REVIEW ON ABSORPTION TECHNOLOGY WITH EMPHASIS ON SMALL CAPACITY ABSORPTION MACHINES

by

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The aim of this paper is to review the past achievements in the field of absorption systems, their potential and possible directions for future development. Various types of absorption systems and research on working fluids are discussed in detail. Among various applications, solar assisted air-conditioning, and refrigeration and combined cooling heating and power are identified as two most promising applications for further development of absorption machines. Under the same framework, special attention is given to the small capacity absorption machines and their current status at the market. Although this technology looks promising, it is still in development and many issues are open. With respect to that fact, this paper covers all the relevant aspects for further development of small capacity absorption machines.

Key words: *absorption, chiller, small capacity, solar cooling, combined cooling heating and power*

Introduction

The roots of absorption technology can be traced to the mid of 17th century and the works of Dr. William Cullen and Nairne, as indicated in the comprehensive study of Burgett *et al.* [1]. The period between two World Wars was marked mostly by disclosures of two companies in the field of refrigeration: Electrolux in Sweden and Servel in the USA. The period after the Second World War is known as the *golden age of absorption*, especially in the USA where the HVAC industry was booming with respect to absorption machines. The use of LiBr-H_2O as working pair, new disclosures and fast development of large capacity single-effect absorption machines, first by Carrier (1945) and then by other leading HVAC companies (Trane, York, Worthington) contributed to the penetration of absorption technology on the US market. The sale of absorption machines reached their peak in 1969, with one quarter of the US market (1000 sold units). Primarily the oil crisis in 1973 as well as the development of higher efficient vapour compression equipment caused the sharp fall of interest for the absorption technology, leaving the share of annual sales in the USA on the sidelines. On the other side of the globe, Japan started its post-war recovery. Faced with shortage of its own natural energy resources and very expensive electricity produced from Middle East oil, Japanese government promoted natural gas as favoured fuel. Japanese companies Kawasaki, Mitsubishi, Ebara, Sanyo, Hitachi and Yazaki became aware of the possibility to improve efficiency of the absorption equipment by using high temperature energy sources. The era of double-effect, indirect fired absorption units

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have started in 1964, when Kawasaki released their unit to the market. Further improvements of double-effect absorption machines and gas oriented policies caused that large absorption machines surpassed the electric chillers in 1975 for the first time and a decade later, absorption chillers had more than 80% share of Japanese large capacity market. The role of Japan as world leader in this field had a positive impact on other countries in the Far East. Nowadays, India, China, and Korea have a very important role in the distribution of world market for absorption equipment. For example, 6917 absorption units of around 12000 released to the market in 2005 were manufactured in China [2]. Still, the share of absorption equipment in air-conditioning and refrigeration is far from the share of conventional vapour compression equipment.

In the last three decades, after Montreal and especially after Kyoto protocol, the interest in absorption equipment has become topical as a possible solution to the rising concern of protecting the ozone layer. Environmental friendly fluids, as well as possibility to use solar energy and waste heat make this equipment very interesting for further research and development. The technological progress, particularly the progress of solar collectors, has opened new horizons for absorption equipment. Also, the concern about the increasing cooling demand in residential and small size office applications has opened the interest for small capacity absorption machines. The initiative which began with the International Energy Agency (IEA) Task 25 [3] and continued with IEA Task 38 [4] has given the results and today we have few small capacity absorption units released to the market. However, lots of research efforts have to be done in order to make absorption equipment fully competitive with conventional compression equipment in terms of both efficiency and profitability.

Therefore, the main aim of this paper is to provide an overview which will help the reader to fully understand the absorption machines, their fundamental principles and applications. A state of the art of small capacity absorption machines is presented in the framework of the two most promising technologies: solar cooling and combined cooling heating and power (CCHP). Techno-economic aspects as well as the opportunities and obstacles for further development of small capacity absorption machines are covered with the relevant references from the scientific literature and illustrated with practical examples.

The basic principles of absorption cycle

The common approach to explain the absorption refrigeration cycle is by comparing it with the more familiar vapour compression cycle. The working principle of the absorption cycle is similar to that of the vapour compression cycle with two main differences. The first difference is that absorption cycle is heat-driven thermal cycle, where only thermal energy is exchanged with surroundings. No appreciable mechanical energy is exchanged (or conversion of heat to work) as in the case of mechanical compression cycle [5]. The second difference with respect to vapour compression cycle is existence of secondary fluid in addition to the refrigerant, known as liquid sorption medium or absorbent.

Accordingly, the basic idea of absorption cycle is to avoid compression work (W) by using the suitable working pair: a refrigerant and a solution which can absorb the refrigerant.

In the absorption cycle (fig. 1), the role of the mechanical compressor (MC) in compression cycle is replaced by “thermal compressor” which consists of generator (G), absorber (A), solution heat exchanger (SHX), solution pump (P) and throttling valve. Just like the vapour compression cycle, the absorption cycle operates under two pressure levels. High pressure level (refrigerant separation side) corresponds to the condenser-generator while low pressure level of absorption process in vacuum corresponds to evaporator-absorber. The high pressure level is approximately ten times higher than low pressure level in order to allow the heat rejection of the

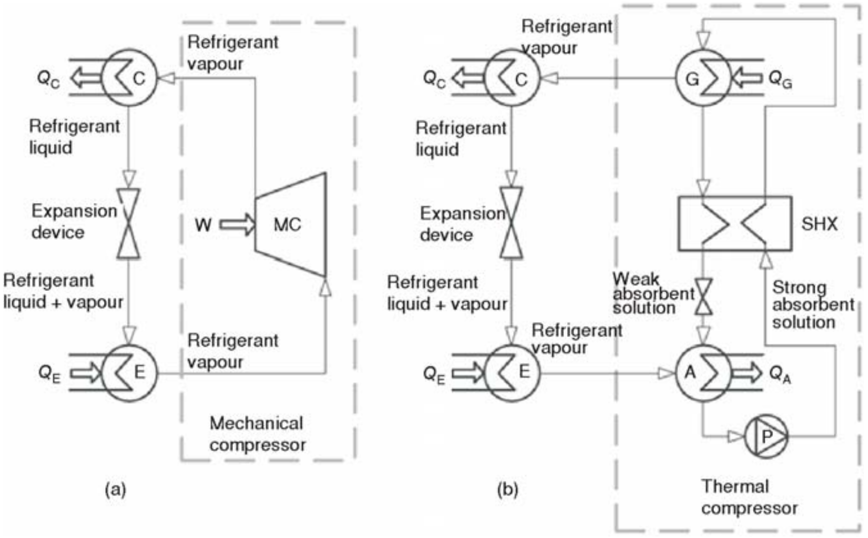

Figure 1. Compression (a) and absorption (b) refrigeration cycles

refrigerant at commonly available temperatures. The working principle is based on different boiling temperatures of the refrigerant and the absorbent. External heat input in the generator (Q_G) causes that refrigerant is boiled out of a solution and compressed to the refrigeration vapour at higher pressure while the concentrated absorbent stays liquid. The hot refrigerant vapour flows to the condenser where heat (Q_C) is removed by external heat sink, condensing the refrigerant vapour to liquid. The high-pressure liquid then passes through an expansion device reducing its pressure to the evaporator pressure level. External heat input (Q_E) causes a refrigerant to evaporate. The low pressure refrigerant vapour is then passed into the absorber where it condenses (Q_A) diluting the concentrated absorbent coming from the generator. The diluted solution (rich in refrigerant) is then pumped back to the generator where it evaporates again, closing the cycle. In other words, the "thermal" compressor of the absorption cycle uses a heat-driven concentration difference to move refrigerant vapour from the evaporator to the condenser.

Classification

The absorption machines can be classified based on several criteria: main function, firing method, number of effects and stages, condensing method, working fluids, application, and capacity.

With respect to the main function, absorption machines can be classified as: absorption chiller (to produce chilled water); absorption chiller/heater (to produce chilled and hot water); absorption heat pump (to produce hot water or steam by heat pump action), and absorption heat transformer (to produce heat on higher temperature level using the mid-temperature level).

With respect to the firing method, an absorption machine can be indirect fired or direct fired. Driving heat for indirect fired absorption machine is recovered from another process or heat cycle machine. This heat is normally delivered to the generator through an intermediate element (heat exchanger). The heat, in the form of steam, hot liquid or hot exhausted gases, is typically supplied by solar collectors, district heating network, boiler, gas turbine or by some other heat recovery device. Driving heat in direct fired absorption machines comes from combustion of fossil fuels. As a result, these systems normally contain a liquid fuel or natural gas burner.

In order to increase the efficiency, the basic absorption cycle which consists of four basic components (generator, absorber, evaporator, and condenser) can be extended with one or more components at different pressures or concentrations. With respect to the number and type of additional components, absorption machines can be categorized by the number of effects or by the number of stages. According to terminology adopted from Dorgan *et al.* [6] the term effect refers to the number of times the driving heat is used by the absorption equipment, or simplified, the number of generators determines the number of effects. In this way, we can distinguish between single-effect, double-effect or triple-effect systems. Similarly, multistage absorption systems (single-stage, double-stage or triple-stage) differ by the number of basic cycles that are combined; where the number of evaporator-absorber pairs at different temperatures in absorption machines determines the number of stages.

With respect to the employed condensation method (which fluid is used for heat dissipation in the absorber and condenser), absorption machines can be classified as: air-cooled or water-cooled. Another classification is by the type of working pair used in the absorption machine. The most common working pairs are water-lithium bromide (H_2O-LiBr) and ammonia-water (NH_3-H_2O) but there are also others which will be discussed in detail latter. Absorption machines can also be classified by working mode. The phases inside the absorption cycle can be processed continuously or shifted periodically; and therefore, we can distinguish between: continuous mode, semi-continuous mode, and discontinuous (batch) mode equipment. With respect to the application purpose and based on cooling temperature demand, absorption machines can be divided into three categories: space air-conditioning (7-18 ºC); food and pharmaceutical storage refrigeration (0-7 ºC), and freezing (<0 ºC) for ice-making or congelation. Finally, absorption equipment (particularly absorption chillers) can be ranged according to the produced cooling capacity: large-scale absorption chillers (cooling capacity higher than 300 kW); mid-scale absorption chillers (cooling capacity between 50 and 300 kW) and small-scale absorption chillers (up to 50 kW or according to some authors up to 30 kW).

Working fluids

The performance and efficiency of absorption systems is directly correlated with the chemical, thermo physical, and thermodynamic properties of the working fluid. A margin of miscibility in liquid phase within the operating temperature range of the absorption cycle is one of the fundamental requirements for suitable absorbent/refrigerant combination. The suitability of the absorbent/refrigerant pairs is determined by several necessary or desirable properties, which have been subject of various studies in the past. It is preferable that the latent heat of the refrigerant is high in order to minimize the circulation rate of the refrigerant and absorbent. Operating pressure of the refrigerant should be moderate while for the absorbent operating pressure is recommendable to be low. The refrigerant should have low freezing temperature and should be much more volatile than the absorbent in order to separate them easily. The refrigerant and absorbent should be chosen in a way to avoid solid phase over the expected range of composition and temperature, otherwise, inappropriate choice can cause operation shut down. Also, the chosen absorbent should have a strong affinity for the refrigerant. High chemical stability is required to avoid unwanted formation of gases, solids, or corrosive substances. Physical properties such as viscosity, surface tension, density, thermal conductivity, specific heat capacity, heat of mixing, and mass diffusivity should be favourable for suitable selection of the working pair. Thus, low viscosity increases heat and mass transfer and reduces pumping power. The low toxicity of the working pair is another important parameter in order to avoid negative impact on the environment. The care has to be taken with respect to corrosion and flammability, too. However, the desirable properties are sometimes mutually exclusive and it is very difficult (if not impossible) to find a working pair which fulfils all the requirements. More precisely, it is a matter of compromise.

Many working fluids have been considered for absorption systems. One of the most exhaustive studies which can be found in the literature is the review of absorption fluids provided by Macriss *et al.* [7] which discloses 40 refrigerant compounds and 200 absorption compounds available. Another exhaustive study is the report of IEA Heat Pump Centre with survey [8] which updates previous report with some additional mixtures. Nevertheless, the most common working fluids with practical application in absorption systems are H_2O-NH_3 and LiBr-H_2O. Recently, with new trends in absorption machines presented by Gluesenkamp *et al.* [9], the promising results have been found in experiments with ternary (LiBr, $LiNO_3$, and LiCl) and quaternary (LiBr, LiI, $LiNO_3$, and LiCl) salt mixtures. These mixtures were subject of investigation of several authors [10, 11]. A summary of the possible working pairs for absorption systems is shown in tab. 1. However, the great majority of commercial absorption equipment uses traditional working pairs such as H_2O-NH_3 or LiBr-H_2O [9]. The only “intruders” are H_2O-LiCl and NH_3-$LiNO_3$ mixture. The following sections discuss more closely the advantages and disadvantages of four working pairs.

Table 1. Summary of working pairs for absorption systems

Refrigerant	H_2O	NH_3	TFE (organic)	SO_2
Absorbent(s)	Salts Alkali halides LiBr $LiClO_3$ LiBr based multi-component salt mixtures (LiBr + single salt, LiBr + binary salt systems, LiBr + ternary salt system) $CaCl_2$ $ZnCl_2$ ZnBr Alkali nitrates Alkali thiocyanates Bases Alkali hydroxides Acids H_2SO_4 H_3PO_4	H_2O $LiNO_3$ $LiNO_3 + H_2O$ Alkali thiocyanates	NMP E181 DMF Pyrrolidone	Organic solvents

Water-lithium bromide (H_2O-LiBr)

One of the two most common working pairs is water-lithium bromide, which has been used in absorption equipment since 1950s. Lithium bromide is a salt and drying agent. The lithium ion (Li+) in the lithium bromide solution has a strong affinity to the water molecules, which is essential to produce absorption cooling effect. The advantages of this working pair include high safety, volatility ratio, affinity, stability, and latent heat. Water is the refrigerant, which evaporates at very low pressures producing the cooling effect. Since water freezes at below 0 °C, the minimum chilled water temperature in the absorption system with

H_2O-LiBr is around 5 °C. This is the reason why these systems are used for air-conditioning applications and cannot be used for low temperature refrigeration. These systems operate under high vacuum pressures. For the large-scale H_2O-LiBr systems, the vacuum pumps are necessary to maintain the vacuum inside the equipment and to eliminate unwanted gases. H_2O-LiBr mixture is miscible if the LiBr mass fraction is lower than 70%, approximately. Consequently, this determines the maximum limit for the absorption temperature. The LiBr crystallization occurs at moderate concentrations, which normally limits the pair where the absorber is water-cooled and the concentrations are lower. On the other hand, some recent systems can use air for heat dissipation. The phase boundaries are usually included on the working fluid diagrams to remind on the proximity of the crystallization risk. Normally, an internal control system is installed inside the absorption equipment to assure operation under predetermined range and to avoid crystallization. The lithium bromide solution is corrosive to some metals used for construction of absorption equipment (*i. e*. steel or copper). Corrosion inhibitors may be used to overcome this problem. These additives protect the metal parts and can improve heat and mass transfer performance.

Ammonia-water (NH_3-H_2O)

Ammonia-water working pair is one of the oldest working pairs, which has been in use since the 18th century. Ammonia as the refrigerant offers the opportunity to operate with evaporating temperatures below 0 ºC. Generally, ammonia-water is used for refrigeration applications in the range from 5 ºC down to –60 ºC. It can also be used for air-conditioning, but sometimes there are restrictions for use in building applications because of risks associated with the use of ammonia. The preferred heat source temperature for ammonia-water equipment is from 95 ºC to 180 ºC. The absorption systems with this working pair operate at moderate pressure and no vacuum is required till –30 ºC. The advantage of this working pair is that ammonia is completely soluble in water (at all concentrations), and therefore, there is no risk of crystallization. Another benefit is that dry coolers can be easily applied since the pressure in any part of the ammonia-water absorption system is higher than atmospheric pressure. The minimum pressure of the ammonia-water cycle is higher than 3 bar, and the pressure drop is not as critical as in the case of other conventional fluids. This also allows the use of plate heat exchanges with extended surfaces and high heat transfer coefficients which further assures compact design with reduced ammonia charge and increased safety of the absorption system. On the other hand, operation at high pressures (in particular the pressure of high temperature generator) is the main reason why there are no double-effect absorption systems with ammonia-water. Also, ammonia is both toxic and flammable. Another disadvantage of ammonia is incompatibility with materials such as copper or brass. For that reason, steel is normally used as the construction material for ammonia-water absorption equipment. Finally, small temperature difference between the boiling points of the refrigerant and the absorbent requires an additional device to obtain a high purity vapour of the refrigerant. This device called rectifier cools the vapour produced in the generator, demanding more supply heat. The consequence is lower coefficient of performance (COP).

Ammonia-lithium nitrate (NH_3-$LiNO_3$)

Ammonia-lithium nitrate as the alternative working fluid for absorption cycles have been studied in the past by several authors. Infante Fereira [12] collected and correlated the thermodynamic properties reported by various authors. Oronel *et al.* [13] reported the study in which ammonia/lithium nitrate has been proposed as a working pair for absorption refrigeration systems driven by low temperature heat sources. The authors pointed out the main advantages and disadvantages of the NH_3-$LiNO_3$ mixture compared with conventional working fluids. When compared with H_2O-LiBr mixture, the advantages of NH_3-$LiNO_3$ are:

- the absorption cycle does not operate under vacuum conditions (this permits less volume and not so heavy raw materials for absorption equipment),
- no risk of crystallization at the operation conditions of interest, and
- no required cooling tower (higher dissipation temperature than H_2O-LiBr).

The refrigeration cycle with NH_3-$LiNO_3$ can be operated at lower generator temperatures than with NH_3-H_2O and does not require rectification of the refrigerant vapour leaving the generator. On the other side, the main disadvantage of this mixture is high viscosity, which penalizes heat and mass transfer processes, especially in the absorber.

Until recently, this working pair was only studied at the laboratory level. However, cycle simplicity and a good potential for solar cooling applications have led to the construction of the first absorption chiller prototype with NH_3-$LiNO_3$. Thus, the first operating results of one air-cooled NH_3-$LiNO_3$ absorption chiller can be found in the study of Zamora *et al.* [14].

Water-lithium chloride (H_2O-LiCl)

The last working pair which can be found with practical application in absorption equipment is H_2O-LiCl. Although H_2O-LiCl is more common in desiccant technology, this working pair is used for a specific absorption cooling technology called triple-phase absorption technology. Term triple-phase indicates that this technology employs three states of matter during the process: liquid, gas (vapour), and solid state. It is important to mention that triple-phase absorption is chemically driven instead of thermally driven absorption we are used to. Crystallization, which might happen in liquid phase and can cause the problems during the operation of the absorption equipment, occurs at lower concentrations than in the case of LiBr. However, in the case of LiCl, crystallization can be beneficial. In the absorption equipment with this technology, charging is achieved by means of a chemical process where energy is stored by the drying of the LiCl. By using the LiCl, the absorption machine differs from other absorption chillers that use LiBr, a chemical that is less sensitive to the low temperatures. Same as H_2O-LiBr, H_2O-LiCl working pair operates under vacuum conditions and the activation temperature are lower than in the case of NH_3-H_2O. Also, one of the drawbacks of this working fluid is a relatively high cost.

Configurations

There are several possible configurations of the absorption cycle which can be found in absorption equipment already present at the market or, at least, in the form of tested prototype.

The simplest absorption cycle configuration is single-effect absorption chiller, already explained in the section *The basic principles of absorption cycle* and shown on the right side of fig. 1. The single-effect configurations are dominant absorption configurations with all the previously mentioned working fluids, however, majority of commercial units use H_2O-LiBr and NH_3-H_2O working pairs. The COP is around 0.7.

In the double-effect absorption chiller, the refrigerant is separated from the absorbent by two stage generation. This means that besides the basic components, which are the same as for the single-effect chiller, it includes an additional generator, solution heat exchanger and pump. In principle, this chiller operates between three pressure levels. The energy source for double-effect chiller has to be at much higher temperature level than for the single-effect chiller. This heat is supplied to the high generator where refrigerant starts to boil and leaves the absorbent solution. The hot refrigerant vapour of the high pressure generator enters to the high condenser where the heat released during the process of condensation is used to drive the low generator at intermediate pressure. In practice, high condenser and low generator are incorporated in one heat transfer device where one side of the heat exchanger is the high condenser and the other side is low generator. The refrigerant vapour then enters to the low condenser together with the liquid refrigerant condensed inside the tubes of the low generator. The refrigerant is then throttled before entering into the evaporator where the cooling effect is produced in the same way as in the case of single-effect chiller. The differences between the variations are mainly due to the preferences of absorption equipment manufacturers. The main benefit of the double-effect absorption chiller is higher efficiency obtained by using the input heat twice. The COP is around 1.2 and only H_2O-LiBr commercial units are available (ammonia-water requires much higher pressures).

The easiest way to explain triple-effect absorption chiller is as an extension of a double-effect absorption cycle which operates between four pressure levels. The triple-effect chiller has three generators and includes two internal heat processes (high condenser/mid generator and mid condenser/low generator). The refrigerant vapour from the high and mid generators is condensed and the heat is used to provide heat to the next lower generator. The refrigerant from all three condensers flows to the evaporator where the cooling effect occurs. The first H_2O-LiBr commercial unit has been developed and released to the market in 2005 with the COP of around 1.7 [15].

The half-effect absorption chiller is considered for use when working with lower activation temperatures, lower than the minimum necessary to activate single-effect chiller [16]. The difference with respect to the single-effect chiller is intermediate pressure level with two additional components: absorber and generator. At this level, the refrigerant vapour from low generator enters to the high absorber. The refrigerant is then transported to the high generator through upper solution circuit where it evaporates a second time and proceeds to the condenser. The penalization for operation at lower temperatures is lower COP; approximately twice lower than of the single-effect cycle. That is the main reason why the cycle has been named half-effect, despite it contains two generators and two absorbers.

In the generator absorber heat exchanger (GAX) cycle, the basic components are similar to the single-effect absorption cycle. The concentration in the absorber and generator are maintained in such a way that there is the possibility of temperature overlap between them. This gives the possibility for a heat recovery process by means of the internal transfer of the "overlapped" heat from the absorber to the generator. In this way, the external heat input required by the generator is reduced which has as a consequence efficiency enhancement visible in a higher COP. The GAX cycle can also be used for heating providing the significant energy savings on

Table 2. Summary of absorption cooling technology

Parameter/ Fluid	LiBr-H_2O				H_2O-NH_3		H_2O- LiCl	NH_3-$LiNO_3$
Effect	SE	DE	TE	HE	SE	GAX	SE	SE
Nominal cooling capacity [kW]	4.5->7000	17->20000	530-1400	10	12-1000	10-250	10-20	10
Thermal COP	0.6-0.75	1.1-1.3	1.4-1.7	0.3-0.35	0.5-0.7	0.7-0.9	0.6-0.7	0.6-0.7
Heat source temperature range [°C]	70-120	120-170	200-250	50-70 (60-110)	70-140	150-220	65-110	80-110

an annual basis. The $COP_{cooling}$ for GAX chiller is around 0.9, while the $COP_{heating}$ for GAX heat pump is around 1.8. GAX chillers and heat pumps are potentially an ideal complement to the micro turbines and fuel cells due to the high operating temperatures of the cycle.

Table 2 shows a summary of main parameters concerning different absorption cooling configurations existing at the market.

Applications and trends

Synergy of absorption technology with other technologies can be performed by using various applications. However, synergy with absorption does not guarantee that these applications will be efficient and able to compete with other technologies, in particular with conventional compression technology. The absorption becomes attractive in specific applications when there are possibilities to use waste heat or thermal energy from renewable energy sources. Some of specific applications when absorption technology can be beneficial are: when there is a large amount of thermal energy generated through solar collectors or waste energy usually discarded from industrial processes; in facilities that have simultaneous need for heat and power; in cases when electricity is unreliable, costly or when absorption can help to decrease peak loads; and in cases when governmental policies support the use of clean energy. The absorption technology is the most abundant in two types of applications: solar assisted systems for air-conditioning and refrigeration and polygeneration systems.

The use of solar energy is maybe one of the most prominent ways of harnessing natural resources to conserve the energy. The increasing cooling demand in both residential and tertiary sectors all over the world is visible at every step. The solar assisted systems for air-conditioning and refrigeration offer opportunities to meet this increasing cooling demand in a very efficient way. The heat from the solar radiation is used to drive a thermally-driven machine such as absorption chiller. The solar radiation is converted to the heat through the solar collectors. The continuous interest in the field of solar collectors together with recent advances have led that today there is a wide range of products for possible use in applications with absorption technology. Table 3 provides an insight into what type of solar collectors is suitable for chosen absorption technology [17, 18].

Table 3. Absorption chiller-solar collector matching

Chille type	Single-effect	Double-effect	Triple-effect
Heat source temperature [ºC]	90 (60-140)	130 (120-180)	220 (200-250)
Solar collector type	Flat-plate Evacuated tube	Evacuated tube Parabolic trough Linear Fresnel Compound parabolic Cylindrical trough	Parabolic trough Linear Fresnel Cylindrical trough

Polygeneration systems, and particularly combined cooling, heating and power systems are another alternative for solving energy-related problems and also another attractive application where absorption technology can be implemented to enhance the efficiency and productivity. Polygeneration usually refers to simultaneous production and delivery of more than one form of energy to the final user, from one or more primary energy sources such as several fossil fuels and renewable primary energy sources. Thus, term poly-generation stands for the combined production of electricity, heat, cold and products (fuels and chemicals), district heat-

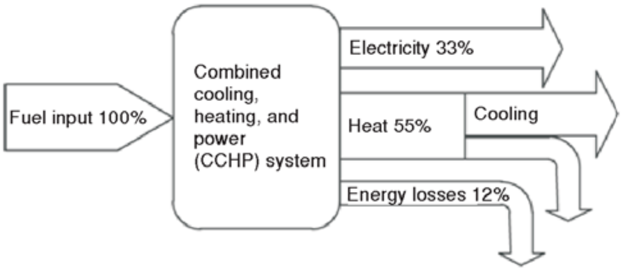

Figure 2. Energy flow of typical tri-generation system

ing and cooling systems or other advanced energy services and CO_2 capture. CCHP systems (known as tri-generation) are in fact derived from combined heat and power systems (also called co-generation) where exists simultaneous production of electrical and useful thermal energy from the same energy source. In tri-generation, the useful thermal energy is further used to provide cooling by coupling it with suitable thermally activated technology such as absorption chiller. The energy flow of typical tri-generation system with a theoretical calculation of prime energy calculation is shown in fig. 2. A review of Wu and Wang [19] explains in detail all the basic elements of tri-generation systems: the prime mover, electricity generator, heat recovery system, thermally driven equipment, and control system. Prime movers can be chosen between various options: steam turbines, combustion engines, combustion turbines, micro-turbines, reciprocating internal combustion engines, biomass power plants, fuel cells and Stirling engines. Among the thermally driven technologies which include absorption, adsorption and desiccant dehumidifiers, the absorption is by far the most exploited technology.

Within the polygeneration systems, solar assisted and co-generation technologies are in many cases complementary technologies combined with absorption machines. Industrial processes with waste heat are another application where absorption machines can be implemented efficiently both for cooling and heating. Absorption equipment has also found its place in district cooling and heating networks where it can be implemented in various ways. To avoid confusion, district cooling and heating networks can be considered as a part of polygeneration since they normally serve for energy distribution, but also can be observed as an individual concept which can be coupled with absorption technology. Very interesting conceptual solutions with absorption machines such as plant processing heating and boiler water heating, district heating with waste heat recovered from industrial processes or by utilizing hot underground water and well water used for greenhouse floriculture or for fish farm are suggested in [20]. Absorption technology can also be used for desalination as reported in one of the studies of Alarcon-Padilla *et al.* [21] on solar thermal desalination system in Almeria, Spain. The existing desalination system based on multi-effect desalination was connected to a double-effect absorption heat pump. The results of the study showed that 50% reduction of the required solar field area can be achieved in this way compared to solar multi-effect desalination. Hybrid systems with coupled compression-absorption refrigeration cycles are also among the actual applications. Hwang [22] presented the integrated refrigeration system with micro turbine and absorption chiller. The absorption chiller was used to subcool the refrigerant in a vapour compression system, enhancing the efficiency of the cycle and consequently reducing the required size of the micro turbine. Another example are hybrid refrigeration systems for mobile applications as one presented in the paper of Monsberger *et al.* [23] where the solid oxide fuel cell was used to power compression-absorption cycle for transport refrigeration. As it can be seen from the examples described above, the absorption technology is not only attractive for refrigeration, air-conditioning and freezing, but also can meet the demand for energy conservation and protection. There are many other applications, which are not described above, because they are still in development or not mature yet. Actually, a great number of the absorption applications are in the stage of demonstration and prototyping. With respect to the trends in absorption machines, research and development of new working fluids is inexhaustible subject of interest. The advantages of promising binary, ternary and quaternary salt mixtures are depicted and discussed thoroughly in section with working fluids. Lower efficiency and cost of absorption machine are still the flaming issue. That is the reason why a lot of research work is focused on enhancing the heat and mass transfer in order to improve the performance. Gluesenkamp *et al.* [9] pointed out the importance of inexpensive, compact components (compact heat exchangers primarily) for further efficiency improvement. The developments in solar energy collecting and transferring technology have produced the positive impact on absorption technology. Thus, the use of parabolic trough collectors and linear Fresnel collectors which can produce water at medium temperatures have opened the interest in the fields of power and cooling cycles [24] and multi-effect absorption equipment [25, 26]. In order to achieve higher efficiency, the hybrid and GAX cycles become very interesting, especially in the USA. The focus is more on system integration. How to integrate absorption machines in complex, polygeneration systems in the most efficient way. This further implies the interest in optimization and control strategies of the absorption machine and whole system. Ziegler [27] points out the importance of appropriate control strategies for whole absorption system with external pumps and fans in order to reduce their parasitic power consumption and increase overall efficiency of the system. Thermal storage for the (ab)sorption machine is another important issue since lots of objects in residential and tertiary sector needs cooling during the night. Phase change materials (PCM) and ice-storage are some of the interesting solutions [28]. Historical trend in absorption research, summarised by Gluesenkamp *et al.* [9], shows increased number of publications from 1996 till 2010 in all areas, with especially rising interest for absorption heat transformers. Finally, a lot of effort has been made lately in commercialization of a small scale absorption equipment and their integration with solar and micro-co-generation systems for residential and light-commercial applications [29-31]. In the development of small scale absorption equipment a special attention has been given to the development of air-cooled chillers. The following sections will highlight the relevant achievements in the field of small capacity absorption chillers.

Small capacity absorption machines – state-of-the-art

The development of small capacity absorption machines has been mostly connected to the research in the field of solar powered systems for air-conditioning. The milestone was the moment when the IEA started Task 25 “Solar assisted air conditioning of buildings”. Under this task, thermally driven chillers (mainly absorption chillers) have been identified as a very promising technology for solar assisted air conditioning in order to meet the increased demand for cooling in the residential sector. As one of the main objectives, the IEA has set the intensive R&D in the field of small capacity thermally driven chillers and preparation for market entry of these chillers. IEA Task 38 “Solar air-conditioning and refrigeration” and Annex 34 “Thermally driven heat pumps for heating and cooling” has continued the same trend. Several European projects such as SOLHEATCOOL, ASODECO, SACE, NEGST, ROCOCO, SAHC, CAMELIA, SolarCombi+, *etc.* have promoted and supported the development of the small capacity absorption chillers as a part of the IEA SHC initiative. Another important factor which has contributed to the development of small capacity absorption machines are micro CHP systems which has been identified as one of the possible solutions to reduce energy consumption and CO_2 emission by 20% until 2020. These small systems can help the operation of the local electricity distribution grid as well as to provide heating and hot water for small commercial buildings, apartments and individual houses. The heat from micro CHP systems can be used to drive small capacity thermally driven chillers opens new opportunities and market potential for small capacity absorption machines as has been identified in one of the deliverables of the POLYSMART project [32]. All these factors have contributed the rapid development of the small capacity absorption machines and, as a consequence, several units released to the market and remarkable number of research studies and prototypes has been reported.

Commercial units

Table 4 summarises the information on small capacity absorption machines released to the market which has been compiled from various papers [9, 33], reports [34, 35] and manufacturers' websites.

Table 4. Absorption machines released to the market (until 2012)

Manufacturer	Country	Type	Working pair	Nominal capacity [kW]	COP	Heat source [ºC]	Application	Coolant
AGO	Germany	Single effect	NH_3-H_2O	50	0.61	HW* (95)	R	Water
Broad	China	Double effect	H_2O-LiBr	16/23	1.2	GF PHW (160)	AC	Water
Cooltec5	USA	GAX	NH_3-H_2O	17.6/35	0.68	GF	AC	Air
Climatewell	Sweden	Single effect with storage	H_2O-LiCl	10	0.68	HW (110)	AC	Water
EAW Wergcall	Germany	Single effect	H_2O-LiBr	15/30	0.75	HW (90)	AC	Water
Pink (SolarNext)	Austria (Germany)	Single effect	NH_3-H_2O	10/12	0.63	HW (85)	AC/R	Water
Rinnai Osaka gas	Japan	Double effect	H_2O-LiBr	6.7	1.2	GF	AC	Water
Robur	Italy	Single effect	NH_3-H_2O	17.7 12.8	0.7 0.53	GF PHW	AC/R	Air
Rotartica	Spain	Single effect	H_2O-LiBr	4.5	0.67	HW (90)	AC	Water Air
Solarice	Germany	Single effect	NH_3-H_2O	25/40	0.6	HW (80)	R	Water
Sonnenklima (Phonix)	Germany	Single effect	H_2O-LiBr	10	0.78	HW (75)	AC	Water
Termax	India	Single effect	H_2O-LiBr	17.5/35	0.7	HW (90)	AC	Water
Yazaki	Japan	Single effect	H_2O-LiBr	17.6/35	0.7	HW (88)	AC	Water
Yazaki	Japan	Double effect	H_2O-LiBr/ LiCl/LiI	28	0.85	GF	AC	Air

* HW – hot water, GF – gas fired, PHW – pressurized hot water, R – refrigeration, AC – air-conditioning

Research and development, prototypes

Despite the increased interest in the last two decades and a number of commercialized units, the development of small capacity absorption machines has started much earlier. This fact is supported by a large number of scientific papers, research efforts and numerous prototypes developed worldwide. An overview of the scientific achievements is given to complete the image of the possibilities which small absorption machines can offer, but also to point out the deficiencies of the technology. With emphasis on use of renewable energy sources, this review covers all the relevant applications, disclosures and prototypes connected to the small absorption machines.

In the period from 1975-1984, the Carrier Corporation made lots of efforts on research and development of solar powered absorption chillers which can dissipate directly to air [34, 36]. As a result of this research, a prototype of air-cooled, single-effect absorption chiller with cooling capacity of around 35 kW was developed. Sun powered with H_2O-LiBr working pair, the prototype could achieve a COP of 0.71. Unfortunately, this prototype has never entered into serial production. The double-effect air-cooled absorption machine with a compact body and suitably small installation area is described in the patent of Kurosawa *et al.* [37]. The disclosure was based on the 15 kW prototype which used H_2O-LiBr working pair. The COP of this double-effect absorption chiller was 0.93. Gas Research Institute from Chicago was also involved in research with small capacity air-cooled machines. The result of the research was direct-fired double-effect absorption machine [38]. A 10 kW prototype used H_2O-LiBr working pair could operate both as chiller and as a heat pump. This air-cooled absorption machine had a COP around 0.95 in cooling mode and was intended for small residential applications. The Yazaki Company was also working on development of small air-cooled absorption chiller/heater [39]. The reported COP of the 4.5 kW double-effect absorption chiller prototype was 0.8 and it was working with their newly developed LiBr-LiCl-LiI solution [40]. This solution, also called Carroll mixture, offers a safer operation of the absorption chiller due to sufficiently low crystallization temperature. Another absorption product from Yazaki can be found in the experimental study of Li and Sumathy [41] on solar air-conditioning system with storage tank. The absorption chiller used in system is Yazaki WFC-400S with nominal capacity of 4.7 kW. The chiller has a generator inlet temperature range of 75-100 ºC and a cooling water temperature range of 24-31 ºC. It is based on single-effect cycle which uses H_2O-LiBr working pair, but with one difference. This chiller belongs to the group of the self-circulate absorption refrigeration systems or, more precisely, to the systems which use hot-air-bubble pump principle. The difference of these systems with respect to the classical absorption system is that they do not require any electricity to drive a circulation pump. With water as a refrigerant, the difference between pressure levels of the condenser and the evaporator becomes very low and can be maintained by using the principle of hydrostatic-head. The bubble pump circulates the solution strong in refrigerant from the absorber to the generator while the gravitation force enables the return of the solution weak in refrigerant back to the absorber. Also, it is worth to mention that Yazaki is one of the first who started the mass production of small capacity absorption chillers for air-conditioning applications. In 1970, Yazaki launched first "Aroace" absorption chiller/heater series with CH-1000 (12.25 kW capacity) and CH-1500 (17.5kW) models. In 1978, the company started with production of models WFC-400 and WFC-600 (7 kW), water fired chillers which use bubble pump principle [42]. These models are not available at the market any more. At the Gazi University in Turkey, Sozen *et al.* [43] developed a prototype of an NH_3-H_2O absorption heat pump. This absorption system was designed to operate with a parabolic solar collector, having an optimum performance at generator inlet temperature of 90 ºC. Typical COP values for cooling mode were in the range of 0.58-0.8 and in the range of 1.5-1.8 for heating mode. Due to the minimum evaporator temperature of 3 ºC, the authors recommended the use of the system both for food preservation and for air-conditioning. Also, authors recommended the modification of the evaporator and absorber in order to decrease high exergy loss of the heat pump. An experimental prototype of 10 kW single-effect H_2O-LiBr absorption heat pump was developed and evaluated by Argiriou *et al.* [44]. A 10 kW prototype, suitable for residential and small building applications, was connected to a cooling tower and driven by solar heat at low driving temperatures through solar collectors. The maximum obtained COP was 0.74. The comparison with a conventional cooling installation using a compression type heat pump showed that this type of system could achieve 20-27% of energy savings. The University of Applied Sciences in Stuttgart, Germany, developed several prototypes of solar heat driven ammonia-water diffusion absorption cooling machine for air-conditioning applications [45]. A diffusion absorption cooling machine also belongs to self-circulate absorption systems. Since now ammonia was the refrigerant, a bubble-pump was not sufficient to overcome differential pressure between the condenser and the evaporator. The solution was to charge an auxiliary gas to the evaporator and absorber in order to keep the partial pressure of ammonia low enough to correspond with the required temperatures inside the evaporator. In this way, the pressure difference of the system was decreased which further enabled the utilization of the bubble-pump. The designed cooling capacity of the diffusion absorption cooling machine was 2.5 kW and Helium was used to keep the pressure equilibrium. The best results were obtained with the third prototype when the initially chosen plate heat exchangers were replaced by coaxial solution heat exchangers. In the operating range of the generator inlet temperature from 100 to 150 ºC, the experimental results of the prototype showed cooling capacities from 0.7 kW up to 3.0 kW with maximum reached COP of 0.38. Another ammonia-water absorption chiller prototype was also developed in Germany, at the ITW, Stuttgart, Germany, [46]. The designed cooling capacity of this single-effect absorption chiller is 10 kW and it is powered directly with the hot water from the solar collectors, without any thermal storage tank in between. The solution circulation to the required high pressure level is achieved by a membrane pump. According to the experiments reported by Zetzsche *et al.* [46] the cooling capacity was in the range of 5.4-10.7 kW and the COP in the range 0.58-0.74. Around the same time, the Technical University Graz in Austria built another prototype of an ammonia-water absorption heat pump with 5 kW cooling capacity [47]. The prototype was indirectly driven through a heat medium circuit which can use any type of renewable energy. Although mainly designed for solar air-conditioning, the operating temperature range of cold water (form –10 to 20 ºC) makes it suitable for refrigeration as well. The reported COP for cooling mode was in the range of 0.4-0.75. At the University Politecnica de Cataluna, Castro *et al.* [48] developed and tested the prototype of an air-cooled absorption chiller of about 2 kW cooling capacity using H_2O-LiBr working fluid. The prototype has a mechanical solution pump, horizontal-tube falling film generator, an evaporator and the air-cooled absorber and condenser consisted of vertical finned tube batteries. The maximum obtained COP of the chiller was 0.65 with the electrical consumption of the fan of approximately 250 W. In a period from 2001 to 2002, the German Aerospace Centre (DLR) developed the prototype of a double-effect H_2O-LiBr absorption chiller driven by parabolic solar collectors. For the generator inlet temperature range of 150-180 ºC the COP was in the range of 1.2-1.4. An air-cooled GAX prototype powered by natural gas and solar energy was developed in Mexico, at the University Autonoma de Baja California. The prototype with a cooling capacity of 10.6 kW could achieve COP of 0.86 [49]. Kim and Infante Ferreira [50] were investigating the development of half-effect parallel-flow absorption chiller for solar air-conditioning in hot weathers. Based on the theoretical design, a prototype of an air-cooled H_2O-LiBr absorption chiller with the purpose to be combined with low-cost flat solar collectors was constructed at Delft University of Technology, the Netherlands. After performing the experiments, during which the heat rejection temperature was varied in the range of 30-50 ºC and the generator inlet temperature in the range of 67-108 ºC, the maximum reached COP was 0.35 [16]. Another market ready prototype of ammonia-water chiller was developed by Austrian company SolarFrost [51]. Actually, it is diffusion absorption cooling machine with cooling capacity of 2 kW, and COP in the range of 0.6-0.7. A steam driven solution pump was developed for that purpose. It is based on the principle that hot ammonia solution has a high steam pressure while cold ammonia solution absorbs ammonia gas. The company developed two versions, one with plate heat exchangers and the second with tube heat exchangers. In Portugal, under the framework of the EU project Polysmart, the institute INETI together with the company AoSol developed another prototype of an air-cooled ammonia-water absorption chiller. This single-effect absorption chiller had a cooling capacity between 5 and 6 kW and could achieve COP of approximately 0.65. One of the most recent disclosures was the newly developed ammonia-lithium nitrate mixture patented by Bourouis *et al.* [52]. Using the patented solution, several single-effect prototypes were recently developed at Rovira i Virgili University in Spain [14]. First developed prototype was water-cooled, with designed cooling capacity of 10 kW. Experimental results showed that for generator inlet temperature and chilled water temperature of 90 ºC and 15 ºC, respectively, chiller can produce 11.5 kW of cooling. The maximum obtained COP was 0.69. The second developed prototype was air-cooled, which could obtain slightly lower capacity of 9.1 kW and COP of around 0.64.

The use of absorption technology in the low temperature applications like food and medicament storage or ice-making is also possible. Small capacity absorption machine with refrigeration purpose were subject of interest for many researchers. The absorption technologies become very attractive for refrigeration purpose in remote or rural areas where the electricity is unavailable. This fact is supported by numerous research studies and developed prototypes [53-56].

In addition, the example of small capacity absorption machine which operates as absorption heat transformer can be found in the work of Abrahamsson *et al.* [57]. The authors designed and tested a 10 kW absorption heat transformer unit based on self-circulation principle and using NaOH-water working pair. Viewed from the perspective of the absorption components, very interesting research studies were conducted by Bourouis *et al.* [58] and Lorton *et al.* [59]. Bourouis *et al.* [58] investigated the possibility of using multi component salt solutions in the air-cooled absorbers. The conclusion was that these solutions have the advantage over the conventional H_2O-LiBr working pair due to the higher solubility at higher salt concentrations and, in accordance with that, these solutions are very suitable for the air-cooled absorbers. Lorton *et al.* [59] presented the prototype of the double-effect absorption machine based on rotational technology which intensifies heat and mass transfer inside the components. More in depth information about recent developments in absorption cooling as well as more exhaustive R&D analysis can be found in review articles [60-62].

Installations

The progress in the field of small-scale absorption machines is also visible by the number of installed units in the solar cooling systems around the world. One of the surveys under the IEA Task 38 [63] showed that the number of the solar cooling systems has been multiplied by factor 6 in a period from 2004 to 2009, according to documented installations (fig. 3). The esti-

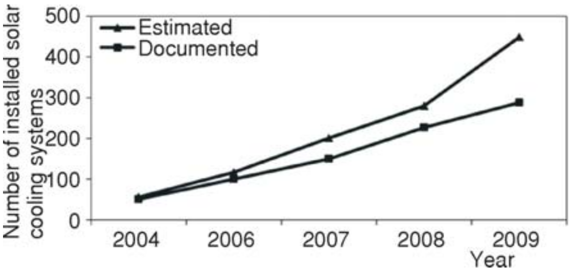

Figure 3. Number of installed solar cooling systems in the period 2004-2009 [63]

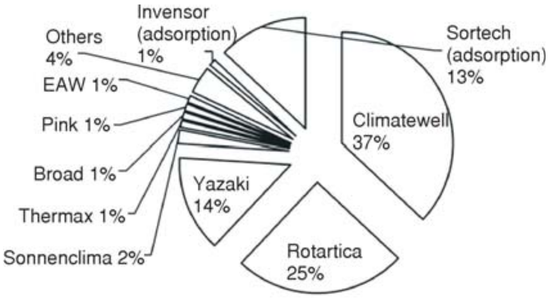

Figure 4. The share of installed small capacity absorption chillers [64]

mate is that this factor is higher and close to 9. The growth was more than evident during the 2009 when the number of installed systems increased by 100.

This trend is based on the list of existing solar heating and cooling installations made by Sparber *et al.* [64]. Among the 288 collected systems, 223 systems belong to the small-scale systems with cooling capacity less than 50 kW. Within the small-scale systems, the number of installed absorption unit is 198 (89%) while the rest are adsorption (8%), and desiccant units (3%).

It is almost certain that larger number of these systems exists, however, they are not documented. Market analysis illustrated in fig. 4 shows that the among the installed absorption units the largest share has Climatewell with 37%, followed by Rotartica with 25%, Yazaki with 14%, Sonnenklima with 2%, *etc*.

With a market size of 50 million potential installations, micro-co-generation technology gives another opportunity for development of small-scale absorption machines. Despite this large potential, micro tri-generation systems are still under development. The number of micro tri-generation systems with absorption units is very small and mostly limited on experimental set ups. Thus, several demonstration systems were built to investigate the tri-generation potential under the framework of PolySMART project [32]. One of these demo systems was located in a recreation centre in Madrid. Mini-CHP unit DACHS which provides 5.5 kW of electricity and 12.5 kW of heat is coupled with Climatewell absorption chiller to produce 10 kW of cooling. The same system was installed in the Technological Park Boecillo, Valladolid, with only difference that absorption chiller was working with 7 kW cooling capacity. In Vitoria-Gasteiz, 5.5 kW_e Senertec DACHS and 4.5 kW Rotartica were used to supply laboratory hall with heating, cooling and electricity. Joaneum Research from Austria used 3 kW_e Stirling engine and Pink absorption chiller for winery process application. In Portugal, two AoSol prototypes of 8 kW cooling capacity were used in micro-trigeneration systems in office buildings in Lisboa and in Samora Correira. The first prototype was driven by heat from biodiesel engine while the second was driven by mini-CHP unit. For the purpose of air-conditioning a laboratory hall in Milan, 17.8 kW Robur unit and desiccant system were powered by 52 kW_e Avesco CHP unit. In Germany, one Sonnenklima chiller with 10 kW capacity was installed in Diessen as a part of show room while the second chiller was installed in a computer centre in Berlin. The first chiller was connected to mini-CHP unit and the second to district heating network [65]. Small capacity tri-generation application has been installed in Central Forum building of Districlima Association in Barcelona as a part of EU project Hegel. The exhaust gasses of 28 kW_e micro gas turbine (MGT) were used to drive an air-cooled absorption chiller (Robur). Southern California Gas has built another micro tri-generation system with 30 kW$_e$ gas MGT and 35 kW absorption chiller in Downey, USA. More powerful, 115 kW$_e$ MGT was installed in tri-generation system to drive 35 kW absorption chiller (Yazaki WFC 10) in Graz-Thondorf, Austria [66]. In order to evaluate the performance of tri-generation system for supermarket applications, an experimental set up was built at Brunel University, UK [31]. The system designed to satisfy concurrent need for electricity, heating and cooling consisted of 80 kW$_e$ recuperated micro turbine generation package and ammonia-water absorption chiller with 12 kW cooling capacity (Robur ACF-60LB). Khatri *et al.* [67] investigated the feasibility of using micro tri-generation systems for small village houses in India. For that purpose, they designed and constructed a set-up which is based on the internal combustion engine of 3.7 kW typically used in agricultural sector of India. The refrigeration effect was achieved through an NH_3-H_2O vapour absorption refrigerator (Electrolux). Finally, 16 kW double-effect absorption chiller provided by Broad was installed in test facilities of Carnegie Mellon University [68]. A micro co-generation system which provides driving heat for this chiller was designed with the main purpose to study the technical feasibility of using co-generation systems at micro-scale level in buildings.

Technology cost

The cost of an absorption installation is directly dependant on the design of whole system and on choice of technology. Since the solar cooling and micro-CCHP have proved to be the most promising technologies for small capacity absorption machines, the economic aspects have been analysed with respect to these two technologies. One of the main task of ROCOCO project [69] was to identify the main costs in solar cooling systems and to reduce them. The investment cost distribution was assessed based on different case studies for both small-scale and large-scale installations. The average cost distribution in the case of small-scale solar cooling systems showed that 35% goes for pumps, fans, storage tanks and other type of auxiliary equipment; absorption chiller can contribute up to 30% of total cost; solar collectors make 20%; control system around 10% and 5% are other costs. An example of a small-scale installation can be found in the same report. The installation was located in Italy, with 20 m^2 solar collector field and air-cooled absorption chiller. The cost and the share for each part of solar system are shown in tab. 5. Significant savings have been achieved by avoiding storage tanks, cooling towers and back-up system.

Table 5. Investment costs of two small solar systems

Item	Price [€] (Share [%])	
	Small solar system in Italy [69]	Small solar system in the USA [70]
Auxiliary equipment	5.573 (19)	20.510 (20)
Solar collector	10.258 (35)	28.000 (28)
Chiller	9.535 (32) – Rotartica 4.5 kW	14.000 (14) – Yazaki 35 kW
Control, valves, piping	4.050 (14)	38.500 (38)

A small-scale solar system with slightly higher cooling capacity and different design can be found in the paper of Dickinson *et al.* [70]. Solar collector having 72 m^2 array and 35 kW cooling capacity absorption chiller were installed in a government building in Phoenix, USA. The investment cost of this system is also presented in tab. 5. A comparison with previously described system in Italy shows that different design with auxiliary equipment such as cooling tower and storage tank significantly increase the investment cost. On the other hand, if we compared the cost of these two systems per kW of produced cooling capacity, the US installation with 2886 €/kW$_c$ seems to be twice cheaper compared to 6537 €/kW$_c$ of the Italian installation. Also, approximately 30% should be added to the total sum for installation and mark-up. Finally, annual costs for maintenance, electricity and water consumption must also be taken into consideration.

In order to decrease high investment cost, some companies have started the production of small pre-fabricated solar cooling systems called solar cooling kits. Solar cooling kit usually include: solar collectors, hot and cold storage, thermally driven chiller, cooler and system control. The cost of these kits in Europe is around 4000-4500 €/kW with the expectation to fall to 3000 €/kW in 2012 [63].

The cost of solar collectors and storage could be lowered by 10% in the next 2-3 years while the cost reduction potential for (ab)sorption chillers is around 20% with new components, with possibility to increase up to 50% if serial production starts.

Sugiartha *et al.* [71] and Worek *et al.* [72] analysed the cost of micro tri-generation technology. Sugiartha *et al.* [71] analysed the MGT of 80 kW$_e$ coupled with 12 kW$_c$ absorption chiller in their evaluation study of micro tri-generation system for supermarket applications in the UK. The installed cost of the MGT was £1009 per kW of produced electricity with the operation and maintenance cost estimated to 0.0051 £/kWh. The installed cost of the absorption chiller was £569 per kW$_c$ with additional £40/kW$_c$ per year for the operation and maintenance. Worek *et al.* [72] analysed a tri-generation system with 28 kW$_e$ MGT and a 17 kW air-cooled ammonia-water absorption chiller (Robur ACF 60-00TK) installed in Central Forum building in Barcelona. The exhaust gases from MGT heat the thermal oil used to drive the absorption chiller which produces cooling effect. For that purpose, two additional heat exchangers were necessary: the exhaust gas/hot water and the exhaust gas/thermal oil heat exchanger. The installation cost of the system is presented in tab. 6 and it can be seen that absorption chiller participates with only 8% in total cost of the tri-generation system.

Table 6. Investment cost of the tri-generation system in Barcelona [72]

Item	Price [€] (Share [%])
MGT Capstone C30	51.408 (45.9)
Exhaust gas/hot water heat exchanger	3.500 (3.1)
Exhaust gas/thermal oil heat exchanger	7.578 (6.8)
Absorption chiller	9.000 (8.0)
Material for the installation	19.506 (17.4)
Control system	2.660 (2.4)
Installation	18.345 (16.4)
Total cost	111.997 (100)

From the economical point of view, both small-scale solar cooling systems and micro-CCHP with absorption chillers are worse than comparable conventional systems with compression chillers. Despite the relatively high energy savings on annual level, very high initial cost of these technologies makes them less favourable. Best practice examples in the case of small solar cooling installation show that 800-2600 € per year can be saved, depending on load hours, location and system design. Still, payback period is very long, around 20-30 years without any incentives. With incentives and also using these systems for DHW and space heating, payback period can be reduced to less than 10 years. The economic analysis from Worek *et al.* [72] can be taken as a reference for energy savings in the case of micro-CCHP. In the case of large residential building, annual energy savings are 12094 € with a payback period of 5.2 years. This is very close to the payback period for micro-CCHP system reported in Sugiartha *et al.* [71] which is around 6 years. Around 6 years is the first-rate payback period under the current conditions and indicates a very good design of micro-CCHP system. More realistic scenarios are micro-CCHP systems with payback periods in range of 10-15 years. In addition to system design, payback period is directly dependant on the number of full load hours and on the ratio of gas-electricity price. If the current ratio of gas-electricity price increases from standard 0.3 to 0.4 or more, the payback period will be significantly reduced. This fact indicates that the right incentives are necessary factor to make both small-scale solar cooling and micro-CCHP closer to the conventional technology with compression chillers.

Regulations and incentives

It has become clear that small capacity absorption machine hardly will be able to compete with comparable compression machines in the near future if adequate promotions do not support their further development. This primarily refers to the integrated energy systems based on renewable energy sources which use absorption technology: CCHP and solar thermal systems. These systems have a great potential for saving primary energy (fossil fuels) and to reduce environmental impact.

EU promotes the use of renewable energy for heating and cooling in order to reduce primary energy dependency and decrease greenhouse gasses emissions. The member countries have developed their own strategies and introduced a range of incentives to meet the EU targets for 2020. A very exhaustive study on existing incentives in EU-27 countries has been reported by Cansino *et al.* [73]. According to the authors, the common types of incentives introduced in the EU countries are: subsidies, tax incentives, financial support, and feed-in tariffs. Technologies based on renewable energy sources such as biomass, solar, and geothermal can benefit from public subsidies if they are used for heating and cooling purposes. The most subsidized technology is biomass micro-co-generation followed by solar thermal technologies. European Parliament promotes the high-efficiency cogeneration based on heat demand and potential benefits of the same with regard to saving primary energy, avoiding network losses and reducing greenhouse gasses emissions. Besides subsidies, there are also some regulations which demand implementation of renewable systems in new buildings. In Germany, there is a minimum use of 15% of renewable energy for all new buildings while in Spain all DHW installation have to be with solar thermal energy. Tax deduction, exemptions and reduced tax rates are other types of public instruments from which CCHP and solar thermal systems can benefit within the EU. In fact, at the moment there are no special incentives for CCHP systems but they can benefit from incentives for CHP systems bearing in mind that CCHP systems are/can be derived from CHP systems. One of the best examples for tax incentives is Sweden, where households can benefit from 30% tax credit when converting from direct electric heating and oil-based heating to systems based on co-generation or heat pumps. Another example is Italy, where there is a possibility of reduced VAT (10% instead of 20%) for energy consumption if the refurbished house includes solar thermal system. Tax exemption from distribution and consumption taxes on natural gas is present in Spain to promote CHP, by promoting biomass green certificates, where the tariff is valid in the first 15 years and corrections apply after. Austria, Luxemburg, and the UK have feed-in tariffs incentives for heating and cooling derived from renewable energy sources. Finally, low-interest loans are also type of incentives which has been offered, for instance, in Germany for the financing of solid biomass and solar thermal plants for heating and cooling. Building certification programs like Leadership in Energy and Environmental Design (LEED) are another way to promote solar cooling and micro-CCHP systems opportunities through a rating system for buildings which evaluates if the building is environmentally responsible, operationally efficient and in a healthy environment.

As can be seen, the majority of the energy policies and regulations differ from country to country due to different patterns of energy demand and supply, fuel prices, climate and environmental conditions. With respect to that, each country adapted policy measurements toward its own energy resources and adjusted them to the current situation. It is evident that progress has been made, but it is still necessary to put more efforts by making energy policies more consumer-friendly. Finally, of great importance is to harmonize policies at local, national and international levels in order to facilitate the further development of renewable energy based technologies, especially solar thermal and micro-CCHP technologies.

Conclusions

The potential on the field of primary energy savings and environmental benefits are the main advantages which encourage further development of small capacity absorption machines. Reduced electricity consumption and low CO_2 emission has been confirmed by numerous studies. Beside the space cooling and refrigeration purposes, it is also possible to use small capacity absorption machines for DHW production and space heating. Also, there is a possibility to use them in remote and isolated areas where the infrastructure does not meet energy requirements. Very promising application are supermarkets and small agro-food industry applications. Very intensive researches on this topic and numerous studies have pointed to solar thermal and micro-CCHP technologies as the main carriers for future development of small capacity absorption machines. It seems that these two technologies are the right path which can lead to the economic attractiveness of small capacity absorption machines, making them competitive with conventional compression machines. However, the problem is that the both solar thermal and micro-CCHP technologies are still under development. It is truth that several micro-CHP units such as gas micro turbines and fuel cells which can be coupled with small absorption machines are now available at the market, but the cost is high. In the field of solar collectors has been made a great progress in the last few years which resulted in much accessible prices. Overall progress is evident; however, there are still lots of obstacles that impede the full expansion of small absorption machines. The main obstacle remains the high first cost and lack of serial production, which would inevitably lead to price reduction. The lower performance is another obstacle, small absorption machines are mainly single-stage with the COP lower than comparable compression units (0.7 compared to around 3). However, the first commercial small absorption double-stage unit looks promising with respect to the efficiency. There are many factors that affect the efficiency and effectiveness of the systems with small capacity absorption machines. Design and sizing are of great importance. The minimum solar fraction of around 50% is necessary that solar thermal system with single-stage absorption chiller starts saving primary energy. This indicates the need for increased number of hours operating at full load. Full load operation stands for micro-CHCP systems as well. The energy storage is another factor to which has been devoted a lot of research attention lately. In order to prevent inefficient systems, it is necessary to optimize the electricity consumption of external system components such as cooling towers. This is why the control is very important factor. On the other hand, the control also has to be simple in order to decrease the high first cost. Progress and cost reduction of electronic components for control should contribute to that. As already mentioned above, new opportunities have been introduced with small solar kits which make small absorption machines more accessible.

Two very important factors for further development are lobbying and subsidies. The financial incentives for the installation of these systems are another important factor which may be a driving force for successful market penetration. However, maybe the most important issue is to create a sense of responsibility among people about the fatal ecological consequences that can bring increasing use of electric cooling systems.

At the end, all the facts mentioned above indicate that small capacity absorption machines have a good potential for further development under the two emerging technologies such as solar thermal and micro-CCHP, but a lot of research work is ahead. Appropriate standards, test procedures and best practices guides together with intensified work on simulations, optimization and control strategies improvement are some of the needs which are necessary to accelerate the progress and to fill the gap with respect to the conventional systems.

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