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Evaluation of Modular Thermally Driven Heat Pump Systems

Corey Blackman

MÄLARDALEN UNIVERSITY
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Corey Blackman

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Abstract

The building sector accounts for approximately 40% of primary energy use within the European Union, therefore reductions in the energy use intensity of this sector are critical in decreasing total energy usage. Given that the majority of energy used within the built environment is for space conditioning and domestic hot water preparation, prudence would suggest that decreasing primary energy used for these end purposes would have the biggest overall environmental impact. A significant portion of the energy demands in buildings throughout the year could potentially be met using solar energy technology for both heating and cooling. Additionally, improving the efficiency of current heating and cooling appliances can reduce environmental impacts during the transition from non-renewable to renewable sources of energy. However, in spite of favourable energy saving prospects, major energy efficiency improvements as well as solar heating and cooling technology are still somewhat underutilised. This is typically due to higher initial costs, and lack of knowledge of system implementation and expected performance.

The central premise of this thesis is that modular thermally (i.e., sorption) driven heat pumps can be integrated into heating and cooling systems to provide energy cost savings. These sorption modules, by virtue of their design, could be integrated directly into a solar thermal collector. With the resulting sorption integrated collectors, cost-effective pre-engineered solar heating and cooling system kits can be developed. Sorption modules could also be employed to improve the efficiency of natural gas driven boilers. These modules would effectively transform standard condensing boilers into high efficiency gas-driven heat pumps that, similar to electric heat pumps, make use of air or ground-source heat.

Based on the studies carried, sorption modules are promising for integration into heating and cooling systems for the built environment generating appreciable energy and cost-savings. Simulations yielded an annual solar fraction of 42% and potential cost savings of €386 per annum for a sorption integrated solar heating and cooling installation versus a state-of-the-art heating and cooling system. Additionally, a sorption integrated gas-fired condensing boiler yielded annual energy savings of up to 14.4% and corresponding annual energy cost savings of up to €196 compared to a standard condensing boiler.

A further evaluation method for sorption modules, saw the use of an artificial neural network (ANN) to characterise and predict the performance of the sorption module under various operating conditions. This generic, application agnostic model, could characterise sorption module performance within a ± 8% margin of error. This study thus culminates in the proposal of an overall systematic evaluation method for sorption modules that could be employed for various applications based on the analytical, experimental and simulation methods developed.

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When you are unclear about your why, what you do has no context.

Simon Sinek

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*This thesis is based on work conducted within the industrial post-graduate school REESBE – **R**esource-**E**fficient **E**nergy **S**ystems in the **B**uilt **E**nvironment. The projects in Reesbe are aimed at key issues in the interface between the business responsibilities of different actors in order to find common solutions for improving energy efficiency that are resource-efficient in terms of primary energy and low environmental impact.*

Reesbe

Resource-Efficient Energy Systems in the Built Environment

The research groups that participate are Energy Systems at the University of Gävle, Energy and Environmental Technology at the Mälardalen University, and Energy and Environmental Technology at the Dalarna University. Reesbe is an effort in close co-operation with the industry in the three regions of Gävleborg, Dalarna, and Mälardalen, and is funded by the Knowledge Foundation (KK-stiftelsen).

Summary

The building sector accounts for approximately 40% of primary energy use within the European Union, therefore reductions in the energy use intensity of this sector are critical in decreasing total energy usage. Given that the majority of energy used within the built environment is for space conditioning and domestic hot water preparation, prudence would suggest that decreasing primary energy used for these end purposes would have the biggest overall environmental impact. Using solar energy technology for both heating and cooling has the potential of meeting an appreciable portion of the energy demands in buildings throughout the year. By developing an integrated, multi-purpose system, that can be exploited all twelve months of the year, a high utilisation factor can be achieved which translates to more economical systems. Additionally, improving the efficiency of current heating and cooling appliances can go a long way to reducing environmental impacts during the transition from non-renewable to renewable sources of energy.

However, in spite of favourable energy saving prospects, major energy efficiency improvement measures and solar heating and cooling technology are still somewhat underutilised. This is typically due to higher initial costs, and lack of knowledge of system implementation and expected performance. For improved cost-effectiveness and thus widespread uptake, the market calls for standardised, plug-and-function, small and medium sized solar heating and cooling kits as well as easy-to-install cost-optimised heating appliances.

The central premise of this thesis is that modular thermally (i.e. sorption) driven heat pumps can be integrated into heating and cooling systems to provide appreciable energy cost savings. These sorption modules, by virtue of their design, could be integrated directly into a solar thermal collector. With the resulting sorption integrated collectors (SIC) cost-effective pre-engineered solar heating and cooling system kits can be developed. Sorption modules could also be employed to improve the efficiency of natural gas driven boilers. These modules would effectively transform standard condensing boilers into high-efficiency gas-driven heat pumps that, similar to electrical heat pumps, make use of air or ground-source heat.

This thesis thus aims to describe the performance characteristics of the sorption module integrated systems leading to evaluation of their energy and cost saving potential.

Analytical, experimental, and simulation-based evaluations of individual sorption modules were carried out where the principal performance characteristics of cooling and heating power and energy delivery as well as heating and cooling conversion efficiencies were investigated. Further evaluations were then carried out on a system level studying the key performance indicators and the energy use of the sorption integrated system compared to the state-of-the-art reference.

Results showed that individual sorption modules for solar applications delivered cooling for 6 hours at a power of 40 W and temperature lift of 21°C. The implementation of these SIC to form a so-called sorption integrated solar heating and cooling system (SISHCS) was evaluated. Simulations were performed to determine system energy and cost saving potential for various system sizes over a full year of operation for a single-family dwelling located in Madrid, Spain. Simulations yielded an annual solar fraction of 42% and potential cost savings of €386 per annum for a solar heating and cooling installation employing 20 m^2 of sorption integrated collectors.

In the case of sorption modules for integration as a gas-driven sorption heat pump (GDSHP) two sorption module prototypes were evaluated. Prototype 1 was a basic ammoniated salt module while Prototype 2 was a resorption module. Test results showed that Prototype 2 produced 1105 W of heating capacity at a temperature lift of 50°C and Prototype 1 demonstrated higher heating capacity of 3280 W at the same temperature lift. Simulations were carried out for a single-family house under different climatic conditions. This resulted in annual energy savings of up to 14.4% for an optimally sized GDSHP located in New York, USA and up to 8.1% in Minnesota, USA compared to a standard condensing boiler. This led to potential energy cost savings of up to $215 (€196) and $92 (€84) per annum in New York and Minnesota respectively.

A further evaluation method for sorption modules, saw the development of an automated test platform and the use of an artificial neural network (ANN) trained with experimental data. The ANN was used to characterise and predict the performance of the sorption module under various operating conditions. The testing and modelling approach devised was envisioned to streamline the process of developing and evaluating sorption modules for various applications. This generic, application agnostic model, could characterise sorption module performance within a ± 8% margin of error. The present studies thus culminate in the proposal of an overall systematic evaluation method for sorption modules that could be employed for various applications based on the analytical, experimental and simulation methods developed.

Sammanfattning

Byggnader står för omkring 40% av den primära energianvändningen i EU varför energibesparing inom detta område är ytterst väsentligt för att minska den totala energianvändningen. Då merparten av energin som används i byggnader används till luftkonditionering, uppvärmning och varmvattenberedning, är det rimligt att en minskning av den primärenergi som behövs för att uppfylla dessa ändamål sammantaget skulle ge den största påverkan på miljön. Nyttjandet av solenergiteknik både för uppvärmning och nedkylning har potentialen att tillhandahålla en väsentlig del av energibehovet i byggnader året om. Genom att utveckla ett mångsidigt och integrerat system, som kan användas året runt, åstadkommer man en hög nyttjandegrad vilket i sin tur innebär att systemet blir mer ekonomiskt. Dessutom kan förbättringar av effektiviteten hos befintliga värme- och kylsystem minska miljöpåverkan under övergångsperioden från icke förnybara till förnybara energikällor.

Trots goda utsikter för energibesparing finns det fortfarande utrymme för grundläggande effektivisering av energianvändning och nyttjandet av solenergi för uppvärmning och nedkylning. Detta beror vanligtvis på höga kapitalkostnader och bristfällig kunskap om systemtillämpning och förväntad prestanda. För ökad kostnadseffektivitet, och därmed ökat upptag, kräver marknaden standardiserade, så kallade ”plug-and-function” lösningar för värme- och kyla. Både små och mellanstora storlekar. Värmeanläggningarna behöver också vara lättinstallerade och kostnadsoptimerade.

Utgångspunkten för denna avhandling är att modulära värmedrivna (dvs. sorption) värmepumpar kan integreras i befintliga värme- och kylsystem i syfte att minska kostnader för energianvändning. Dessa sorptionsenheter kan, tack vare sin specifika utformning, integreras i en solfångare. Med dessa sorptionsintegrerade solfångare (SIC) kan uppsättningar av kostnadseffektiva prefabricerade solvärme- och kylsystempaket framställas. Sorptionsmoduler skulle också kunna nyttjas för att förbättra effektiviteten hos gaspannor. Dessa enheter skulle på ett effektivt sätt förvandla vanliga kondenseringsbaserade varmvattenberedare till högeffektiva gasdrivna värmepumpar vilka liksom elektriska värmepumpar använder sig av luft- eller bergvärme.

Syftet med denna avhandling är att beskriva de integrerade sorptionsmodulsystemens prestandakaraktäristik för bedömning av potentialen för energi- och kostnadsbesparingar.

Analytiska, experimentella och simuleringsbaserade utvärderingar av individuella sorptionsmodulers huvudsakliga prestandakaraktäristik utfördes, där

deras kyl- och värmeeffekt, samt deras kyl- och värme-omvandlingseffektivitet undersöktes. Ytterligare utvärderingar genomfördes sedan på systemnivå där de integrerade sorptionssystemens nyckeltal och energianvändning jämfördes med de mest aktuella referenssystemen.

Resultaten visade på att individuella sorptionsmoduler anpassade för solanläggningar levererade kyla motsvarande 40 W med en temperaturlyft på 21°C i sex timmar. Implementeringen av dessa så kallade sorptionsintegrerade sol värme- och kylsystemen (SISHCS) utvärderades. För att bedöma olika systemstorlekars årliga energi- och kostnads-besparingspotential genomfördes simuleringar baserade på ett enfamiljshus i Madrid, Spanien. Utförda simuleringar visar en årlig soltäckningsgrad på 42% och möjliga besparingar på 386 euro per år för ett solvärme- och kylsystem med 20 m^2 sorptionsintegrerade solfångare.

En gasdriven sorptionsvärmepump utvärderades i två prototypmoduler. Prototyp 1 var en enkel ammoniaksaltmodul medan Prototyp 2 var en resorptionsmodul. Tester visade att Prototyp 2 producerade 1105 W värme med en temperaturskillnad på 50°C medan Prototyp 1 visade på en högre värmekapacitet på 3280 W vid samma temperaturskillnad. Simuleringar utfördes för enfamiljshus i olika klimatförhållanden. Dessa visade på att en optimalt dimensionerad GDSHP lokaliserad i New York, USA medför årliga energibesparingar på upp till 14,4% medan en i Minnesota, USA medför 8,1% besparing, jämfört med en traditionell kondenserande gaspanna. Detta skulle i sin tur innebära årliga besparingar på $215 (€196) eller $92 (€84) i New York respektive Minnesota.

En utökad metod för utvärdering av sorptionsmoduler utvecklades i form av en automatiserad testplattform där ett artificiellt neuralt nätverk (ANN), tränat med experimentella data, används. Det artificiella neurala nätverket användes för att kartlägga och prognostisera sorptionsmodulers prestanda under olika driftförhållanden. Metoden för testning och modellering som utformades har som mål att strömlinjeforma förfarandet för utveckling och utvärdering av sorptionsmoduler för olika ändamål. Denna generiska modell kan bestämma sorptionsmodulens prestanda med en felmarginal på ± 8%. Följaktligen föreslår denna studie en övergripande metod för systematisk utvärdering av sorptionsmoduler som kan tillämpas till olika användningsområden baserat på de analytiska och experimentella metoder, samt simuleringsmetoder, som utvecklades.

List of papers

This doctoral thesis is based on the following papers:

I. Zhu, C., Gluesenkamp, K., Yang, Z., **Blackman, C**., 2019. Unified Thermodynamic Model to Calculate COP of Diverse Sorption Heat Pump Cycles: Adsorption, Absorption, Resorption, and Multistep Crystalline Reactions, *International Journal of Refrigeration*, 99, pp. 382-392.

II. **Blackman, C.**, Bales, C., 2015. Experimental Evaluation of a Novel Absorption Heat Pump Module for Solar Cooling Applications, *Science and Technology for the Built Environment*, 21(3), pp.323–331.

III. **Blackman, C.,** Bales, C., Thorin, E., 2017. Experimental Evaluation and Concept Demonstration of a Novel Modular Gas-Driven Sorption Heat Pump, *The 12th IEA Heat Pump Conference*. Conference paper: refereed.

IV. **Blackman, C.**, Bales, C., Thorin E., 2015. Techno-economic Evaluation of Solar-Assisted Heating and Cooling Systems with Sorption Module Integrated Solar Collectors, *Energy Procedia*, 70, pp.409–417.

V. **Blackman, C.**, Gluesenkamp, K., Malhotra, M., Yang, Z., 2019. Study of Optimal Sizing for Residential Sorption Heat Pump System, 2018. *Applied Thermal Engineering*, 150(5), pp. 421-432.

VI. **Blackman, C.**, Pressiani, M., Bales, C., 2020. Test Platform and Component Model for Modular Sorption Heat Pumps. Manuscript.

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Author's Contribution

Publications included in the doctoral thesis:

I. Corey Blackman supported the conceptualisation and development of the analytical model. Corey Blackman assisted with the writing and analysis of results, discussion, and conclusions.

II. Corey Blackman planned, prepared for and carried out the tests. Corey Blackman analysed the test results along with Dr Chris Bales. Corey Blackman did the writing for the article with support from Dr Chris Bales.

III. Corey Blackman planned the simulations along with Dr Chris Bales. Corey Blackman carried out the simulations and did the writing of the paper. Evaluation of the results was a collaborative effort between Corey Blackman, Dr Chris Bales and Dr Eva Thorin.

IV. Corey Blackman planned, prepared for and carried out the tests. Corey Blackman analysed the test results along with Dr Chris Bales and Dr Eva Thorin. Corey Blackman did the writing for the article with support from Dr Chris Bales and Dr Eva Thorin.

V. Corey Blackman conceptualised, planned and carried out the analyses along with Dr Kyle Gluesenkamp and Dr Mini Malhotra. Corey Blackman evaluated the results along with the co-authors. Corey Blackman wrote the introduction, sorption module description, results, discussion and conclusions. Corey Blackman wrote the methodology along with Dr Mini Malhotra with support from Dr Kyle Gluesenkamp and Zhiyao Yang.

VI. Corey Blackman designed the test platform, planned and prepared for the tests. Michele Pressiani assisted with the development of and carried out the ANN training, testing and verification. Corey Blackman analysed the test results along with Michele Pressiani and Dr. Chris Bales. Corey Blackman did the writing of the article with support from Dr Chris Bales.

Other related publications that are not included in this thesis:

Blackman, C., Hallström, O. & Bales, C., Demonstration of Solar Heating and Cooling System using Sorption Integrated Solar Thermal Collectors, *EuroSun Conference Proceedings*, 2014.

Blackman, C., Bales, C., Thorin, E., Test Platform and Methodology for Model Parameter Identification of Sorption Heat Pump Modules, *International Sorption Heat Pump Conference*, 2017. Conference proceedings extended abstract: refereed.

Laurenz, E., Füldner, G., Doell, J., **Blackman, C**., Schnabel., L., Model based assessment of working pairs for gas driven thermochemical heat pumps, *Heat Powered Cycles Conference*, 2018, Conference paper: refereed.

Gluesenkamp, K., Frazzica, A, Velte, A., Metcalf, S., Yang, Z., Rouhani, M., **Blackman, C.**, Qu, M., Laurenz, E., Rivero-Pacho, A., Hinmers, S., Critoph, R., Bahrami, M., Füldner, G. and Hallin, I., Experimentally Measured Thermal Masses of Adsorption Heat Exchangers, *Energies*, 2020

Parts of this thesis were previously published in the licentiate thesis – '*Evaluation of a Modular Thermally Driven Heat Pump for Solar Heating and Cooling Applications'*.

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List of principal symbols and acronyms

AC	Alternating current
ANN	Artificial neural network
ASM	Ammoniation sorption module
CE	Condenser/Evaporator
CCE	Combined condenser/evaporator
COP	Coefficient of performance
COP_{el}	Electrical coefficient of performance
COP_{cl}	Cooling coefficient of performance
COP_{ht}	Heating coefficient of performance
COP_{solar}	Solar coefficient of performance
CPC	Compound parabolic solar thermal collector
DC	Direct current
DHW	Domestic hot water
DTM	Dead thermal mass
DTM_{design}	Design dead thermal mass
$DTM_{inherent}$	Inherent design dead thermal mass
DTMR	Dead thermal mass ratio
E_{chill}	Cooling energy during absorption phase (individual sorption modules) (Wh)
E_{cool}	Cooling energy during absorption phase (kWh)
ECOP	Electrical coefficient of performance
EDHW	Heating energy delivered to domestic hot water (kWh)
E_{drive}	Process driving energy
E_{el}	Electrical energy consumed by the installation (kWh)
E_{heat}	Heating energy during absorption phase (Wh)
$E_{re\text{-}cool}$	Heating energy during desorption phase (condensation energy dissipated) (Wh)
ETC	Evacuated tube solar thermal collector
FPC	Flat plat solar thermal collector
GCOP	Gas coefficient of performance
GDSHP	Gas-driven sorption heat pump
GDSHPA	Gas-driven sorption heat pump type A
GDSHPB	Gas-driven sorption heat pump type B
GUE	Gas utilisation efficiency
HEX	Heat exchanger
HTF	Heat transfer fluid

HTHU	Hybrid thermosyphon heating unit
HTR	High temperature reactor
HTS	High temperature salt
HVAC	Heating ventilation and air conditioning
L_{des}	Enthalpy of desorption
L_{evap}	Enthalpy of evaporation
LTS	Low temperature salt
LTR	Low temperature reactor
MPPT	Maximum power point tracking
PCM	Phase change material
PV	Photovoltaic
PVT	Hybrid solar photovoltaic and thermal collector
Q_{boiler}	Heating capacity of condensing boiler (kW)
Q_{chill}	Average cooling power during absorption phase (W)
Q_{cool}	Average cooling power during absorption phase (W)
Q_{drive}	Process driving power (W)
Q_{heat}	Average heating power during absorption phase (W)
Q_{peak}	Peak heating capacity (kW)
$Q_{re\text{-}cool}$	Average heating power during desorption phase (condensation power dissipated) (W)
R	Reactor
RA	Reactor A (high temperature reactor)
RB	Reactor B (low temperature reactor)
RES	Resorption cycle
RM	Resorption module
RQ	Research question
SCE	Separate condenser and evaporator
SHCS	(Combined) Solar heating and cooling system
SIC	Sorption (module) integrated collector
SISHCS	Sorption integrated collector solar heating and cooling system
SM	Sorption module
SMA	Sorption module type A (basic ammoniation sorption module)
SMB	Sorption module type B (resorption module)
SoC	State of charge
T_{abs}	Absorption temperature (°C)
T_{cond}	Condensation temperature (°C)
T_{cxi}	Average inlet temperature to condenser/evaporator heat exchanger (°C)
T_{cxo}	Average outlet temperature from condenser/evaporator heat exchanger (°C)
T_{des}	Desorption temperature (°C)
T_{evap}	Evaporation temperature (°C)
T_r	Average surface temperature of reactor and absorber (°C)
T_{rxi}	Average inlet temperature to reactor heat exchanger (°C)

T_{rxo}	Average outlet temperature from reactor heat exchanger (°C)
Y_{min}	Minimum salt loading
Y_{max}	Maximum salt loading

Greek symbols

ΔH_{DES}	Enthalpy change of reaction
ΔT_{lift}	Temperature lift (°C) [Papers II, III, IV & V]
ΔT_L	Temperature lift (°C) [Papers I & VI]
ΔT_D	Driving temperature difference (°C)
η_{total}	Total Efficiency
ψ	Thermodynamic maximum cooling COP
θ_1	Dead thermal mass ratio for CCE/LTR/CCE
θ_2	Dead thermal mass ratio for reactor/HTR

1 Introduction

1.1 Background

Many homes and most commercial and industrial facilities would be rather uncomfortable most of the year without some form of indoor climate control. In the built environment a substantial percentage of energy use is thus geared towards keeping us comfortable year-round within our wooden, steel or concrete cocoons. Our buildings protect us from the ever more frequent harshness and temperature extremes of nature, allowing for improved health and productivity. A positive shift has come in improving building façades, insulation and general building planning as more governments and organisations take heed of climate change warnings.

Reducing indoor comfort energy requirements for the entire year, incorporating both heating and cooling requirements is of paramount importance. Employing technologies that consider both energetic and exergetic efficiency, which use environmentally benign substances and materials, that are easily maintained, have good technical longevity and are economically viable, is key to sustainability within the built environment.

This has seen an increasing number of policies geared towards generating the impetus necessary to transition towards renewable energy sources being put in place [1]. Further policies have also been implemented to improve the efficiency of current appliances to reduce the use of fossil-fuel derived energy sources [2]. However, whilst adhering to typical open market forces, it is unlikely that many companies would move in the direction of improving energy efficiency and increasing renewable energy share in the built environment. This has been manifested as a rather slow, tentative march towards investing in sustainable energy technologies, a pace that due to the gravity of environmental issues is seen as too ‘lethargic’. With extended payback periods and difficulty to recoup all benefits within typical 5 to 10-year investment windows, private companies hesitate to make the investments necessary to deploy renewable energy and energy efficiency technologies. Fortunately, many of the policies needed to achieve the increasing efficiency and expanding renewable energy goals are consistent with programmes needed to encourage innovation and productivity growth throughout the economy [3].

In the field of heating, ventilation and air conditioning (HVAC), climate control units for heating and cooling contribute substantially to CO_2 emissions. For example, in Spain, heating accounts for 42% of the country's energy consumption in homes [4]. The European average stands at 57% of building energy use going towards heating where 42% of this is covered by gas-driven appliances [2,5]. In the case of space cooling yearly electricity consumption for air conditioning units can be quite significant the closer to the equator one comes. However, arguably the more alarming effect of air conditioner use is its influence on electricity demand. Air conditioning units can place significant strain on the electricity grid since they are generally all operating at the same time. In the summer months, demand often peaks rapidly between 15:00 and 18:00 [4]. In Europe, small capacity air conditioning systems (i.e. systems up to 12kW) are set to quadruple in primary energy consumption in 2020 compared to the levels in 1996. This rise is mainly due to improvements in living standards and the architectural characteristics and trends such as increasing insulation [6].

The European Union directive for the promotion of the use of energy from renewable sources seeks to establish binding objectives where 20% of the gross end consumption of energy should be provided by renewable sources by 2020 [1]. The aim within construction is for the erection of low or 'zero-energy buildings' in all new constructions also by 2020. Within the policy all public buildings constructed after that year would generate as much energy as they consume. Within this field of thought a plausible roadmap for zero energy buildings has been suggested where these energy self-sufficient buildings could be developed by [7]:

- Reduction of energy demand.
- Efficient energy conversion chains (i.e. minimisation of exergy losses).
- Covering of remaining energy demand employing renewable energy.

Even though policy for new buildings is a critical step in the right direction, in order to make a dent in the current energy consumption tendency, the retrofitting of buildings towards 'zero energy' is also necessary.

Heating and cooling can be produced by a wide range of technologies giving a myriad of options to the end-user. These options can be based on the energy input/fuel type or based on the operating principle (i.e. the type of appliance used). However, these options have different availabilities, efficiencies, and desirability [2]. This creates a challenge for policymakers, technology providers and end-users alike in choosing the best technology to provide heating and cooling services in the built environment.

In this thesis, heating and cooling technologies from two large segments are tackled. The segments are categorised by energy input due to their relative abundance and ubiquity; solar energy and natural gas.

In several parts of the world including Europe, North America and various parts of Asia, natural gas has become a staple for providing heating using fossil fuel-fired boilers. Within the European Union, policies have been introduced to successively improve the efficiency of fuel-fired equipment in efforts to reduce emissions [8]. Further policies seek to shifting use to renewable combustible gases such as biogas and hydrogen. However, this has proven to be a huge undertaking due to the very high penetration of antiquated fuel-fired heating equipment, as well as lack of incentives for replacement by the end users [9]. In analyses carried out in [9] it was postulated that in spite of various technological choices the push away from natural gas will be more difficult in retrofit scenarios compared to new builds. Customers and policymakers alike need to be provided with high efficiency and cost-effective gas-driven appliance options in order to undercut emissions over the upcoming decades with minimal investment requirements [9].

Given its availability in most regions, solar energy is poised to be a key renewable energy source for the built environment. Solar energy has long been known to be valuable for both passive and active heating of buildings along with the preparation of domestic hot water (DHW). In Europe, heat from solar energy sources needs to become 50% cheaper by 2020 to reach fossil fuel cost parity [10]. Potential cost savers have been cited as the use of cheaper materials, integration with heat pumps and passive solar thermal heating system that eliminate pumps and controls [10]. An additional possibility is to extend the utility of solar energy systems to include cooling as well as heating at marginal or no incremental cost compared to today's systems to offer higher energy savings [11]. Solar thermal technology for both heating and cooling is capable of providing an appreciable portion of the energy requirements for space conditioning in buildings [12,13]. In many cases, high upfront costs of solar driven cooling systems compared to standard compressor driven cooling systems may be considered the principal obstacle for the widespread uptake of small and medium scale solar thermal cooling systems. Furthermore, market penetration for these heat-driven chillers has been hampered by not only cost, but also technical limitations as well as reliability concerns [14,15]. Additionally, in most cases, specialised knowledge and understanding of the technology is necessary for installation, commissioning and operation to be carried out effectively, leading to a general unattractiveness of these solar thermal cooling installations [6].

A vision for the future of efficient and cost-effective alternatives to conventional heating and cooling systems that can be employed in large and small applications is an intriguing one. Proliferation of sorption technologies for heating and cooling could bestow both developed and developing nations with tools to combat current environmental issues whilst promoting renewable energy transition, energy efficiency and eventually fossil fuel energy independence in the built environment.

Presented in this study are novel modular sorption heat pumps developed in order to address the aforementioned market transition limitations. They are devised to improve heating and cooling systems in the built environment. Currently, most commercially available sorption systems are of large capacity and are not suitable for the domestic or medium to small-scale commercial markets [15]. Another major challenge which plagues sorption technologies is the potential of high parasitic energy (namely electricity) usage which quickly diminishes the overall primary energy saving benefits of sorption appliances [16]. Modular sorption heat pump units could address many of the present market penetration challenges; namely system size and cost, parasitic energy usage, as well as, technical complexity limitations.

Sorption modules can be developed for direct integration into a solar thermal collector to provide for small and medium-sized solar heating and cooling kits with plug-and-play functionality to be deployed. Furthermore, high integration of systems for space cooling, heating and hot water would increase year-round usage and therefore reduce overall system payback time.

Additionally, sorption modules may be employed to improve the efficiency of natural gas driven boilers. These modules would effectively transform standard condensing boilers into high efficiency gas-driven heat pumps that, similar to electrical heat pumps, make use of solar energy stored in ambient air or the ground.

By studying and understanding module performance and limitations, sorption process alternatives, sorption module configurations, cost and energy saving indicators, it is envisaged that pre-engineered sorption integrated systems could then be deployed, that have lower complexity and reduced need for highly specialised competencies, for various applications.

1.2 Objectives and Scope

The central premise of this work is that sorption heat pump modules (or simply sorption modules) can be integrated into various systems in the built environment to provide energy and monetary savings compared to the state-of the-art heating and/or cooling systems. These include solar thermal heating and cooling systems as well as thermally-driven heat pump systems for space and/or domestic water heating. The first objective of the thesis was to evaluate the performance of the sorption module as a component as well as their system configurations for various applications. The second objective was to investigate the energy and cost saving potential of the sorption module integrated systems.

The specific research questions (RQ) were:

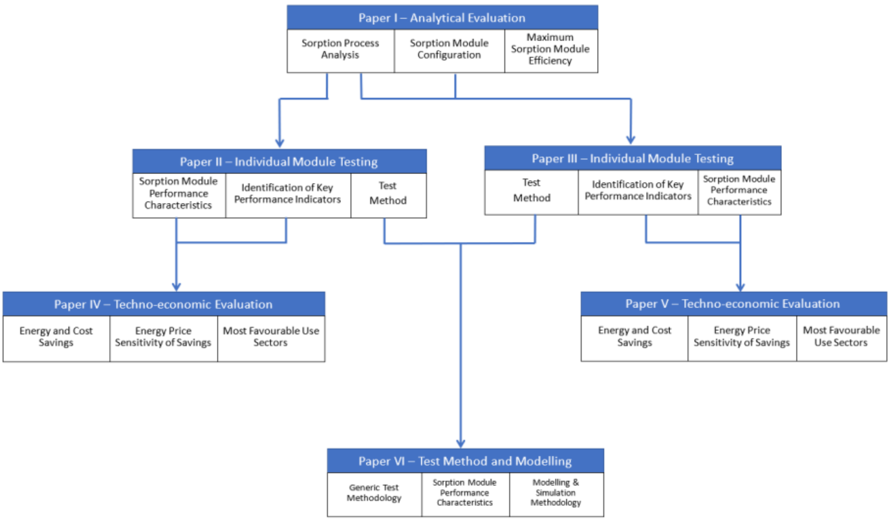
1. What are the primary performance indicators for sorption heat pump modules?
2. How can sorption modules be evaluated in a time-effective and reliable fashion?
3. What are the typical values of the performance indicators for the sorption heat pump modules?
4. How can sorption modules be configured and dimensioned for various applications?
5. What are the energy and monetary savings of different sorption module integrated systems compared to state-of-the-art heating and cooling systems?

The studies cover analytical evaluation of different sorption module configurations and sorption processes as well as experimental evaluation of individual sorption modules under laboratory conditions. The definition of key performance indicators forms an important part of the investigations. Further performance studies were carried out at a sub-system, and subsequently, the system level. In order to evaluate the system performance over a full year, simulations were carried out based in part on the empirical data from system studies. Both static simulations based on simplified performance correlations as well as simulations that partially considered the dynamic nature of the operation of the sorption systems were carried out. Studies were primarily focused on analysis of the test and simulation results as well as the evaluation methodology.

1.3 Overall Research Methodology

The studies summarised in this thesis were structured to allow for building on the findings of each study (see Figure 1). The methods used to evaluate sorption module integrated systems by, analytical, experimental and simulation methods, are presented in this thesis work.

The foundation study performed in Paper I presented a generic analytical method for evaluation of individual sorption modules, considering their key performance parameters and performance characteristics for various configurations and cycles of operation. Identification and definition of further key performance indicators for different sorption module types were carried out in Papers II and III. Design of test sequences, which varied boundary conditions for experimental evaluations of various sorption module prototypes allowing for comparative assessments of performance, was also reported in Papers II and III. Additionally, given the modular nature of the sorption units, the principal assumption is that their performance could be extrapolated based on the number and/or size of modules used. This gave rise to simulations of the performance of the modules integrated into systems for different applications in Papers IV and V. Papers IV and V built upon information from both Papers II and III as input for full system simulations over a one-year period for techno-economic analyses. This included potential energy and cost savings attributed to sorption integrated systems for solar heating and cooling and gas-driven heating systems respectively.



	RQ 1	RQ 2	RQ 3	RQ 4	RQ 5
Paper I	✓	✓		✓	
Paper II	✓		✓		
Paper III	✓		✓		
Paper IV	✓			✓	✓
Paper V	✓			✓	✓
Paper VI	✓	✓			

Figure 1: Research study progression (above) & research question development for each paper (table below)

Each of the papers also provided the researchers with valuable information on various component and system optimisation possibilities. Additionally, insight is given into the most prolific use cases for the studied solar heating and cooling and gas-driven heating systems. The study thus culminated with evaluations done in Paper VI where a generic, application agnostic method for the experimental evaluation and performance simulation of sorption modules is presented. The learning outcomes from such a generic evaluation method could hence be used for the techno-economic evaluation of sorption modules for different applications and form the scope of continued future research.

1.4 Structure of Thesis

The thesis report is a summary of the main findings from the aforementioned six scientific papers.

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Chapter 1: Introduction

In this chapter a general background is given on the topic of the thesis, objectives, scope and overall methodology.

Chapter 2: Theoretical Background

This chapter provides a basic introduction to solar heating and cooling technology as well as gas-driven space and domestic water heating technology.

Chapter 3: The Sorption Heat Pump Module

The sorption heat pump module is defined and a description of the sorption processes that form the foundation of the operation of the sorption module is given in this chapter. This then segues into the main operating principle of various sorption module types and subsequently various concepts of sorption module integration into solar heating and cooling systems as well as gas-fired boilers and thermal energy storage systems.

Chapter 4: Experimental Evaluation and Simulation

This fourth chapter chronicles the experimental evaluation of individual sorption modules for both solar energy and sorption heat pump applications. Additionally, a generic (i.e. application agnostic) method for the experimental evaluation of sorption modules is introduced. Included is also the methodology used for solar heating and cooling systems and gas-driven sorption heat pump system simulations.

Chapter 5: Results

This chapter presents the results of the experimental evaluations and the key performance indicators derived for the various sorption modules and sorption module integrated systems. This chapter also includes the findings of system simulations with expected energy and cost savings as well as system sizing.

Chapter 6: Discussion

This penultimate chapter discusses the main outcomes of all the studies carried out.

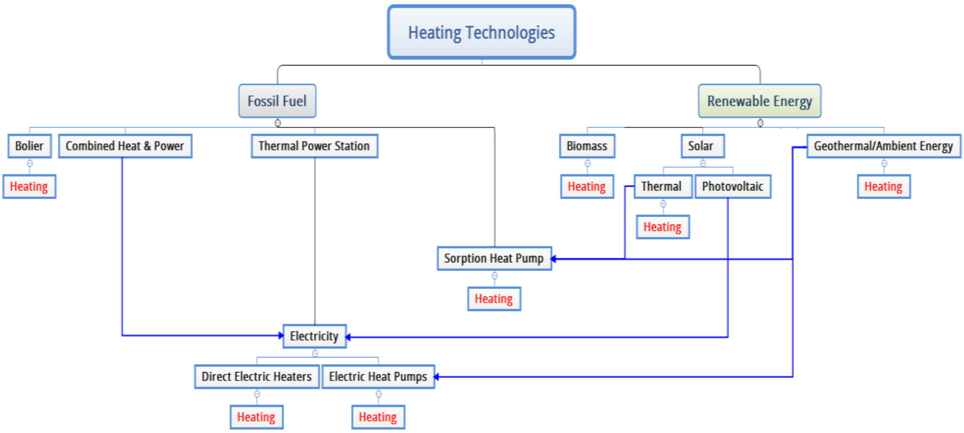
Chapter 7: Conclusions

This chapter draws conclusions based on the studies carried out.

2 Theoretical Background

Indoor comfort in the built environment is derived from the controlled transfer of thermal energy into (i.e. heating) or out of (i.e. cooling) the building envelope. Heating and cooling systems can be classified as centralised; these are the district heating and district cooling systems that provide warm or chilled water or brine. These tempered fluids are generated at a central plant and distributed to the buildings by pipes. Centralised heating or cooling systems have the distinct advantage of being able to use highly efficient generation plants that can use flexible energy sources. However, high capital cost of plant and distribution infrastructure and thermal losses in distribution pipelines are the general limiting factors for centralised heating and cooling systems.

Globally, decentralised heating and cooling systems are the more dominant for the built environment and are generally classified based on the source energy utilised [17,18]. The energy source can be fossil fuel derived or derived from renewable energy sources. Typically, the main form of input energy into decentralised heating and cooling appliances is either thermal energy in the form of heat, electricity, or both. A summary of the main technologies for heating and cooling buildings is shown in Figure 2 [18].



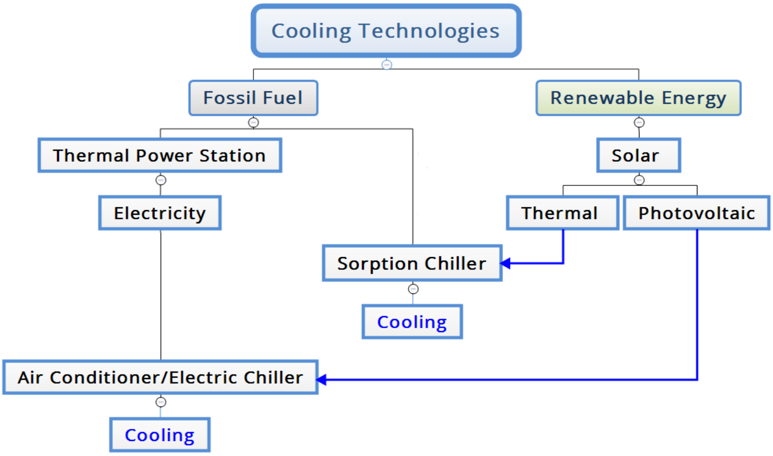


Figure 2: Overview of typical decentralised heating and cooling technologies for buildings and their main driving energy

Sorption systems are an excellent way of utilising heat sources to drive a heat pumping process. Thermal energy is thus transported from a source at low temperature to a source at higher temperature thus producing a cooling effect as well as a heating effect, both of which can be used in buildings. Solar thermal energy and heat from combustible fuels are prime driving heat sources for sorption systems. Solar is of major importance since it is a renewable form of energy available in most locations, especially in locations where there's a significant cooling load. Fuels such as natural gas are also rather interesting heat sources due to the high penetration in various parts of the world [19]. This, in addition to the urgency with which the deleterious effects of fossil fuel use on the environment, needs to be mitigated. Technologies with improved efficiencies, and thus reduced natural gas utilisation per unit useful thermal energy produced, are thus needed [20]. By investigating novel ways of integrating sorption systems with solar systems as well as gas-driven systems, the goal of creating cost-effective methods of reducing the environmental impact of heating and cooling systems in the built environment can hopefully be achieved.

2.1 Solar Heating and Cooling Systems

Dating back to the time of the Romans, solar energy has been used for the passive heating of buildings by trapping heat behind glazed façades [21]. The active use of solar energy for heating is currently recognised as a viable way to have precise control over our indoor environment while reaping the environmental benefits of utilising energy from the sun instead of fossil fuel derived forms of energy. Solar energy can also be extended beyond applications of just heating to also include cooling applications. This versatility gives rise to the possibility of using solar energy year-round; during the winter for space heating, during the summer for space cooling and throughout the entire year for DHW preparation. By developing systems that can be exploited all twelve months of the year a very high utilisation factor can be achieved which translates to more economical systems. That is, for the same system size and price a higher percentage of useable energy can be generated and thus high levels of energy savings can be achieved [22].

2.1.1 Solar Domestic Hot Water (DHW) Systems

Solar thermal energy systems for the production of domestic hot water may be considered to be the most mature out of all solar energy technologies [23]. Employed commercially from the early 1900s solar DHW systems have since been implemented across the globe. Solar DHW systems may even be the principal water heating apparatus for dwellings, as seen in countries such as Israel, Barbados, Cyprus, and Greece, as a way to reduce energy cost by replacing most of the energy used for conventional DHW preparation appliances with solar energy [21,23]. These systems typically comprise solar collectors, a thermal store and an auxiliary heater.

2.1.2 Solar Space Heating

Solar space heating is often carried out by so-called solar thermal combisystems. These solar energy harvesting installations are developed to provide both DHW and space heating. Therefore, as opposed to solar energy systems for just DHW, these combisystems are sized with a larger collector field to meet space heating as well as DHW demand [24]. These systems, typically comprising solar collectors, thermal store(s) and an auxiliary heater, are designed and dimensioned taking into consideration the large seasonal energy demand variations involved in space heating. For this reason, there are often economic limitations in system size due to the potential large heat over-production due to low summertime heat demand.

Active space heating which takes advantage of solar radiation can also be carried out by utilising solar photovoltaic (PV) panels and an electric vapour compression heat pump. In this case, solar energy is converted into electricity that is used to run the conventional heat pump to provide space heating and/or DHW [25]. Research is currently being carried out devising various ways of efficiently carrying out the integration of solar energy with the heat pump. This research includes heat pumps with direct current (DC) motor that drive their compressors allowing the obviation of an inverter to convert DC from the solar PV panels to alternating current (AC) used in most equipment [26]. This direct coupling has the advantage of eliminating a power conversion step that can lead to higher overall efficiency plus reduce the need for an extra component which in turn has the potential to reduce system cost. However, this also brings with it the disadvantage that any excess electrical energy produced by the PV panels will not be possible to feed into the grid without added equipment. Further efforts have also looked at hybrid solar photovoltaic and thermal (PVT) collectors coupled with heat pumps where, PV electricity can drive the heat pump whilst thermal energy captured can be used for increasing the temperature of the heat pump's evaporator, allowing for higher operating efficiency [27].

2.1.3 Solar Space Cooling Systems

Solar energy may also be converted to provide space cooling. There are a multitude of techniques that may be employed in solar radiation to low temperature thermal energy conversions. The most common of these techniques come in two principal categories; thermally driven and electrically driven [26].

Thermally driven cooling techniques have been the most prominently used method for producing 'coolth' from solar energy. This typically involves using the heat from solar thermal collectors to drive a thermochemical or thermophysical process that employs heat as the input to drive a heat pumping process: that is, the movement of thermal energy from a low temperature to a higher one. The aforementioned methods may be subdivided into three principal techniques that have so far reached commercial availability [28]:

- Absorption Cooling - The most popular method of producing cooling from heat is by use of an absorption cooling unit (i.e. absorption chiller). This type of system employs a chemical heat pumping mechanism where refrigerant vapour produced in an evaporator is absorbed by chemical affinity in a salt solution in liquid form. This salt solution is circulated in a piece of equipment aptly called the absorber. From the absorber, the solution is then easily pressurised by means of a pump to a unit called the generator, where heat is used to drive off the previously absorbed refrigerant vapour from the solution. Said vapour is then cooled by a re-cooling (i.e. heat rejection) fluid and condenses in a condenser unit. The liquid refrigerant then makes it way again to the low-pressure evaporator unit. This system works similarly to a typical vapour compression system where, in this case, the compressor is replaced by a liquid pump, the generator and absorber units. Electricity is of course needed to run the pumps, valves and controls of the chiller, however, the quantity of electric power required for a well-designed system is often lower per kW of cooling power generated, than in a vapour compression system of similar capacity. The process is therefore driven mainly by the heat input.

- Adsorption Cooling – Adsorption cooling equipment exploit a chemical heat pumping mechanism similar to that of absorption. The main difference is in the sorption pair used to produce the cooling effect. A solid adsorbent such as silica gel is used in conjunction with a refrigerant such as water. Vapour produced in the evaporator is adsorbed on to the surface of the solid silica gel. After the adsorption process is complete the silica gel is heated up to liberate the attached molecules as water vapour, this vapour then condenses in a condenser unit just as in the case of absorption cooling.

- Desiccant Cooling – Desiccant cooling systems, also known as open adsorption cooling systems, work with an analogous principle to adsorption systems where silica gel may also be employed as the adsorbent. However, in this type of system a stream of air is cooled directly, rather than chilling water for use in fan coils or radiant cooling distribution systems. Moisture is removed directly from the air by passing it over the silica gel, and then this air is sensibly and/or evaporatively cooled and sent directly to the space to be conditioned to provide the required indoor climate.

In the case of space cooling, the cooling distribution system employed for a new building or the existing cooling distribution for retrofit applications is of major importance when determining the technology to use and also the energy efficiency of the systems. The cooling fluid delivery temperature is the key parameter that is determined principally by the type of cooling distribution system employed (see Figure 3). High temperature radiant cooling distribution systems using chilled ceilings have chilled water distribution temperatures typically ranging from 15 to 18°C. These temperatures are most favourable for solar absorption and adsorption cooling systems since higher evaporator temperatures correspond to higher operational efficiency of the system [29]. Direct conditioned air distribution systems are ideal for the application of desiccant cooling technology as it can produce large volumes of cooled dehumidified air which is an excellent means of providing adequate indoor thermal comfort in hot humid regions. In the case of hydronic cooling distribution systems that use fan coil heat exchangers, due to the compact nature of the fan coil and the relatively high heat fluxes required, chilled water distribution temperatures range from 6 to 9°C.

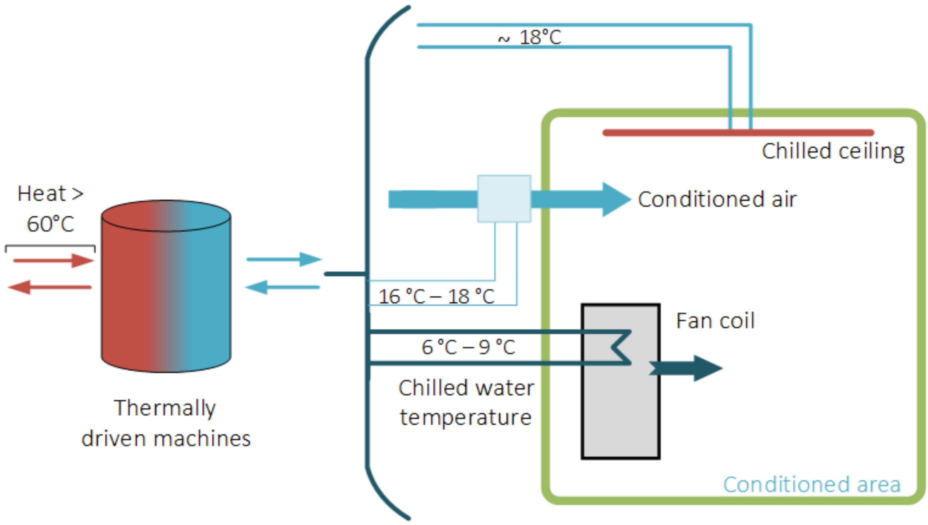


Figure 3: Illustration of different space cooling distribution systems [29].

In a typical solar absorption or adsorption cooling system the primary components are the solar thermal collectors, the absorption or adsorption chiller, thermal store(s), and a cooling tower or dry cooler for heat rejection (i.e. re-cooling) [29].

The photovoltaic conversion process, that is, the conversion of sunlight directly to electricity can also form the basis for the conversion of solar energy to space cooling. This is typically done by connecting (directly or indirectly) solar photovoltaic panels to a conventional vapour compression chilling unit [26]. Though this method has been plausible for some time, it is only in recent years that the prices of PV panels have become low enough to make solar electric cooling systems economically viable [26].

An electrically driven solar cooling system would comprise PV panels, an inverter and a conventional air conditioning or chilling unit that contains an electrically driven compressor. Consequently, there has been a surge of interest in these elegantly simple systems that contain few components, all of which are commercially available. Research has also been done in how the PV system could be directly coupled to a DC motor driven compressor chilling unit [26].

The main premise behind a combined solar heating and cooling systems (SHCS) is to amalgamate all the aforementioned systems for space heating, DHW and space cooling to form a complete solar energy solution to meet year-round thermal demands.

These combined solar energy systems, though not a new concept, with various available technical solutions, have difficulty reaching payback within the lifetime of the system due to high system complexity [11]. This complexity has meant that most SHCS are only demonstrators and little practical knowledge is available for the design of these systems. An integrated approach to system design is essential where optimisation of multiple parameters is necessary [30]. In this case, knowledge of the operation and performance of the solar collectors, thermal energy stores and the heating and cooling distribution systems is pertinent.

2.2 Gas-Driven Heating and Cooling Systems

Natural gas is a relative newcomer to the fossil fuel energy scene where the explosion of its use started in the 1960s. Natural gas has been the fastest growing fossil fuel energy source, increasing in share of global primary energy use from 7.5% in 1950 to 24.5% by 2018 [31]. In modern times, the rise in natural gas consumption can be attributed to its various benefits compared to oil and coal fuels. Natural gas is less environmentally polluting than coal and oil with lower CO_2, SO_2 and NO_x emissions per unit energy delivered. Additionally, its good economics for supply, distribution and power generation, its high security and flexible use (as fuel or chemical), has led to increasing usage [32–34].

Within the EU, countries such as Germany, the UK, Italy, France and the Netherlands have built out extensive networks of gas for heating purposes [2]. Gas, being a relatively abundant and dense energy carrier, is used as the energy source for distributed heating equipment. These networks are rather flexible with relatively low installation costs per unit capacity installed. Given these advantages of natural gas networks, it can be beneficial to combine gas-driven appliances with more intermittent energy sources such as solar to mitigate negative environmental impact as well as reduce overall installation costs [18]. As the shift towards more renewable forms of energy increases, the continued use of natural gas and increases in production are being analysed. Even if natural gas produces lower greenhouse gas emissions than other fossil fuel-based energy sources its environmental impact is still significant. However, given that many nations have invested heavily in high penetration gas networks, ways of leveraging the current networks and mitigating the cost of deploying renewable forms of energy are being explored. One measure studied was the increase in the percentage of biomethane in natural gas distribution networks or complementing natural gas with hydrogen gas produced from renewable sources of energy [2]. Studies have also investigated the retrofitting of existing natural gas delivery lines to carry 100% renewably produced hydrogen gas (power-to-gas electrolysis) for use with adequately retrofitted natural gas to hydrogen combustion heating equipment [35]. In the present study, improvements on the end-user side are explored where incrementing the efficiency of natural gas-driven appliances for heating is evaluated.

2.2.1 Natural Gas-Driven Space Heating

Space heating can be provided by the combustion of natural gas in various types of appliances. The most common ones can be defined as:

Natural gas boilers – these appliances combust natural gas for heating purposes. Combustion is done by a burner where a mixture of air and natural gas is ignited. The combustion process produces both radiant heat as well as hot combustion products. Heat is transferred from the combustion process to heat water which is then distributed to radiators, wall, air and/or underfloor heat distribution systems providing space heating [36]. In traditional boilers flue gas exit temperatures are often rather high signifying a significant loss of heat to the environment. However, modern natural gas fired boilers often have two heat exchangers; a primary heat exchanger and secondary or a so-called condensing heat exchanger. The presence of a second heat exchanger allows for the recovery of heat from the combustion products. These combustion products or flue gases contain both sensible and latent heat attributed to their water vapour content. The secondary heat exchanger, provided that it can cool the flue gas below its dew point (typically < 50°C [37,38]), can recover a large percentage of both sensible heat as well as latent heat released by the condensing of the water vapour. This variant of natural gas boiler with two heat exchangers is aptly called a condensing boiler (see Figure 4) [39]. Condensing boilers can thus achieve higher efficiency levels compared to non-condensing boilers, with reported efficiencies as high as 95% [40]. Boilers can be designed for space heating or as so-called combi-boilers which provide both space heating and DHW [41].

Natural gas furnaces – furnaces are appliances where combustion of gas process heats a heat exchanger which in turn heats a stream of air. The warm air is then ducted to rooms in the building to provide space heating [42].

2.2.2 Natural Gas-Driven Domestic Water Heating

The natural gas-fired water heater is an appliance dedicated to providing hot water for sanitary purposes. These water heaters can be found in storage tank and tankless, condensing and non-condensing variants.

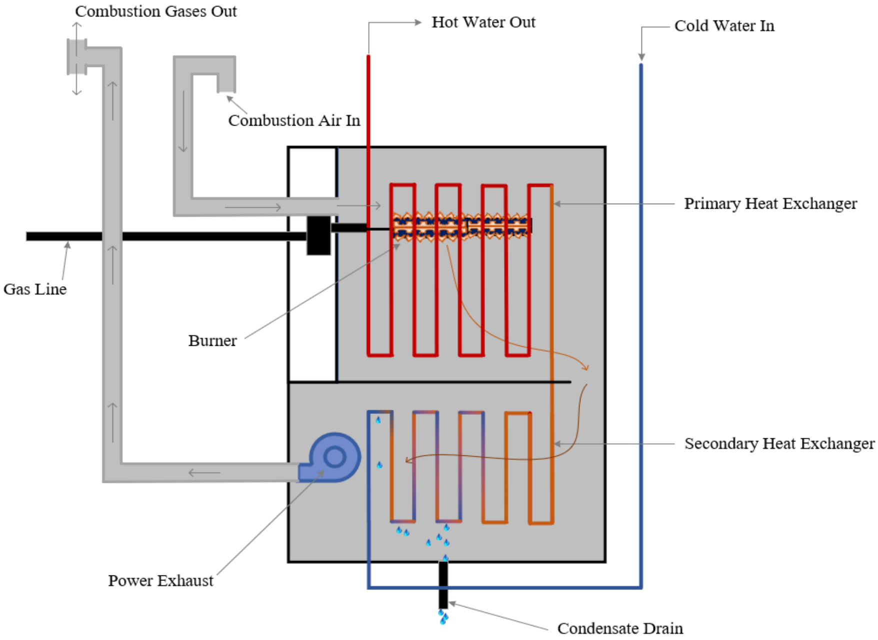


Figure 4: Schematic of a condensing boiler (Redrawn based on [39]).

2.2.3 Hybrid Gas-Driven Heating Systems

Hybridisation of gas-driven heating appliances has been studied over recent years. Such hybrid systems are envisaged for the improvement of energy and/or economic efficiency of natural gas fired heating systems. In the case of bivalent systems, that is, systems with two energy sources, the gas-driven appliance is complemented with an appliance or subsystem with another energy source or operating principle. Studies have been carried out where gas-driven heating systems are complemented with solar energy [43]. Heat delivered from the solar energy system is used to offset heat produced by gas where the system is dimensioned to maximise energy savings compared to heat delivery only from the gas boiler. The inclusion of solar energy offsets the associated environmental impact of combustion of fossil fuels [43].

Hybrid gas-electric heat pump appliances have also been studied and introduced to the mass market [9]. These appliances meld a natural gas fired boiler with an air-source heat pump with the benefits that:

- A smaller electrical heat pump can be used to reduce overall installation costs.

- A reliable and cost-effective backup heating source is available during cold weather where efficiency of the electric heat pump dips and electricity prices often peak.

Gas-electric hybrid appliances are also used to increase the flexibility of the energy source that is used for heating purposes. Some systems incorporate a smart controller which determines which is the most cost-effective energy source at any given time [44]. Additionally, since a relatively small electric heat pump is integrated it can run efficiently at full or high part load when its efficiency, and thus operating costs, are favourable compared to the operation of the gas boiler [45]. These hybrid appliances are however only viable in certain locations where the ratio of natural gas to electricity prices and seasonal and/or diurnal shifts in energy prices favour switching between energy sources [45].

2.2.4 Thermally Driven Heating

Beyond direct heating of water or air with the heat of combustion of natural gas, thermal efficiency can be improved by driving a sorption process with said heat. Thermally driven sorption heating technologies typically share a similar operating principle to thermally driven cooling systems. Heat is used to drive a heat pumping process. The main variance being that for thermally driven heating systems instead of rejecting the heat produced to the ambient it is used for heating purposes within the built environment. Thermally driven sorption heat pumps have been studied extensively with several variants being driven directly from the combustion of natural gas [39]. Most of these systems tend to be of large capacity, useful for multifamily residential buildings, commercial and industrial applications [39]. However, a few lower capacity systems have been introduced to the market with capacities varying from 5 kW to 18 kW geared towards the residential market [46].

Another category of gas-driven heating system is the gas engine heat pump. Gas engine heat pumps use the energy of combustion of natural gas to run an internal combustion engine. The mechanical energy derived from the engine is in turn used to run a vapour compression heat pump. In these types of systems high energy efficiencies can be achieved due to both the heat pumping as well as the heat recovery from the engine exhaust and engine cooling jacket [47]. Where electricity is produced from fossil fuels and the heat from the electricity is not recovered, like in the case of district heating, gas engine heat pumps can have a primary energy efficiency advantage compared to electrically driven heat pumps [48]. Gas engine heat pumps are however typically found in large capacities and thus mostly applicable to industrial, commercial and multifamily residential building applications [49].

2.2.5 Combined Gas-Driven Heating and Cooling Systems

Gas-driven sorption or gas engine heat pumps, by virtue of their principle of operation, can be designed to operate reversibly which allows them to be used for air conditioning purposes during the summer whilst still providing domestic hot water [47,49].

These gas-driven systems are can also combined to not only deliver thermal energy but also electricity. Combined cooling heat and power systems have the advantage that overall efficiencies as high as 88% can be achieved as a result of the cascading use of thermal energy. That is, high exergy heat used for production of electricity whilst low exergy thermal energy is used for space heating and cooling [50].

2.3 Thermal Energy Storage

The demand for energy in the built environment varies from hour to hour, day to day and even weekly and seasonally. This means that energy supplies should be moderated to meet these demands. Often the matching of supply and demand can be improved using thermal energy storage systems [51]. Thermal energy storage systems store and deliver heating and/or cooling to a specific load. These systems are of prime benefit in mitigating the intermittency of renewable sources of energy. Thermal energy stores thus have an important role in improving the operating efficiency of heating and cooling systems whilst simultaneously reducing the required thermal capacity, and therefore cost, of heating and cooling devices [51,52].

2.3.1 Types of Thermal Energy Stores

Thermal energy stores can be categorised into different types by virtue of their method of operation:

- Sensible thermal storage is carried out by the increasing or lowering of the temperature of a material. These types of stores commonly use water, rocks, ground or the building envelope as storage media [53,54].
- Latent thermal storage exploits phase transitions of a substance from solid to liquid to store thermal energy. Typical materials used in these types of stores include water, paraffins and salt hydrates [55,56]. It should also be noted that both sensible and latent storage can be combined with these materials.

- Thermochemical storage systems are developed around a reversible chemical reaction. Typical substances for these types of stores are salt hydrates, salt ammoniates and metal oxides [53].

2.3.2 Thermochemical Energy Storage

Sorption systems are inherently capable of being exploited as thermochemical energy storage systems. An adequately designed sorption system can be charged during low energy demand and this energy stored in the interim until the desired time of discharge providing heating and/or cooling [53,57–59]. The present thesis studies don't explicitly evaluate sorption systems for use solely as thermal energy stores. The studies however address the sorption module's energy storage capacity which allows for the storage of solar thermal energy during the day to be used for heating and cooling purposes at night. Additionally, the decoupling of gas firing and thermal energy delivery under given conditions is a potential system operation advantage. These intrinsic energy storage characteristics are thus important to consider and highlight whilst evaluating decentralised heating and cooling systems.

2.4 Performance Indicators – Heating and Cooling Systems

The quantification of the performance of energy systems is generally carried out by defining various performance indicators. These indicators have various characteristics and can be broken down into [60]:

- *Thermal efficiency indicators* – these describe the thermal performance of the system considering its thermal losses via the hot and/or cold stores, the thermal coefficient of performance of subsystems such as heat driven chillers, heat pumps, etc. Additionally, considerations are made for losses due to energy conversion (e.g. combustion, heat recovery, etc.)
- *Global performance indicators* – these describe the overall system performance taking into account all forms of energy used by the system to carry out its heating and/or cooling functions. These indicators look at the overall energy inputs into the system, be they chemical (as fuel), thermal or electrical, compared to the thermal output of the system.
- *Economic indicators* – these look at the cost of operation of the system, the cost of installation and/or the cost savings associated with the operation of the system (compared to a reference system).

- *Quality indicators* – these indicators are used to evaluate the reliability of the system over time based on the time of operation, maintenance requirements and the ability of the system to meet thermal demands both in terms of magnitude and timing. This includes the indoor and DHW temperature conditions provided by the system versus what is expected or what are defined as standard temperatures. The latter is especially useful for renewable energy systems without backup heating or cooling.
- *Environmental indicators* – these are employed in the evaluation of the environmental impact of heating and cooling systems. These indicators include evaluation of the carbon dioxide and nitrogen oxide emissions and are usually given in terms of grams of emittant per unit thermal energy produced. This can also be represented by the specific water consumption of the installation, for instance, if for heat rejection a cooling tower is employed.

2.4.1 Performance Indicators – Solar Heating and Cooling Systems

For the purpose of the current research studies various indicators were selected as the most important for SHCS and are described in the following selections [60–62]:

2.4.1.1 Collector Efficiency

This solar performance indicator is based on the effectiveness with which solar radiation is converted to thermal energy by the solar collector. Mathematically it is the quotient of the thermal energy yield of the collector divided by the solar irradiation impinging on the solar collector. The global insolation on the collector area is often defined based on the time integrated solar irradiation per unit area during operation of the system and the area through which the solar radiation enters the solar collector (i.e. collector aperture area).

2.4.1.2 System Efficiency

System efficiency indicators are used for the evaluation of the effectiveness with which solar radiation is converted to useful thermal energy by the SHCS. For the purposes of calculation of these indicators, the thermal energy output can be in the form of heating, cooling, DHW or any combination of these. Therefore, for example, a system efficiency indicator can quantify the efficacy with which a given SHCS system converts solar irradiation to cooling. This can thus be referred as the solar cooling coefficient of performance (i.e. solar cooling COP).

2.4.1.3 Useful Solar Productivity

The useful solar productivity is a performance indicator that quantifies the thermal energy produced by the SHCS in the form of heating, cooling and/or DHW. It may be defined as total energy produced by the system over a yearly period (kWh/year) or per unit area of solar collector aperture with typical units of kWh/(m^2 year).

2.4.1.4 Solar Fraction

The solar fraction indicator quantifies the percentage of the thermal demand of the building that is covered by the energy produced by the SHCS.

2.4.1.5 Electrical Coefficient of Performance (COP_{el})

The electrical coefficient of performance (COP_{el}), or electrical energy efficiency ratio, is a solar performance indicator that considers the consumption of electricity in the SHCS. This electricity is used for the running of auxiliary equipment of the SHCS such as pumps, fans, valves and control systems. This indicator is the quotient of thermal energy output of the SHCS (i.e. heating, cooling and/or DHW) divided by the electricity consumption of the system.

2.4.1.6 Energy Cost Savings

This economic indicator is utilised to quantify the monetary savings associated with the shift from using conventional energy sources (e.g. electricity, natural gas, heating oil or district heating) to meet the thermal demands within a given application to the use of solar energy from a SHCS.

2.4.2 Performance Indicators – Gas-Driven Heating Systems

Similar to the studies carried on SHCS, select indicators were used to described gas-driven heating systems [40,63]:

2.4.2.1 Thermal Efficiency

This performance indicator is based the efficacy with which natural gas is converted into usable heat. It is typically calculated as the quotient of useful thermal energy output to embodied energy within the fuel used. However, attention should be paid to the how the embodied energy of the fuel is defined. The two main definitions are the gross calorific value (GCV) and the net calorific value (NCV). The GCV considers the fuel amount of energy that is liberated from full combustion of the fuel including the thermal energy which is used for the conversion of water produced in combustion to water vapour. The NCV however, considers only the heat liberated from full combustion, excluding that used to transform liquid water to water vapour.

2.4.2.2 *System Efficiency*

System efficiency indicators are used for the evaluation of the effectiveness with which chemical energy in fuel is converted to useful thermal energy by the boiler. For the purposes of calculation of these indicators, the thermal energy output can be in the form of heating or DHW preparation.

2.4.2.3 *Seasonal Efficiency*

The seasonal efficiency is a performance indicator that quantifies the thermal energy produced by the boiler in the form of heating and/or DHW. It may be defined as total energy produced by the system over a yearly period (kWh/year) per unit energy input from natural gas.

2.4.2.4 *Electrical Coefficient of Performance*

The electrical coefficient of performance (COP_{el}) or electrical energy efficiency ratio is a performance indicator that considers the consumption of electricity in a natural gas boiler system. This electricity is used for the running of auxiliary equipment of the boiler such as pumps, fans, valves and control systems. This indicator is the quotient of thermal energy output of the boiler (i.e. heating and/or DHW) divided by the electricity consumption of the system.

3 The Sorption Heat Pump Module

3.1 Introduction

Absorption and adsorption processes are the most used and most efficient and cost effective processes for using heat to generate a cooling effect [28,64]. The principle is based on the use of two species, or substances, with high chemical affinity for each other. This chemical affinity may also be exploited as a reversible chemical reaction to store thermal energy (viz. thermochemical storage). An example of substances that undergo these reversible chemical reactions are salt hydrates which dissociate into anhydrous salts when heated. The anhydrous salts formed can then be stored at room temperature until the intrinsic thermal energy, due to their exothermic reactivity of re-association, is required. The re-association reaction is none other than the re-addition of water to the anhydrous salt, which produces an exothermic reaction. The heat of this reaction can be then used for heating purposes. When excess heat is available it may be used to drive-off the water from the newly formed salt hydrate reverting it back to its anhydrous form where the cycle can be continued as needed. Anhydrous salts usually have high energy content when compared to hot water storage and can be stably stored at ambient temperature without energy losses [58].

3.2 Triple-State Thermochemical Sorption Process

In typical sorption systems a liquid gas reaction occurs between the sorbate in liquid phase and the sorbent in the vapour phase. These reactions take place in a range of concentration of 3 to 6% [65,66]. In order to extend this working concentration range, and therefore the energy density of a stored salt hydrate, a triple-state reaction process (also known as the triple-phase sorption process) may be employed.

The triple-state thermochemical sorption process is exploited by using a salt hydrate solution starting with a dilute solution. Charging a triple-state thermochemical heat store starts when the solution is heated up driving off water vapour until saturated solution is formed. If further heated, the saturated solution cedes more water vapour leaving behind an ‘over-saturated’ solution where crystals begin to form. At this point, three phases or states of matter (solid salt crystals, liquid salt-water solution, and water vapour) exist simultaneously giving the process its characteristic name. Upon further heating, complete crystallisation occurs first forming a di- and/or monohydrate (depending on temperature and substance) [67] and possibly the anhydrate (salt molecule with no attached solvent crystals). Figure 5 shows the evolution of the process.

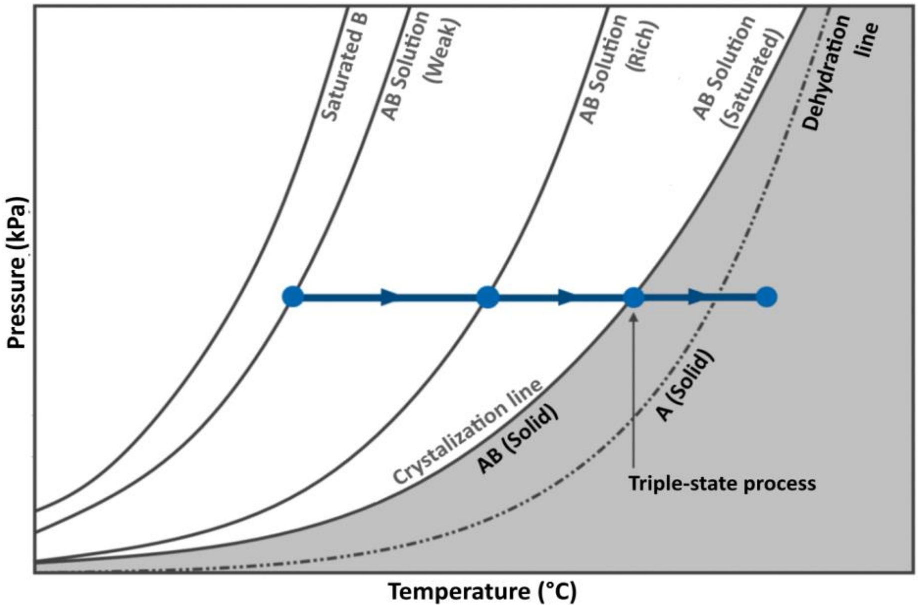


Figure 5: Pressure vs temperature phase diagram depicting the triple-state process (Re-drawn based on [67]).

The discharge, or absorption process, of a triple-state thermochemical system therefore sees the utilisation of a large concentration difference where a solid-gas reaction with the salt hydrate crystals occurs forming a solution and then a liquid-gas reaction ensues. During these processes energy can be harnessed from the thermochemical store for heating and/or cooling. The presence of the crystallisation/solid-gas reaction phase in the cycle has the advantage of significantly increasing the storage density when some or all the water molecules are removed from the salt crystal (see Figure 6).

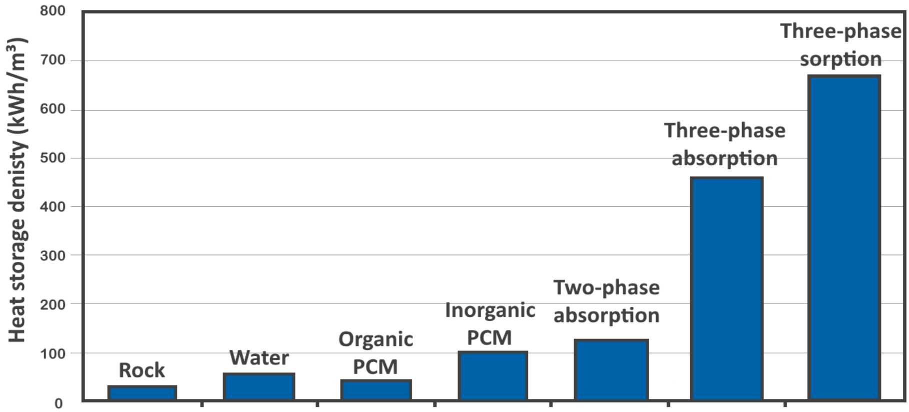


Figure 6: Heat Storage Energy Densities of Various Energy Storage Media (Three-phase absorption: cycle with triple-state crystallisation process. Three-phase sorption: cycle with triple-state crystallisation and dehydration) [67].

Various salts may be used in the triple-state thermochemical process, where some of those studied have been CaCl2, LiCl and LiBr. When selecting a salt for an application it is important to know its properties especially in terms of the solution and crystallisation temperatures. Of the aforementioned salts, with water as the sorbent, LiBr has the highest crystallisation temperatures while LiCl has the highest energy density. This triple-state thermochemical cycle exhibits significantly higher thermochemical energy density (approximately 1250 Wh/kg-salt for lithium chloride) than the more traditional two-state absorption cycles [67].

3.3 Ammoniated Salt Sorption Process

Similar to the triple-state reaction process where water is employed as the sorbate (or refrigerant), ammonia (NH_3) can also be used. Many alkali (metal) halides (i.e. salts) reversibly sorb ammonia allowing them to be exploited in thermochemical storage processes [68]. Additionally, under some conditions, analogous to that encountered with salt hydrates, ammoniates (i.e. salt and ammonia complexes) undergo a phase transition from solid to liquid where a process quite similar to triple-state sorption can occur [69].

The ammoniated salt systems also open another interesting possibility of using the resorption process. In the resorption process two different salts (alkali halides), having different chemical affinities for ammonia, are used. The salt with the higher affinity is referred to as the high temperature salt (HTS) while that with the lower affinity is referred to as the low temperature salt

(LTS). During the desorption process a high temperature (i.e. high exergy) heat source is used to incite the flow of ammonia from the HTS to the LTS. The reverse occurs during absorption in which the refrigerant flows from the LTS to the HTS. During the absorption (or discharge process) the LTS can absorb low temperature (below ambient temperature) thermal energy, whilst the HTS rejects heat at a medium temperature (above ambient temperature) [70]. Salt ammoniates allow for a wide range of salt selection possibilities and cycle combinations. This in turn provides wide ranges of operating pressures and thus operating temperatures [68,71].

The ammonia salt sorption process can therefore be divided into two types:

- *basic ammoniation process* - the desorbed ammonia condenses to form liquid ammonia during the sorption cycle.
- *resorption process* – ammonia is never present in liquid form during the sorption cycle.

3.4 Sorption Heat Pump Module Characteristics

Sorption module is, for the purposes of this study, the name given to the modular heat pump device whose operation is based on the triple-state thermochemical storage cycle, basic ammoniation or resorption cycle. The modular sorption components have been developed with the main premise of addressing the market penetration limitations of sorption systems for heating and cooling system; namely system size and cost, and the technical limitations due to system control, corrosion, crystallisation and leakage.

The sorption module functions in a batch absorption process where there are two main operational modes; absorption and desorption (also known as regeneration) [72]. The module comprises two components; the reactor and the condenser/evaporator. These are made from corrosion resistant materials coupled together and sealed under high vacuum. The reactor component contains a matrix infused with a hygroscopic salt or ammoniated salt, while the other end of the module, the condenser/evaporator, contains pure refrigerant. The latter component may act as either condenser or evaporator depending on the flow direction of the refrigerant vapour within the module.

During the process of absorption, the difference in vapour pressure between the salt and the refrigerant causes refrigerant evaporation from the end of the module (acting as an evaporator in this case) and forms a salt hydrate or ammoniate in the reactor. This process creates a temperature difference between evaporator and reactor where the evaporator can absorb heat at below ambient temperatures, creating a cooling effect, while heat is rejected at above ambient temperature from the reactor. This process continues until all refrigerant (i.e.

sorbate) has been transferred from the condenser/evaporator and absorbed by the reactor salt. The heating and/or cooling capacity of the sorption module can then be 'regenerated' by heating the reactor. This heating forces the desorption of refrigerant from the salt in the reactor matrix where it condenses on the opposite end of the tube (now acting as a condenser) with condensation heat being removed at above ambient temperature. The regeneration process is aptly called desorption.

3.5 Sorption Modules for Solar Heating and Cooling Applications

With an appropriate heat exchanger attached to the reactor and to the condenser/evaporator, thermal energy can be added or removed from the sorption module for the provision of heating, cooling and/or energy storage. The heat exchangers, via which thermal energy is provided to or removed from the sorption module, are therefore critical components for its proper operation. The heat exchangers' designs are based on the intended application for the sorption module; therefore, the operation of the sorption module is governed only by the input temperatures and rate of input and/or removal of thermal energy. Due to their sealed nature, inert materials employed and no internal moving parts, the sorption modules are designed to be completely maintenance free.

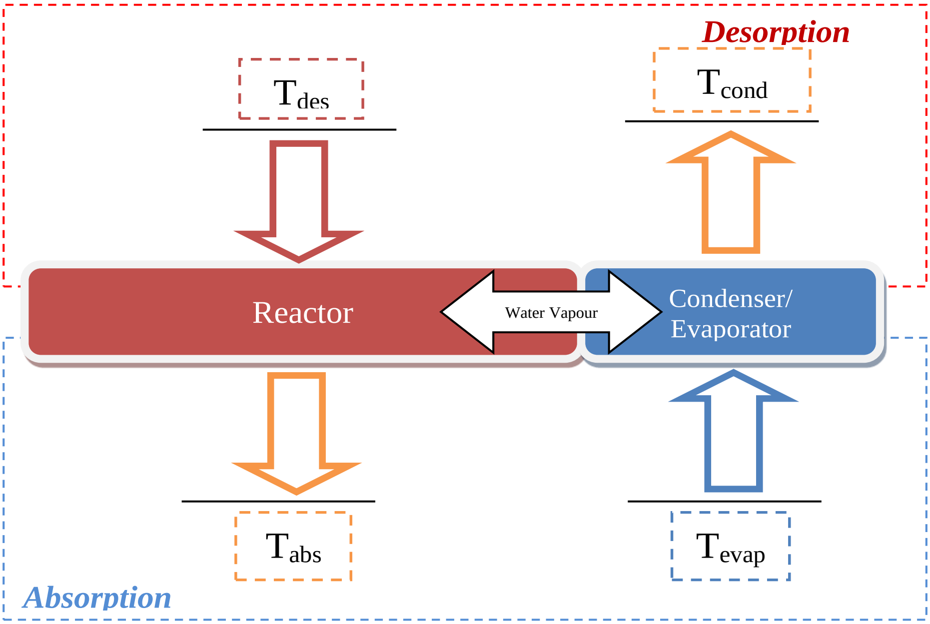


Figure 7: Sorption module operation – showing the thermal energy flows and temperature levels in desorption mode (upper) and absorption mode (lower).

Figure 7 shows schematically the operation and thermal energy inputs and output of a sorption module. The module functions with thermal energy transfers occurring at three principal temperature levels:

- *Desorption temperature* (T_{des}) is the temperature at which heat is supplied to the sorption module to incite the desorption process. This temperature level is determined by the temperature at which heat is rejected from the condensing vapour. There is a minimum temperature difference between salt and condensing vapour that must be reached before the desorption process commences.
- *Heat rejection or re-cooling temperature* is the temperature at which heat is rejected from the sorption module. During desorption it is denoted as the condensation temperature (T_{cond}) where heat is rejected from the condenser/evaporator of the module. During absorption it is denoted as the absorption temperature (T_{abs}) which is the temperature level at which heat is rejected from the reactor.
- *Cooling temperature or evaporation temperature* (T_{evap}) is the temperature at which the module absorbs thermal energy creating a cooling effect on its surroundings.

3.5.1 Absorption chiller integration of the sorption module

The sorption modules may be utilised in a more standard absorption chiller type application where the regeneration heat can be from any source. Thermal energy for regeneration is fed into the modules via a flow of heat transfer fluid in a pipe and flange heat exchanger attached to the reactor side of the module. The condenser/evaporator would possess a similar heat exchanger (see Figure 8). For this application the tubes are placed in two heat exchanger racks allowing for desorption and absorption processes to be performed in each rack separately such that when one rack is in desorption mode the other is in the absorption (i.e. cooling delivery) mode. This alternating phase operation provides for quasi-continuous cooling delivery similar to the operation of standard adsorption chillers. The racks may be built for any number of modules connected in parallel and therefore any cooling power and/or energy storage capacity. Additionally, modules may be interconnected in series to increase effective temperature lift or any combination of series and parallel interconnection as required by the application. This application of the sorption modules is however outside of the scope of the current study.

Figure 8: Concept for absorption chiller integrated sorption modules. Sorption modules (grey) covered by heat exchange flanges (white) interconnected by pipes for heat transfer fluid (orange).

3.5.2 Sorption Integrated Collectors

The sorption module integrated solar thermal collector, sorption integrated collector (SIC) or simply sorption collector can be designed in various ways depending on the system operation attributes and installation requirements. Three designs have been conceptualised and can be subdivided into collectors which use liquid as the heat transfer medium and collectors that employ air as the heat transfer medium:

- *Liquid-Based Collectors:* The sorption module can be integrated into a flat plate collector, which has a flat absorber sheet with attached heat transfer fluid pipes on the underside of the absorber. The absorber is then manufactured such that there are undulations where the cylindrical reactor section of the sorption module can be in direct contact with the absorber. The condenser/evaporator is covered by a jacket heat exchanger for each module, and these are interconnected by hoses within the collector. The sorption integrated solar thermal collector can be made up of as many modules as necessary, connected in series or parallel via their respective heat exchangers. In the collector concept shown in Figure 9 the collector houses 8 sorption modules connected in series on the reactor side to form the reactor loop and on condenser/evaporator sides to form the condenser/evaporator (CE) loop.
  The sorption modules can also be integrated into a solar thermal collector using evacuated tubes (see Figure 10). In this case, the sorption modules are outfitted on the reactor portion with metallic heat exchange flanges to which pipes for heat transfer fluid are welded. This is then covered completely with an evacuated glass tube with integrated absorber (Sydney tube). Just as with the flat plate collector type the condenser/evaporator is covered with a jacket heat exchanger and heat exchangers interconnected in series to form two hydronic loops [73,74].

- *Air-Based Collectors:* Given that sorption modules operate solely by the input or extraction of thermal energy at different temperature levels, it is the heat exchanger type that governs how this thermal energy transfer is carried out. Air is thus a plausible heat transfer fluid where air heat exchangers for the sorption modules can be designed accordingly. Similar to a liquid-based sorption module integrated solar thermal collector, the air-based collector comprises a solar absorber attached to the reactor of the sorption module which allows for direct solar absorption and heat transfer to the reactor. This solar absorber also comprises fins that allow for efficient heat rejection when air is blown across its surface. The condenser/evaporator is surrounded by a finned heat exchanger for heat rejection during desorption mode and for producing chilled air when air is blown across it in absorption mode. This type of sorption collector has been developed for integration into a roof (Figure 11) or building façade (Figure 12).

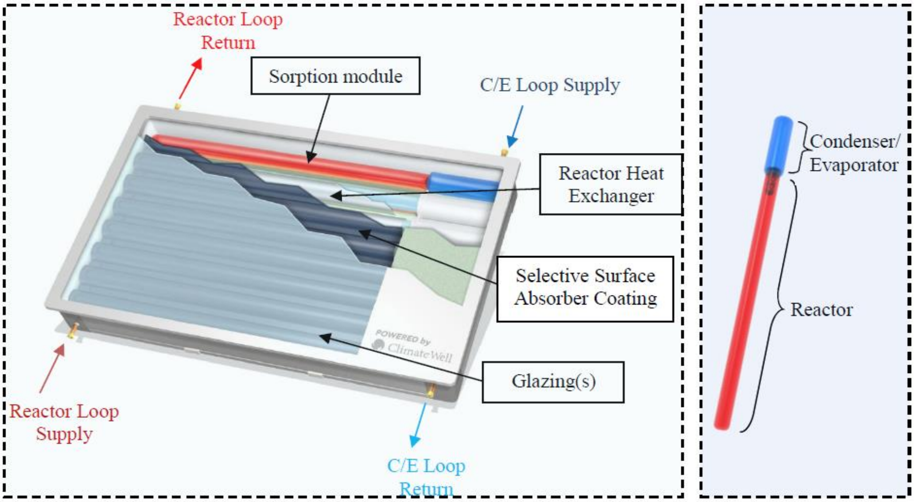


Figure 9: Sorption module integration in a flat plate solar thermal collector.

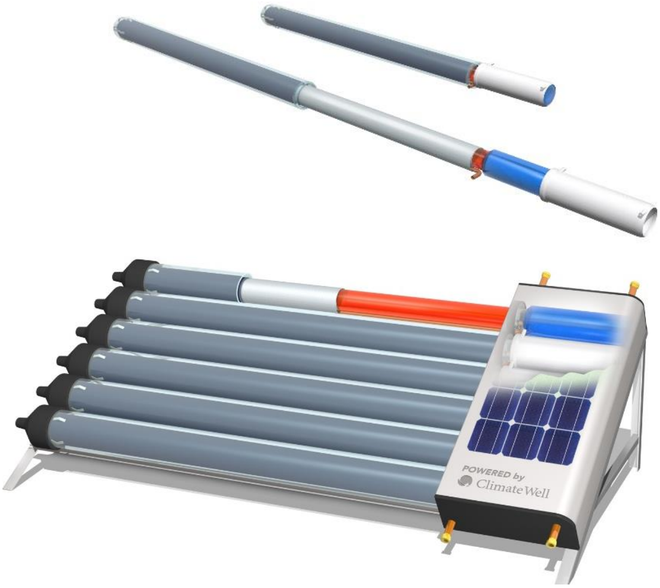


Figure 10: Evacuated tube sorption integrated solar thermal collector.

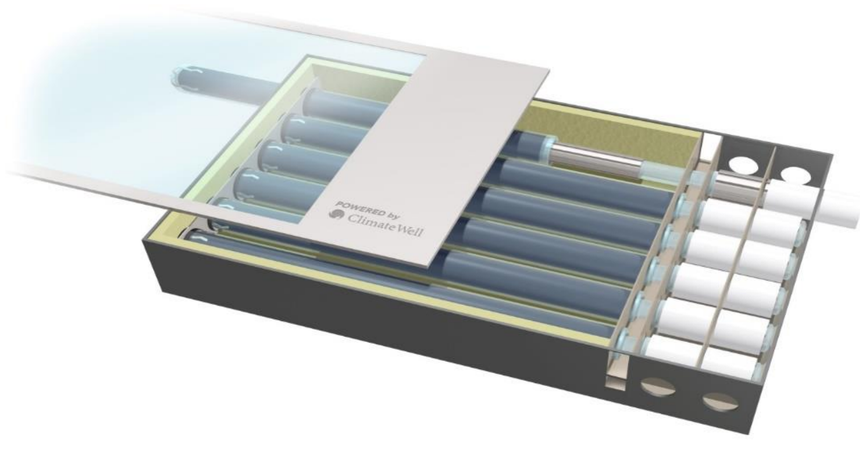


Figure 11: Air-based sorption integrated collector for roof mounting.

Figure 12: Air-based sorption integrated collector integrated into a façade.

3.5.3 Sorption Integrated Collector System Operation

The sorption integrated solar thermal collector solar heating and cooling system (SISHCS) has three primary modes of operation; two modes in the summer and one in the winter.

In winter, the system functions like a conventional solar thermal installation where, when solar radiation heats the collectors' absorber to a useful temperature, a pumped flow of heat transfer fluid is commenced to capture the thermal energy for heat supply and/or storage. If the absorber temperature falls below a useful level then the pump is stopped, terminating the flow of heat transfer fluid to the absorber heat exchanger until sufficiently high temperatures are obtained to recommence pump operation. The sorption modules integrated into the solar thermal collectors are thus 'dormant' during winter operations as cooling is generally not required.

In summer, during the day, the system operates in desorption mode. The collectors' solar absorbers and thus the reactors of the sorption modules are heated by solar radiation with the condenser/evaporators shaded from the sun and cooled by a re-cooling fluid. There is no circulation of fluid in the solar absorber heat exchanger in this mode. When the solar absorber temperature reaches the required level to provide the requisite pressure difference between reactor and condenser/evaporator, desorption begins, and refrigerant vapour evaporates from the salt in the reactor and condenses in the condenser/evaporator. This condensation heat is transported away by the re-cooling fluid and exhausted via a heat sink (this can be a dry cooler, ground source heat exchanger, or low temperature heat load). This desorption process continues with the drying of the salt in the reactor (i.e. concentrating of the salt solution) until radiation levels are too low to maintain it. At sunset the reactor is cooled down via a flow of re-cooling fluid. In this intermediate period between desorption mode and absorption mode, also known as swap mode, the absorber needs to be cooled down from between 80°C and 120°C (typical desorption level temperatures) to around 30°C to 40°C (typical absorption level temperatures). The resulting sensible thermal energy may be recovered for domestic hot water (DHW) production in the summer period. As the reactor cools the internal pressure falls, causing the condensed refrigerant in the condenser/evaporator (now acting as an evaporator) to evaporate producing a chilling effect, thus the system runs in absorption mode. Chilled fluid can therefore be obtained directly from the condenser/evaporator heat exchanger of the SIC. This chilled fluid may be stored (e.g. for daytime use) and/or serve the cooling load during the night. The SIC therefore operates on a day-night batch process principle similar to that described by [76,77].

3.6 Sorption Modules for Gas-Driven Heating Applications

In the present studies sorption heat pump modules were also evaluated for integration in gas-driven heating applications. Given that winter operation is critical for gas-driven heating appliances, a sorption module with the capability of operating at low ambient temperatures (i.e. below 0°C) is desired. Therefore, sorption modules which operated under the basic ammoniation process or the resorption process, that is, with ammonia as the refrigerant, could be employed.

3.6.1 Basic Ammoniation Sorption Module

The basic ammoniation sorption module (ASM) can be designed based on two cylindrical vessels; one reactor (R) and a combined condenser/evaporator (CE). However, sorption modules operating with ammonia as refrigerant need to be able to withstand higher operating pressures than those utilising water as refrigerant which needs to be considered in the design of vessels. The reactor and condenser/evaporator vessels are thus made of stainless steel rather than glass as is the case for the solar sorption module. A more compact heat exchanger design than the solar integrated sorption module can also be considered for heat addition and removal from the reactor since it is not heated directly by solar energy. The sorption modules designed for the studies carried out thus comprised a heat exchanger made up of disc-shaped stainless-steel plates engineered in such a way as to allow a heat transfer fluid to flow within the discs. The heat exchanger of the reactor vessel was used to provide thermal energy to, or remove thermal energy from, a proprietary matrix material infused with an ammoniated salt. The matrix was thus housed in the spaces between the heat exchanger discs in thermal contact with said discs (see Figure 13). The CE vessel was identical to the reactor with the exception that the matrix material between the discs did not contain salt. Both the reactor and CE vessels had an opening at the top which allows ammonia to flow back and forth between them via a connecting pipe.

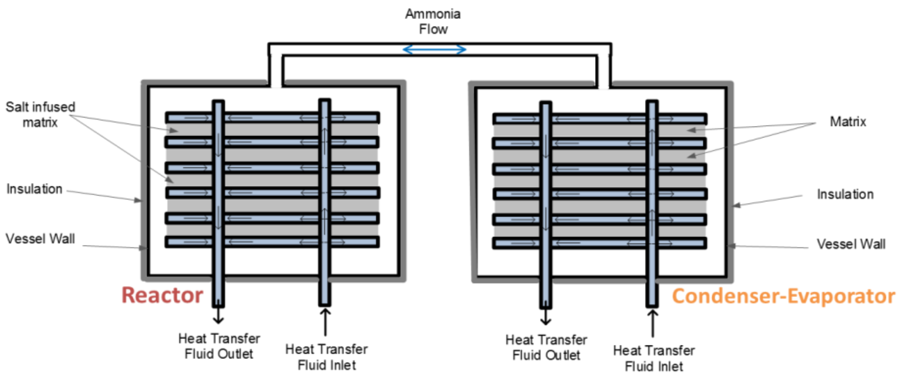


Figure 13: Diagram of a heat exchanger vessel of a sorption heat pump module for gas-driven heat pump applications.

3.6.2 Resorption Module

The sorption module can be designed to operate under the resorption process and would thus be denominated resorption module (RM). It would be similar to the basic ammoniation sorption module with the exception that the matrix of the CE is also infused with a salt, in this case an LTS. Due to this, the second vessel is no longer denominated as CE but as a reactor. Therefore, the resorption module essentially has two reactors; Reactor A (RA) which houses the HTS, and reactor B (RB) which houses the LTS. Similar to the basic ammoniation sorption module the resorption prototype was operated to provide useful heating during both the desorption and absorption phases.

3.6.3 Sorption Integrated Gas-Driven Boiler System Operation

With sorption heat pump modules designed for integration with a gas burner, the modules are desorbed with combustion heat from natural gas. Therefore, a sorption module integrated with the relevant subcomponents gives rise to a Gas-Driven Sorption Heat Pump (GDSHP) which can be employed for DHW and space heating applications.

Utilising the heat from the gas burner, desorption of ammonia occurs from the R flowing to the CE in the case of the ASM or from the RA to RB in the case of the RM. This results in condensation (ASM) or reaction heat (RM) that is harnessed for space heating and/or DHW purposes (see Figure 14). The desorption mode is therefore characterised by heat rejection/delivery from the CE or RB. When the R or RA is fully desorbed, that is, all ammonia (possible to be desorbed under the conditions) has been transferred from the R or RA to the CE or RB, the unit is switched to the absorption mode.

During the absorption operation phase, the gas burner is shut off and heat is recovered and rejected from the hot R or RA. The CE or RB is connected to an outdoor fan coil where low temperature thermal energy is absorbed from outdoor air inciting the transfer of ammonia to the R or RA. Heat is thus delivered from the sorption module via the R or RA (see Figure 14) in the absorption mode.

The GDSHP system can be monovalent, where all heat is provided by the sorption unit, or it could be bivalent where peak heating loads are met by an auxiliary heater. In the current studies, a bivalent GDSHP is considered, the R or RA requires a high temperature heat source of 140°C to 250°C in desorption mode followed by medium temperature heat rejection of 40°C to 80°C in the absorption mode. For this purpose a proprietary integrated hybrid thermosyphon heating unit (HTHU) was developed. The HTHU is a thermosyphon designed to allow for heating of the R or RA units with saturated steam during desorption and water re-cooling via a pumped water flow during absorption. Rejected heat is extracted directly from the HTHU via a pumped flow of heat transfer fluid. By virtue of its design, steam generation in the HTHU can be done with a gas burner or any heat source with a temperature high enough to create steam to incite desorption. During desorption, the heat delivery temperature from the unit is pre-determined by the needs of the heating load (i.e. space heating temperature or DHW temperature). Heating temperatures required for the R or RA are therefore modulated by the required heat delivery temperature given that the heating temperature of the R or RA is directly proportional to the heat delivery temperature from the CE or RB [78,79]. Correspondingly, on the CE or RB side of the module, switching between outdoor air heat absorption (absorption mode) and heat rejection to the heating load (desorption mode) is done by 3-way valves. Additionally, heat is also recovered from the flue gases of the burner via a flue gas heat exchanger in order to improve the overall efficiency of the GDSHP. The system also contains an auxiliary burner which allows for direct heat delivery to the load (i.e. bypassing the sorption component) if the sorption component is unable to fulfil the full heating demand at any given point.

In the GDSHP setup the sorption module is fully modular where the number of discs and thus the amount of substance within each vessel can be varied as necessary when dimensioning and designing the system.

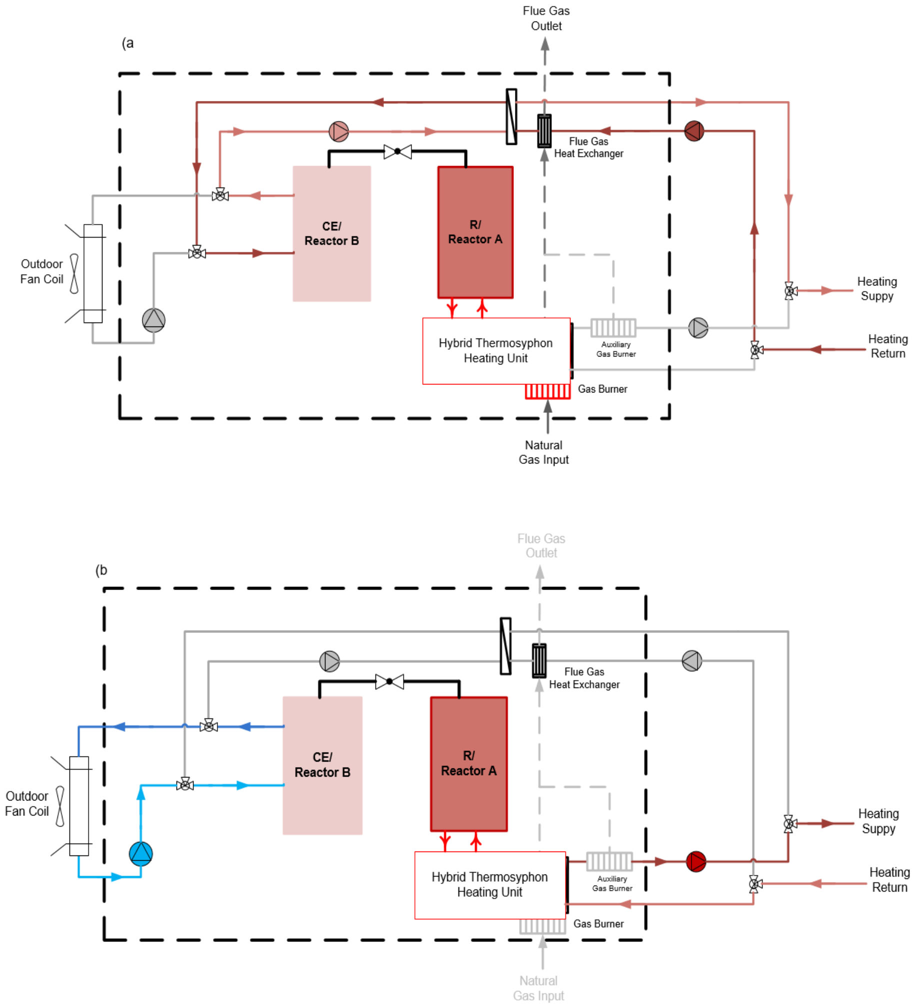


Figure 14: Schematic diagram showing the operation of a bivalent GDSHP. Desorption mode (above). Absorption mode (below).

4 Methods

The methods used to evaluate sorption module integrated systems by, analytical, experimental and simulation methods, are presented in this chapter.

4.1 Analytical Evaluations

Analytical evaluations of sorption systems are often carried out based on the thermodynamic principles of absorption and adsorption cycles [80]. In Paper I the maximum achievable COP of sorption cycles was investigated not only on the basis of thermodynamics but also including the design characteristics of the sorption system.

4.1.1 Analytical Evaluation of Ammoniated Salt Modules and Resorption Modules

In ammoniated salts sorption processes, there are several possibilities for salts that can be used in a gas-driven sorption heat pump. In Paper I a generic analytical model was developed to systematically evaluate the possible salt choices for both an ammoniated salt and resorption process. The best cycle configurations and working pairs for a sorption heat pump used in the space heating application were investigated. The design target for the sorption heat pump was 50°C fluid delivery temperature at an ambient of -10°C and heat source temperature of 250°C. Selection of the most suitable ammoniates was done based on operating temperature and pressure equilibria detailed in a Clapeyron diagram (Paper I). Additionally, to capture possible sorption module designs, three design configurations were considered:

- An ASM with combined condenser/evaporator (CCE) – in this case ammonia condenses (during desorption) and evaporates (during absorption) in the same vessel (see Figure 15a).

- An ASM with separate condenser and evaporator (SCE) – this sorption module configuration is characterised by one or two reactors connected to two separate vessels; one dedicated to condensation and the other dedicated to evaporation (see Figure 15b).
- A RM operating under a resorption cycle (RES) – this is characterised by having two reactors; one housing an HTS, i.e. the high temperature reactor (HTR) and one housing an LTS in its low temperature reactor (LTR). Ammonia is desorbed from the HTS and absorbed by the LTS during desorption mode and the opposite occurs during absorption mode (see Figure 15c).

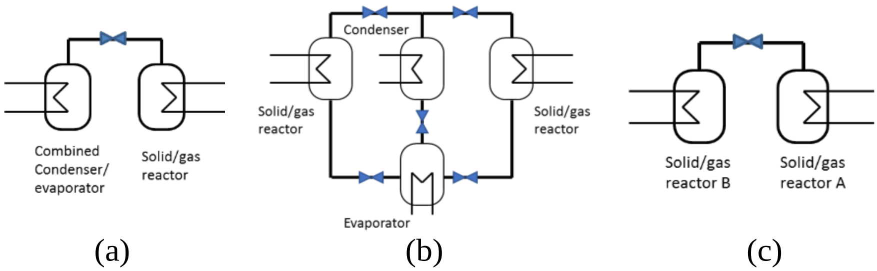


Figure 15: Three diagrams of possible sorption module configurations: (a) CCE, sorption with combined evaporator/condenser; (b) SCE, sorption with separate (dedicated) evaporator/condenser; and (c) RES, resorption (Paper I).

4.1.2 Analytical Model - Cycle COP Expressions

In Paper I expressions for the heating and cooling coefficients of performance (COP) of diverse cycles were developed. These included the conventional absorption and adsorption cycles [81,82] as well as the ammoniated salt cycle configurations; CCE, SCE and RES. For a sorption heat pump, the useful heat usually includes heat from both the absorber/reactor and the condenser, and the driving heat is the heat into the desorber. The expressions can however be derived from the classical definition of cooling COP (COP_{cl}). This is defined as the ratio between the useful cooling delivered and the driving heat input. Based on energy balance, the heating COP (COP_{ht}) of a sorption heat pump can be expressed as one plus the ratio of evaporator heat to desorber heat, that is, one plus the cooling COP (if losses are neglected) (Equation I).

$$COP_{ht} = 1 + COP_{cl} \tag{1}$$

Derivations of COP_{ht} based on the heat absorbed by the evaporator and heat required to drive the sorption process are also presented in Paper I. However, in order to produce a generic expression, these thermal energy flows were defined in terms of heat per unit mass flow of refrigerant. For sorption cycles, the evaporation heat per unit mass flow of refrigerant is expressed based on both the enthalpy of evaporation (or latent heat of vaporisation) (L_{evap}) and the vapour quality of the refrigerant entering the evaporator. However, during cyclic steady state operation, only the enthalpy of evaporation is considered. An additional consideration is the temperature lift $\Delta T_L = T_{cond} - T_{evap}$ which stipulates the degree to which the refrigerant temperature changes from condensation to evaporation. In absorption cycles, the desorber heat is composed of the latent heat (L_{des}) and the sensible heat, with the latent portion being the main part. This is also true for adsorption cycles.

In absorption cycles, only the sensible heating of the solution through the desorber is considered. The sensible heat depends on the inlet solution mass flow per unit mass flow of refrigerant, and the driving temperature difference between the desorber and absorber ($\Delta T_D = T_{des} - T_{abs}$). The differential refrigerant loading in the desorber $\Delta Y = Y_{max} - Y_{min}$, (i.e. is the difference between the maximum and minimum refrigerant loading) is also a considered parameter (Paper I). However, in the case of the sensible heat, there is a difference between absorption and adsorption cycles. For an adsorption (or batched-type absorption) cycle, the desorption and adsorption processes occur separately in the same reactor. The sensible heat should thus include heating of the adsorbent, retained refrigerant, heat transfer fluid (HTF), bed material, and other possible so-called "dead thermal masses" (DTM) in the adsorber/desorber. Paper I details further analyses of DTM where the DTM was divided into two parts:

- The design dead thermal mass (DTM_{design}) – which represents the dead thermal mass of HTF and heat exchanger material. DTM_{design} is highly dependent on the physical design and dimensions of the sorption unit. This is therefore a parameter that can be optimised during the design phase of a given sorption module where a DTM_{design} tending towards zero provides better performance of the sorption module.

- The inherent dead thermal mass ($DTM_{inherent}$) - which represents the dead thermal mass of salt and refrigerant. This depends primarily on inherent thermophysical properties.

The term dead thermal mass ratio (DTMR) is also presented in Paper I, a term used to capture the relative size of these dead thermal masses compared to the L_{des}. For ammoniated salt and resorption cycles, expressions analogous to the those derived for the adsorption cycle were developed in Paper I. In this case, DTMR for each component; reactor, combined condenser/evaporator, dedicated condenser and dedicated evaporator were derived. The basis of the analytical model is a universal expression for the COP_{ht} of a sorption heat pump, regardless of the cycle employed (Equation 2).

$$COP_{ht} = 1 + \psi \frac{1-\theta_1}{1+\theta_2} \tag{2}$$

In this expression, ψ represents the thermodynamic maximum cooling COP derived from the ratio of the ammonia evaporation enthalpy to the enthalpy of reaction of the ammonia with the given salt (ΔH_{des}). θ_1 represents the dead thermal mass ratios for SCE/LTR/CCE. Correspondingly, θ_2 represents the dead thermal mass ratio for the reactor (for an ASM) or HTR (for an RM). Table 1 summarises the expressions that form the basis of the analytical model developed in Paper I for comparison of the different sorption module configurations.

Table 1: Expressions employed in the analytical modelling of different sorption module configurations.

Sorption Module Configuration	**Abbreviation**	$\boldsymbol{\psi}$	$\boldsymbol{\theta_1}$	$\boldsymbol{\theta_2}$
Absorption	ABS	$\frac{L_{evap}}{L_{des}}$	$\frac{C_{p,ref,liq}\Delta T_L}{L_{evap}}$	$C_{p,sol}\Delta T_D \frac{(1+Y_{min})}{\Delta Y L_{des}}$
Separate condenser/evaporator	SCE	$\frac{L_{evap}}{\Delta H_{des}}$	$\frac{C_{p,ref,liq}\Delta T_L}{L_{evap}}$	$DTMR$
Combined condenser/evaporator	CCE	$\frac{L_{evap}}{\Delta H_{des}}$	$DTMR_E$	$DTMR_D$
Resorption	RES	$\frac{\Delta H_{LTS}}{\Delta H_{HTS}}$	$DTMR_{LTR}$	$DTMR_{HTR}$

The possibility of employing internal sorption module heat recovery is also tackled in Paper I. For each configuration, heat recovery was considered where sensible heat could be transferred between coupled reactors when shifting from desorption to absorption modes. That is, the heating of the one reactor with the fluid used to cool the other. Correspondingly, heat recovery can also be done by transfer of heat from the warm condenser/evaporator at the end of desorption to a cold condenser/evaporator at the end of absorption mode. The main premise of heat recovery would be to improve the performance of the unit by mitigating the effect of DTM_{design} on performance of the sorption module.

The sorption module configurations were compared on the basis of COP_{ht} with and without the implementation of heat recovery.

4.1.3 Model Limitations

In the analytical model developed in the Paper I only single effect cycles were considered, therefore, for all derivations the desorption process occurs in a single step [83]. Temperature and refrigerant loading parameters were considered only for complete cycles thus these parameters were assumed to be the same at the beginning and end of the cycle. No mass transfer limitations were considered and all temperatures across the sorbent bed as well as during condensation and evaporation were taken to be constant. Additionally, the model does not consider thermal losses to the ambient. The model is therefore in essence static which takes no considerations for the dynamics of the sorption processes involved.

4.2 Experimental Evaluations of Sorption Modules for Solar Applications

Analytical evaluations of triple-state sorption systems were carried out in [84]. This showed that 3 salt and water sorption pairs undergo the triple-state sorption process with $CaCl_2$ having the lowest energy density while LiCl exhibited the highest. Given that LiCl has the most favourable operating temperature range it was employed for development of the sorption modules presented in Paper II.

Two-metre-long sorption module prototypes were designed and fabricated for integration directly into a flat plate solar thermal collector (see Figure 16) as described in Paper II. The modules were theoretically optimised in terms of their energy storage capacity and energy dissipation potential (power) based on the quantity of hygroscopic salt and refrigerant within. For this solar application, the quantity of salt employed was calculated such as to (theoretically) fully utilise a complete day's worth of solar insolation (approximately 5.5kWh/m^2) for maximum night-time cooling potential. Within the sorption module, the matrix structure in the reactor component enhances heat and mass transfer to and from the hygroscopic salt. The matrix materials were developed by the manufacturer based on overall costs. The requirements of these matrix materials were according to specific indices used by the developers and divided into two types; type A and type B. Sorption module prototypes were manufactured for testing, employing the two different hygroscopic salt infused matrix types; module A contained matrix type A while module B contained matrix type B. All other manufacturing parameters were kept constant to achieve a fair comparison of the sorption module performance with the different matrix types.

4.2.1 Test Methodology – Solar Sorption Modules

Congruent with the principle of operation of the module in a solar thermal collector, tests were devised to parametrise the performance of each module type in terms of cooling and heating power and cooling and heating energy. Tests of the sorption modules as described in Paper II were carried out in a test rig with solar simulator (see Figure 17). The sorption modules were placed horizontally, parallel to the solar lamps where the reactor heat exchanger was connected to one hydraulic loop and the condenser/evaporator heat exchanger coupled to a separate loop (see Figure 18). Heat transfer fluid flow rate, inlet and outlet temperatures were measured which allowed for the calculation of heat transfer rates with an uncertainty of ± 12%. Additionally, solar irradiation, reactor and condenser/evaporator surface temperatures were employed to derive various operation parameters of the sorption modules as described in Paper II.

Tests were run in two modes; desorption and absorption (emulating day and night operations), which when run in succession constitute one cycle. The maximum mode (and therefore cycle) times are governed by the quantity of active substance in the sorption module, the solar irradiation level, temperature of the reactor heat exchanger, and temperature of the condenser/evaporator heat exchanger. Detailed information on the test equipment employed can be found in Paper II.

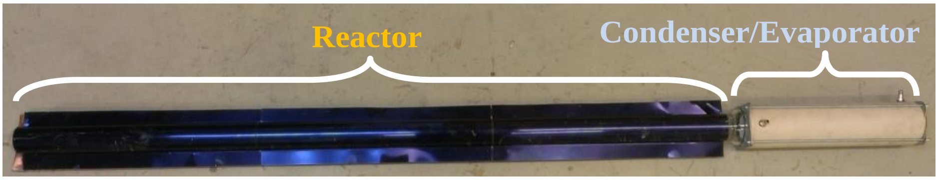


Figure 16: Sorption module prototype with heat exchangers.

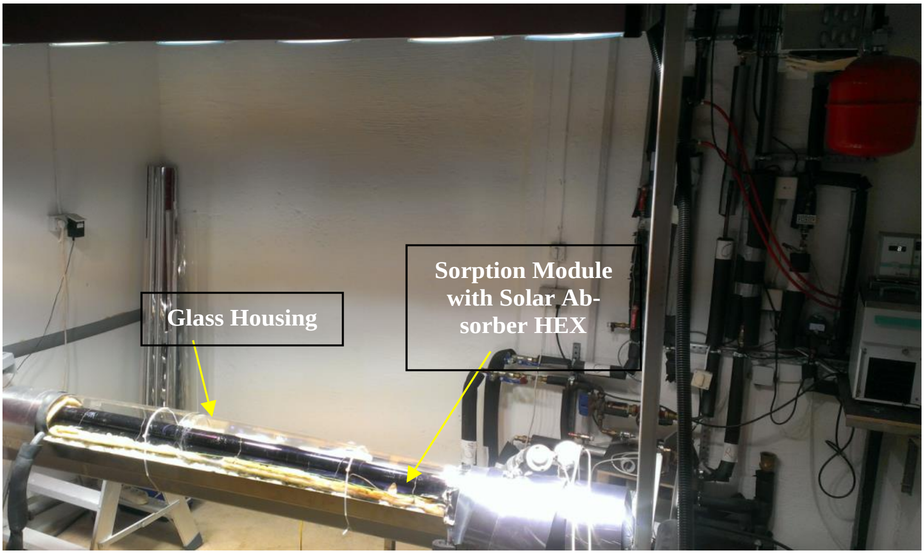


Figure 17: Test setup for sorption module evaluation in the solar simulator test rig.

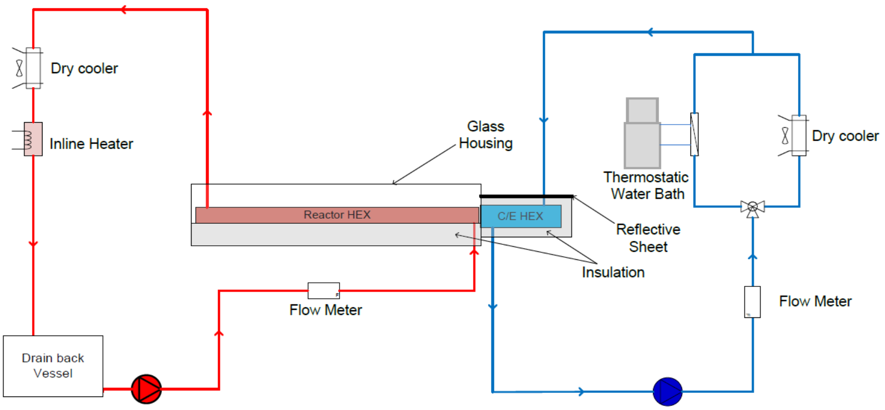


Figure 18: Hydraulic schematic of individual sorption module test setup.

4.2.2 Desorption and Absorption Modes

Tests carried out in Paper II described that in the desorption mode (also called desorption phase), the solar lamps were switched on and fluid in the reactor heat exchanger was drained to the drain back tank. Fluid was circulated in the condenser/evaporator heat exchanger recovering the condensation heat of desorption and exhausting it to the ambient via a dry cooler. In the case of complete desorption, the desorption phase was continued until the heating power due to condensation fell below 5W.

Immediately after the end of desorption, the reactor is cooled rapidly via a flow of heat transfer fluid in its heat exchanger. Input fluid temperature to the condenser/evaporator heat exchanger was controlled by the thermostatic water bath whilst inlet fluid temperature to the reactor heat exchanger was regulated via combined control of the dry cooler and an electric heater. These temperature regulations allowed for performance to be evaluated at a range of temperature lifts where the temperature lift (ΔT_{lift}) is defined as the difference between re-cooling fluid inlet temperature to the reactor and chilled fluid outlet temperature from the condenser/evaporator heat exchanger. The absorption process was considered complete when cooling power fell below 5 W.

4.2.3 Test Sequences

In the individual sorption module tests (Paper II) various test sequences were carried out to ascertain the operational parameters and performance indicators for the two module types. Tests were done at different temperature lifts during absorption after a full desorption phase had been carried out. This was done by varying the temperature of the heat transfer fluid supplied to the condenser/evaporator heat exchanger during absorption whilst maintaining the temperature at the inlet to the reactor heat exchanger as constant as possible. Test sequences were also run at varying desorption levels, in order to simulate days with different amounts of solar insolation which would translate to incomplete desorption of the module. Desorption level was determined by comparing the amount of re-cooling energy dissipated for a complete desorption with that for any given cycle. Therefore, a cycle with desorption level 0.8 or 80% signifies that the re-cooling energy dissipated during desorption was 80% of that observed in a complete desorption. The full set of test sequences carried out is listed in Table 2.

Table 2: Test sequences carried out for each sorption module type.

Desorption Level	**100%**	**80%**	**70%**	**60%**	**40%**
Module A	ΔTlift = 17°C to 25°C	-		-	-
Module B	ΔTlift = 16°C to 25°C	ΔTlift = 21°C	ΔTlift = 21°C	ΔTlift = 21°C	ΔTlift = 21°C

4.2.4 Sorption Integrated Collector and Combined Solar Heating and Cooling System Evaluation System Tests

Further evaluations of the sorption modules were carried out in the form of outdoor laboratory-scale installation comprising 4 sorption integrated collectors (see Figure 19). During the outdoor testing period, the collectors were operated with a constant re-cooling temperature of 25°C during desorption mode. Throughout the testing period chilled water outlet temperatures were maintained at 9 ± 1°C. Half of the test period was used for operation at 20°C re-cooling temperature during absorption and the other half with a re-cooling temperature of 30°C inlet temperature to the reactor heat exchanger of the collectors [85]. This permitted the evaluation of collector performance at various temperature set points and the comparison with individual sorption module performance.

Figure 19: Photograph of outdoor laboratory sorption collector test installation [85].

Studies described in [85] further examined tests and evaluations carried out on a large-scale sorption integrated collector solar heating and cooling system (SISHCS). The demonstration plant comprised 130 sorption integrated collectors with a total aperture area of 180 m^2 (see Figure 20). The solar heating and cooling system was connected to the existing cooling and heating distribution system within the building via cold and hot stores. The main measurement points were placed at the supply and return of the heating, cooling and the re-cooling circuits to investigate system performance.

Further performance indicators were derived (see Results Section 5.1) and used for comparisons at the individual sorption module, SIC and SISHCS levels [85].

Figure 20: Photograph of the full sorption integrated solar heating and cooling demonstration plant [85].

4.3 Experimental Evaluations of Sorption Modules for Gas-Driven Heat Pump Applications

Paper III describes two sorption module prototypes that were designed and fabricated for integration with a gas boiler in the development of a gas-driven sorption heat pump (GDSHP). The modules were designed to maximise power and COP employing salt combinations with thermal properties that allow for heat pumping in sub-zero temperatures and heat delivery at temperatures 40°C and above. These temperature levels are deemed adequate for space heating and/or domestic water (pre)heating purposes. One sorption module prototype was an ammoniated salt module (ASM) (Prototype 1) whilst the other was a resorption module (RM) (Prototype 2). Both modules had the same heat transfer areas and high temperature salt (HTS) with the only difference being the sorption process. The RM contained a low temperature salt (LTS) and the ASM a combined condenser/evaporator. This allowed for a direct comparison of module performance for the different sorption processes.

4.3.1 Test Methodology – Gas-Driven Heat Pump Sorption Modules

Experimental evaluations were carried out to characterise the performance in terms of heating power and energy as well as COP under different temperature conditions. Tests for both sorption module prototypes, as described in Paper III, were carried out in a test rig developed to provide controllable heat rejection and desorption temperatures (see Figure 21 and Figure 22). The sorption module was connected to two hydraulic circuits; circuit 1 connected to the R or RA and circuit 2 connected to the CE or RB. Circuit 1 was connected to the R or RA via the hybrid thermosyphon heating unit (HTHU). The HTHU was developed for saturated steam heating of the R or RA during desorption employing an electric heater. The HTHU could also provide water re-cooling via a pumped flow during absorption for the experimental evaluations carried out in this study. The use of an electric heater as opposed to a gas burner, as described in Paper III, was due to cost and convenience factors involved in the measurement of the heat input during desorption in the laboratory tests.

With the laboratory setup, it was possible to heat and/or reject heat from the R or RA with the HTHU controlling both heating and heat rejection temperatures. Therefore, the test setup was used to emulate the desorption and absorption temperature and flow rate parameters expected during operation of the sorption module to produce space heating and/or domestic hot water. Circuit 2 allowed for heat rejection from the CE or RB as well as a low temperature heat load to be applied with Heater B. Tests were run in two phases; desorption immediately followed by absorption which constituted one operation cycle of the sorption module. Detailed information on the test equipment employed can be found in Paper III.

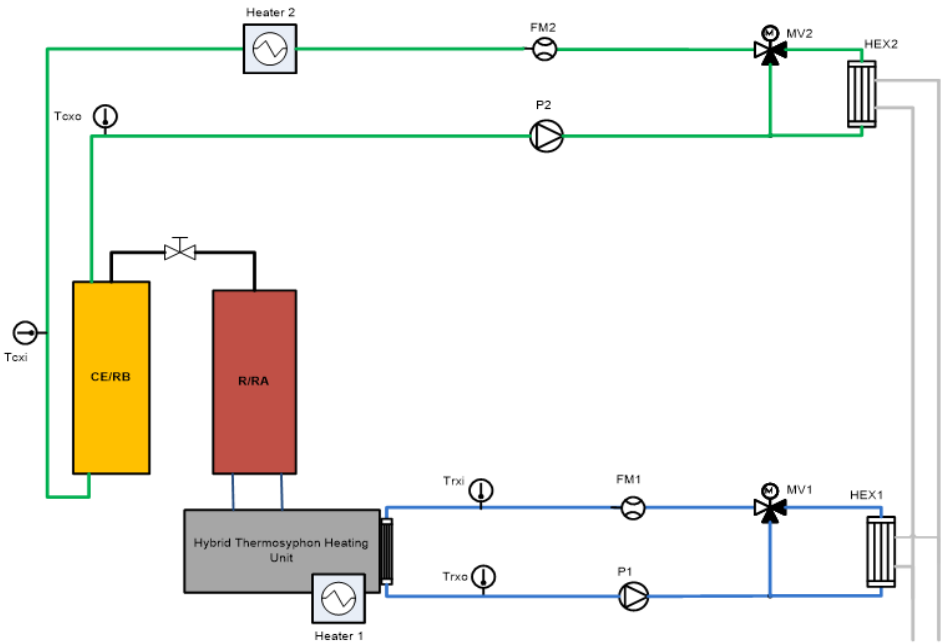


Figure 21: Schematic diagram of laboratory setup for ASM and RM evaluations [circuit 1 (blue), circuit 2 (green), ground source loop (grey)] (Paper III).

Figure 22: Photograph of the laboratory test rig for ASM and RM evaluations (Paper III).

4.3.2 Desorption and Absorption Modes

Tests carried out in Paper III described that in desorption mode the electric heater of the HTHU heated the R or RA to between 160°C and 180°C. Maximum R and RA temperatures and thus maximum heat rejection temperatures were limited by maximum pressure tolerance of the HTHU heater in the test setup. Fluid was circulated in circuit 2 allowing for heat to be rejected from the CE or RB and ejected to the ground-source heat exchanger via HEX2. Desorption mode continued until heat rejection power fell below 100 W.

During the absorption mode the heater of the HTHU was turned off and its integrated pump started for heat rejection from the R or RA. Heat rejection temperatures from the HTHU were between 30°C and 70°C depending on the test sequence carried out and the prototype involved. Fluid was circulated in circuit 2 with Heater B regulating fluid temperature into the CE or RB. For both prototypes the reduction of heat rejection power from the R or RB to below 100 W signalled the end of absorption.

4.3.3 Test Sequences

For the sorption module tests various test sequences were carried out (Paper III). Test parameters were derived considering a GDSHP operating with an outdoor air source unit. Typical heat delivery at temperatures required for space and/or domestic water heating as well as the thermodynamic limitations of the sorption processes were also considered. That is, sorption modules operating at various temperature lifts. During the experiments, a temperature drop of 15°C between outdoor air temperature and circulating heat transfer fluid in the outdoor fan coil was assumed. Therefore, various test sequences were carried out with each sorption module prototype with temperature lifts (ΔT_{lift}) up to 78°C during the absorption phase to determine their performance sensitivity to temperature lift. All absorption phases were carried out immediately after a full desorption phase. At least 40 cycles were run for each prototype to evaluate the repeatability of the measurement results. The test sequence parameters are summarised in Table 3.

Table 3: Test sequence parameters for Prototype 1 and Prototype 2.

Desorption Level	**100%**
ASM (Prototype 1)	ΔTlift = 45°C to 78°C
RM (Prototype 2)	ΔTlift = 30°C to 59°C

4.4 Simulation of Sorption Integrated Solar Heating and Cooling Systems

Studies in Paper IV sought to investigate the technical and economic performance of different solar heating and cooling systems. The main objective of the study carried out in this paper was to investigate energy and cost saving potential of solar heating and cooling systems compared to a reference system. This study was considered a first step for future more detailed investigations. Consequently, the study only comprised simplified simulation models where average efficiencies of conventional components were used in the calculation of their performance and thus energy usage. Performance characteristics and expected energy yields for the sorption integrated collector system were simulated based on empirical data obtained from Papers II and [85].

4.4.1 Simulated Systems

As described in Paper IV, a reference system was chosen to represent a typical heating and cooling system for a single-family house in Europe. This comprised a centralised vapour compression chiller unit which distributes chilled water to fan coil units within the house for air conditioning. Wintertime space heating is provided by a natural gas fired boiler that also produces DHW throughout the year.

System 1 (solar PV only) is an addition or complement to the Reference system to improve overall energy efficiency by replacing a portion of energy used for heating and cooling with solar energy. System 1 consists of a supplementary solar photovoltaic (PV) installation with modules connected to a generic maximum power point tracking (MPPT) inverter. The PV system is used to provide electrical energy for the chiller unit with the electric grid acting as both storage and backup power. Space heating and DHW loads are completely covered by the boiler.

System 2 (sorption integrated system) supplements the reference system with solar energy with double-glazed flat plate sorption integrated collectors. Each collector is equivalent to those previously tested in the full system test following the same operational principle [85]. Therefore, the SISHCS provides space heating and DHW during winter months when it operates as a standard solar thermal collector. The sorption collectors then provide chilled water and DHW during the summer months when they operate in their batch triple-state sorption process.

System 3 (hybrid system) is a hybridisation of the solar elements of Systems 1 and 2 where the flat-plate sorption integrated collector is outfitted with a solar PV module on the unutilised sun-facing portion of the collector that covers the condenser/evaporator of the sorption modules within the collector (see Figure 23). The sorption collector was considered to have the same characteristics and dimensions as those in System 2 but with an addition of 0.5 m^2 of PV module area per sorption collector. Further details can be found in Paper IV.

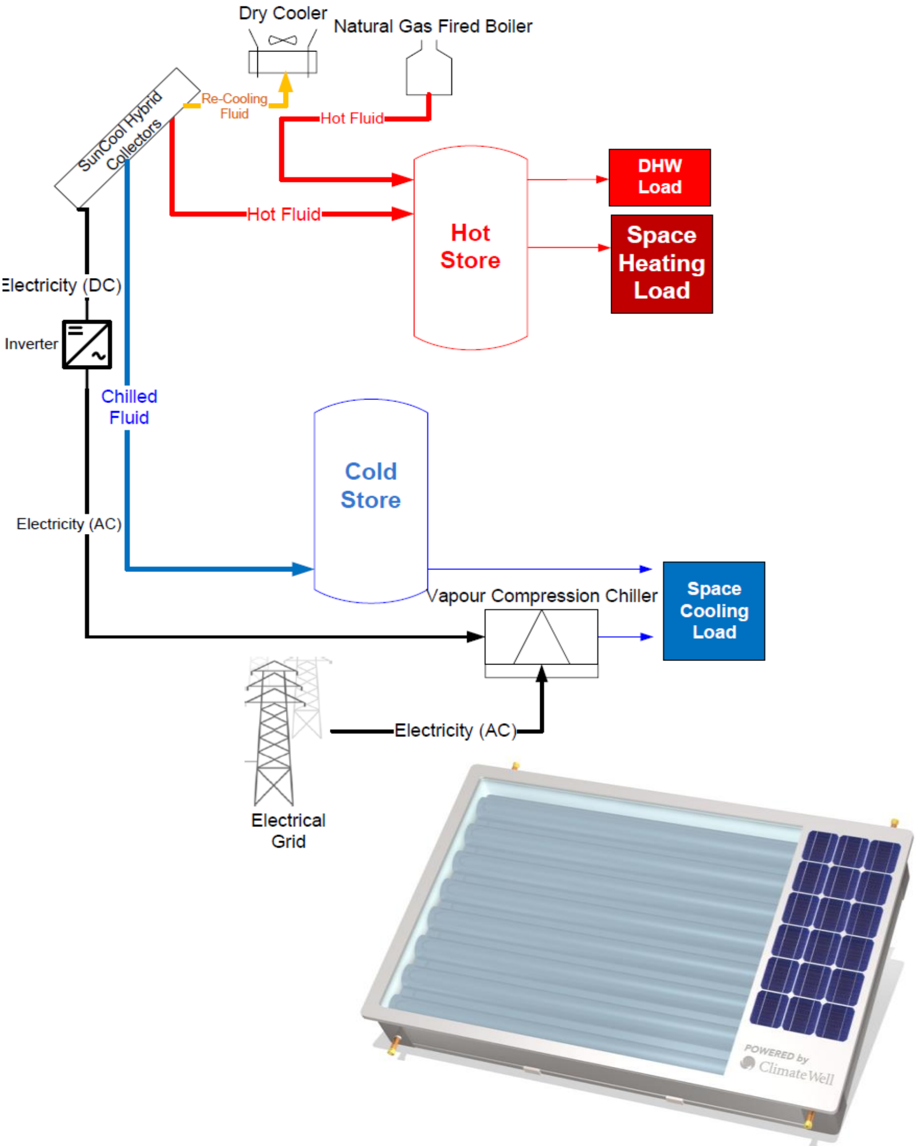


Figure 23: System 3 schematic (top). Hybrid PV- sorption integrated collector concept (bottom) (Paper IV).

4.4.2 Simulation Tools

Simulations were carried out using TRNSYS (Transient System Simulation Tool) [86,87] for simulation of the behaviour of transient systems. TRNSYS was employed to determine the space cooling and heating loads via a generic multi-zone building model for a 140 m^2 single-family house. This simulation tool was also utilised to perform separate simulations of the electricity output of a generic solar photovoltaic installation and also of the heat production of the sorption integrated collector during the winter which was modelled as a standard flat-plate solar thermal collector (Paper IV).

4.4.3 Simulation Method and Techno-economic Analysis of Sorption Integrated Solar Heating and Cooling System

Using a generic building model as defined in Paper IV, space heating and cooling demands were simulated for Madrid, Spain. Hourly heating and cooling energy demands were generated for a typical year and data exported to a Microsoft Excel file. In the case of the reference system, a fixed boiler efficiency of 0.8 and fixed vapour compression chiller COP of 3 were used to calculate the natural gas and electricity consumption respectively, based on the previously simulated space heating and cooling demands. System 1 was simulated using the TRNSYS Type 194 PV module model (see Paper IV), where hourly average solar electricity output from the system was generated in terms of kW/m^2 for an entire year. System 2 employed the TRNSYS Type 1 solar collector model for simulation for the SICs when they operate in winter mode. For this winter mode model, the sorption collectors delivered hot water to a thermal store that provided thermal energy for DHW and/or space heating where possible. The summer mode model for the sorption collector system was an empirical model based on laboratory and field measurements of the SISHCS [85] and sorption modules (Paper II). This empirical model was used to generate an hourly cooling and heating energy production profile for the sorption integrated collector system for summer months. All generated simulation data was collected in a Microsoft Excel file and an energy balance carried out where energy demands were compared with energy supply and stored energy on an hourly basis over the period of one year. A pictorial representation of the simulation methodology is shown in Figure 24.

Techno-economic analyses were performed to determine the energy and potential cost savings of each system type compared to the reference system for installed solar collection areas of 5, 10, 15 and 20 m^2. Additionally, sensitivity analyses were carried out to investigate the influence of natural gas and electricity prices on the energy cost savings.

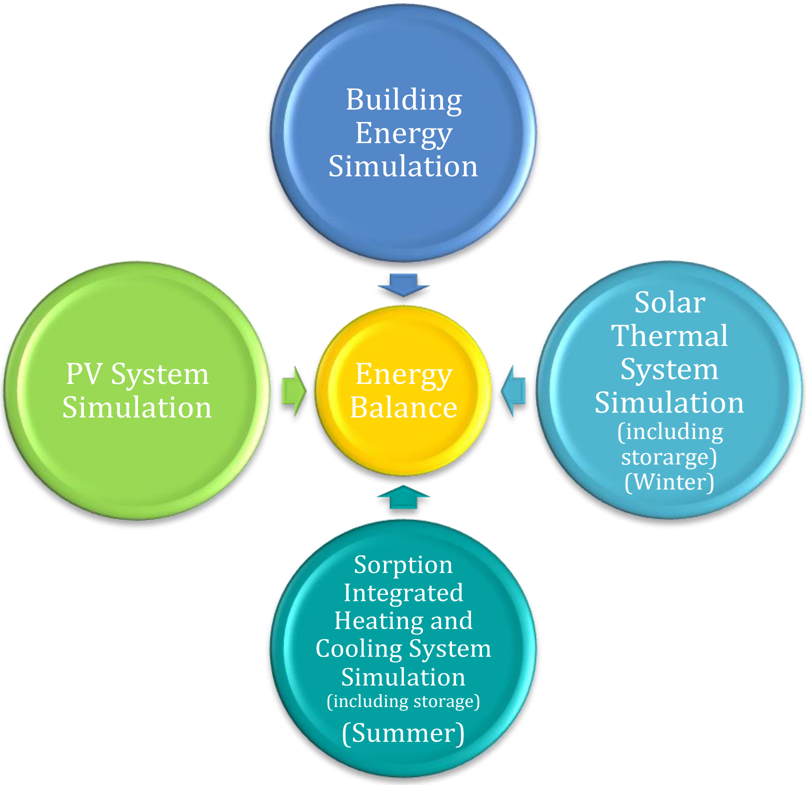


Figure 24: Pictorial representation of the system simulation and analysis process (Paper IV).

4.4.4 Model Limitations

As described in Paper IV, no dynamic or part load efficiencies were considered in the studies for the equipment in the systems. Thus, the potential impact on operation efficiency when equipment such as the boiler and vapour compression chiller operate below their rated capacities has not been investigated. Consequently, the influences of different estimated efficiencies, part load efficiencies or system dynamics are not accounted for in the economic analyses. Additionally, in the case of simulations of the solar electricity production, self-consumption of the electricity for purposes other than cooling has not been considered.

4.5 Simulation Method and Techno-economic Analysis of Gas-Driven Sorption Heat Pump

Studies in Paper V investigated the technical and economic performance of gas-driven sorption heat pumps. The studies proposed a method to determine the optimum design heating capacity of a sorption module to be integrated into a GDSHP. Additionally, the energy and cost savings as well as simple payback times for the GDSHP were compared to the state-of-the-art (i.e. reference) heating system. Two different sorption module types were investigated: one ammoniated salt module (ASM) and one resorption module (RM).

4.5.1 Simulated Systems

A generic natural gas fired condensing boiler which provides hot water to a connected hydronic air handling unit (AHU) was chosen as the reference system. The AHU would in turn distribute warm air throughout a house with central ducting. This was considered representative of a GDSHP installation in the USA. The unit would provide all thermal energy required for space heating during the winter.

As detailed in Paper V, the GDSHP systems are divided into system types. The GDSHP Type A (GDSHPA) was a bivalent GDSHP comprising an integrated ASM and an auxiliary condensing boiler. The GDSHP Type B (GDSHPB) was a bivalent GDSHP comprising an integrated RM and an auxiliary condensing boiler. The schematic of the system concept is shown in Figure 25.

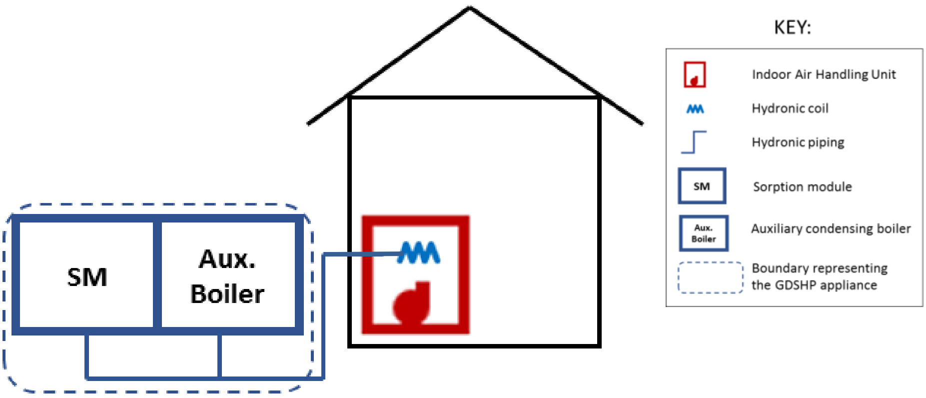


Figure 25: Schematic of bivalent gas-driven sorption heat pump concept in a house with centrally ducted heating (Paper V).

4.5.2 Simulation Tools

The space heating loads were modelled in EnergyPlus 8.4.0 using TMY3 climatic and publicly available residential prototype building models. The model represents a two-story, 223 m^2 single-family detached house with a vented attic and a crawlspace. The simulation tool was used to perform climate specific hourly space heating load simulations.

4.5.3 Simulation Method and Techno-economic Analysis of Gas-Driven Sorption Heat Pumps

As described in Paper V, for a climate specific generic house model, residential space heating loads were simulated. For each hour with a space heating load, the required heating fluid supply temperature to the AHU was calculated according to outdoor temperature.

An empirical model based on laboratory measurements of the sorption modules (Paper III) was used to determine the average heating capacity and COP of the sorption modules in accordance with the required temperature lift to meet the space heating demand. The sorption module heating capacity was translated into units of power per square metre of heat transfer area (i.e. as a heat flux). The heating capacity of the sorption modules was considered to scale linearly with heat transfer area, with the assumption that larger or smaller sorption modules would demonstrate the same efficiencies at given operating conditions. The GDSHP operation strategy was devised where the sorption module covered 100% of the heating demand when ambient temperatures were at or above the bivalent temperature. The bivalent temperature was defined as the ambient temperature at which the maximum capacity of the heat pump is equivalent to the building load. At temperatures below the bivalent temperature both the sorption module and the condensing boiler operate simultaneously to meet the required heating demand. The sorption module is however limited to a minimum operating temperature called cut-off temperature, below which the sorption module operates in a non-heat pumping mode with efficiency equivalent to a condensing boiler. In the simulations carried out, efficiency of the condensing boiler (and of the sorption module in non-heat pumping mode) was fixed at 0.92. Derived from the empirical model of the sorption module and the operating strategy of the GDSHP, hourly heating delivery and efficiency profiles were generated and collected in Microsoft Excel. A pictorial representation of the simulation methodology is given in Figure 26.

In the case of the economic analyses, energy and cost saving potential of each GDSHP type as well as the simple payback time were calculated for different scenarios. These scenarios included high and low energy prices, high and low sorption module cost, GDSHP Type A and Type B as well as cold and moderate climates.

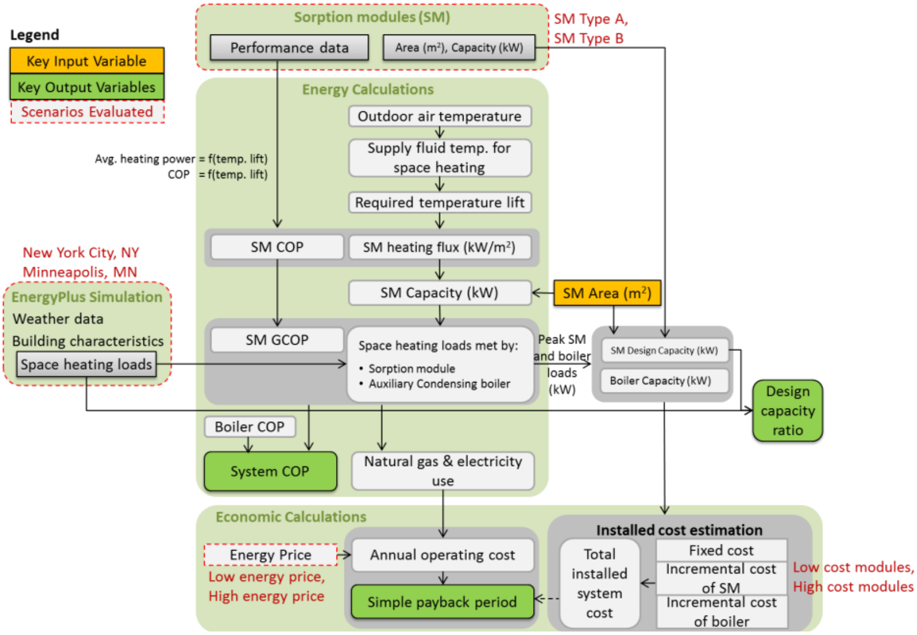


Figure 26: Pictorial representation of simulation process for gas-driven sorption heat pump analysis.

4.5.4 Model Limitations

As described in Paper V, simplified empirical performance correlations based on the evaluations carried out in Paper III were utilised. Therefore, no dynamic or part load efficiencies were considered in the studies and only full desorption and absorption cycles were considered. Additionally, the potential impact on operation efficiency when the auxiliary condensing boiler operates below its rated capacity was not investigated. The economic analysis therefore does not reflect the influence of the system dynamics and part load efficiencies on energy cost savings and payback times. Only two scenarios were considered which were on the upper and lower extremes of energy prices and installed costs of the sorption modules.

4.6 Testing and Modelling of Sorption Modules for Various Applications

Paper VI describes a test platform designed for the experimental evaluation of sorption modules that could potentially be employed for various different applications. A representative sorption module was employed for testing in the platform. It comprised a 0.25 m-long cylindrical reactor vessel housing an alkali halide salt and an equal dimension combined condenser/evaporator vessel containing a porous matrix material. The condenser/evaporator and reactor were connected by a one-inch (25.4 mm) diameter stainless steel pipe via a series of valves. The platform was designed to be sorption module and process agnostic able to employ sorption modules operating under different sorption processes and with different substances. That is, adsorption, triple-state absorption and chemisorption.

4.6.1 Test Methodology

An automated test platform which served for experimental evaluation was employed to hydronically heat and cool the sorption module was used in the studies carried out in Paper VI. The test platform consisted of two hydronic loops: one for the heating and cooling of the reactor via the sorption module's reactor heat exchanger. In this first pressurised water loop driving temperatures of up to 200°C were achievable. The second loop was connected to the condenser/evaporator heat exchanger of the sorption module allowing for heat transfer to and from the refrigerant housed in the sorption module's condenser/evaporator. The heat transfer fluid used for the condenser/evaporator was also water allowing for operation at temperatures between 5°C and 80°C.

Based on measurement uncertainty of the equipment employed and the range of operation of the test rig, overall test measurement uncertainty of the heat flows to and from the sorption modules was ± 7.6%. A detailed description of the test platform can be found in Paper VI.

4.6.2 Cycling

Testing for the sorption module was divided into 4 different phases or modes. This differs from previous experimental evaluations carried out in Papers II & III where only 2 modes were considered: desorption and absorption. In evaluations, these modes were further subdivided to include pre-charge; a pre-cursory mode to charge (or desorption) and pre-discharge the corresponding to discharge (or absorption). This test strategy considers the introduction of valves between the reactor and condenser/evaporator of the sorption module which allows for each section to be independently cooled without the movement of refrigerant. This control thus increases the flexibility of the test platform as it could potentially also be run excluding the pre-charge and pre-discharge modes by keeping the valves open at all times. That is, emulating valve-less operations. Pre-charge was carried out where the reactor was heated by electrically heated circulating heat transfer fluid whilst the condenser/evaporator was heated or cooled to a specified setpoint temperature. This pre-charge was carried out with the valves between the reactor and condenser/evaporator closed where the sorption module was being conditioned for the charge (or desorption). Charge was started when the reactor reached the requisite temperature to incite the flow of refrigerant to the condenser/evaporator signalling the opening of the valve between the condenser/evaporator and reactor. Pre-discharge saw the closing of the refrigerant valves and the cooling of the reactor. Discharge (or absorption) started when the reactor was cooled to the desired set-point, at which point the refrigerant valve was opened with refrigerant evaporating in the condenser/evaporator and re-associating with the salt in the reactor (Paper VI).

4.6.3 Test Sequences

Test sequences for the characterisation of the sorption module were considered based on the main operating temperatures of the sorption module during its operating modes. In the testing of electrochemical accumulators reference tests based on expected optimal operation conditions are carried out, as well as off-reference tests, which consider other conditions that the batteries could operate under [88,89]. Similarly, the sample sorption module was put through a number of reference and 'off-reference' cycles where input HTF temperatures, cycle times and the maximum state of charge (SoC) were varied. The SoC during charge was defined as the ratio of total heating energy rejected from the sorption module compared to maximum heating energy rejection at reference conditions. During discharge the SoC was the ratio of total delivered cooling energy from the sorption module to maximum cooling energy delivery at reference conditions. During charge, the maximum difference between supply temperature to the R and that to the CE is defined as the maximum driving temperature difference (ΔT_D). While during discharge the difference between supply temperature to the R and that to the CE is defined as the temperature lift (ΔT_L). Figure 27 summarises the principal test sequence strategy carried out for characterising performance (power, energy, and COP) of the sorption module. Further details on the test sequences can be found in Paper VI.

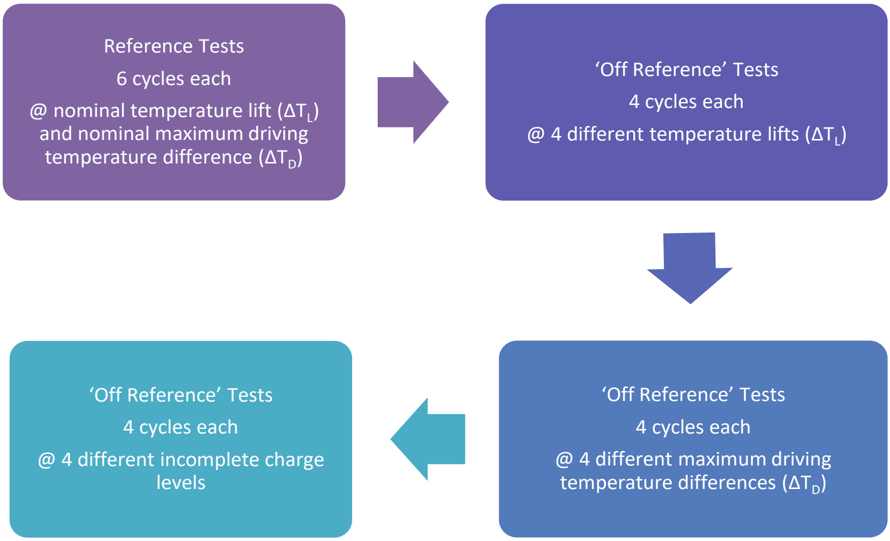


Figure 27: Principal test sequence strategy (Paper VI).

Additionally, for the purposes of model validation, a supplementary test sequence with a set of 6 random cycle measurements was run. This test set comprised various 'off-reference' conditions including different temperature lifts, maximum driving temperatures and incomplete charge level. Each unique cycle was run 4 times for a total of 24 cycles.

4.6.4 Modelling and Simulation

In Paper VI a model based on an artificial neural network (ANN) was explored. This model type was selected for its ability to decipher and learn relationships between given input and output data that are used for 'training the network'. It was thus used to characterise the thermal behaviour of the sorption module, predicting the heat transfer rates to and from the reactor and condenser/evaporator.

ANN models have an input layer, one or more hidden layers containing processing neurons and output layers. In the study carried out in Paper VI 4 time-dependent inputs; reactor and condenser/evaporator input temperatures, SoC of the sorption module and its operating mode were considered. The 2 time-dependent outputs were the heat transfer rate to/from the reactor heat exchanger and the heat transfer rate to/from the condenser/evaporator heat exchanger. Additionally, the state of charge was used as a feedback parameter for the training of the ANN. The ANN was trained and tested using data from the principal test sequence. Validation of the ANN was subsequently done employing data from the supplementary test sequence.

5 Results

This section presents the results from the analytical, experimental and simulation studies carried out on the sorption modules and sorption module integrated systems.

5.1 Performance Indicators

Within the bounds of the studies in Papers I through VI various key performance indicators were investigated and adapted to the evaluations carried out. This resulted in the devising of the most important performance in the study of sorption modules. These indicators can be broken down into:

- *general indicators* - similar for all individual sorption module types
- *application specific indicators* – particular for a given application

In Papers I, II, VI general performance indicators were devised. These performance indicators were used to describe the performance of the individual sorption modules during their main modes of operation, desorption and absorption. Sorption modules are devices that convert heat into useful streams of thermal energy destined for use in heating and/or cooling applications. Therefore, the general performance indicators devised characterise the basic performance of any sorption module irrespective of its application. Based on the studies carried out general performance indicators should manifest the rate at which the sorption modules can deliver thermal energy as well as how much thermal energy can be delivered during a given mode of operation. That is, how much power and energy are delivered by the module. The number of sorption modules for a given application can therefore be readily calculated by simply dividing the total power and/or energy demand by that delivered by an individual sorption module. Correspondingly, how efficiently the sorption module can deliver this thermal energy is also key to determining the potential energy savings from any given sorption module. Since all sorption modules use energy from a given source and deliver it to a given end-user, where both input and output energy often have value, the energy cost savings of employing a sorption module is of importance.

The most important general performance indicators have been summarised in Table 4 below:

Table 4: Summary of most important general sorption module performance indicators.

Symbol	Name	Description
Q_{chill}	*Cooling Power*	The average useful cooling capacity of the sorption module during absorption mode given in W.
E_{chill} *or* E_{cool}	*Cooling Energy*	The useful cooling energy during absorption mode given by the time integrated value of the cooling power. This indicator is given in Wh or kWh.
$Q_{re\text{-}cool}$	*Re-Cooling Power*	The average rate at which heat is rejected during desorption given in W.
$E_{re\text{-}cool}$	*Re-Cooling Energy*	The thermal energy dissipated from the condenser/evaporator during desorption, given by the time integrated value of the re-cooling power given in Wh.
Q_{heat}	*Heating Power*	The average rate at which heat is dissipated from the reactor during absorption given in W.
E_{heat}	*Heating Energy*	The thermal energy dissipated from the reactor during the absorption phase given by the time integrated value of the heating power given in Wh.
Q_{drive}	*(Process) Driving Power*	The average rate at which heat is delivered to the reactor to drive the desorption process. This is given in W.
E_{drive}	*(Process) Driving Energy*	The heating energy delivered to the reactor during the desorption process given by the time integrated value of the driving power given in Wh.
COP_{cl}	*Cooling Coefficient of Performance*	This indicator quantifies the efficiency with which thermal energy is converted into usable cooling energy. It is calculated as the quotient of usable cooling energy divided by the thermal energy input that drives the sorption process.
COP_{ht}	*Heating Coefficient of Performance*	This indicator quantifies the efficiency with which thermal energy is converted

		into usable heating energy. It is calculated as the quotient of usable heating energy divided by the thermal energy input that drives the sorption process.

In Papers II and IV further key performance indicators specific to the solar collector integration of the sorption module were derived for the characterisation of the operation of the SISHCS. SISHCS harness solar energy to provide useful thermal energy, therefore most metrics have been calculated per unit aperture area. This allows for comparison of different system sizes and exploit the modular nature of the SISHCS to determine the required system size. The performance indicators describe the rate and efficiency with which these conversions are carried out allowing for calculation of the size of the system required for a given application or conversely the performance of a system with a given aperture area. Additionally, since the system requires an input of electrical energy in addition to thermal energy input, this too must be accounted for in analyses. The percentage, quantity and value of energy savings compared to other thermal energy delivery systems is also of interest when carrying out techno-economic analyses of SISHCS.

Key performance indicators for sorption module integrated systems for solar energy applications have been summarised in Table 5 below:

Table 5: Summary of most important performance indicators for sorption module integrated solar energy systems.

Name	**Description**
Solar Cooling COP (COP_{solar})	The efficiency with which solar irradiation is converted to cooling energy. Calculated as the quotient of E_{cool} divided by the solar insolation on the SIC. This indicator was defined in the present studies based on the fact that the sorption module is desorbed by heat generated directly from incident solar radiation with no intermediate heat transfer step.
Heating Energy Density	The heating energy delivered during absorption mode per unit volume of the sorption module (i.e. the outer dimensions of the vacuum enclosure of the sorption module). This indicator was derived in the study to quantify the heating energy storage potential of the sorption module. Another metric could be to use the volume of the sorption module including its heat exchangers for delivering to and

	extracting heat from the reactor as well as the condenser/evaporator. This would allow for a truer comparison with other sorption module types that might include internal or integrated heat exchangers [75,90].
Cooling Energy Density	The cooling energy delivered during absorption mode per unit volume of the sorption module. This indicator was derived in the study to quantify the cooling energy storage potential of the sorption module.
Cooling Power Index	The average cooling power per unit aperture area during the absorption mode of operation of the SISHCS. Calculated by dividing average cooling power, Q_{cool}, by the total aperture area of the SIC or field of SICs given in kW/m^2. This performance metric allows for the comparison of SISHCS with various other solar driven cooling systems.
Cooling Energy Index	The cooling energy delivered in absorption mode per unit aperture area during a given day. Calculated by dividing cooling energy delivered by the total aperture area of the SIC or field of SICs given in kWh/m^2-day.
Heating Energy for DHW	This indicator quantifies the energy delivered per day per unit aperture area of SIC that may be used for DHW preparation. Calculated by dividing DHW heating energy delivered by the total aperture area of the SIC or field of SICs it is given in kWh/m^2-day.
Thermal Energy Dissipated to the Environment (i.e. Re-Cooling Energy)	The low-grade heat that needs to be dissipated from the collector during desorption and absorption modes, that is, over a full day of operation of the SISHCS. This is, like the previous indicators, also calculated in terms of SIC aperture area and given in kWh/m^2-day. This indicator is key for the design or dimensioning of the heat rejection equipment required for the SISHCS. This equipment tends to have a large impact on both the thermal and electrical performance of solar thermal cooling systems [91].
Electrical (Cooling) COP (COP_{el})	This indicator quantifies the electricity consumption of the SISHCS per unit of cooling energy delivered during absorption mode. Calculated by dividing the cooling energy delivered on a given day of operation by the total electricity consumption of the SISHCS during that entire day. This indicator is often overlooked in solar thermal heating and cooling system developments [85,91] but as shown in present studies has a significant impact on the economic viability of said systems.

(Thermal) Energy Savings	The quantity of useful thermal energy for heating, cooling and/or DHW that is delivered by the SISHCS over a year of operation. This is given in the units of kWh/year.
Energy Cost Savings	The monetary savings associated with the energy savings from the operation of the sorption module integrated system compared to a reference system. Calculated by summing the monetary value of each thermal energy unit delivered by the sorption integrated system over the course of a year and subtracting the cost of energy input for running the sorption integrated system.
Solar Fraction	The percentage of the overall thermal energy demand, including space cooling, heating and DHW preparation, covered by solar energy. Calculated by summing the thermal energy delivered for space cooling, heating and DHW preparation over an entire year of operation and dividing this total by the total annual thermal energy demand of the (simulated) building. This indicator is often a precursor to calculating other indicators such as environmental impact of the solar heating and cooling system [62,92].

In Papers III and V further key performance indicators specific to the integration of the sorption module into natural gas boilers were derived. These sorption modules were primarily employed as a complement to natural gas boilers to reduce the required natural gas use to meet space and water heating demand. The key performance indicators of GDSHP are thus formulated to consider heating capacities at peak and design conditions as well as the efficacy with which this heat is delivered, that is, how well the natural gas is utilised for heating purposes. In the evaluation of GDSHP it was found that both performance over a given cycle as well as on an annual basis were of interest for sizing of the sorption modules as well as determining their energy saving benefits. For techno-economic analyses these efficiencies in the use of natural gas were accounted for as well as the use of electricity of the GDSHP. The monetary benefit of employing a GDSHP versus a state-of-the-art natural gas boiler was also a consideration in the determination of these indicators.

The key performance indicators used to characterise the operation of a GDSHP have been summarised in Table 6 below:

Table 6: Summary of most important performance indicators for sorption module integrated gas driven heat pump systems.

Name	**Description**
Specific Heating Capacity	The heating power per unit heat transfer area provided by the sorption module during absorption mode. This indicator can be found in literature and is often given per unit volume or per unit mass of sorbent [93,94]**.** Given the linear scalability of the sorption modules, in this study, heat exchange area was used for this indicator. This indicator gives information about the compactness of the sorption module and the size requirements to deliver a given heating capacity.
Design Heating Capacity	The heating capacity of the sorption module in kW/m^2 during absorption mode at design conditions.
Peak Heating Capacity of System	The maximum capacity at which the overall system can provide heat. The overall system includes both the sorption module and the auxiliary condensing boiler. This, also known as the full load capacity, is a key performance parameter in the design of any gas driven heating system [40].
Sorption Module Design Capacity Ratio	The ratio of the design heating capacity of the sorption module and the peak heating capacity of the system. This is a key indicator in the sizing of the sorption module.
Gas Coefficient of Performance (GCOP) the combustion process.	The efficiency with which heat produced via combustion of gas is converted to usable heat by the GDSHP. This indicator was derived within the studies as an adaptation of the gas utilisation efficiency (GUE) often used in literature [95]**.** Given that the GUE is typically a quantity that is measured experimentally, the GCOP was used for calculation or simulation of the performance of the GDSHP. This considers the COP_{ht} of the sorption module, the burner combustion efficiency as well as the heat recovery efficiency from flue gases created by the natural gas combustion.
Seasonal Gas Coefficient of Performance (SGCOP)	The average GCOP over the entire heating season.

Electricity Use	This indicator quantifies the electricity consumption of the GDSHP. It considers the electrical COP (ECOP), i.e. the heating power delivered per unit electrical power used, for both the sorption module and the auxiliary condensing boiler.
Energy Cost Savings	The monetary savings associated with the energy savings from the operation of the sorption module integrated system compared to a reference system. Calculated by summing the monetary value of each thermal energy unit delivered by the sorption integrated system over the course of a year and subtracting the cost of energy input for running the sorption integrated system.
(Simple) Payback Period	This indicator quantifies the length of time it takes for the additional cost of the sorption module integration to be recuperated by means of energy cost savings during operation compared to a state-of-the-art condensing boiler. This is a key metric in the determination of the economic viability of a GDSHP.

The equations used for calculation of the key performance indicators used in this work can be found in the Appendix.

5.2 Analytical Evaluation of Ammoniated Salt Modules and Resorption Modules

The analytical model presented in Paper I compared the most suitable configurations of the sorption modules, employing a method for evaluation of diverse cycle types.

5.2.1 Comparison of the Analytical Model with Numerical and Experimental Evaluations

The analytical model presented in Paper I was shown to compare well with both numerical and experimental results for conventional absorption and adsorption cycles. A comparison of the COP_{cl} for a single effect absorption chiller studied in Paper I calculated via the analytical model showed a COP_{cl} of 0.735, while (for the same absorption chiller) the COP_{cl} calculated from a detailed numerical model was 0.720 (Paper I). A difference of only 2%. Similarly, the analytical model was compared to a numerical model for the resorption cycle using two solid–gas reactors studied in [96]. The results of which are shown in Table 7.

Table 7: Comparison of coefficient of performance (COP_{cl}) calculation result between analytical and numerical models from Paper I.

	With dead thermal mass of adsorbent	**With dead thermal mass of adsorbent + heat exchange material**
$\boldsymbol{DTMR_{HTR}}$	0.31	0.58
$\boldsymbol{DTMR_{LTR}}$	0.09	0.14
$\boldsymbol{COP_{analytical}}$ [Paper I]	0.56	0.44
$\boldsymbol{COP_{numerical}}$ [96]	0.54	0.45

The authors of [96] used their numerical model to calculate COP_{cl} under different conditions where they considered; in one scenario the dead thermal mass (DTM) of the sorbent bed only and in a second scenario the DTM of the sorbent bed and heat exchanger material. The COP_{cl} calculated by the authors' numerical model and that correspondingly calculated by the analytical model in Paper I had less than ±4% difference.

Additionally, the analytical model was compared to experimental results from two resorption cycle experiments. One experiment employed $MnCl_2$ as high temperature salt (HTS) and NH_4Cl as low temperature salt (LTS) while the other used the same HTS with NaBr as LTS [70]. In this comparison the deviation of the maximum COP_{cl} was less than 0.04 (i.e. 13%) when comparing the analytical model and experimental results (see Table 8).

Table 8: Comparison of coefficient of performance (COP) between analytical model and experiment result from Paper I.

	Working Pair	
	$MnCl_2/NH_4Cl$	$MnCl_2/NaBr$
$\boldsymbol{DTMR_{HTR}}$	0.368	0.759
$\boldsymbol{DTMR_{LTR}}$	0.246	0.232
$\boldsymbol{COP_{analytical}}$ [Paper I]	0.33	0.27
$\boldsymbol{COP_{experiment}}$ [70]	0.35	0.31

Based on the results of the comparisons in Paper I, the analytical showed reasonable agreement with the classical numerical model as well as experimental evaluations. Given that the COP_{ht} can be derived from the COP_{cl} the analytical model was deemed useful for calculating both. The analytical model also used less calculation time than the classical numerical models which allows for a more time-effective evaluation of sorption systems (Paper I).

5.2.2 Sorption Module Performance Based on Configuration

In Paper I various salt and ammonia working pairs were considered and compared based on COP_{ht}. The best pair for each sorption module configuration was then downselected.

Table 9 summarises the results of the sorption module configurations for each of the three studied sorption module configurations. For the ASM, LiCl was the best candidate, even though it did not exhibit the highest thermodynamically possible COP_{ht}, its low DTM of the sorbent bed meant it had the highest overall COP_{ht}. A RM employing LiCl as HTS and NaBr as LTS was found to have the best performance according to Paper I. The expected difference in performance between an ASM with a separate condenser and evaporator (SCE) and combined condenser/evaporator (CCE) was also shown. The main difference between the SCE and CCE being that the separate condenser and evaporator unit had a lower dead thermal mass ratio (DTMR) compared to the combined condenser/evaporator vessel. This difference manifested itself as a 4% increase in COP_{ht} for SCE compared to CCE.

Table 9: Comparison of different sorption module configurations.

Configuration	Working pair	COP_{ht}, with no heat recovery	COP_{ht}, with heat recovery effectiveness of 50%
SCE	LiCl	1.21	1.29
CCE	LiCl	1.16	1.27
RES	LiCl/NaBr	1.34	1.50

Studies carried out in Paper I also showed the impact of heat recovery on the performance of the sorption modules. With an estimated heat recovery effectiveness of 50% (reasonable to reach in practice), i.e. 50% of the thermal energy from the hot reactor at the end of desorption mode can be transferred to the warm reactor at the end of the absorption mode. The ability to remove 50% of the sensible heat of the condenser/evaporator using the thermal mass of the cold condenser/evaporator was also considered. The results showed that heat recovery can improve overall COP_{ht} by 6.7%, 9.5% and 11.9% for the SCE, CCE and resorption (RES) sorption module configurations respectively. If one focuses solely on performance, then an RM using the LiCl-NaBr pair with 50% heat recovery would be the most promising option for a sorption heat pump according to Paper I.

5.3 Experimental Evaluation of Individual Sorption Modules for Solar Applications

The experimental evaluations of the two individual sorption modules Module A and Module B (Paper II) revealed the operational characteristics of these modular heat pumps. Desorption periods lasted between 7 and 11 hours with the shorter periods occurring at higher average solar irradiation levels (≈760 W/m^2) and lower re-cooling temperatures than the longer periods. Insolation levels between 4.9 and 7.7 kWh/m^2 were necessary to fully desorb both module types, these levels were dependent on the re-cooling temperature during desorption. This range encompasses the theoretically determined 5.5 kWh/m^2-day design insolation level required for full desorption of the sorption module at a nominal condenser/evaporator re-cooling temperature of 30°C.

From the tests, the general operation characteristics of the sorption modules corresponded well with expectations based on triple-state thermochemical process theory [67,72]. According to sorption theory the temperature of the salt affects the rate of absorption, with higher temperatures corresponding to lower rates of absorption. Similarly, this rate is governed by the vapour pressure of the evaporating water which is in turn governed by the temperature of evaporation. This gave rise to the investigation of the sensitivity of the cooling power to the difference in temperature between the salt and the evaporating water (i.e. the temperature lift).

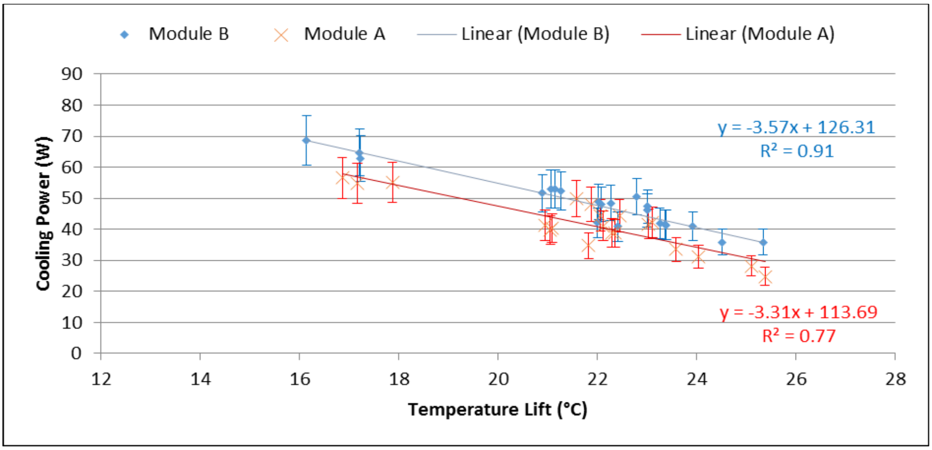


Figure 28: Graph of average cooling power versus temperature lift with characteristic equations for Module A (lower) and Module B (upper).

The temperature lift (ΔT_{lift}) was used as a parameter to characterise modules operation as described in Paper II. At a ΔT_{lift} of 21°C, Module A produces an average of 40 W of cooling power for just over 6 hours while Module B had an average cooling capacity of 52 W under a similar time period. For both modules the cooling power as shown in Figure 28 was inversely proportional to the temperature lift with Module B outperforming Module A by almost 27 % in terms of cooling energy at the nominal temperature lift of 21°C. By characterising the sorption module performance under various conditions, it is possible to use the equation of the trendline to calculate the expected cooling power of the sorption module under any temperature lift condition (within the test range).

Table 10: Sorption module performance results with respect to desorption level with colour code - highest value per row (dark green) to lowest value (yellow).

	Module A	Module B				
Desorption Level	**100%**	**100%**	**80%**	**70%**	**60%**	**40%**
Temperature Lift (°C)	**21**	**21**	**21**	**21**	**21**	**21**
Q_{chill} (W)	40.3	52.6	51.9	51.7	48.0	42.4
Q_{heat} (W)	54.6	62.1	55.2	53.7	53.0	47.3
E_{chill} (Wh)	255.4	323.8	303.5	275.9	207.6	156.9
E_{heat} (Wh)	343.7	385.3	323.2	286.4	228.8	174.9
Desorption Time (hrs)	10.7	7.4	6.2	4.8	4.1	3.0
Absorption Time (hrs)	6.3	6.1	5.9	5.3	4.3	3.7
Energy Density $_{chill}$ (kWh/m^3)	51	65.1	60.6	55.1	41.5	31.4
Energy Density $_{heat}$ (kWh/m^3)	68.7	77.0	64.6	57.2	45.7	34.9
COP_{solar}	0.23	0.35	0.40	0.42	0.41	0.41

In tests with incomplete desorption, only a small decrease in average cooling power was observed down to a 70% desorption level. However, it was seen that cooling energy decreased proportionally to decreasing desorption levels. Further performance indicators for the sorption modules established in Paper II included the heating energy density and cooling energy density (see Table 10), which characterised the heating and cooling capacity of the sorption module per unit volume of the module. This was devised to get an understanding of the practical energy density of the unit as a thermochemical store.

Module A converts 23% of the incident solar irradiation to cooling energy under nominal conditions while that figure stands at 35% for Module B with its enhanced matrix material. Evaluations performed at different desorption levels with Module B showed that solar cooling COP peaked at a desorption level of 70%. This is demonstrated by the reduced condensation energy close to the end of the desorption phase even at constant solar irradiation levels. This suggests that, near the end of the desorption phase the solar irradiation required to dissociate the last molecules of water bound to the salt, is relatively large thus giving rise to lower overall efficiency at higher desorption levels. This finding suggests that full desorption should be avoided, which has implications for the design of the sorption module where the amount of salt solution within the reactor could be optimised based on intended installation location of the SIC to avoid total drying of the salt.

The aforementioned performance indicators form the foundation of the design of a SIC based on the characteristics of the sorption module prototypes. This allows for the calculation of the expected cooling capacity and cooling energy of a sorption integrated solar collector. Additionally, the dimensions and characteristics of the equipment required for heat dissipation can be determined. Even though Module B showed better performance characteristics, practical manufacturing limitations prohibited mass production for use in SICs at the time of the study. Therefore, Module A was used for further evaluations and simulation of SISHCS carried out as described in [85]. Further studies are required to be carried out on Module B which are beyond the scope of the current thesis work.

5.4 Individual Sorption Modules for Gas-Driven Heat Pump Applications

Similar to the experimental evaluations carried out in Paper II, Paper III described the evaluation of an ammoniated salt sorption module (ASM) and a resorption module (RM). For the prototypes tested, desorption phases lasted up to 60 minutes and absorption phases lasted for between 19 and 24 minutes for the ASM and between 23 and 30 minutes for the RM. Average heating powers during absorption were measured for both prototypes at various temperature lifts (see Figure 29). Once again, corresponding well with sorption theory, increased temperature lift reduces the vapour pressure difference between the R or RA and CE or RB vessels reducing ammonia flow rate and therefore heating power [78]. For both sorption module prototypes, the average heating power during absorption was inversely proportional to the temperature lift. The results showed that for every degree increase in temperature lift there was a 1.4% and 3.4% reduction in heating capacity for the ASM and RM respectively.

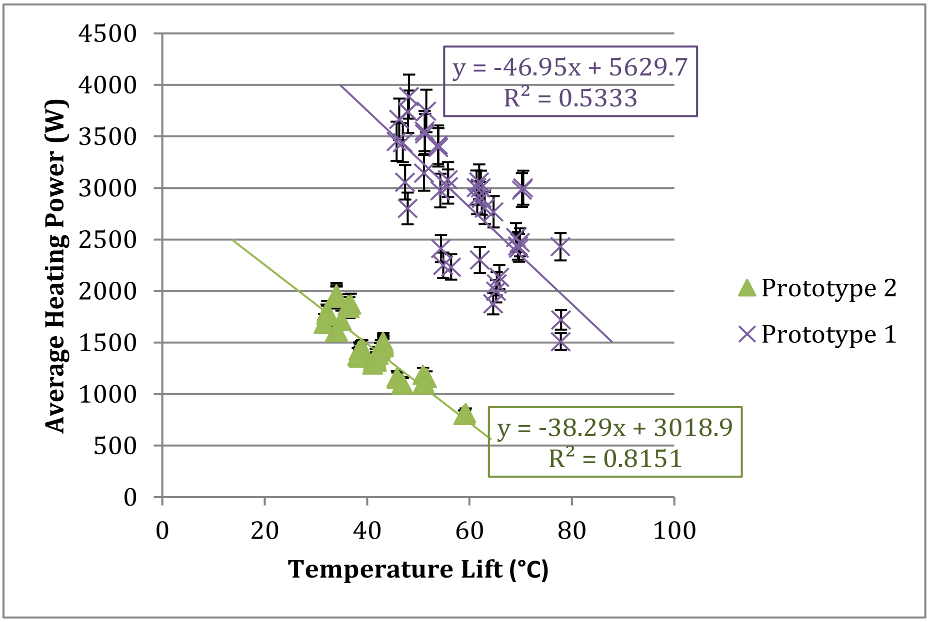


Figure 29: Heating power versus temperature lift for ASM (Prototype 1) and RM (Prototype 2) (Paper III).

Given that the sorption modules were intended for heat pumping applications (i.e. heating only) only the heating capacity of the modules was taken into consideration. During evaluations, the ASM performed reasonably stably throughout the range of temperature lifts tested though a relatively large spread of results was observed coupled to hysteresis/overshooting/undershooting of setpoint temperatures of the control system at higher heating/recooling powers. However, in the case of the RM, stable performance was only exhibited up to a temperature lift of 60°C. The instability at higher temperature lifts was due to the very low pressure difference between RA and RB as temperatures and thus pressures tended towards equilibrium conditions. Therefore, for the RM, all tests done at ΔT_{lift} greater than 60°C were not considered for performance analysis. COP_{ht} values for both prototypes were also determined as a function of temperature lift (see Table 11).

Table 11: Coefficient of performance of prototypes 1 and 2 with respect to temperature lift.

Temperature Lift (°C)	COP_{ht} Prototype 1	COP_{ht} Prototype 2
50	1.28	1.38
55	1.21	1.26
60	1.16	1.15
70	1.10	-

For comparison, at a temperature lift of 50 °C, the heating power of the ASM was 3.3 kW compared to 1.1 kW for RM at the same temperature lift. Therefore, ASM showed 3 times the heating capacity compared to RM at similar conditions. However, under the same conditions at ΔT_{lift} = 50°C, the COP_{ht} of the RM is almost 8% higher than the ASM. Increases in ΔT_{lift}, nevertheless reduced the COP of both prototypes though the ASM exhibited lower sensitivity to increasing temperature lift compared to the RM.

From the experimental evaluations it was surmised that the ASM would be a better option for GDSHPs that require high heat delivery temperatures at low ambient temperatures (i.e. high temperature lifts). While, in the case of the RM, in spite of the increased susceptibility of its heating power to higher temperature lifts, it shows higher COP compared to the ASM when operating at lower temperature lifts. This makes the RM an interesting candidate for GDSHPs which operate at lower temperature lifts (for instance, in warm climates or for floor heating only systems). However, given the significantly lower heating capacity of the RM, further analysis would be required to fully assess its applicability. Similar to the triple-state sorption modules (for solar applications), via the characterisation of the ASM and RM performance under the various temperature lift conditions, it is possible to use the equation of the trendline to calculate the expected heating power and COP.

5.5 Techno-economic Analysis of Sorption Integrated Solar Heating and Cooling Systems

In Paper IV thermal energy delivery of three solar-assisted heating and cooling systems types were simulated with the aforementioned energy balance method and compared with a simulated reference system. The simulated single-family house showed an overall annual thermal energy demand of 15.8 MWh where space heating accounted for approximately 55% of the total demand and space cooling and DHW accounting for 32% and 13% respectively (see Figure 30).

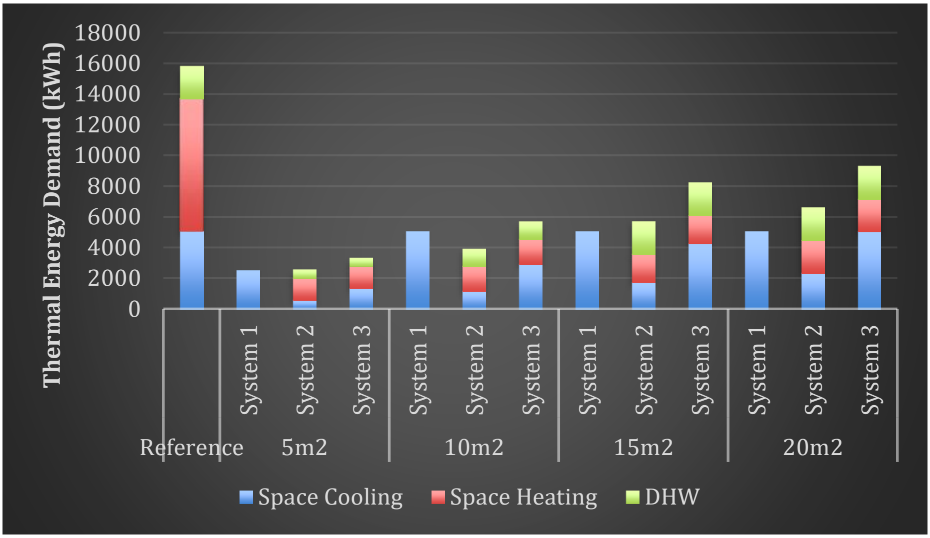


Figure 30: Annual thermal energy demand based on the reference system and total annual energy savings for each system type and size simulated.

The results of the simulations carried out showed that the solar PV only system (System 1) only displaces cooling energy demand by providing electricity to the vapour compression unit. The sorption collector integrated system (System 2) mainly offsets space heating and DHW demand in the smaller system sizes. However, the energy savings for each thermal energy demand sub-group is similar when simulated for the larger system sizes. The solar PV and sorption integrated collector hybrid system (System 3), provides a larger percentage of cooling energy savings than System 2.

Analysis of the performance of the solar PV only system in Paper IV shows that this system type would be more suited to applications where space cooling is the dominating thermal energy demand. The sorption collector integrated system (System 2) exhibits better suitability for situations where space heating and DHW demand is more significant compared to the space cooling requirements. This is due to the System 2's covering more of the heating demand (both space and DHW) than the cooling demand. The hybrid system (System 3) with its combined sorption integrated collector and PV design shows promise in applications where, on an annual basis, space cooling and heating demands (i.e. space heating and DHW) are in similar proportions.

Analyses carried out in Paper IV also looked into the solar fraction of the studied systems to ascertain the percentage of the thermal energy demand that can be covered by solar energy (Figure 31). Solar aperture areas of 5 m^2 yield 16% solar fraction for both Systems 1 and 2 however the proportion of each load type covered, i.e. space heating, DHW and space cooling are different for these two systems. System 3 exhibits a solar fraction of 21% at its smallest size iteration. System 1 has a maximum solar fraction of 32% which corresponds to total coverage of the cooling load. Combination of System 1 with a reversible heat pump is a possible option for increasing the solar fraction at larger system sizes. A solar fraction of 42% is the highest value from a 20 m^2 installation of System 2. System 3 with its hybrid sorption and PV technologies has the potential of displacing up to 64% of the thermal energy demand with solar energy.

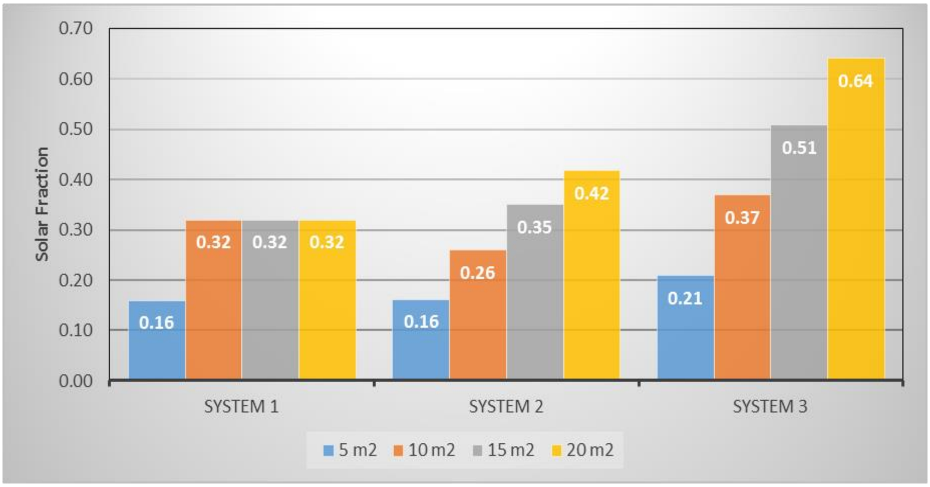


Figure 31: Solar fraction of simulated systems.

Annual energy cost saving calculations were carried out in Paper IV on the three system types at different systems sizes, as shown in Table 12. Costs were based on average electricity and natural gas prices for a typical household in Spain between 2010 and 2013.

Table 12: Annual energy cost savings

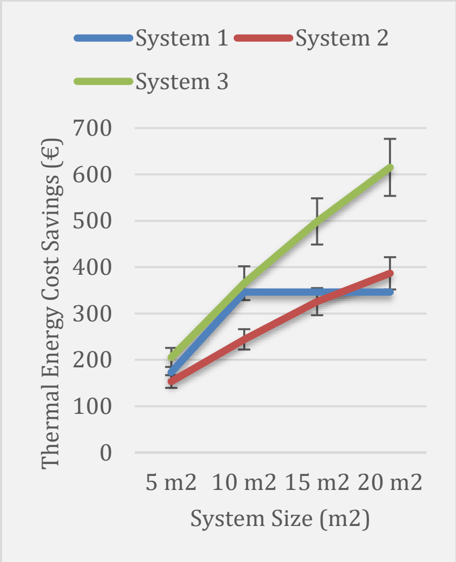
	System 1	System 2	System 3
5 m^2	€173	€153	€205
10 m^2	€346	€244	€365
15 m^2	€346	€325	€498
20 m^2	€346	€386	€615

Energy cost savings increase for each system, as expected, with increased system size as more solar energy can be harnessed to displace electricity and natural gas. Given the fact that the price of electricity is almost 4 times the price of natural gas per respective kWh the offset of conventional electricity by solar electricity has a bigger impact on cost savings than offsetting natural gas use. The saving potential of System 1 is however capped by the fact that in the study, electricity for cooling is the only thing that this solar PV system can displace. This is achieved by a system size of 10 m^2 and any larger system, though producing more electricity, is not considered to be savings in energy or costs for the cooling system. This excess energy could be harnessed for heating purposes if a (reversible) electric heat pump were employed to provide both heating and cooling. Alternatively, this electricity surplus could be used to supply other electrical loads not related to heating or cooling or sold to the grid. In simulations, it was seen that about 36% of the annual energy output of System 1 occurred outside of the cooling season. Therefore, for this grid-tied solar PV systems used in the simulations (System 1 and 3) grid interaction is an important part of the overall yearly energy balance and thus energy and cost savings. If a favourable net-metering or feed-in tariff is not available this would negatively impact the potential cost savings of System 1 and 3 (unless self-consumption for other loads is considered). The hybrid nature of System 3 allows for it to supplement both daytime and night-time cooling loads as well as space heating and DHW demonstrated by its superior cost saving potential.

For a 5 m^2 system Systems 1 and 2 have identical solar fractions yet monetary savings from System 1 are higher due to the more favourable cost savings from electricity versus saving natural gas.

5.5.1 Energy Price Sensitivity Analysis

The impact of electricity and gas prices on the energy saving potential of each system was also investigated in Paper IV. Figure 32 shows the effect of a 15% increase and a 15% decrease in electricity prices and natural gas prices on the annual energy cost savings.



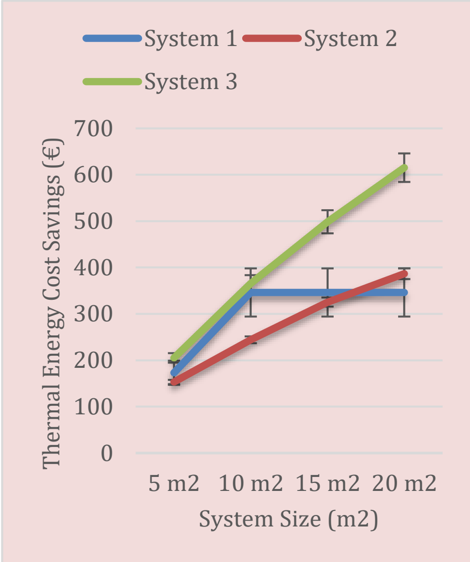


Figure 32: Energy cost savings based on the average and ±15% variation of natural gas (left) or electricity prices (right) according to system size (Paper IV).

System 1, as was expected, is not sensitive to gas prices, since it does not offset any of the heating demand. However, for Systems 2 and 3 there is significant sensitivity to gas prices especially for larger system sizes which have higher monetary saving potential. For a 20 m^2 System 3, an increase in gas prices by 15% leads to an increase of cost saving by 7% while for System 2 this increase is 11% for the same system size. Electricity prices directly impact the cost savings of System 1 by an expected ± 15% and has a significant impact on energy cost savings for System 3 especially at larger system sizes when PV electricity is at a higher proportion. However, System 2 is the least sensitive to electricity prices.

From the results of the study carried out in Paper IV it can thus be surmised that for maximum cost savings System I is more suited to applications with year-round cooling demand and high electricity prices. Additionally, if coupled with a reversible electric heat pump System 1 could provide additional monetary saving benefits by displacing some of the heat demand as well.

System 2 is most favourable in applications with high natural gas prices and with a substantial heating demand (since it offsets mostly heat (see Figure 30). Additionally, if it were possible to harness the abundant low-grade heat rejected to the ambient to carry out useful heating in a given application, then cost savings benefits for System 2 might be greatly increased.

System 3 takes the benefits of both Systems 1 and 2 melded into a single system. If an installation cost advantage can be had from this hybridisation, if the installation of the two technologies in a single collector were cheaper than installing both technologies separately. It might prove to be the most cost-effective solution for most applications due to its high energy and thus cost savings and broad range of thermal energy delivery possibilities (i.e. space heating, DHW & space cooling).

5.5.2 Considerations for Sorption Integrated Solar Heating and Cooling Systems

Based on the studies carried out, opportunities exist for further optimisation of the sorption integrated collector solar heating and cooling system. On the module level, this would be by optimisation of salt solution for more efficient desorption along with further studies into the better performing Module B. For the entire system, implementation of improved control strategies could increase thermal and electrical performance. On average, more than 50% of the thermal energy from the collectors is ejected as waste heat to the environment. Therefore, finding applications that can exploit even some of this otherwise wasted output could have a significant impact on overall economic viability of the sorption integrated collector solar heating and cooling system.

5.6 Techno-economic Analysis of Gas-Driven Sorption Heat Pumps

The performance and energy cost savings of GDSHPs operating in the moderate climate of New York City, New York as well the cold climate of Minneapolis, Minnesota were investigated in Paper V. The influence of the design capacity ratio on the seasonal performance of the system for the respective GDSHP types is shown in Figure 33.

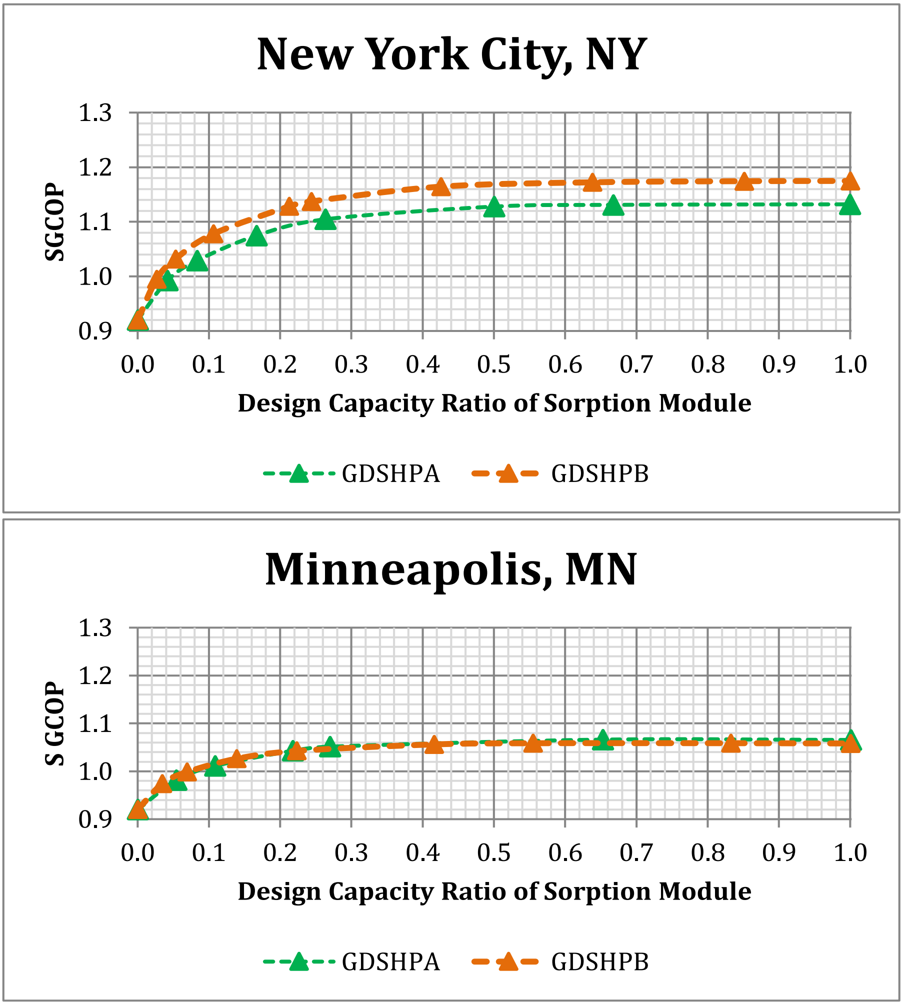


Figure 33: System SGCOP versus SM design heating capacity ratio for New York City and Minneapolis, MN.

Results from Paper V showed that the GDSHPB, the system which integrated with the resorption module (RM) exhibited higher SGCOP than GDSHPA in the New York City climate. This was attributed to the ammoniated salt module (ASM) integrated into the GDSHPA showing lower COP and thus lower GCOP compared to the RM in the New York City climate. However, in the case of Minneapolis, GDSHPA very narrowly outperforms GDSHPB at higher design capacity ratios. This was due to the fact that the

Minneapolis climate is characterised by a higher proportion of the heating demand occurring at low ambient temperatures. The GDSHPA's lower heat pumping cut-off temperature (i.e. the ambient temperature below which no heat pumping occurs) allows it to run as a heat pump at lower outdoor temperatures and thus with a higher GCOP. Another important result was the marginal increase of the SGCOP at design capacity ratios greater than 0.4 in the case of New York City and above 0.3 in the case of Minneapolis. This alludes to the fact that increasing sorption module capacity only provides incremental savings up to a certain level. Coupled to the assumption that a sorption module with a higher heating capacity will cost more than one with a lower heating capacity, an optimum sorption module capacity was found that maximised energy savings whilst minimising cost and thus payback time of the GDSHP appliance. Evaluations presented in Paper V found that the payback times at optimum SM design capacity ratios varied between 4.2 and 92 years for the New York City climate. In the case of Minneapolis, payback times were longer ranging between 9.2 years and 252 years.

For each scenario; low and high sorption module cost, system type and climate zone, an optimum sorption module design capacity was found, and the corresponding savings calculated compared a reference condensing boiler. Table 13 summarises these findings from Paper V.

Table 13: Optimum sorption module design capacity ratio for each climate.

Climate/ Location	System Type	Low SM Cost Scenario		High SM Cost Scenario	
		Optimum SM design capacity ratio	Energy Savings	Optimum SM design capacity ratio	Energy Savings
New York	GDSHPA	0.42	14.4%	0.26	11.8%
	GDSHPB	0.34	13.0%	0.24	11.1%
Minnesota	GDSHPA	0.41	8.1%	0.27	7.0%
	GDSHPB	0.32	5.1%	0.22	4.5%

Interestingly, for all scenarios the optimum design capacity of the SM was below 50% of the peak capacity of the GDSHP. It was observed that lower SM module costs shifted the optimum design capacity ratios to higher levels as it became more cost-effective to incorporate a larger capacity SM leading to greater savings. Energy savings for New York City were between 11.1% and 14.4% compared to a condensing boiler, while in the case of Minneapolis, savings ranged from 4.5% to 8.1%. The milder New York climate coupled with higher heating energy demand compared to Minneapolis meant that the SM module operates in heat pump mode for more hours of the year producing higher energy savings and thus energy cost savings. Studies in Paper V found that under the most favourable scenarios, i.e. GDSHPA, high energy prices and low SM cost, led to:

- In New York the GDSHPA with a SM design capacity ratio of 0.42 provided energy savings of 14.4%, corresponding to a yearly monetary saving of $215 and a payback time of 4.2 years compared to a standard condensing natural gas boiler. The SMA covered over the course of a year 86.6% of the space heating load.

- In Minnesota with a SM design capacity ratio of 0.41 the GDSHPA provided 8.1% energy savings over a standard condensing boiler. That provided yearly monetary saving of $92 and a payback time of 9.2 years whilst covering 74.1% of the space heating load (see Paper V).

5.6.1 Considerations for Gas-Driven Sorption Heat Pumps

In the studies carried out in Paper V the type of sorption module was found to have a significant impact on the achievable energy savings within a given climate. For colder climates a SM with a low cut-out temperature is required to maximise energy savings. For both climates analysed, the SMA proved to be the superior sorption module type due to its comparatively low cut-out temperature and lower cost, however, for warmer climates, SMB with its superior COPs at higher outdoor temperatures, might have an advantage. An additional consideration is the acceptable payback period for a given application. Considerations beyond cost might also be applicable, for instance, reduction of emissions or regulations on minimum renewable energy mix in the heating system (Paper V). Moderately higher SGCOP and thus energy savings would be achievable if slightly longer payback periods were allowed.

5.7 Testing and Modelling of Sorption Modules for Various Applications

Similar to the empirical evaluations carried out in Papers II and III, Paper VI evaluated the performance of the sorption module on the basis of heating, cooling and heat rejection powers and energies as well as efficiencies. It was observed that COP_{cl} varied between 0.09 and 0.39. Similar to findings from experimental evaluations reported in Papers II and III, the maximum cooling COP was found to be when the sorption module is charged to a state of charge between 0.6 and 0.8 (i.e. level of desorption between 60% and 80%). This can be explained by the fact that at the end of the charge cycle the flow of ammonia decreases rapidly (shown by a decrease in condensation power), therefore a relatively high amount of energy is required to remove a relatively small amount of ammonia left in the salt.

It was also noted that in this test method the heat transfer fluid is continuously heated by an external source before reaching the setpoint temperature. This led to a relatively long pre-charge phase of 31 minutes in the test before the reactor temperature was high enough to incite desorption of ammonia from the salt. The charge phase lasted 112 minutes followed by the pre-discharge phase, which was also relatively long, lasting for over 100 minutes. This was followed by a discharge of 45 minutes. The long pre-charge, charge and pre-discharge times were attributed to the relatively large volume (mass) of heat transfer fluid in the test rig setup compared to the size of the sorption module. This would need to be taken into consideration for future test rig and sorption module designs to reduce the time needed for experimental evaluations in the pursuit of increased time-effectiveness.

5.7.1 Artificial Neural Network Simulation Results

The principal goal of the ANN model described in Paper VI was to determine if it could adequately characterise the thermal behaviour of the sorption module based on experimental data. The performance of the model was evaluated by regression analysis comparing the output values predicted by the model and the measured values. The main performance indicators used for evaluation were relative error (ε) (i.e. percentage deviation of the simulated result from the measured result) and correlation coefficient (R^2). The number of neurons in the hidden layer was varied by trial and error, where 3 neurons were found to give both good correlation with a reasonable relative error (error $<\pm$ 10%) and good time-efficiency (simulation time $\leq$ 10 mins for all test sequences). The final model had the so-called 4-3-3 architecture, 4 input layer neurons, 3 hidden layer neurons and 3 output layer neurons.

In the case of ANN, given that the results of the simulation are dependent on the randomly generated initial weight coefficients associated with processing neurons, the simulations were run 10 times where the average errors and standard deviation were determined. The results from the ANN model runs yielded average relative errors for the reactor heat transfer rate of 3.7% and a standard deviation of 7.0%. In the case of the condenser/evaporator the error in the heat transfer rate is 4.2% with a standard deviation of 11.5% over the entire validation dataset. The results were also subdivided by operation mode (see Table 14). During the pre-charge and pre-discharge phases the prediction accuracy is reduced. This is evident both from the average error as well as the standard deviation. This suggests that more cycle data might be required for the training of the ANN to reduce the relative errors of the performance prediction of the condenser/evaporator, especially during pre-discharge operation.

Table 14: Relative errors and standard deviation for heat transfer rates to and from the reactor and condenser/evaporator heat exchangers of the sorption module.

Mode	Heat Transfer Rate Reactor		Heat Transfer Rate Condenser/Evaporator	
	Relative Error (%)	Standard Deviation (%)	Relative Error (%)	Standard Deviation (%)
Pre-Charge	3.4	2.8	3.6	12.4
Charge	3.7	5.6	0.4	0.5
Pre-Discharge	3.6	2.9	13.5	16.2
Discharge	4.2	3.6	0.3	0.2

From the 10 simulation runs of the ANN model, the model with the lowest average error and highest correlation coefficient was selected. The selected ANN model was able to determine both the COP_{cl} and COP_{ht} with reasonable accuracy showing an error of $<\pm$ 8%. It should also be noted that the model tends towards underestimating both COP_{cl} and COP_{ht}.

5.7.2 Model Limitations

The model employs a balanced approach that seeks sufficient accuracy whilst simultaneously reducing computational power and testing requirements. It avoids detailed calculations of thermochemical processes while allowing for the dynamic characteristics of the modular sorption components to be described. Though reasonably good results were achieved, various limitations of the ANN model were described in Paper VI. Since the model doesn't consider any reaction kinetics of the sorption module it would be limited by the range and accuracy of measurement data used for training the ANN and the specific configuration of the particular sorption module.

Additionally, the way the tests were carried out could be considered a limiting factor for the ANN since fully dynamic test sequences weren't included. The test sequences were mostly done for "steady state" inlet temperature conditions, which could limit model accuracy when predicting shorter time frame dynamics (i.e. quick variations in reactor and/or condenser/evaporator temperatures). Determination of test sequences that adequately cover expected (i.e. real) operating conditions, are required. This could also be a challenge when considering the diverse range of applications of the sorption module.

6 Discussion

Currently the need to shift from fossil to renewable energy is becoming all the more alarming. The 'holy grail' would be finding cost-effective ways to harness, convert, store and use renewable energy as well as augment the energy efficiency in the current energy system and energy using appliances. In this thesis the concept of sorption modules was presented; modular thermally driven heat pumps that can be designed to harness renewable energy to produce heating and cooling or to improve the efficiency with which fossil fuels are utilised.

Paper I introduces the method for choosing the best sorption cycle and sorption module configuration for a given application considering various working pairs, operating conditions and system configurations. Even though the focus of the studies were on the basic ammoniation and resorption cycles this method could be employed for any given sorption cycle, including absorption and adsorption cycles. The influence of the dead thermal mass ratio (DTMR) on performance on sorption cycles is studied in Paper I. This accounts for the thermal mass of the sorption materials as well as that of the main subcomponents of the sorption module; the reactor and condenser/evaporator. Both the sorption material selected, and the design of the sorption module are thus critical to characterising its performance under given operating conditions. Another critical aspect of the DTMR is the contribution of the heat transfer fluid (HTF) housed in the sorption system. In the resorption cycle configuration analysed in Paper I the HTF contributed to almost 50% of the dead thermal mass. This was corroborated in Paper VI where the high mass of HTF in the test rig produced long heat up and cooldown times of the sorption module. A high DTMR has a deleterious effect on the COP of the sorption system and must therefore be adequately accounted for when evaluating the expected performance of a given sorption cycle. It can also be noted from the studies carried out in Paper I that heat recovery from one phase of operation, that is, from desorption to absorption and vice versa can improve performance by up to 12%. This improvement should however be weighed against the potential increase in cost of the sorption system due to the integration of heat recovery. This is further compounded by studies carried out in Paper V where the best performing system (GDSHPB in New York) did not provide the best return on investment (i.e. lowest payback time).

Individual sorption module tests for the solar applications were described in Paper II. The sorption modules for solar applications were specifically designed for rather long cycle times with desorption phases upwards of 7 hours and absorption phases around 6 hours. They exhibited high energy delivery and low power characteristics, a staple of the triple-state absorption process. The modules were thus apt to their diurnal operation, where desorption occurs during the day, absorbing as much solar energy as possible and discharging the energy at night principally to produce space cooling. In Paper II empirical knowledge was gained on the influence of the temperature lift on both the power output of the sorption module as well as the COP. With higher temperature lifts causing reduction in both power output and COP of the sorption module similar to that expected from studies carried out in Paper I. The experimental evaluations from Paper II also highlighted an optimum desorption level for maximum COP that was around 70% desorption. This might suggest that to maximise sorption module performance full desorption should be avoided and the module should only be fully desorbed if waste heat is available or if its maximum thermochemical energy storage potential would like to be exploited. Similar optimum desorption levels (i.e. state of charge) were also found in experimental evaluations carried out in Paper VI.

Paper III built upon knowledge gained from studies carried out in Paper II, similar test methods and performance indicators were used to characterise the sorption modules. The studies saw a switch from the low power high energy density solar sorption module to a high-power variant employing ammoniated salts. The shift in application requirements from solar collector to gas heating appliance integration saw a shift in the sorption module design characteristics opting for a more compact heat exchanger design. The design of the sorption module for a gas-driven sorption heat pump (GDSHP) must take critical consideration of the DTMR given that the heat exchangers, reactor and condenser/evaporator vessels must be more robust to withstand higher pressures involved with having ammonia as a refrigerant. Additionally, the use of ammonia imposes various material compatibility considerations where copper and copper-based alloys and several other metals are not viable for use [97]. This sets more limitations on mitigating the DTMR compared to the solar sorption modules which utilise glass which has a thermal mass 50% lower than stainless steel [98]. Adding the relatively low energy density and short cycle times of the ammoniated salt working pairs compared to triple-state absorption pairs, the potential influence of the dead thermal mass is even higher. Paper III also highlighted the influence of temperature lift on the output power of the sorption module during the absorption phase but added another aspect showing the stark difference between the basic ammonation sorption module (ASM) and the resorption module (RM). The latter having markedly lower heating capacity compared to the ASM. The RM was also somewhat more sensitive to increases in temperature lift for both heating capacity and COP.

Paper III also touched on the applicability of the ASM vs the RM based on performance. At lower temperature lifts the RM outperforms the ASM in terms of heating COP. The ASM was however able to operate at temperature lifts up to 70°C whilst the RM operation was capped at 60°C. Therefore, for the GDSHP application, the design of the sorption module should also consider the expected location of installation. This is more critical than for the solar application where summertime production of cooling sees less variation in operating temperature lift.

Techno-economic analyses of the sorption integrated solar heating and cooling systems (SISHCS) were the highlight of the studies carried out in Paper IV. In Paper IV 3 hypothetical system types were compared: a solar photovoltaic cooling system, the SISHCS and a hybrid version incorporating both solar photovoltaic cooling and SISHCS. The method of calculation demonstrated the use of test data collected from empirical evaluations in Paper II to develop a basic simulation model for determining the performance of the sorption module under given climatic conditions. Although the model was limited to conditions under which the experiments were conducted, a quantification of the performance of the SISHCS was carried out and the optimum application of the SISHCS system was devised. The SISHCS being more suitable for application in high gas/heating cost and low electricity cost situations. Various key performance indicators were adapted for the characterisation of said systems where solar cooling COP provides a direct metric for how effectively the SISHCS can transform solar irradiation into useful cooling. One consideration for the further development of this metric is that it might be more relevant to use gross surface area as the metric for comparison rather than aperture area. This holds with conventions for solar thermal collectors [99] and would give a more relevant comparison to other solar-driven heating and cooling systems employing different types of solar collection devices. Paper IV also discussed the desire for finding use for the abundant low temperature heat rejected from the SISHCS to improve overall energy and thus cost savings. The electrical cooling COP is also of importance since it gives a direct comparison of the SISHCS with conventional electrically driven cooling apparatus. If the electrical cooling COP of a SISHCS is comparable to that of a traditional electrically-driven vapour compression chiller the competitiveness of the SISHCS could be questioned since its increased size and complexity would almost certainly make it more expensive than a conventional chiller.

Paper V built upon the method for techno-economic evaluation used in Paper IV but applied to GDSHPs. For the system concepts considered in the solar application, backup/auxiliary systems were considered to meet the heating and/or cooling demand under the conditions when the SISHCS could not. However, taking evaluations a step further in the case of the GDSHP, the sizing of the overall system comprising both the sorption as well as the auxiliary system was studied. This was a critical adaptation of the method based on the typical design and installation process of gas-driven heating systems also considering that the source from which the sorption module derives its driving heat, natural gas, is a high cost commodity. It could thus be argued that the consideration of the conditions of application for the sorption module is critical and that the key performance indicators as well as other industrial nuances such as installation expectations are to be closely considered. In Paper V various optimisation parameters were identified, namely, sorption module type, the sorption module size versus overall system capacity (i.e. design capacity ratio), the climate of the installation location, the heating load of the building and the cost of the sorption module. One of the key findings of Paper V was that the sorption module with the highest COP might not necessarily be the optimum sorption module when factoring in sorption module cost. It can thus be argued that when developing sorption modules, for a given application the energy cost savings must be weighed against the cost of the specific module type or configuration as well as the system complexity (as also alluded to in Paper I). Additionally, though only addressed implicitly in the analyses carried out, greenhouse gas emissions reductions might need to be evaluated more explicitly in determining system viability.

The final paper included in this thesis, Paper VI, built upon the knowledge and findings of all previous Papers I through V to develop a generic test, evaluation, modelling and simulation method that could encompass (most) potential applications of sorption modules. Paper VI described a flexible test installation for sorption module prototypes that would allow for automated cycling of the sorption module under varying conditions. The starting conditions based on so-called reference conditions, that is, the optimum conditions for the specific working pair and sorption module configuration under investigation. The other test conditions, denoted off-reference conditions, would then run the module through cycling paces varying the temperature lift, desorption level or state of charge and the driving temperature difference. In Papers II and III evaporator temperatures were limited to only 3 settings only 10°C apart. This is a limitation in the testing that has been considered in Paper VI. However, for any given application a detailed investigation of the expected operating conditions should be carried out to ensure testing ranges are representative. Additionally, previous experimental evaluations had not considered driving temperature differences which can have a large impact on cycle length and efficiency especially when the input energy source is variable in nature, e.g. in the case of solar energy. Paper VI also presented the use of an artificial neural network (ANN) which when trained with experimental data was able to characterise the performance of the sorption module predicting the performance of the module using input data from separate validation test cycles data. The testing and modelling approach devised in Paper VI was envisioned to streamline the process of developing and evaluating sorption modules for various applications.

The analytical model developed in Paper I only provides a snapshot of the performance of the module at a given temperature level and provides the foundation for selecting a working pair, sorption module configuration and considerations for the sorption module design. This would provide a first look at the potential performance of the sorption module when integrated into a certain application and allow for comparison with other technologies. In some cases, an early prototype might be required to better characterise the DTMR of a specific design and the practical performance of the sorption module. After adequate sorption module prototypes are developed, their dynamic performance characteristics could be experimentally evaluated as per description in Paper VI. With the implementation of the recommended improvements to the ANN model as discussed in Paper VI, especially the consideration for having a large number of continuously varying cycles for ANN training. Significant improvements, not only on the accuracy but also the time-effectiveness with which modelling, simulation and eventual techno-economic analysis of sorption modules could probably be made.

Based on the different testing and modelling approaches developed in Papers I through VI a general approach for sorption module integrated system development and evaluation is proposed (see Figure 34). The approach is broken down into three subsequent phases:

- ***Phase 1:*** The first phase of analyses would employ the analytical evaluation methods described in Paper I. It would see the selection of the heating and cooling application type considering the heat source used for driving the sorption process and the various operating conditions. The type of sorption cycle should also be considered as well as the working pair, that is, the salt and refrigerant to be used. With the aforementioned information and an understanding of the design operating conditions for the sorption integrated system, a preliminary sorption module design can be taken forth. The outcome from this phase would be an indication of the maximum energy saving potential of the sorption integrated system. This should be used to consider the viability of the system based on the desired energy saving or emissions reduction levels compared to a state-of-the-art system. If this is adequate, then Phase 2 evaluations should be carried out. Otherwise Phase 1 evaluations could be repeated considering a different sorption cycle and/or working pair selection.

- ***Phase 2:*** The second phase would entail more detailed analyses of operating conditions and identification of the key performance indicators and the design of the range of tests to be performed (similar to Papers II III & VI). Subsequent to the design and development of an adequate prototype empirical evaluation of said sorption module prototype should be carried out. The experimental data generated would then be used to train an ANN leading to the characterisation of the dynamic performance of the sorption module. Simulations could then be conducted to characterise the performance of the sorption integrated system. The more detailed dynamic performance characteristics of the system would give a more in-depth picture of the performance of the sorption integrated system which provides further indications of the viability of the system depending on the prescribed energy saving requirements and/or environmental benefits.

- ***Phase 3:*** The third and final phase, building on from Phase 2 would involve the identification of system level performance indicators and system level techno-economic optimisation (Papers IV & V). This would entail, for instance, the varying of system configuration, operation strategy and/or sizing to find the most cost-effective variant. This phase would thus culminate in a fully techno-economic evaluation of the sorption integrated system compared to the incumbent heating and cooling systems in the built environment.

The present thesis provides various methods for evaluation of sorption modules and their corresponding integration into heating and cooling systems. The main contribution of the thesis is to provide a streamlined approach through the conception, dimensioning and development of a sorption integrated heating and/or cooling system towards techno-economic analyses. These analyses are desired to understand both the technical as well as economic viability of sorption systems compared to state-of-the-art systems. This addresses the current need for further understanding and development of energy efficient, environmentally benign, and cost-effective space conditioning and water heating systems for the built environment.

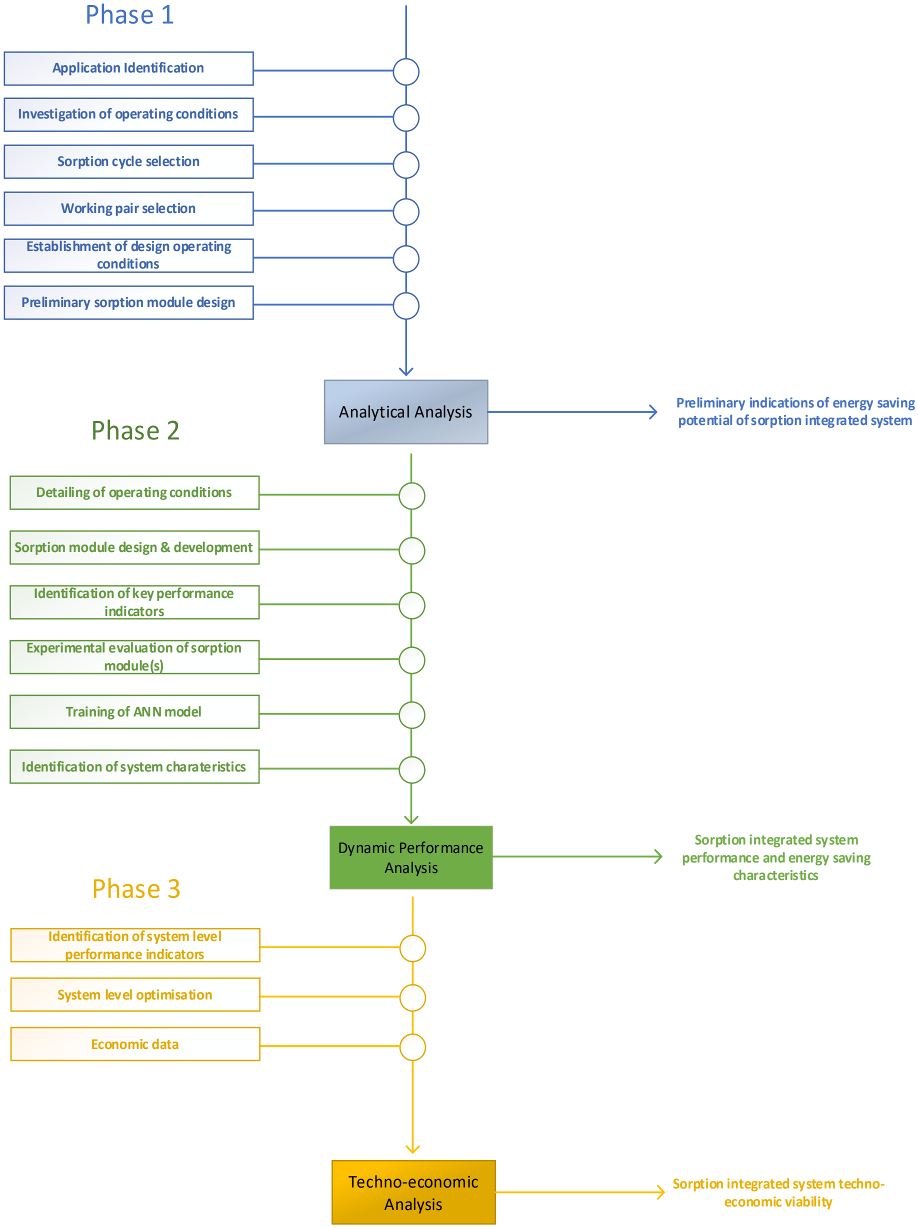


Figure 34: Schematic diagram of general sorption integrated system evaluation approach.

7 Conclusions

This thesis advances knowledge of sorption systems, summarising the methods, results and learning outcomes from studies carried out on modular sorption heat pumps. The studies considered that sorption modules can be designed and developed for various applications with two main applications being studied in depth: solar heating and cooling systems; and gas-driven heating systems. Sorption modules for solar thermal heating and cooling applications were integrated directly into thermal solar collectors, allowing for the development of modular pre-engineered solar heating and cooling system kits. Sorption modules for gas-driven heating applications could be integrated with condensing boilers where the design capacity of the sorption module could be tailored to the location to provide an optimum cost to performance ratio.

The investigations concluded that the most important primary performance indicators for any given sorption module should manifest the rate at which the sorption modules can deliver thermal energy as well as how much thermal energy can be delivered during a given mode of operation. That is, how much power and energy are delivered by the module. The number of sorption modules for a given application could therefore be readily calculated by simply dividing the total power and/or energy demand by that delivered by an individual sorption module. Correspondingly, how efficiently the sorption module can deliver this thermal energy, namely its coefficient of performance (COP), is key to determining the potential energy savings from any given sorption module (Research Question 1).

For solar applications solar cooling COP and electrical COP were of primary importance. For gas-driven sorption heat pumps (GDSHP), of principal importance are the design heating capacity, COP and the specifically devised gas coefficient of performance (GCOP) that encompasses the COP of the sorption module, the efficiency of the natural gas burner and the effectiveness of heat recovery from flue gases after combustion (RQ1).

The studies showed that the sorption modules could be evaluated in a time-effective and reliable fashion employing various evaluation methods. These methods included analytical, experimental and simulation techniques. Analytical evaluations can be employed to determine the maximum expected performance of the sorption modules under given operating conditions. In analytical evaluations, an optimal selection of the configuration and working pair of the sorption module for a given application can be carried out. Sorption modules can be configured based on the cycle of operation, namely, absorption, adsorption or chemisorption cycles. More specifically as it pertains to the studies carried out, the more novel subcategories of triple-state absorption process, basic ammoniation and resorption cycles were evaluated. Additionally, by analytical evaluation dead thermal mass ratio (DTMR) can be determined. A high DTMR has a deleterious effect on the COP of the sorption module and must therefore be adequately accounted for when evaluating the expected performance of a given sorption cycle. As shown by the experimental results from this thesis, the performance of the sorption modules can be characterised, and the results used to simulate the performance of sorption module integrated systems over a period of a year. This gives valuable insight into the annual performance metrics of the sorption modules without the need for running full system tests over extended periods (RQ2 & RQ4).

Based on the results from the experimental analyses it was shown that for the solar application studied, individual sorption modules with a reactor and combined condenser/evaporator were apt for this application. This sorption module, designed completely in glass, delivered cooling for 6 hours at a power of 40 W and temperature lift of 21°C. Several sorption modules were connected in series integrated into a solar collector, by varying the number of collectors a solar heating and cooling system of any capacity could thus be designed (RQ3 & RQ4).

In the case of sorption modules for integration as a gas-driven sorption heat pump two sorption module prototypes were evaluated. Prototype 1 was a basic ammoniated salt module while Prototype 2 was a resorption module. Test results showed that Prototype 2 produced 1105 W of heating capacity at a temperature lift of 50°C and Prototype 1 demonstrated higher heating capacity of 3280 W at the same temperature lift. In this application dimensioning of the system could be done by varying the size of the sorption module to develop systems of different capacities (RQ3 & RQ4).

The simulation studies carried out in this thesis showed that for a 20m^2 aperture area SISHCS installed on a typical single-family house in Madrid, Spain yearly energy savings up to 42% are to be expected with corresponding energy cost savings of €386 per annum. Additionally, in the case of GDSHP, the simulation studies highlighted the importance of sizing of a GDSHP for specific climatic conditions and heating demand. For a single-family dwelling in New York, USA an optimally sized GDSHP could provide energy savings between 11% and 14% compared to a condensing boiler. These figures were somewhat lower for a GDSHP installed in a single-family house in Minnesota, USA with energy cost savings ranging from 4% to 8% due to the colder climate which lowers heat pumping efficiency of the sorption modules (RQ4 & RQ5).

Based on the results from the techno-economic analyses, it can be concluded that various opportunities exist for the optimisation of sorption module integrated systems for both the solar and gas-driven heat pump applications. Optimisation parameters included sorption module configuration and size, backup/auxiliary system type and size, as well as sorption module and system costs. Considering the limitations of the initial studies carried out in this thesis work, for more in-depth analyses into the dynamic behaviour of the sorption module and for enhanced optimisation evaluations, a generic, application agnostic method for performance evaluation of sorption modules was thus described. With this more evolved evaluation method employing an artificial neural network (ANN), the performance of the sorption module could be characterised within a ± 8% margin of error. This ANN-based simulation model trained from experimental data method could thus also be applied in answering RQ3 and RQ4. The learning outcomes from this generic evaluation method could hence be used for future techno-economic evaluations where, based on the desired application, the potential energy and energy cost savings can be determined. If the sorption module cost is not well-known then hypothetically how much it is allowed to cost could be determined. The methods and evaluations developed in the present work can therefore be used to evaluate the potential of the use of sorption modules for various applications in the built environment (RQ2).

7.1 Future Work

Given the limited number of studies which cover the techno-economics of sorption integrated systems, future work should include further developments in this area. Research with focus on multi-objective optimisation of system performance, both thermal and electrical as well as system costs, are recommended. The studies in this doctoral thesis culminate in a first attempt at characterising the performance of a modular thermally driven heat pump using an ANN-based model. Correspondingly, energy and energy cost savings for sorption module integrated systems should be further explored. These evaluations should be based on the sorption module's dynamic performance characteristics over a wide range of experimentally evaluated operating conditions characterised by an adequate ANN model. It would be also desirable to evaluate the economic viability of a given sorption integrated system compared to state-of-the-art systems complemented by including environmental and energy policy considerations in the optimisation activities.

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Appendix

The equations used for calculation of the key performance indicators used in this work can be found below.

Summary of most important general sorption module performance indicators

Nomenclature	**Equations**
Cooling Power (Q_{chill} or Q_{cool})	$\dot{Q}_{\mathrm{chill}} = c_p \dot{m}(T_{cxi} - T_{cxo})$
Cooling Energy	$\mathrm{E}_{\mathrm{cool}} = \int_0^t \dot{\mathrm{Q}}_{\mathrm{chill}}$
Re-Cooling Power	$\dot{Q}_{re-cool} = c_p \dot{m}(T_{cxi} - T_{cxo})$
Re-Cooling Energy	$E_{re-cool} = \int_0^t \dot{Q}_{re-cool}$
Heating Power	$\dot{Q}_{heat} = c_p \dot{m}(T_{rxo} - T_{rxi})$
Heating Energy	$\mathrm{E}_{\mathrm{heat}} = \int_0^t \dot{\mathrm{Q}}_{\mathrm{heat}}$
(Process) Driving Power	$\dot{Q}_{drive} = c_p \dot{m}(T_{rxo} - T_{rxi})$
(Process) Driving Energy	$E_{drive} = \int_0^t \dot{Q}_{drive}$
Cooling Coefficient of Performance	$\mathrm{COP}_{\mathrm{cl}} = (\mathrm{E}_{\mathrm{cool}})/\mathrm{E}_{drive}$
Heating Coefficient of Performance	$\mathrm{COP}_{\mathrm{ht}} = (\mathrm{E}_{\mathrm{heat}} + \mathrm{E}_{\mathrm{re-cool}})/\mathrm{E}_{drive}$

Summary of most important performance indicators for sorption module integrated solar energy systems

Nomenclature	Equations
Solar Cooling COP (COP_{solar})	$COP_{solar} = \frac{E_{chill}}{IA_{abs}t}$
Heating Energy Density	$\text{Energy Density}_{\text{heat}} = \frac{\text{E}_{\text{heat}}}{\text{Physical Volume of Module}}$
Cooling Energy Density	$\text{Energy Density}_{\text{chill}} = \frac{\text{E}_{\text{chill}}}{\text{Physical Volume of Module}}$
Cooling Power Index	$Cooling\ Power\ Index = \frac{\dot{Q}_{chill}}{A}$
Cooling Energy Index	$\text{Cooling Energy Index} = \frac{\text{E}_{\text{cool}}}{\text{A}}$
Heating Energy for DHW	$\dot{Q}_{DHW} = c_p\dot{m}(T_{rxo} - T_{rxi})$
Thermal Energy Dissipated to the Environment (i.e. Re-Cooling Energy)	$E_{re-cool} = \int_0^t \dot{Q}_{re-cool}$
Electrical (Cooling) COP (COP_{el})	$COP_{el} = \frac{E_{cool}}{E_{el}}$
Energy Cost Savings	$Energy\ Cost\ Savings = Annual\ operating\ cost\ reference\ system - Annual\ operating\ cost\ SISHCS$
Solar Fraction	$Solar\ Fraction = \frac{Thermal\ energy\ delivered\ by\ SISHCS}{Total\ thermal\ energy\ load}$

Summary of most important performance indicators for sorption module integrated gas driven heat pump systems

Nomenclature	Equations
Specific Heating Capacity	$\text{Specific Capacity}_{\text{heat}} = \dot{Q}_{\text{heat}}/(\text{Physical Volume of Module})$
Peak Heating Capacity of System	$\dot{Q}_{peak} = \dot{Q}_{boiler} + \dot{Q}_{SM}$
Sorption Module Design Capacity Ratio	$Design\ capacity\ ratio\ of\ SM = \frac{design\ heating\ capacity\ of\ SM}{peak\ heating\ capacity\ of\ system}$
Gas Coefficient of Performance (GCOP) the combustion process.	$GCOP = \eta_{post\ burner} + \eta_{main\ burner} \times COP, if\ \Delta T_{lift,required} \leq \Delta T_{lift,max}\ ; else\ 0$

Seasonal Gas Coefficient of Performance (SGCOP)	$SGCOP = f\dot{Q}_{SM} * GCOP + f\dot{Q}_{boiler} * \eta_{boiler}$
Electricity Use	$Elec_{use} = \frac{\dot{Q}_{boiler}}{ECOP_{boiler}} + \frac{\dot{Q}_{SM}}{ECOP_{SM}}$
Energy Cost Savings	$Energy\ Cost\ Savings = Annual\ operating\ cost\ condensing\ boiler - Annual\ operating\ cost\ GDSHP$
(Simple) Payback Period	$Payback\ period = \frac{Total\ installed\ cost\ GDSHP - Total\ installed\ cost\ condensing\ boiler}{Annual\ operating\ cost\ condensing\ boiler - Annual\ operating\ cost\ GDSHP}$