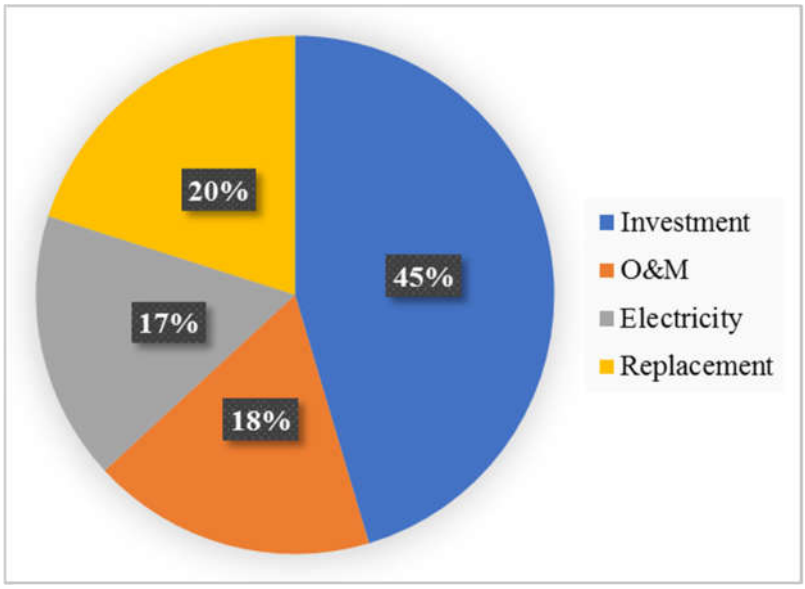


Figure 4. Composition of annualized cost in the base case.

Taking a further look of the operation status of the installed AC, it operates for 1410 hours per year but more than 85% of the time it is operating under 50% load. Figure 5 shows the histogram of the installed AC.

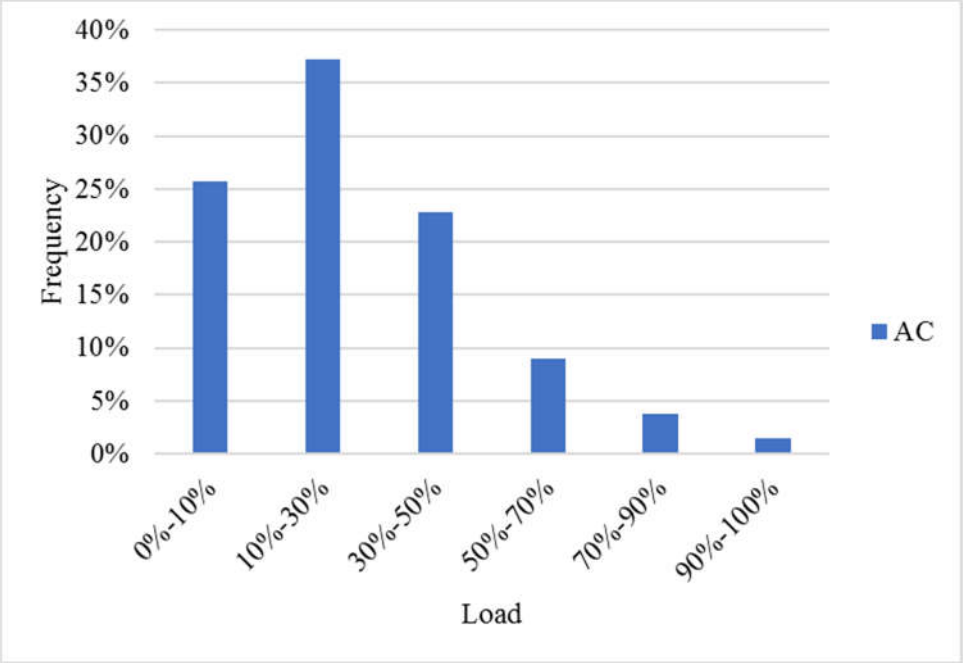


Figure 5. The histogram of the operation load of the installed technology in the base case.

Although in the optimal result of the base case no ADS installed, it is intriguing to see the result with ADS installed. Therefore, the integer variable of installed capacity of ADS is fixed at 10 kW and the result shows that still 82 kW of AC is installed and in fact the installed ADS is only operating for two out of 1410 hours with cool demand. As compared in figure 6, the NPC increased more than 15% mainly due to the installed ADS, while other cost components do not change much.

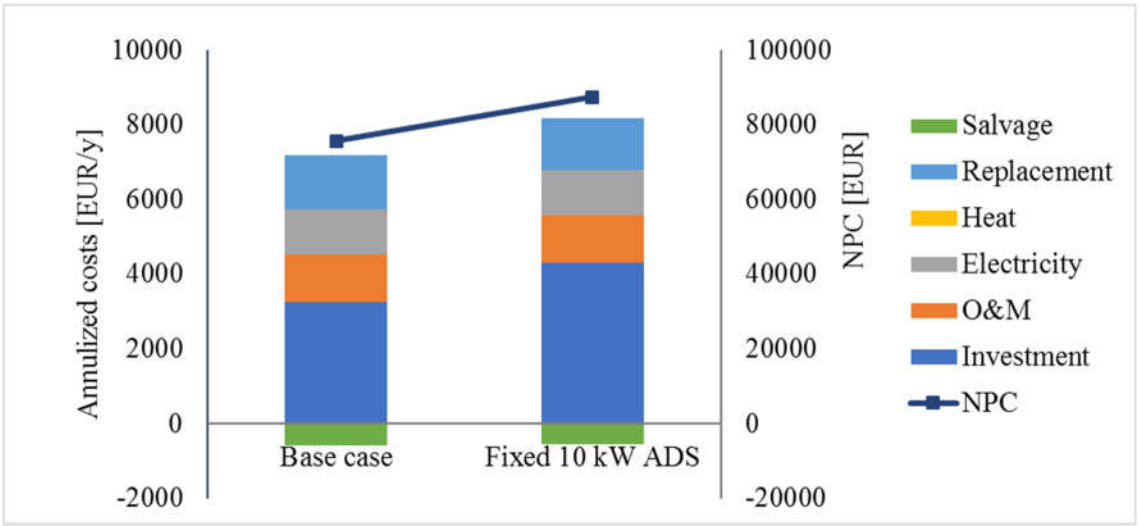


Figure 6. Cost comparison of the base case and the result with 10 kW ADS installed.

4.2. Sensitivity analysis

Four parameters are discussed in the sensitivity analysis: investment cost of ADS, heat price, electricity price and the discount rate. Table 6 lists the results compared to the base case. The change of ADS investment cost only has impact if it is significant. For instance, if the ADS investment cost is 80%-off, the choice of cooling technology keeps the same, while the change is 90%-off, the model

will install 12 kW AC and 193 kW ADS and the impact on the NPC is only 15% lower. If the ADS investment is for free, the model will install only ADS for 225 kW and the impact on NPC is 46%-off. Electricity price also have insignificant effects. The results do not change with two times higher of electricity price and even with ten times higher of electricity price, the NPC increases approximately two times more. The changes of heat price and the discount rate do not affect the choice of technology, even if heat would be for free. To sum up, a single change of any of these four parameters do not contribute to significant change of the results.

Table 6. Main inputs and results of sensitivity analysis.

Change of parameter		Main inputs					Main results		
		C_{AC}^{Inv}	C_{ADS}^{Inv}	E^{price}	H^{price}	i	Installed capacity [kW]		Change of NPC
							AC	ADS	
Base	**100 %**	440	1327	0.13	0.035	0.06	85	0	100%
Investment cost of ADS	**80%**	440	**1062**	0.13	0.035	0.06	85	0	100%
	50%	440	**664**	0.13	0.035	0.06	85	0	100%
	20%	440	**265**	0.13	0.035	0.06	85	0	100%
	10%	440	**133**	0.13	0.035	0.06	12	193	85%
	0%	440	**0**	0.13	0.035	0.06	0	225	46%
Heat price	**60%**	440	1327	0.13	**0.021**	0.06	85	0	100%
	40%	440	1327	0.13	**0.014**	0.06	85	0	100%
	0 %	440	1327	0.13	**0**	0.06	85	0	100%
Electricity price	**200 %**	440	1327	**0.26**	0.035	0.06	85	0	118%
	500 %	440	1327	**0.65**	0.035	0.06	82	8	169%
	1000 %	440	1327	**1.30**	0.035	0.06	74	29	214%
Discount rate	**67 %**	440	1327	0.13	0.035	**0.04**	85	0	92%
	133 %	440	1327	0.13	0.035	**0.08**	85	0	108%
	167 %	440	1327	0.13	0.035	**0.10**	85	0	116%

4.3. Scenario - location

In this scenario temperature profiles of three other European cities are examined. Figure 7 displays the outdoor temperature distributions of the four cities and table 7 lists the results. Hamburg has similar numbers of hours with warm temperatures as Krakow and the results are similar to the base case. Rome has more hours with warm temperatures, while Stockholm has much less and the highest temperature in Stockholm is less than 30°C.

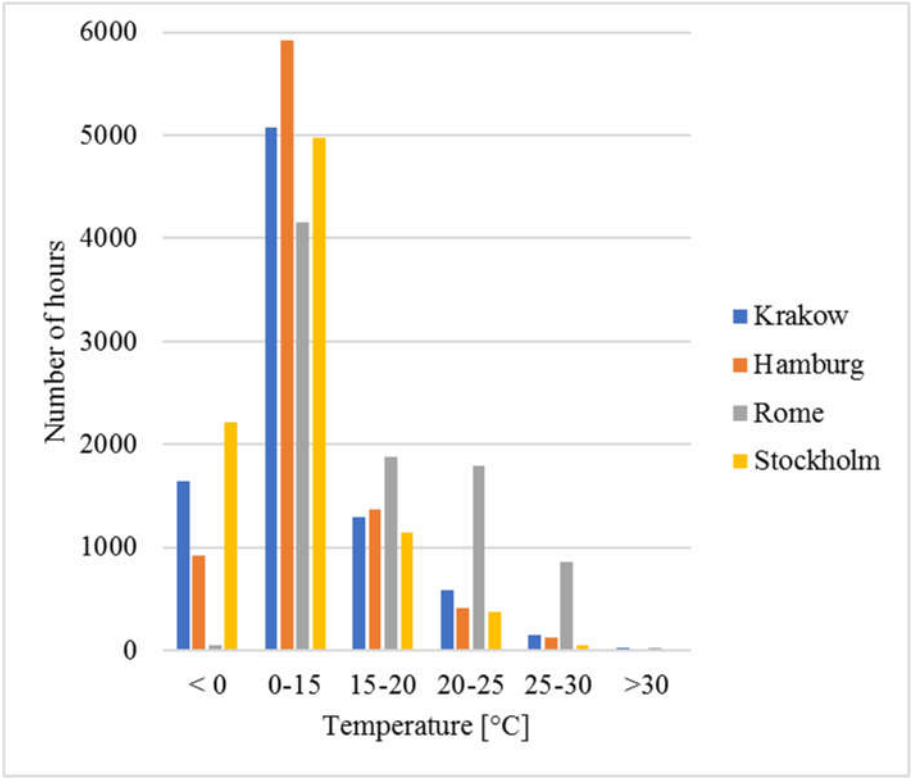


Figure 7. Histogram of typical annual outdoor temperature distribution of four cities.

There are 84 kW of AC installed in Rome providing 115 MWh of cool. As a result, the LCOC in Rome is only one-third as in other cities. There are only 57 kW of AS installed in Stockholm to meet the cool demand. However, the same conclusion as in the base case can be drawn that ADS is not preferable.

Table 7. Results in other locations.

	Hamburg		Rome		Stockholm	
	AC	ADS	AC	ADS	AC	ADS
Installed [kW]	85	0	84	0	57	0
NPC [EUR]	72210.48		110131.86		48652.93	
Annualized cost [EUR/y]	6295.64		9601.80		4241.78	
LCOC [EUR/kWh]	0.2605		0.0836		0.2530	
Cool production [MWh]	24.166	-	114.872	-	16.764	-
Electricity consumption [MWh]	6.91	-	32.83	-	4.79	-
Heat consumption [MWh]	-	-	-	-	-	-

Figure 8 shows the operation of AC in the three cities. In Hamburg and Stockholm, it is similar to the base case because they have similar numbers of hours with warm temperatures. The load distribution of AC in Rome shows another profile. The frequency of higher operating load is higher and this contributes to the low LCOC.

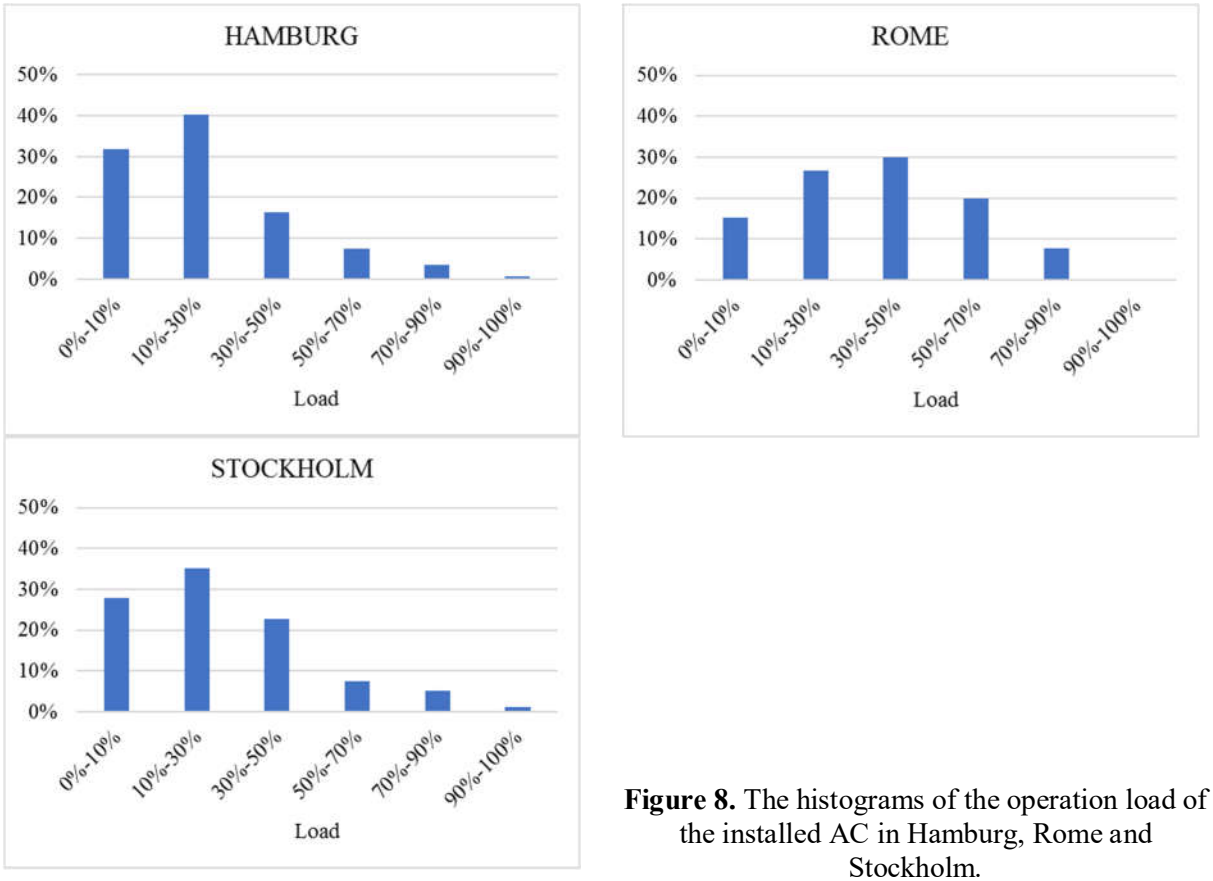


Figure 8. The histograms of the operation load of the installed AC in Hamburg, Rome and Stockholm.

4.4. Scenario – constant temperature profile

In this scenario, a constant outdoor temperature profile is assumed at 20, 25, 30 and 35°C (T-0). Three additional cases are discussed under each temperature level: free heat (T-1), free installation of ADS (T-2) and free heat plus free installation of ADS (T-3).Results of the installed cooling technologies at different temperature levels are shown in figure 9. While case T-0 shows only AC installed as in the base case, results in other cases are interesting and discussed further.

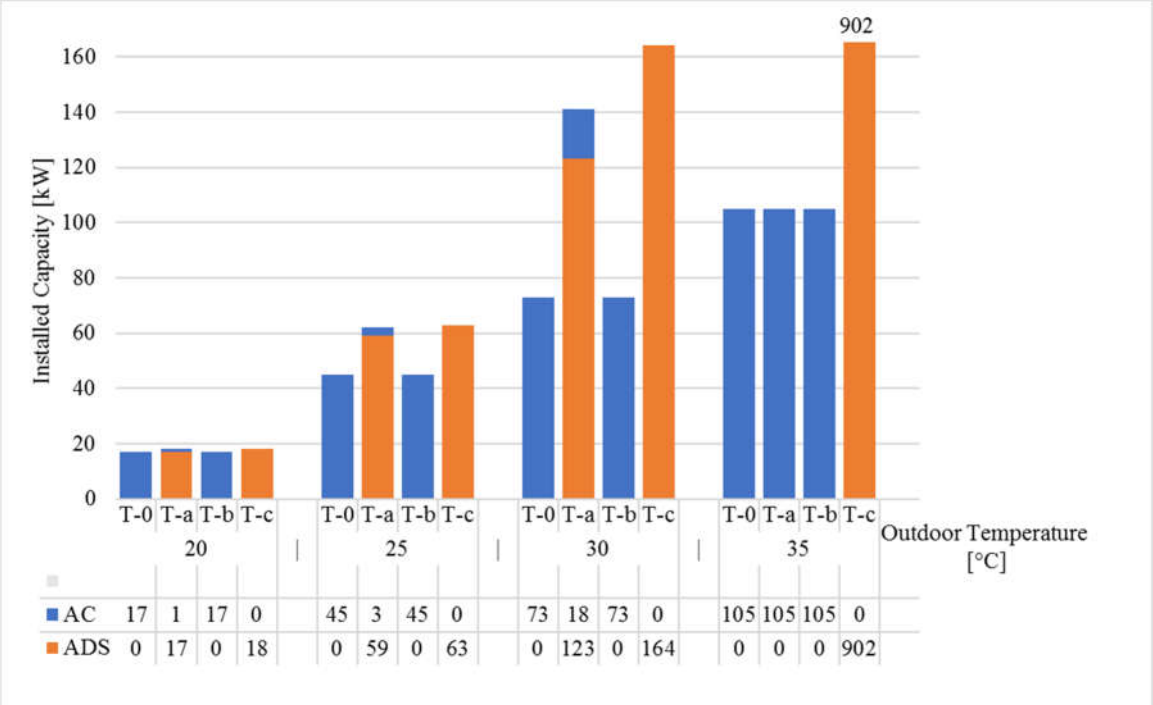


Figure 9. Installed capacity of cooling technologies with constant outdoor temperature of four cases.

Before the temperature level reaches 35°C, unlike in the base case, free heat (T-a) has larger impact than free installation of ADS (T-b) in this scenario. Due to the free heat and low electricity consumption of ADS, in case T-a the installed ADS is used to satisfy the basic cool demand and operates all year around at its maximum capacity constrained by outdoor temperature and DH temperature. The AC operates partially to serve the peak demand. Figure 10 shows an example of T-c at 30°C.

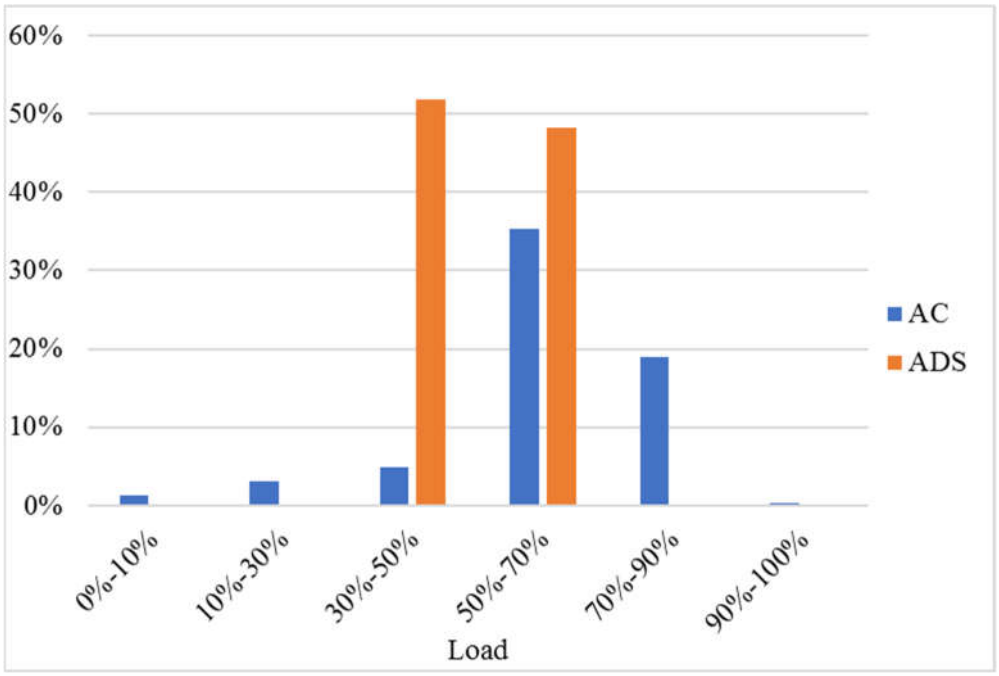


Figure 10. Histogram of operating load of cooling technologies in case T-a at 30°C.

Case T-b, however, does not show a different result than T-0. The reason behind, in addition to the cheap price of AC, is that the difference between $COP^{el,r}$ of AC (3.5) and $COP^{th,r}$ of ADS (0.72) is too large and the price difference of electricity (0.13 EUR/kWh) and heat (0.035/EUR/kWh) is not enough to cover. Figure 10 demonstrates the impact on NPC and cost components if there are only AC or ADS installed in case T-b at 20°C. The NPC increases 30% mainly due to the cost of heat.

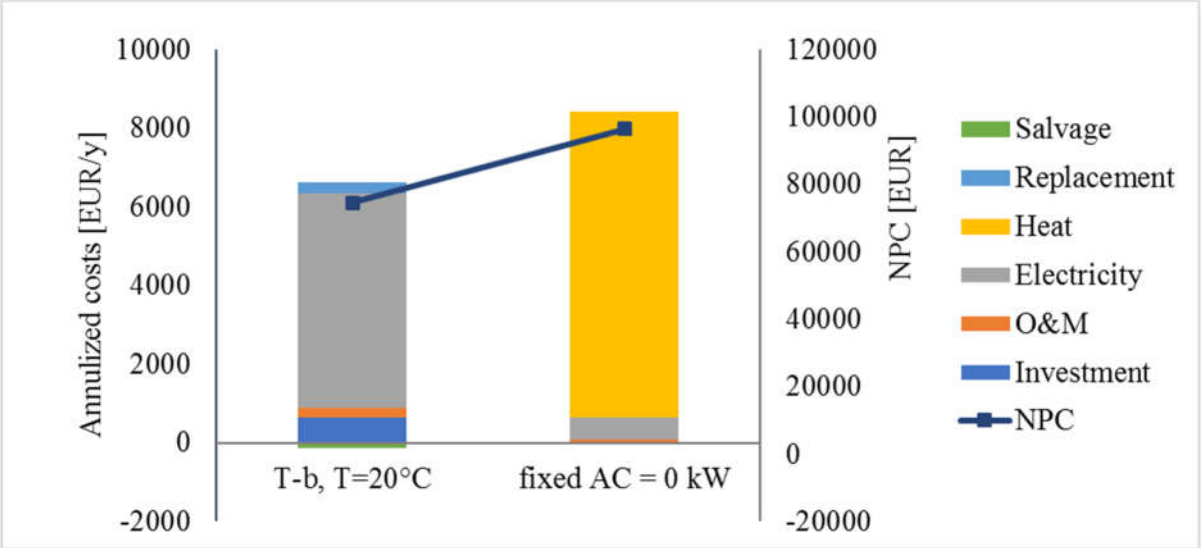


Figure 11. Comparison of the result of case T-b at 20°C and the result with none of AC installed.

When the temperature level reaches 35°C, the maximum cool capacity of ADS is decreased to 11%. Due to the poor performance, it is not advised to be installed. Only when both heat and ADS installation are for free, the cost for ADS systems is so low that large capacity can be installed.

To sum up, in this scenario although AC is still preferable than ADS, the decrease of heat price has higher potential to alter the results. It implies that cities with mild temperature profile, a business model utilizing free heat (waste heat) to provide cool by adsorption systems might have potential to compete with conventional AC.

5. Conclusions

This study analyses the techno-economic potential of heat-driven adsorption systems for cool. A model is built in GAMS to minimize the NPC. Furthermore, there are four parameters examined in the sensitivity analysis including the investment cost of ADS, the heat price, the electricity price and the discount rate. In addition, two other scenarios regarding outdoor temperature are tested. One uses typical temperature profiles of other three European cities, Hamburg, Rome and Stockholm, and the other assumes constant temperature throughout the year. The impacts of heat price and adsorption investment cost are also examined in the latter scenario.

Overall, the results suggest strong preference of AC over ADS and the investment is the major cost. In the real temperature profiles, neither the four parameters in the sensitivity analysis or the location would change the results significantly. Only when the investment cost of ADS has extreme reduction (90%-off or for free)or the electricity price increases over five times, ADS would be chosen. In addition to the high investment cost of ADS, the major factor is its poor performance caused by warm outdoor temperature. The impact can reach even over 60% reduction of cooling capacity. This is the main obstacle of using heat-driven ADS to cool in summer.

The scenario with constant outdoor temperature from 20 to 35°C also shows the preference of AC unless the heat would be for free and the outdoor temperature is not extremely high. In this scenario the heat price has larger impact than the ADS investment. Constant temperature profile leads to

constant cool demand and, as a result, the variable costs (costs of O&M, electricity and heat) become more critical than the investment cost. It can also be observed that in the cases where both AC and ADS are installed, ADS are always operating at the maximum capacity while AC serves the insufficient part caused by the instability of DH temperature.

To conclude, the DH-driven adsorption cooling system is not competitive with conventional solutions under current conditions with European climate. Economically, the investment cost of ADS is more than three times higher than AC and technically, the warm outdoor temperature would cause significant drop of available capacity of ADS and this is believed to be the main obstacle. However, the impact of high ADS investment cost would be suppressed by costs of heat and electricity with all-year-around cool demand and if the waste heat is used, its cost would consequently drop. Therefore, the potential of ADS is worth investigating driven by waste heat or solar for the regions with continuous cool demand but not warmer than 30°C in future studies.

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