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The cost of manufacturing adsorption chillers

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Abstract

Adsorption chillers are more environmentally sustainable than other types of chillers but the trade-off between price and performance makes it impossible for them to seize a significant market share in cooling. The increase of performance has been the primary focus so far, neglecting to assess if it would lead to a reduced manufacturing cost. This study estimates a specific manufacturing cost and an end-user price for silica gel adsorption chillers. At maximum Coefficient of Performance (COP) of 1 and maximum Specific Cooling Power of 300 W kg^{-1}, the specific selling price of a silica gel adsorption chiller is €1018 per kW of cooling power. The analysis is extended first across a range of different (COP; SCP) combinations and then on the most significant factors influencing the price. We identify a minimum annual selling volume of 14 units and the possibility for the profit to increase by 75% if higher selling volumes are achieved. The silica gel results mark a market-accepted benchmark that is finally used to assess the economic viability of adsorption chillers integrating advanced adsorption materials, i.e. Metal-Organic Frameworks (MOFs) and zeotypes. None of the chillers integrating advanced adsorption materials can rival silica gel chillers in cost.

Keywords: Adsorption chiller, cost, price, manufacturing, Cost-Volume-Profit analysis, Profitability analysis.

Introduction

Cumulative 1992–2013 losses from extreme anthropogenic heat have been estimated at around $5-$29.3 trillion globally [1]. As a consequence of climate change, the International Energy Agency estimates that the global stock of air conditioners will increase to 275 million units in the European Union alone by 2050 [2]. Heat-driven cooling technologies such as adsorption chillers should play an essential role in reducing the reliance on a stressed electricity system and enable a reduction of cooling-related CO_2 emissions when compared to vapour compression chillers. When powered by waste heat, adsorption chillers can recover energy that would otherwise be lost [3]. Despite the promise, the technology is only available in a specific market segment and has not yet met expectations. One of the primary reasons for scepticism on the resilience of an eventual business is its profitability, given the current relatively poor technology performance. This is a perception rarely supported by data, given that there are only a few open rough estimates of the cost of manufacturing, most of which involve adsorption desalination rather than cooling. The total cost of ownership for a 24t silica-gel adsorption desalination system was estimated at €88.5k in [4]. This is equivalent to an adsorption chiller with a cooling capacity of 402 kW, which results in a capital cost of €220 per kW of cooling capacity. The same authors indicate a value of €330 per kW of cooling in [5], comparable with the capital cost of 314 euros per kW of cooling reported in [6] for a single-stage absorption chiller, a more mature technology. In [7], a significantly different figure is reported of €13k for an adsorption chiller with a cooling capacity of 8 kW, which results in €1625 per kW of cooling capacity. The significant price gap results from the fact that the cost of capital investment is not the only factor determining the selling price (or cost of ownership). A large body of previous research has solely focused on the optimisation of the performance, neglecting whether advanced technical solutions would favour a stable presence in the market, which ultimately depends on how the selling price meets the demand. Companies such as FAHRENHEIT (Germany), SOLABCOOL (Netherlands), AYEKAWA (Australia) and Bry-Air (India) provide commercial units today. Despite this, the market for adsorption chillers is still limited, and growth is not guaranteed.

Several issues hinder widespread implementation, the most significant being the unbearable upfront investment costs. There is a dearth of understanding of how performance and economic variables might contribute to a profitable adsorption chiller business. In all prior insights, the cost of producing an adsorption unit is shown as a lump sum, with no breakdown of its parts. This analysis is the first open study breaking down all the contributors associated with the cost of producing an 8-kW commercial adsorption chiller. Additionally, profit is included to arrive at a price for the end user. A sensitivity analysis leads to define the business's cost drivers and the conditions to maximise profitability. Finally, this study compares the economic viability of adsorption chillers that integrate silica gel with eventual other higher-performance adsorption material.

Description of the system

The smallest commercially available adsorption cooling system in the European market produces around 8kW of cooling and consumes about 12kW of waste heat, with a rated coefficient of performance (COP) of 0.65 [8]. Such a system is available in two common forms: the first with a single adsorber with a single-phase changer integrated into the same vessel [9], and the second form with two adsorbers, one evaporator, and one condenser. The first design configuration does not offer continuous cooling power, whereas the second design configuration does. As shown in Fig. 1, the initial design's flaw of producing intermittent cooling power can be mitigated by adding a second module to the system that functions out of sync with the first module. This work focuses on the first design since it is intrinsically more affordable. The absence of vacuum valves provides a significant competitive advantage by reducing the overall manufacturing costs and making the final selling price more appealing to buyers. In addition to the cost of the adsorption material, we analyse the price of the hydraulic group, which includes the heat exchangers, and the cost of the control unit, sheet metal, and labour to create one 8-kW adsorption chiller.

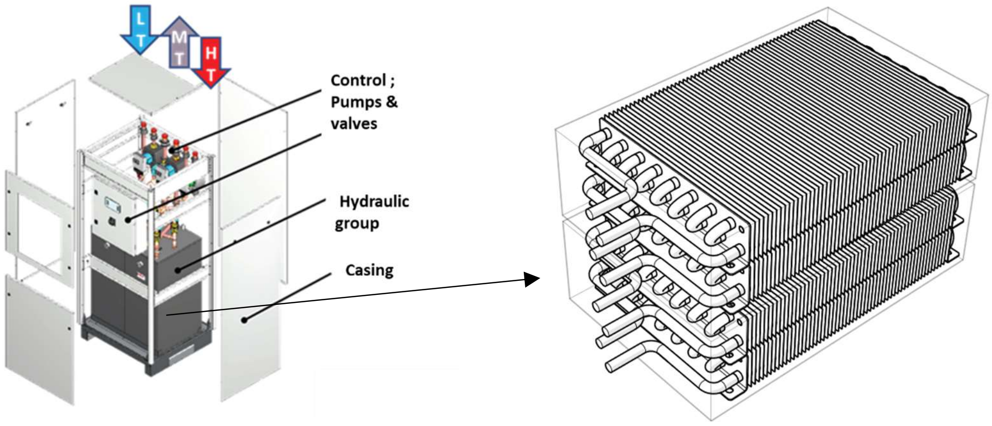

Figure 1: Exploded view of the adsorption chiller design covered by this analysis of the manufacturing cost [adapted from Fahrenheit] (left); Each of two vacuum-sealed modules that operate out of sync has two finned heat exchangers. The upper heat exchanger serves as an adsorber, while the lower heat exchanger functions as a condenser/evaporator (right).

Tools and data on materials and manufacturing

The manufacturing cost estimated in this study is mainly from the data and tools available in CALC4XL (Hamburg, Germany), a transparent and accurate platform that follows a bottom-up cost approach and requires the specification and quantity of all chiller components. CALC4XL has an extensive and reliable database explicitly developed for the industry, containing costs of items such as labour, raw material and industry-dependent overhead for different manufacturing processes in different countries.

The estimation of the adsorption chiller cost of manufacturing requires all direct or indirect contributors. When reliable data and technical specifications are available, a class 3 estimate can be achieved. Table 1 collects the sources used in this study. Quotes were supplemented from the Emerging Sustainable Technologies Lab (ESTech Lab) in The University of Edinburgh [10] whenever there was a need to fill information gaps. The reliance on laboratory quotes, however, was kept at minimum, recognising that quotes for large quantities benefit from scale economy. Adsorption chillers must meet strict manufacturing standards because of the need to maintain vacuum over extended periods, ideally decades. Typically, the vacuum level should not exceed a threshold detrimental to the device's efficiency. For this reason, the vacuum is usually restored periodically after one or few years and a maintenance programme can sometimes be included in the costs, which this analysis excludes. Adsorption chillers are manufactured using metal materials requiring operations performed by skilled workers. Tungsten inert gas (TIG) arc welding is the principal among these operations and a manufacturing step that significantly influences the cost of manufacturing. TIG welding is a process used for welding stainless steel vacuum-tight vessels and feed-throughs that conform to the required vacuum leak rate of 10^{-6} Pa m^3 s^{-1} [14].

Case study: cost of manufacturing of an 8kW cooling power adsorption chiller

An adsorption chiller with rated cooling power of 8 kW is used as a basis for setting a manufacturing cost and accordingly a selling price. After gathering all the values in Table 1, however, the analysis can be generalised by referring to a specific cost per kilowatt of cooling and applied to different rated powers using correct scaling factors. This approach is particularly beneficial when the chiller results from the assembly of modular subunits.

Table 1: Contributors to the cost of manufacturing

Costing Contributor	Cost Type	Source	Source Type
Adsorption material	DC – materials	Oker Chemie Siogel (Germany)	Quote
Sheet metal	DC – materials	The Metals Warehouse (UK)	Quote
Control unit	DC – materials	ESTech Lab [10]	Quote
Hydraulic unit	DC – materials	[11]	Scientific Article
Materials overhead	INDC	CALC4XL	Software
Indirect labour	INDC	CALC4XL	Software
Direct Labour	DC	CALC4XL	Software
TIG welding	DC	[12, 13] and CALC4XL following the costing process detailed in Table 2.	Software

Notes:
DC stands for Direct Cost, INDC for Indirect Cost.
Profit and fixed costs are excluded from the table and discussed later in the manuscript.

First, it is necessary to determine the nature of the industry as well as the size of the business, given it is correlated with the overheads. The current size of a typical adsorption chiller is medium, operating in the metalworking industry with a moderate number of employees. Subsequently, a list of both direct and indirect materials is required. Components falling under direct materials include the cost of the adsorption material, metal, hydraulics and controls (Table 1). Indirect material costs are estimated by CALC4XL. For the type and size of the business, CALC4XL assumes overheads at 1.94% of the total cost of raw materials and purchased components. Labour can be direct and indirect. Direct labour is related to employing a TIG welder who produces the metal housing of the chiller's components. Table 2 details the process of costing linked with TIG welding.

Table 2: Process followed for costing TIG welding.

Calculation steps	Description	Ref
1. Full-time or on-demand labour.	We assume the job is on demand and based on the hourly rate of a skilled welder. This is because hiring a full-time skilled welder can increase the selling price.	--
2. TIG welding database	The database contains the necessary data to calculate the cycle time for TIG welding.	[12]
3. Welding cycle time	Estimation of the time needed to weld parts of one adsorption chiller (assumed at 1 hour in this study).	[13]
4. Machine cost and operator rate.	The machine cost is €11 per hour, and the operator rate per hour is €100.	CALC4XL

TIG welding is only a fraction of the whole direct labour cost. Direct labour also includes the planning and execution of the machine's commissioning and pre- and post-processing activities such cleaning the containers, assembling, and packing. Within 30 days, we anticipate these activities will be completed by a trained full-time engineer. There may be more personnel engaged in some of the operations. The assumption of a flat-rate specialist is assumed equivalent to the total costs of all people involved in the manufacturing. Labour wages rely on CALC4XL's extensive and accurate database, which distinguishes on skill levels for specific manufacturing processes and industry sectors. A competent worker in the metal business ought to earn around €15.5 per hour, €2,471 per month. In addition, CALC4XL assumes typical production overheads (indirect labour) in the metalwork industry at 7.6% of the overall cost of production. Finally, CALC4XL recommends a minimum profit margin of 16% of the selling price, based on nature and production volume of the business. Adding together manufacturing cost and profit margin, the selling price of a 8kW cooling power adsorption chiller totals €8,144.

As Fig. 2 shows, the cost of manufacturing is the 84% of the selling price, while profit margin 16%. The hydraulics affects 34%, the direct labour 21% of the selling price. These are both country-specific factors, which can be mitigated by strategically relocating the factory to areas where labour and materials are less expensive.

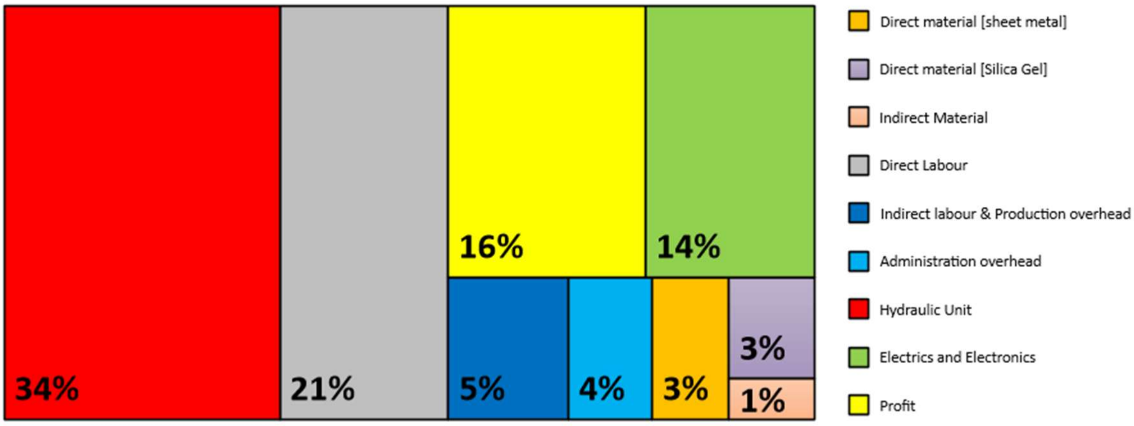

Figure 2: The hierarchy of the contributors to the manufacturing cost and selling price of an adsorption chiller with a maximum cooling power of 8 kW.

Business profitability

The profitability of a business requires a Cost, Volume and Profit (CVP) analysis, which estimate the amount of profit generated during a specific time period on a specific annual number of unit sold [15]. In addition, the CVP analysis identifies the minimum number of units that must be sold to generate profit and the costs that could become negligible when a particular manufacturing volume is achieved. The CVP analysis starts with the calculation of the variable cost *V* based on the selling price *S* = €8144 for a 8kW chiller:

$$V = S \cdot - C_m = €5774 \quad (1)$$

Where C_m = €8144 = 0.3**S* is the contribution margin.

The dimensionless break-even point (*BEP*), a fundamental parameter for the identification of the minimum number of sold units to generate profit, is:

$$BEP = F / (S - V) \quad (2)$$

Where $(S - V)$ = €2443 and F = €2799 is the monthly fixed cost that remains constant regardless of a company's output. This is based on an annual fixed cost of €33591 for a medium-size enterprise as the current adsorption chiller industry is. The annual fixed cost includes the expenses such as rental leasing, insurance, property taxes, and utility bills not accounted in the overheads.

The total cost T is the sum of the annual fixed cost F and the variable cost V of the manufacturing process:

$$T = F + V \tag{3}$$

The base profit P in Euros from the sale of a certain number of units (Q) is given by:

$$P = (S\ Q) - (V - Q) - F \tag{4}$$

According to the data in Fig. 3, a small or medium business must sell at least 14 units per year to break even. When the base profit from the sale of 384 units reaches €905k, expanding the production of adsorption chillers is a viable option for the advantage of amortising the fixed costs over more units.

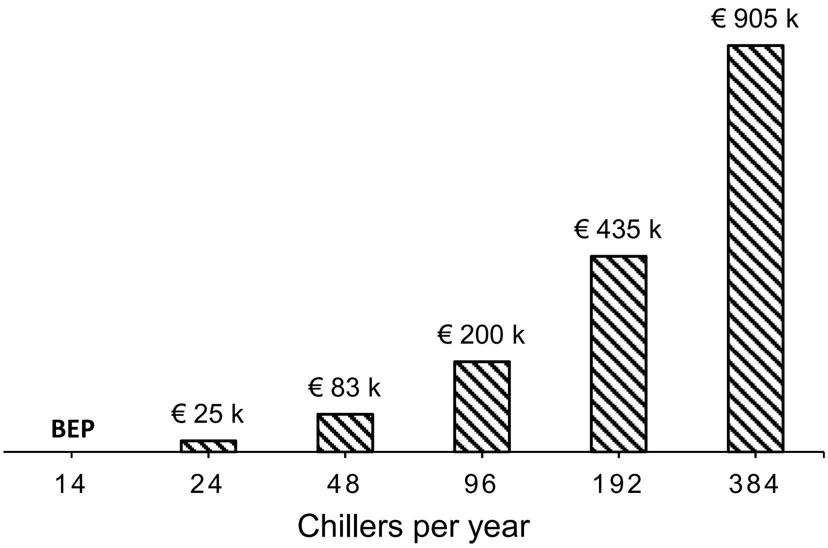

Figure 3: The minimum number of units (*BEP*) for the adsorption chiller industry is 14. The *BEP* defines the minimum annual production volume that should be sold for a zero-profit small or medium-size enterprise producing adsorption chillers. The height of the column is the annual profit generated at each number of sold units.

A wide variety of factors can influence the profits in Fig. 3 and sensitivity analysis can assist in determining which of these factors is the most significant. The outcomes from a two-level Full Factorial Design (FFD) sensitivity analysis [16, 17] show that the two aspects with the most significant leverage effect on a profit increase are the retail selling price and the total number of units sold. The most important factor contributing to the annual profit of 1.2 million Euros is the rise in unit sales, which is moved from 14 to 384 units. However, if the variable cost was raised from € 5701 to € 9100, a rise in the annual number of units sold to 384 units would result in a catastrophic loss of €0.6 million. In addition, two iterations of the sensitivity analysis showed that a price increase of the 8kW chiller from € 8144 to € 13000 would result in a maximum profit of € 1 million. In order to achieve a 75% increase in the base profit, it is necessary to achieve a 10% rise in the unit price as well as a 10% decrease in both the variable costs and the fixed expenditures. Finally, when the total number of units sold exceeds 384, the abovementioned variables will no longer significantly influence the overall profit.

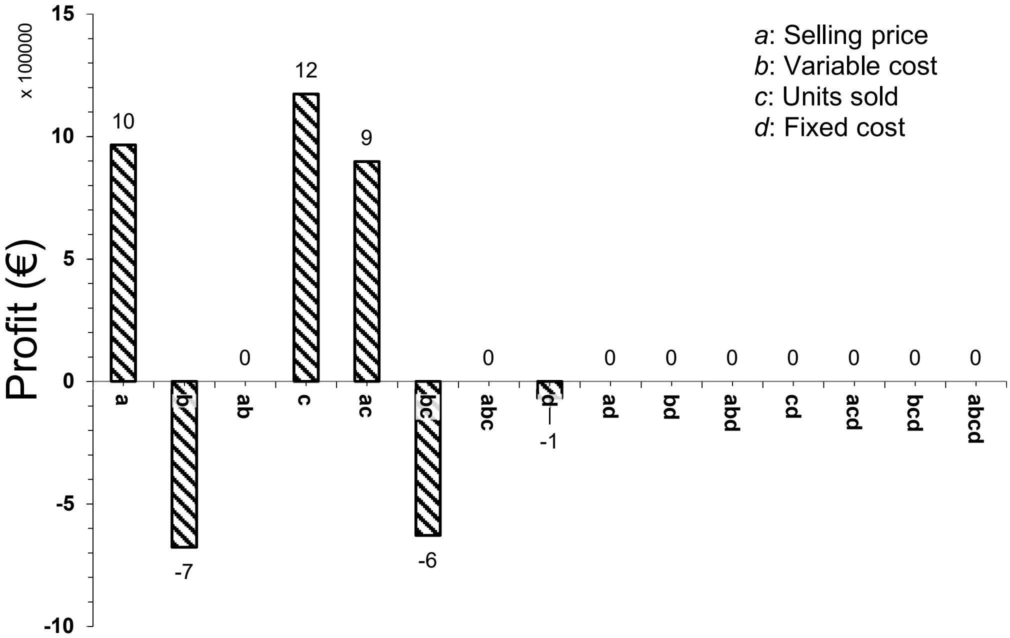

Figure 4: Two-level full factorial design (FFD) shows the significance of Selling Price (*a*), Variable Cost (*b*), Units Sold (*c*) and Fixed Cost (*d*) on one objective function (Profit).

The effect of system performance on the manufacturing cost

Specific cooling power (SCP) and coefficient of performance (COP) are the two key performance indicators in adsorption chillers. In most cases, higher SCPs and COPs are made possible by more expensive, innovative technical solutions. An exemplary case concerns novel adsorption materials, where the performance increase often comes along with a significant increase in the material price. The introduction of more efficient innovative solutions should be evaluated within a framework that considers the whole problem, from material to market, and determining the technology manufacturing cost is the fundamental element in a material-to-market evaluation. Due to their wide use and cost, the present analysis focuses exclusively on silica gel adsorption chillers. Despite the reduced focus, the complexity of the analysis remains significant, as several different silica gel coolers have been tested in the past, showing significant discrepancies in SCP and COP due to different internal heat and mass transfer patterns and designs. Table 3 samples the maximum SCP and maximum COP achieved in a series of laboratory or pilot-scale silica gel chillers.

Table 3: Maximum SCP and COP achieved in different silica-gel adsorption chillers and consequent total cost of the heat exchangers.

SCP_{max} [W kg^{-1}]	COP_{max} [-]	Silica-gel for 8 kW cooling [$kg_{silica-gel}$]	Silica-gel total cost[1] [€]	Adsorber Heat transfer surface area[2] [m^2]	The total cost of Adsorber Heat Exchangers [€]	Ref
146	0.51	55	440	102	1510	[18]
168	0.60	48	384	89	1427	[19]
111	0.50	72	576	134	1692	[20]
250	0.64	32	256	60	1211	[21]
113	0.45	71	568	132	1682	[22]
181	0.50	44	352	82	1379	[23]
106	0.30	75	600	140	1723	[24]
300	0.65	27	216	50	1123	[25]

Note:
[1] the silica gel price is €8 per kg
[2] 1.84 m^2 per each kilogram of silica-gel grains is taken from [26]. Experimental data from the other sources reported in this table have shown similar values ranging between 1.85 m^2 to 1.88 m^2 per kilogram of silica-gel grains.

SCP and COP affect the heat power of each heat exchanger according to the following relations:

$$SCondP = \left(1 + \frac{1}{COP}\right) SCP \tag{5}$$

$$SAHP = \frac{SCP}{COP} \tag{6}$$

Where *SCondP* is the condensing power per kg of silica gel [W kg^{-1}], and *SAHP* is the adsorber heating power per kg of silica gel [W kg^{-1}]. By taking the temperature change of the heat transfer fluid across each heat exchanger (condenser, evaporator and adsorber) and the heat transfer coefficients identical, each heat power can be correlated proportionally with the heat transfer surface area, which is one of the main assumptions of this study. The analysis here sets the SCP at its highest value among those in Table 3, which is 300 W kg^{-1}, linked to the lowest heat transfer surface of area of the adsorber of 50m^2. SCP and COP allow the definition of the specific powers of each heat exchanger according to the following:

$$SCondP = (1 + COP)\ SAHP \tag{7}$$

$$SCP = COP \times SAHP \tag{8}$$

SCondP + SCP = (1 + 2 COP) SAHP (9)

From eq. (9), the heat transfer surface area of the condenser and evaporator is proportional to the heat transfer surface area of the adsorber by a factor of *(1 + 2 COP).* At *COP* = 1 (maximum theoretical COP), the heat transfer surface area of the evaporator is equivalent to the adsorber, while the condenser features a heat transfer surface area twice the adsorber. This condition requires the largest heat transfer surface areas in the condenser and evaporator. In this study, the evaporator and condenser are integrated. Therefore, the maximum between the two (twice the surface area of the adsorber) is taken as the heat transfer surface area of the integrated evaporator/condenser heat exchanger.

SCP and COP are dependent on the operating temperatures. By defining a reduced temperature T_{red}, the operating temperatures can be reduced to only one parameter. This parameter has in multiple experimentations proven useful for the identification of one single performance curve characteristic of particular of a specific design [20, 27]:

$$T_{red} = \frac{T_{cond} - T_{evap}}{T_{hot} - T_{cond}} \quad (10)$$

Fig. 5 highlights that a typical adsorption chiller should operate in a range of reduced temperature from 0.4 to 0.5.

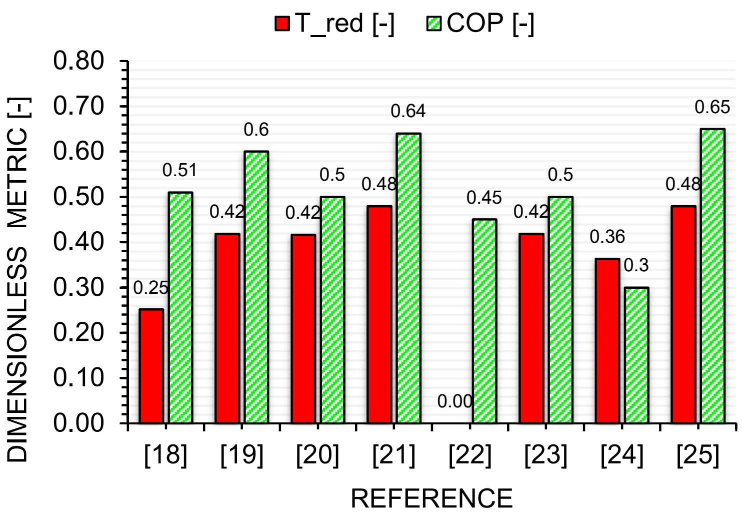

Figure 5: Optimal operating temperatures vary from design to design for adsorption chillers and the maximum COP ranges from 0.25 to 0.65.

The sources in Table 3 either do not disclose manufacturing costs or neglect them entirely, making it impossible to analyse their selling price, which is essential information for assessing their market penetration potential. From the data disclosed, by using the methodology described above, we calculated the Specific Manufacturing Cost (*SCOM*) of each design, obtaining the following relation:

$$SCOM\ (COP,\ SCP) = 2599 - 3450\ COP + 0.31\ SCP + 2820\ COP^2 - 3.194\ COP\ SCP \qquad (11)$$

The specific selling price of an adsorption chiller disclosed in [7] equals €1625 per kW of cooling, close to the value of 1550 € kW^{-1} from eq. (11). This match reassures on the applicability of the assumptions taken to identify the cost. Fig. 6 depicts the effect of different designs on the *SCOM*.

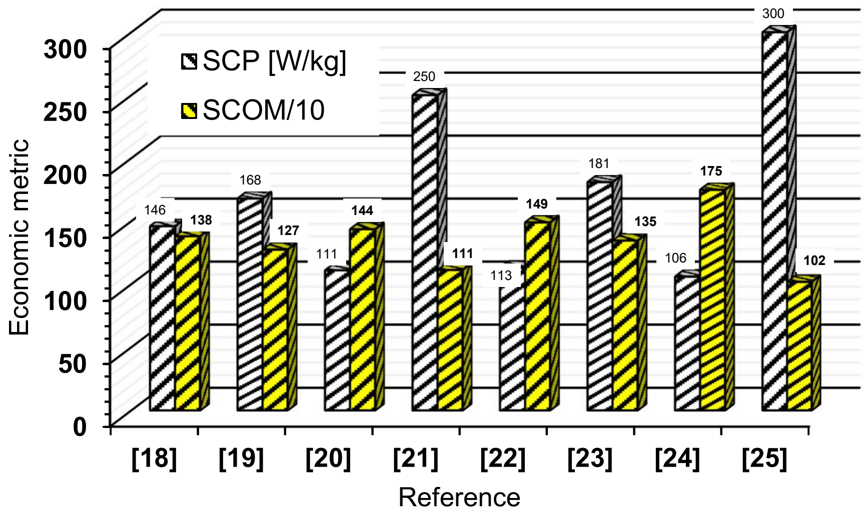

Figure 6: The effect of the system performance on the manufacturing cost. SCP is the Specific Cooling Power [W kg^{-1}] and SCOM is the Specific Cost of Manufacturing [Euros per kW of cooling].

Because the hydraulic unit accounts for 34% of the total manufacturing cost, typical designs must employ efficient and inexpensive heat exchangers, such as finned tube heat exchangers, to keep the *SCOM* value low. The benchmark design of silica gel-water adsorption chiller taken into account in this study uses a compact aluminium plate heat exchanger containing 1.45 kg of silica gel, resulting in an outstanding packing ratio of one. The design features minimal void volume, exceptional vacuum tightness and the maximum SCP of 300 W kg^{-1} ever proven, leading to the lowest value for the *SCOM* of €1018 per kW of cooling, which marks a low limit benchmarking value.

The economic viability of innovative adsorption materials

Silica gel chillers are currently the most established solutions of proven market viability. Keeping the approach above, here we assess the market viability of chillers integrating a number of innovative adsorption materials proposed for adsorption cooling applications. The estimate assumes all manufacturing cost contributions are identical to silica gel, except for hydraulics and material costs. This assumption is legitimate since the market already accepts silica gel arrangements, and any eventual reduction in hydraulics and material costs will enable solutions that are even more market-attractive than silica gel.

The earlier discussion of the impact of system performance on manufacturing costs was crucial to determining a benchmark *SCOM* limit that is currently accepted by the market. However, no prior research has studied or explained whether the use of advanced adsorption materials would drive this cost down. Table 4 compares silica gel with a range of innovative nanoporous materials proposed for adsorption cooling. These materials can be significantly expensive if purchased as laboratory chemicals, undermining the present analysis. To circumvent the issue, we used the method to estimate their eventual cost as special chemicals based on the pricing of laboratory-scale quantities [28]. We define two parameters, the Performance Ratio *PR* and the Cost Ratio *CR*, as:

$$PR = SCP_{MAX} \text{ of adsorption material } i \,/\, SCP_{MAX} \text{ of silica gel} \quad (12)$$

$$CR = \text{Cost of adsorption material } i \,/\, \text{Cost of silica gel} \quad (13)$$

All the measures are taken to give expensive nanoporous materials a fair chance against inexpensive materials, such as silica gel.

Table 4: Performance Ratios (PR) and Cost Ratios (CR) of various adsorption materials for cooling.

Adsorption material	SCP_{MAX} [W kg^{-1}]	PR [-]	Material Price [€ kg^{-1}]	CR [-]	Ref
Silica Gel	300	1	8	1	Quote
Clay	100	0.33	1	0.13	Quote
AQSOA Z02	500	1.67	136	17	Quote
MIL-100 (Fe, Al, Cr)	250	0.83	3021	378	[29]
Al-Fumarate	600	2	364	45	[30]
HKUST-1	300	1	5167	646	[30]
CAU-23	1500	5	400	50	[30]
MIL-160	2000	6.67	400	50	[30]
MOF-801	1500	5	364	45	[30]

To evaluate *COH* and *COAM* for other innovative materials, *PR* is integrated into *COH* and *CR* into *COAM* as follows:

$$COH = (PR)\ 2286\ (\text{Cooling Power in kW})^{-1} + 63.12 \quad (14)$$

$$COAM = (CR)\ 177.8\ (\text{Cooling Power in kW})^{-1} + 4.878 \quad (15)$$

We can now systematically evaluate the (*COH* + *COAM*) of the adsorption materials in Table 4 by comparing them with silica gel. Silica gel establishes the market acceptance zone (MAZ) with a *COH* of 350 € kW^{-1} and a *COAM* of 27 € kg^{-1}. Fig. 7 depicts the market viability of all materials assuming their maximum SCP regardless of the process conditions. Despite high performance of the majority of innovative materials evaluated, any of them have chances to see commercialisation because the buyer will opt for silica gel. Only materials that achieve *PR* = 8.33 (2500 W kg^{-1}) and *CR* = 13, resulting in a (*COH* + *COAM*) = 380 € kW^{-1}, can be in line with the benchmark *SCOM* of 1018 € kW^{-1} and able to compete. The most direct rival to silica gel is the AQSOA FAM Z02, with a *COH* = 210 € kW^{-1}, lower than silica gel but a higher *COAM* of 461 € kg^{-1}. With a cost ratio of 0.13, clay is cheaper than silica gel but additional research is needed to enhance its performance ratio to 1, which would reduce its *COH* + *COAM* from 1054 € kW^{-1} to 354 € kW^{-1}, 6.7% lower than silica gel.

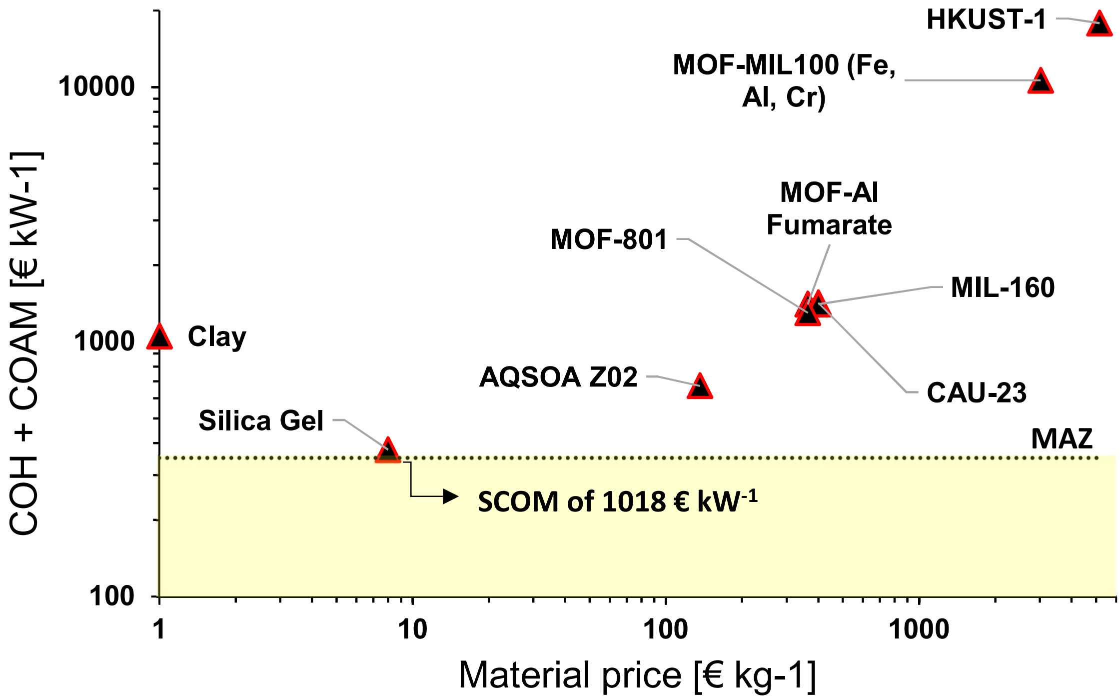

Figure 7: Viability of different adsorption materials for adsorption cooling applications

All innovative materials analysed show improved performance but none of them will be able to have in the future a market-viable *SCOM* lower than 1018 € kW^{-1}.

Conclusions

Adsorption chillers are struggling to penetrate the market. New and efficient adsorbent materials are often too expensive for an already expensive technology. There is consensus that the performance can be significantly increased from those currently achieved leading to stronger market position for this technology. However, the market still features silica-gel adsorption chillers that achieve in the best case specific cooling powers in the range 250-300 W kg^{-1} and are currently priced not less than €1018 per kW of cooling power. This study highlights how specific cooling power and coefficient of performance contribute to this price.

However, other factors as influential as performance contribute to the technology price — for example, the manufacturing process. An analysis of the economic viability of innovative adsorption materials concluded that none will be able to succeed in the market if eventually commercialised because no material has properties to break through the market acceptance zone defined by silica gel chillers.

NOMENCLATURE

BEP	Break-even point [-]
C_m	Contribution margin ratio, [%]
COP	Coefficient of performance [-]
P	Profit, [€]
PBP	Payback period, [Years]
S	Selling price per unit, [€]
SAHP	The adsorber heating power per kg of silica-gel [$W\ kg^{-1}$]
SCondP	The condensing power per kg of silica-gel [$W\ kg^{-1}$]
SCP	Specific cooling power per kg of dry silica-gel [$W\ kg^{-1}$]
T	Total costs, [€]
V	Variable costs per unit, [€]

References

[1] C.W. Callahan, J.S. Mankin, Globally unequal effect of extreme heat on economic growth, Sci Adv. 8 (2022) eadd3726. https://doi.org/10.1126/sciadv.add3726.

[2] The Future of Cooling – Analysis - IEA, (2022). https://www.iea.org/reports/the-future-of-cooling (accessed November 21, 2022).

[3] R. Gupta, I.K. Puri, Waste heat recovery in a data center with an adsorption chiller: Technical and economic analysis, Energy Convers Manag. 245 (2021) 114576. https://doi.org/10.1016/j.enconman.2021.114576.

[4] K.C. Ng, K. Thu, Y. Kim, A. Chakraborty, G. Amy, Adsorption desalination: An emerging low-cost thermal desalination method, Desalination. 308 (2013) 161–179. https://doi.org/10.1016/j.desal.2012.07.030.

[5] K. Thu, A. Chakraborty, B.B. Saha, W.G. Chun, K.C. Ng, Life-cycle cost analysis of adsorption cycles for desalination, Desalination Water Treat. 20 (2010) 1–10. https://doi.org/10.5004/dwt.2010.1187.

[6] U.S. Department of Energy, Advanced Manufacturing Office, Combined Heat and Power Technology Fact Sheet Series - Absorption Chillers CHP Systems, DOE/EE-1608. (2017)., (2016) 1–4. https://www.energy.gov/eere/amo/downloads/absorption-chillers-chp-systems-doe-chp-technology-fact-sheet-series-fact-sheet (accessed November 21, 2022).

[7] S. Vasta, V. Palomba, A. Frazzica, G. di Bella, A. Freni, Techno-Economic Analysis of Solar Cooling Systems for Residential Buildings in Italy, Journal of Solar Energy Engineering, Transactions of the ASME. 138 (2016). https://doi.org/10.1115/1.4032772.

[8] FAHRENHEIT Adsorption chiller (eCoo S), (2022). https://fahrenheit.cool/en/product/ecoo-s/ (accessed November 21, 2022).

[9] T. Núñez, W. Mittelbach, H. Henning, Development of a small-capacity adsorption system for heating and cooling applications, HVAC and R Research. 12 (2006) 749–765. https://doi.org/10.1080/10789669.2006.10391205.

[10] C. Olkis, S. Brandani, G. Santori, Design and experimental study of a small scale adsorption desalinator, Appl Energy. 253 (2019) 113584. https://doi.org/10.1016/j.apenergy.2019.113584.

[11] R. Li, Y. Dai, G. Cui, Multi-objective optimization of solar powered adsorption chiller combined with river water heat pump system for air conditioning and space heating application, Energy. 189 (2019) 116141. https://doi.org/10.1016/j.energy.2019.116141.

[12] TIP TIG Welding database, (2022). https://tiptig.com/arc-welding-process/ (accessed June 17, 2020).

[13] Esab UK, Weld Cost Calculator, (2022). https://esab.com/gb/eur_en/select-language/ (accessed November 3, 2022).

[14] S. AL-Hasni, G. Santori, 3D printing of vacuum and pressure tight polymer vessels for thermally driven chillers and heat pumps, Vacuum. 171 (2020) 109017. https://doi.org/10.1016/j.vacuum.2019.109017.

[15] M. Cafferky, J. Wentworth, Breakeven Analysis: The Definitive Guide to Cost-Volume-Profit Analysis, Second Edition., Business Expert Press, 2014.

[16] A. Freni, G. Maggio, S. Vasta, G. Santori, F. Polonara, G. Restuccia, Optimization of a solar-powered adsorptive ice-maker by a mathematical method, Solar Energy. 82 (2008) 965–976. https://doi.org/10.1016/j.solener.2008.05.002.

[17] G. Santori, A. Frazzica, A. Freni, M. Galieni, L. Bonaccorsi, F. Polonara, G. Restuccia, Optimization and testing on an adsorption dishwasher, Energy. 50 (2013) 170–176. https://doi.org/10.1016/j.energy.2012.11.031.

[18] Q.W. Pan, R.Z. Wang, L.W. Wang, D. Liu, Design and experimental study of a silica gel-water adsorption chiller with modular adsorbers, International Journal of Refrigeration. 67 (2016) 336–344. https://doi.org/10.1016/j.ijrefrig.2016.03.001.

[19] K.C. Ng, K. Thu, A. Chakraborty, B.B. Saha, W.G. Chun, Solar-assisted dual-effect adsorption cycle for the production of cooling effect and potable water, International Journal of Low-Carbon Technologies. 4 (2009) 61–67. https://doi.org/10.1093/ijlct/ctp008.

[20] T. Núñez, W. Mittelbach, H.M. Henning, Development of an adsorption chiller and heat pump for domestic heating and air-conditioning applications, Appl Therm Eng. 27 (2007) 2205–2212. https://doi.org/10.1016/j.applthermaleng.2005.07.024.

[21] R.J.H. Grisel, S.F. Smeding, R. de Boer, Waste heat driven silica gel/water adsorption cooling in trigeneration, Appl Therm Eng. 30 (2010) 1039–1046. https://doi.org/10.1016/j.applthermaleng.2010.01.020.

[22] A.S. Alsaman, A.A. Askalany, K. Harby, M.S. Ahmed, Performance evaluation of a solar-driven adsorption desalination-cooling system, Energy. 128 (2017) 196–207. https://doi.org/10.1016/j.energy.2017.04.010.

[23] K.C. Ng, K. Thu, B.B. Saha, A. Chakraborty, Study on a waste heat-driven adsorption cooling cum desalination cycle, International Journal of Refrigeration. 35 (2012) 685–693. https://doi.org/10.1016/j.ijrefrig.2011.01.008.

[24] K.C.A. Alam, B.B. Saha, A. Akisawa, Adsorption cooling driven by solar collector: A case study for Tokyo solar data, in: Appl Therm Eng, Pergamon, 2013: pp. 1603–1609. https://doi.org/10.1016/j.applthermaleng.2011.09.028.

[25] R. de Boer, S. Smeding, R. Grisel, Development and testing of a sorbent filled heat exchanger for use in compact solid sorption cooling systems, in: International Sorption Heat Pump Conference, Denver, USA, 2005: pp. 22–24.

[26] A. Sapienza, S. Santamaria, A. Frazzica, A. Freni, Influence of the management strategy and operating conditions on the performance of an adsorption chiller, Energy. 36 (2011) 5532–5538. https://doi.org/10.1016/j.energy.2011.07.020.

[27] C. Olkis, S. Brandani, G. Santori, Cycle and performance analysis of a small-scale adsorption heat transformer for desalination and cooling applications, Chemical Engineering Journal. 378 (2019) 122104. https://doi.org/10.1016/j.cej.2019.122104.

[28] P.W. Hart, J.T. Sommerfeld, Cost estimation of specialty chemicals from laboratory-scale prices, Cost Engineering. 39 (1997) 31.

[29] N. Makhanya, B. Oboirien, J. Ren, N. Musyoka, A. Sciacovelli, Recent advances on thermal energy storage using metal-organic frameworks (MOFs), J Energy Storage. 34 (2021) 102179. https://doi.org/10.1016/j.est.2020.102179.

[30] L. Biswal, J.E. Goodwill, C. Janiak, S. Chatterjee, Versatility, Cost Analysis, and Scale-up in Fluoride and Arsenic Removal Using Metal-organic Framework-based Adsorbents, 51 (2021) 408–426. https://doi.org/10.1080/15422119.2021.1956539.