Small-scale polygeneration integrated with membrane distillation for Swedish community

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Contents

1. Background

Water, in general, has evolved as a social and economic commodity in many parts of the world [Rogers et al., 2005] and several regions realize the shortage of existing freshwater sources to meet ever growing water demands not only in domestic and agriculture sectors but also in power plants and industries. The water circumstances in Sweden has become cause for concern over the last decade and cannot be ignored any longer [Widegren, 2017]. Sweden is used to being proud of top quality drinking water, but since 2010 there have been thousands of cases where people have fallen ill with stomach bugs, diarrhea and even ended up in hospital because of quality of the drinking water has been affected badly. Hundreds of thousands of people have had to boil tap water before being able to drink it [Swedish Radio, 2011]. More than 20,000 people in Östersund and Skellefteå got parasites from drinking water in 2010 and 2011 respectively [Swedish Radio, 2011]. There have also been recent incidents in Gothenburg, Helsingborg, Karlstad and Öckerö. Furthermore, record-low groundwater levels have been recorded on the islands of Öland and Gotland in southeastern Sweden and may lead to a severe shortage of drinking water this summer [Swedish Radio, 2011].

A reliable irrigation water supply is a vital component of any greenhouse and ecological farming. In the earlier, the quality of the water source was not a social issue considered by farmers. They did, however, incur fertility problems that often defied explanation. Over the last decade, a better thoughtful of how water quality can impact preserving media pH, soluble salts, fertility, and plant growth has made water quality a critical issue in greenhouse/horticulture crop production. Moreover, even freshwater used for irrigation, contain salts and if the salt is not removed, it accumulates first in the root zone and then in lower soil depths leading to salt-induced land degradation [Qadir et al., 2015].

On the other hand, as greenhouse wastewater/drained water contains high concentrations of all plant nutrients, recovered precipitate could be a source of other nutrients (such as K, Mg, and micronutrients) [Saxena and Bassi, 2012; Yi et al., 2005]. The recovery and reuse of plant nutrients from waste water/digested sludge are given high priority from Swedish government and authorities. Nutrients recovery from wastewater/digested sludge has been a significant research interest for the last decade. Separating the nutrients upstream would also reduce the amount of energy needed for nutrient elimination at the waste water treatment plants [Dunets and Zheng, 2015].

Water recovering and reusing technologies present a way for vegetation to mitigate water scarcity risks and become less dependent on raw water supplies. Therefore, the need for utilizing saline waters from the oceans and other brackish and wastewater sources and the processes that convert saltwater into freshwater have become rational and logical approaches in these regions [Gude, 2016].

In Sweden at least 500 people are estimated annually to fall ill with Legionnaires' disease [Boverket, 2001]. The Legionnaires' disease is a kind of pneumonia, which is caused by bacteria of the Legionella group, partly driven in water systems in apartment buildings, public institutions, such as shower installations in swimming pools, sports halls, hospitals and nursing homes. Statistically 15 out of 100 infected people die of Legionnaires' disease [Boverket, 2001].

In earlier time industrial practices, effluent water used to be discharged to the drain, but that practice got no more acceptances and hence plants included facilities treating that water and recycling it back for use as boiler feed water or in other processes [Morrow et al., 2011]. Since blow down water tends to be much polluted, it requires higher levels of purification technology depending on the type of production involved. However, the cost associated with implementing advanced treatments for the purpose of water recycling may sometimes become costlier as compared to purchasing influent water in some countries like Sweden.

Though the water associated complications are part of the national and global sustainability agenda and addressed by various governmental institutions and organizations, but water scarcity is still an existent threatening issue and therefore needs enhanced attention. As a result, there is the need for new tactics and approaches in order to manage water related problems.

1.1 Industrial waste heat recovery

While desalination of saline waters has now been accepted as a promising alternative for freshwater source, the energy demands by the existing desalination technologies for water production continue to pose challenges in their applications. In general, desalination technologies require large quantities of high grade thermal energy and/or prime quality electricity for freshwater separation which results in release of waste heat, greenhouse gas emissions and concentrates (brine) into the environment [Gude, 2016].

Significant amount of waste heat is available in power plants, pulp and paper mills, cement and process industries and food industries. The total economy is then dependent on whether the heat can be utilized and that this can happen even during the warmer seasons.

Recently, technologies for the recovery and utilisation of industrial low grade excess/waste heat have gained increased attention because they offer an opportunity for industry to be more energy efficient and, at the same time, reduce its CO_2 emissions. Excess heat can be distributed to district heating systems or exported to other purchasers with a demand for heat (e.g. greenhouses and algae cultivation systems). By recovering industrial waste heat, energy efficiency can be increased, greenhouse gases emissions can be reduced [Patil et al., 2009], the cost of waste disposal can be lowered [Kiang, 1981] and large amounts of water can be saved, which would otherwise evaporate during the cooling process [Fang et al., 2013]. However, if there are no heat sinks in the area, the heat can be converted into electricity. Since a high proportion of industrial excess heat has a low temperature, the development of technologies that recover and utilise heat with low temperatures is worthwhile. Moreover, even technologies with low conversion efficiencies can be of interest if there is no other use for the excess heat [Johansson and Söderström, 2013].

1.2 Polygeneration (combined heat, power, nutrients and fresh water production)

While energy use is an essential indicator of development and social welfare, it also exemplifies one of the most key sources of environmental pollution and greenhouse gas emissions [WWF, 2006], which hampers the overall sustainable development of society. In this context, polygeneration (also called multigeneration) came into light as a way of increasing the conversion efficiencies and economic savings beyond those seen for cogeneration and trigeneration [Hernández-Santoyo and Sánchez-Cifuentes, 2003; Chicco and Mancarella, 2009; Serra et al., 2009; Fumo et al., 2009; Gandiglio et al., 2014]. Electricity, cooling and cooking fuel are obvious energy carriers which would be useful if they were provided for the given application, and these items (along with heating) are often considered in polygeneration systems. Water purification or desalination has also been considered, although in fewer studies, i.e. Rubio et al. [2008] and Maravo et al. [2012].

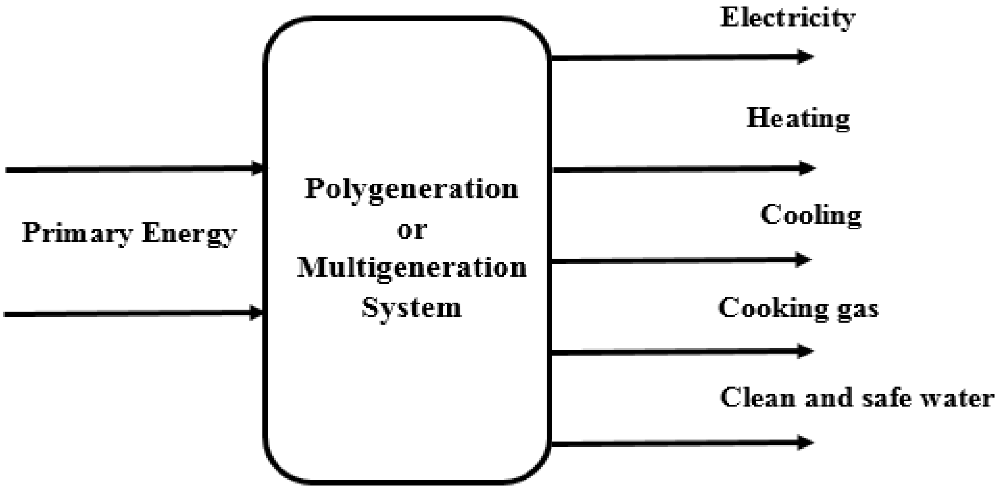

Fig. 1: General layout of an integrated polygeneration system [Khan, 2017]

The purpose of polygeneration is to improve the utilization of primary resources (fuels) through an energy recovery system. This is a method of improving the efficiency of energy provision processes for better sustainability. For example, less fuel is required to produce a given amount of electrical and thermal energy in a single unit than is needed to generate the same amount of both types of energy with individual, conventional technologies (e.g., gas generator sets and steam boilers) [Dincer and Zamfirescu, 2011]. Apart from supplying "energy products" through a polygeneration system, one can also fabricate by-products with added value, such as pure water, fertilizer, nutrient etc. In water-scarce rural and coastline areas, pure drinking water obtained from a water purification unit could be that additional product, when the purification unit is integrated in the polygeneration plant. High-grade water purification technologies are energy intensive, so it is crucial that they are linked to a renewable energy source/industrial waste energy even in a polygeneration scenario [Khan, 2017].

2. Motivation of the project

With this limited amount of usable fresh water, introducing an alternative source for fresh water production is a critical subject. Besides the desalination of sea water, water recovery by wastewater (which has been generated in various industries) treatment can be investigated as an emerging and promising resource for the perspective of global fresh water demand [Shirazi & Kargari, 2015].

Many processes industries involve consumption of large amount of water for different purposes including as process water, for cleaning, cooling or warming materials or components. In many cases, significant amount of this water ends up as effluent which should be either reclaimed in order to minimize the water to be supplied from outside the plant or shall be released to the surrounding water body. But before the waste is handled in either of the above ways, it needs to be cleaned in order to remove the contaminants that are mixed to it in the production process so that it won't pose problem for the system or pollute the environment.

The problem of water shortage affects not only human and industrial activities but also an adequate and sustainable food production. Water quality in agriculture does not have the same requirements as that of drinking water and also properly treated waste waters can be used for irrigation. Wastewater nutrient recovery holds promise for more sustainable water and agricultural industries. For sustainable food production, greenhouse producers are therefore expected to take the necessary measures to reduce their environmental impact, not only with regard to their carbon footprint (i.e. energy management), but also use of raw materials (i.e. water and fertilizers) and their emission into the environment [grodan, 2016]. Current fertiliser production heavily relies on the consumption of non-renewable energy and finite mineral resources. This energy intense nutrient removal also contributes to greenhouse gas emission of 0.9 kg CO_2 per cubic litre of treated wastewater [Hall et al., 2011; Rothausen and Conway, 2011]. The large energy and environmental footprint of nutrient removal from wastewater, in turn, aggravates the sustainability of fertiliser production for food security.

The conventional wastewater treatment methods cannot be applied to the purification and separation of industrial/agricultural waste water since the purification process should give full consideration to its stability, small volume, low energy consumption, robust and easy operation and other factors [Khan, 2017; Zhao et al., 2013]. The widely applied desalination technologies are usually energy intensive and the conventional energy sources are either cause environmental pollution or are being consumed near completion. Hence a strong need to develop a less energy intensive, high separation efficiency and environment friendly water purification or separation technology. Among the different wastewater treating methods, membrane-based water recovery unit operations are highlighted due to their various advantages.

Membrane technique for water purification or dewatering, ex. of a nutrient solution, can also utilize low-value thermal energy as a source of power. This provides the opportunity to combine bio-based power generation including waste heat recovery with a high value-added efficiency with a different value-added process, thus improving the profitability of both processes.

3. Objectives

Membrane technology as reverse osmosis, ultrafiltration (UF) and nano-filtration (NF) is commonly used. But even if these processes are well developed, there is a need to investigate other technologies that can lead to more robust performance, lower energy consumption and less environmental loads and lower costs. Membrane distillation (MD) is one such option which can be capable when low grade heat is available in or outside of the process and when high purity of water and/ high separation efficiency is desired.

The aim here improved overall performance of small-scale polygeneration system using waste heat from renewable energy/CHP plants/process industry unit for water purification or dewatering of nutritional solutions using membrane distillation technology. The aim is to zero liquid discharge/zero liquid emissions…

The main objectives of this study are to:

- Demonstrate MD as a novel separation and purification technology

- Design MD-industrial waste heat system integrations trying to replace some energy intensive and chemical consuming steps

- Evaluate MD process’s performance (separation and purification efficiency) integrated with available waste heat for industrial/domestic household applications

- Perform system analysis for integrated industrial process (product water quality, influence of composition (nutrients, pesticides and slats) present on water, energy demand, system requirement etc.)

- Optimize parameters for reduced energy demand and optimum production performance related to the separation and purification

- Life cycle analysis (LCA) of the integrated system

The goal of this project is to further develop and optimize the membrane distillation (drive by low grade waste heat) purification and recovery system. These projects will be carried out by performing a series of laboratory experiments to find the optimal operational conditions, recovery efficiencies, recovered water and fertilizer qualities. Moreover, energy and cost constraints are the major focus for research in this area. However, enhanced water recovery scheme incorporating brine mixing with feedwater (in a closed-circuit configuration) to optimize both water and energy recovery is an interesting option.

4. Air-gap membrane distillation (AGMD)

Reverse osmosis (RO), a widespread membrane technology for a broad range of capacities, exhibits very good to excellent separation efficiencies and has a potential as a water treatment technology in this context. Examples of relevant studies conducted during the past five years include Schmidt et al. [2016], Abejon et al. [2015], and Teychene et al. [2013]. However, drawbacks like the formation of a polarization film, fouling, and high electricity demand are limiting factors [Pangarkar et al., 2011]. One way to apply desalination to agricultural use is minimizing the cost of electrical energy requirements in RO, responsible for 60% of the water cost [Lenntech, 2015]. In addition, RO has been shown to experience difficulties when groundwater contaminants and saline water concentrations are very high [Figoli et al., 2010].

Hence, there is a critical need for robust separation and purification processes for desalination/nutrient recovery/fresh water from challenging wastewater/saline water streams [Xie et al., 2016]. Due to this unique transport mechanism, MD processes have been explored for the recovery of valuable components/fresh water. Based on the volatility and vapour pressure, these components can be concentrated either in the feed stream or permeate streams. Indeed, the MD process achieved a high concentration factor of three for seawater RO brine volume reduction [Martinetti et al., 2009].

The present investigation focuses on membrane processes as the most promising alternative; other techniques require regular supplies of chemicals and other consumables, or are otherwise too complex to consider for decentralized systems in remote areas in Sweden.

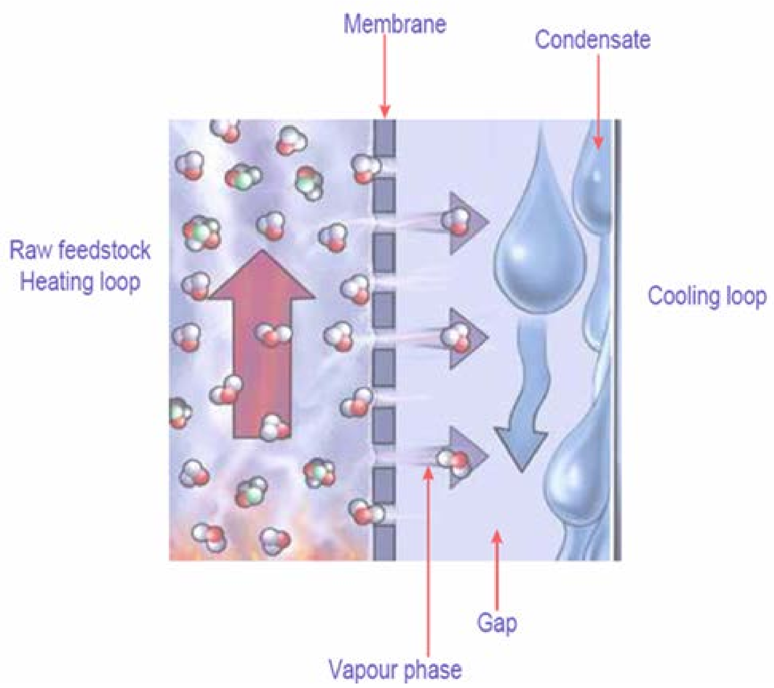

Fig. 2: Air-gap membrane distillation (AGMD) [Xzero AB]

In short, MD is a thermally-driven water purification process involving a hydrophobic, microporous membrane. Hot feed is kept on one side of the membrane, and a vapor pressure difference is established across the membrane via cooling on the opposite side. Water evaporates from the feed, passes through the membrane, and condenses; all non-volatile components are retained in the liquid phase, thus ensuring extremely high separation efficiency and high product water purity. Energy demand in MD systems consists of thermal energy required to heat the feed and to cool the permeate, and the electrical energy required to drive the circulation pumps. Air gap membrane distillation (AGMD, Fig. 2) has been proposed as a promising approach that combines the excellent separation characteristics of direct-contact membrane distillation (DCMD) and vacuum membrane distillation (VMD) with lower specific thermal energy demand [Sääsk, 2009]. The integration of membrane distillation with industrial or power plant waste heat or with solar thermal systems offers several advantages including reduction of overall energy demand, reduction of greenhouse gas emissions, reduction of pure water production costs due to waste heat recovery, and effective process integration for multiple products. Temperature levels on the hot side (up to 90^{o}C) are amenable to thermal integration with a variety of heat sources [Khan and Martin, 2014].

4.1 Energy balance of integrated MD system

The present investigation addresses this issue via an experimental investigation of a household AGMD water purifier prototype (2 L/h nominal capacity) supplied by HVR Water Purification AB, Stockholm (subsidiary of Scarab Development AB). A parametric variation of coolant-side inlet temperature was conducted for unaltered and the resulting yield and thermal energy demand were determined. The AGMD experimental results consist of analyzing the performance of the system under different operating conditions. On the hot side temperature was maintained at levels around 80^{o}C, which was the system's upper limit. (MD performance favors as high feed temperatures as possible while maintaining operation under the boiling point.) Cold-side temperature levels varied from 15 to 70^{o}C in order to investigate the role of temperature difference across hot and cold sides, which is of importance when investigating different integration strategies and for estimating the performance of cascaded modules (see subsequent sections for more details). Flow rates were adjusted to 3.8 L/min and 1.9 L/min for hot and cold sides, respectively. This approach enables yield to be high while keeping the pressure drop (linked to pumping power requirements on both hot and cold sides) and absolute pressure (linked to membrane liquid entry pressure limitations on hot side) at reasonable levels. Maintaining the cold-side flow rate at a lower value than the hot side allows for a higher cold outlet temperature, which is important for cases involving subsequent heat recovery. (More detailed study on flowrate dependency, along with investigations of inter-channel temperature gradients and other aspects are beyond the scope of the present study.)

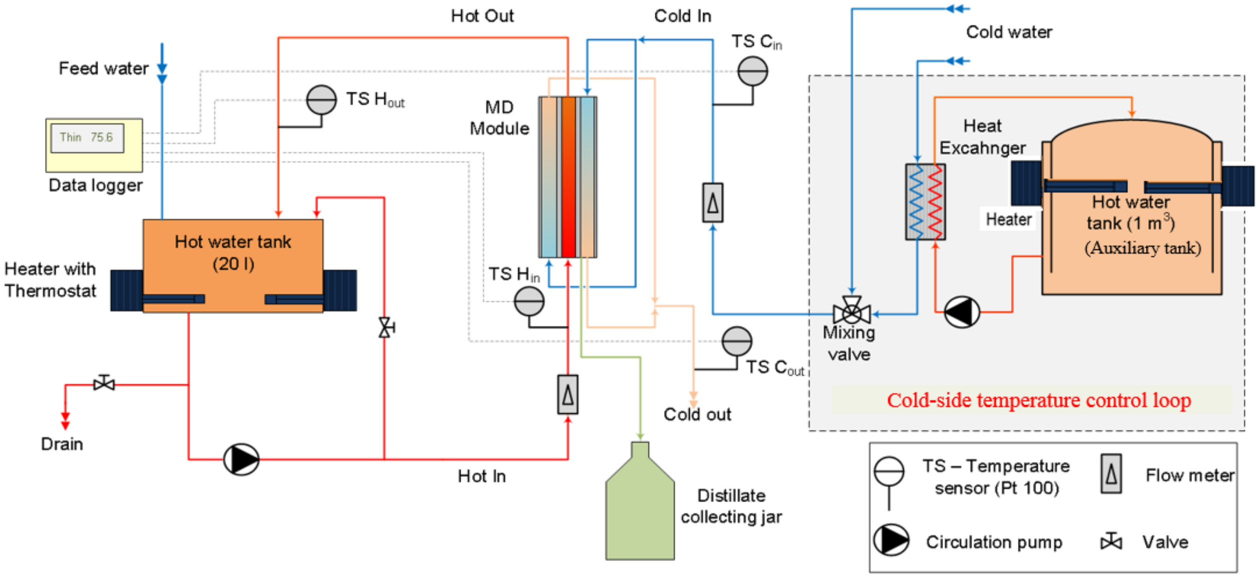

Fig. 3: Detailed schematic diagram of AGMD bench scale unit experimental setup at KTH [Khan, 2017]

The performance of the AGMD prototype is evaluated by analyzing pure water flow rates and specific thermal energy requirements (kWh/m^3) as a function of feed and coolant temperature difference. A feedstock-to-coolant inlet temperature difference ΔT_i is defined for reference purposes:

$$\Delta T_i = T_{hi} - T_{ci} \tag{1}$$

where T_{hi} and T_{ci} are the inlet temperatures of the feed and coolant, respectively. (Recall that feed temperate is maintained constant, while coolant temperature is allowed to vary.)

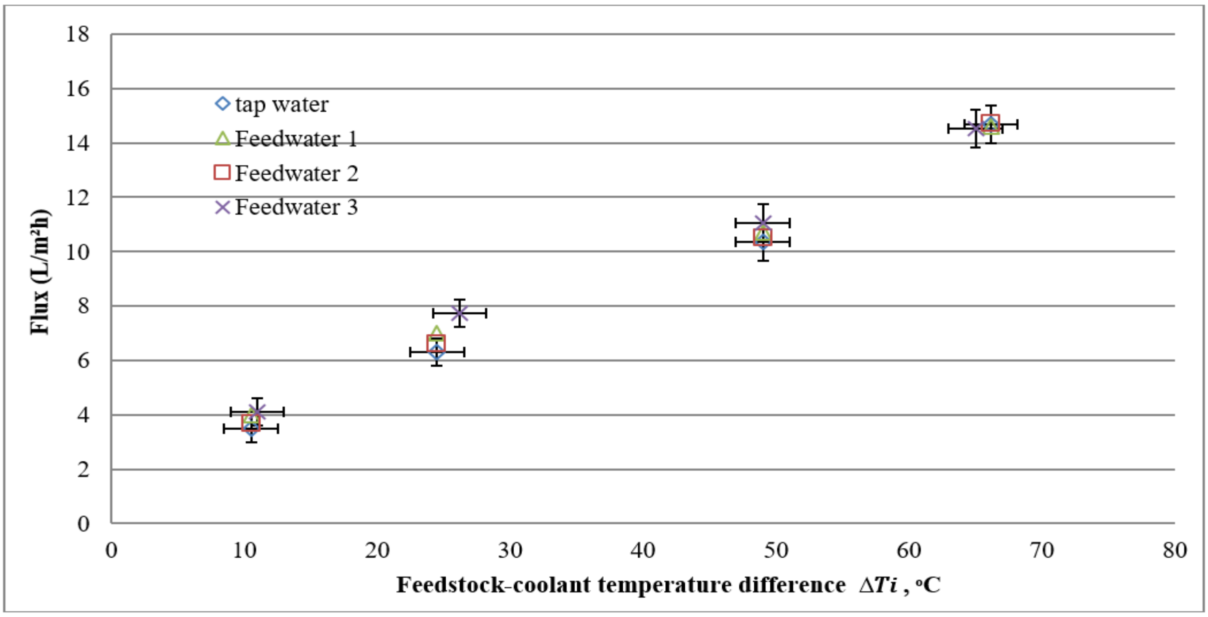

Fig. 4: Product water flux as a function of feed-coolant inlet temperature difference (feedwater flow 3.8 L/min, coolant flow 1.9 L/min, feedwater inlet temperature ca 80°C, coolant inlet temperature varying) [Khan, 2017]

The specific thermal energy demand has been estimated in two ways (both neglect the small change in hot-side mass flow owing to evaporation):

Enthalpy drop across the hot (feed) side,

$$Q_1 = \dot{m}_h c_{ph}(T_{hi} - T_{ho})/\dot{m}_p \qquad (2)$$

Net enthalpy change, i.e. enthalpy drop across hot side with cooling enthalpy recovered,

$$Q_2 = \left[\dot{m}_h c_{ph}(T_{hi} - T_{ho}) - \dot{m}_c c_{pc}(T_{co} - T_{ci})\right]/\dot{m}_p \qquad (3)$$

where $\dot{m}$ is the mass flow rate and c_p is the specific heat for cold (subscript *c*), hot (subscript *h*), and permeate (subscript *p*) streams; subscripts *i* and *o* denote inlet and outlet, respectively. Q_1 is directly related to the amount of heat needed to maintain the feed at the desired temperature level for a given yield. If there is no subsequent heat recovery, then the specific thermal energy demand is equivalent to this value. On the other hand, if heat can be recovered from the cooling side for use in other thermally-driven processes (e.g. low-temperature heating), or to provide heat to a cascaded module, then Q_2 is the appropriate value to consider. For cases with no heat recovery, Q_2 provides a means for determining the amount of heat to be dissipated [Khan, 2017].

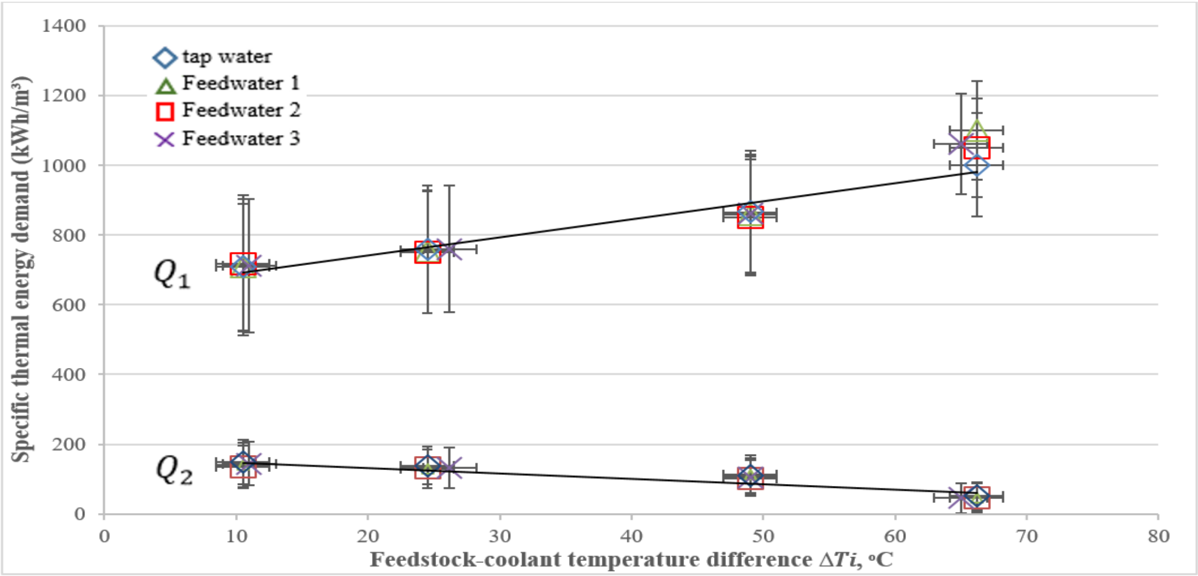

Fig. 5: Specific thermal energy demand for AGMD module (feedwater flow 3.8 L/min, coolant flow 1.9 L/min, feedwater temperature ca 80^{o}C, coolant temperature varying) [Khan, 2017]

The single-cassette MD module considered in this chapter serves as a basis for determining performance in larger systems. In the simplest design two or more cassettes are placed in parallel within a module, with total heat input, feed and coolant flow rates adjusted proportionally. The total number of cassettes can be estimated by the amount of available heat for a given temperature difference across the module, assuming that the hot inlet temperature is at the same level as experimentally tested conditions (80^{o}C). Alternatively, the desired total yield can be used to estimate the total number of cassettes for a given temperature difference across the module; thereafter the corresponding amount of heat required can be determined. The scale-up procedure is exemplified through the latter approach, as described below:

1. Set a value for ΔT_i, and determine the single-cassette permeate flux from Fig 4. Multiply permeate flux by membrane area (0.19 m^2) to obtain the volumetric flow rate (L/h); mass flow rate $\dot{m}_p$ is obtained by multiplying this value by density (1 kg/L).
2. The required number of cassettes, N, is found via

$$N = {\dot{m}_{tot}} \Big/ {\dot{m}_p} \tag{4}$$

where $\dot{m}_{tot}$ is the desired total permeate flow rate. N should be an integer, so fractions are rounded up to the nearest whole number.

3. The required heat supply, $\dot{Q}_s$, is equated to the total enthalpy difference across the feed side of the module (heat exchange losses are considered to be negligible):

$$\dot{Q}_s = N\left[\dot{m}_h c_{ph}(T_{hi} - T_{ho})\right] = \dot{m}_{tot} Q_1 \tag{5}$$

Eqn. (3) is used to relate the total enthalpy difference to the specific thermal energy demand. Q_1 is obtained from Fig. 6 for the given ΔT_i.

4. The amount of heat that can be recovered on the cold side, $\dot{Q}_{rec}$, is found in a similar way with combination of Eqn. (3) and (4):

$$\dot{Q}_{rec} = N\left[\dot{m}_c c_{pc}(T_{co} - T_{ci})\right] = \dot{m}_{tot}(Q_1 - Q_2) \tag{6}$$

Q_2 is also obtained from Fig. 5 for the given ΔT_i. (For cases without heat recovery, $\dot{Q}_{rec}$ represents the amount of heat that must be dissipated in order to maintain proper operation.)

Once the number of modules is established, the total permeate yield for part-load cases (i.e. instances when $\dot{Q}_s$ is lower than the design value) can be estimated by rearranging Eqn. (5) to solve for the new $\dot{m}_{tot}$, assuming ΔT_i is maintained:

$$\dot{m}_{tot} = \dot{Q}_s / Q_1 \tag{7}$$

This situation implies that the number of active cassettes is reduced from the original design value.

Yields are maximized by increasing the temperature difference between feedstock and coolant, yet there is scope to utilize high coolant temperatures to achieve low specific thermal energy demand and thus enhance heat recovery [Khan, 2017].

4.2 Hybrid separation and purification technology

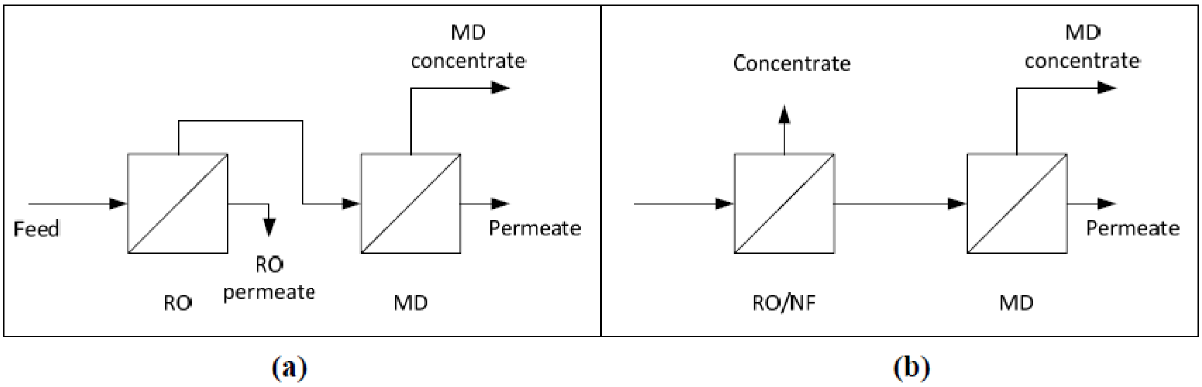

Fig. 6: Simplified flow diagrams of hybrid RO/NF-MD systems. MD connected to RO concentrate (a) and to RO/NF permeate (b) [Camacho et al., 2013]

One of the most sound technology associates for MD is RO, NF or FO (forward osmosis). There are two ways in which they can be integrated. The first is by using the NF/RO brine as feed to the MD, or the FO or RO permeate as feed to the MD [Camacho et al., 2013] (see Fig. 6]. A combination of two technologies (hybrid) has shown to be more efficient and promising than the utilization of a single technology by its own (see Fig. 6 & 7) [Husnain et al., 2015; Xie et al., 2016]. Further it showed that treatment of the RO concentrate using a membrane distillation system can reduce the brine volume generated and increase the overall feed water recovery of the desalination process [Subramani and Jacangelo, 2015]. For example, the RO-MD process, the individual RO recovery was 89%, and MD recovery was 80%, giving a total water recover of 98% for the combined system [Martinetti et al., 2009].

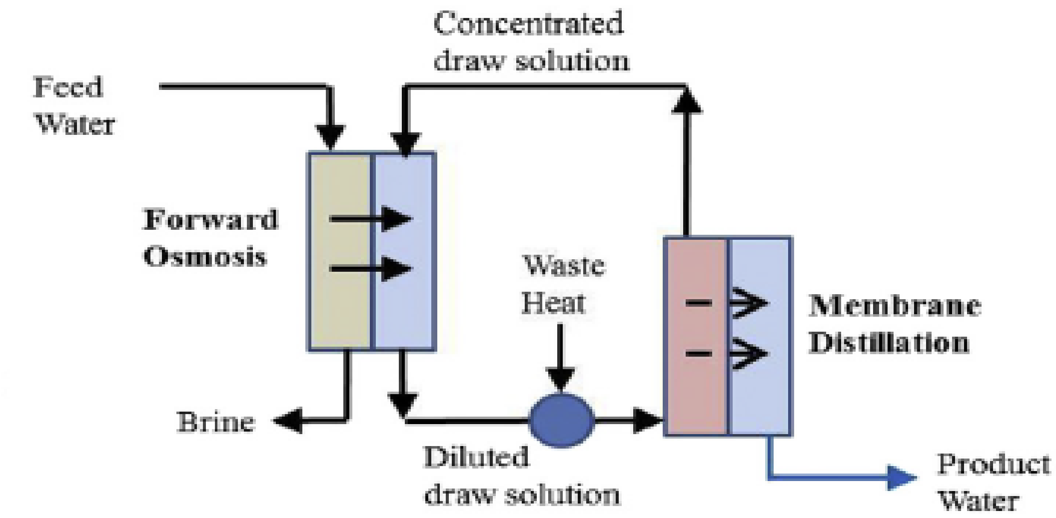

Fig. 7: Application of hybrid separation and purification technologies [Subramani and Jacangelo, 2015]

Hybrid membrane processes complement each other, thereby maximizing overall nutrient recovery efficiency. Forward osmosis (FO) is an osmotic process that uses semi-permeable membrane to achieve separation but one problem that deters the widespread application of FO, when used as a stand-alone process to treat water, is the lack of suitable draw solution that can generate high osmotic pressure [UNESCO, 2008]. Requirement for concentrating the diluted draw solution in an FO (forward osmosis) process opens opportunity for coupling with other membrane processes (e.g., RO or MD) to simultaneously restore the FO driving force and to produce high quality freshwater [Xie et al., 2013, 2014a]. FO is an effective pretreatment barrier for the subsequent MD process. The FO pretreatment step ensured a stable water flux by the MD process in the FO−MD hybrid system when sludge waste water is directly use as feed. FO can be used to reject the nutrients (ammonia nitrogen) from the waste stream and also act as a pre-treatment barrier to reduce or eliminate MD fouling and simultaneously MD helped recover draw solutes for continuous FO operation [Husnain et al., 2015]. MD has been proposed for this second recovery step in novel space or protein concentration applications [Cath et al., 2005; Cath et al., 2011; Wang et al., 2011]. An experimental investigation has found that the combined system was able to achieve almost 100% rejection of solids and acetic acid, and more than 98% rejection of NH_3-N from the feed stream (where by MD system 63% - 72% rejection only) [Husnain et al., 2015]. The high rejection of NH_3-N was mainly achieved by the FO process [Husnain et al., 2015]. Since MD is based on the temperature difference, osmotic pressure does not affect this membrane technique. A high salt concentration does not change the permeate flux significantly and therefore membrane distillation is suitable for concentrating highly concentrated solutions [Xie et al., 2016]. In the combined FO-MD system, FO can mainly use for rejection of contaminants from the feed stream and MD can used to regenerate the draw solution.

5. Membrane distillation integration with existing power plants and process industries/Integrated approach with membrane distillation

It should be possible for most plants to apply a separation technology that uses a low grade waste heat as deriving power and hence potential to replace the high grade heat requiring separation components. By doing so it is possible to reduce the heat demand and so minimize the total cost. Water treatment is an important separation process that occurs in a variety of industrial applications.

Biomass is a key renewable energy source plays an important role in Swedish power and heat generation market. Sweden has a well-developed district heating network mostly using renewable sources. Most CHP production in Sweden today is large-scale cogeneration however, some small-scale CHP units exist. Small-scale CHP plants have a relatively small market share in Sweden. However, the economic conditions are changing rapidly as a result of policy measures like the electricity certificates and tax relief on heat produced in CHP plants. An increase in the electricity prices and the promotion of biomass-based CHP plants could help the development of the market for small-scale CHP units.

The DH (district heating) systems were first introduced in the big cities and have over the decades spread also to smaller towns. But there are a lot of places including remote island with down to 1000 inhabitants or even less where (small-scale) DH and CHP still remains to be implemented. Local DH in combination with small size CHP fills the gap between big scale and individual solutions [Bernotat and Sandberg, 2004]. One way this can foster the development is by creating islands with small-scale CHP and a local DH, energy efficient heating solutions that activates non-utilized potentials in an environmentally sound and energy efficient manner for meeting heat and power demand.

The important aspect of membrane distillation technology that it can be easily integrated and effectively operated with existing power plants, process industries and district heating net. This project will develop membrane distillation system and adapt the technology to meet process functions in industries and integrate with district heating net/ available waste heat.

5.1 MD Integrated with small scale gas engine/gas turbine technology

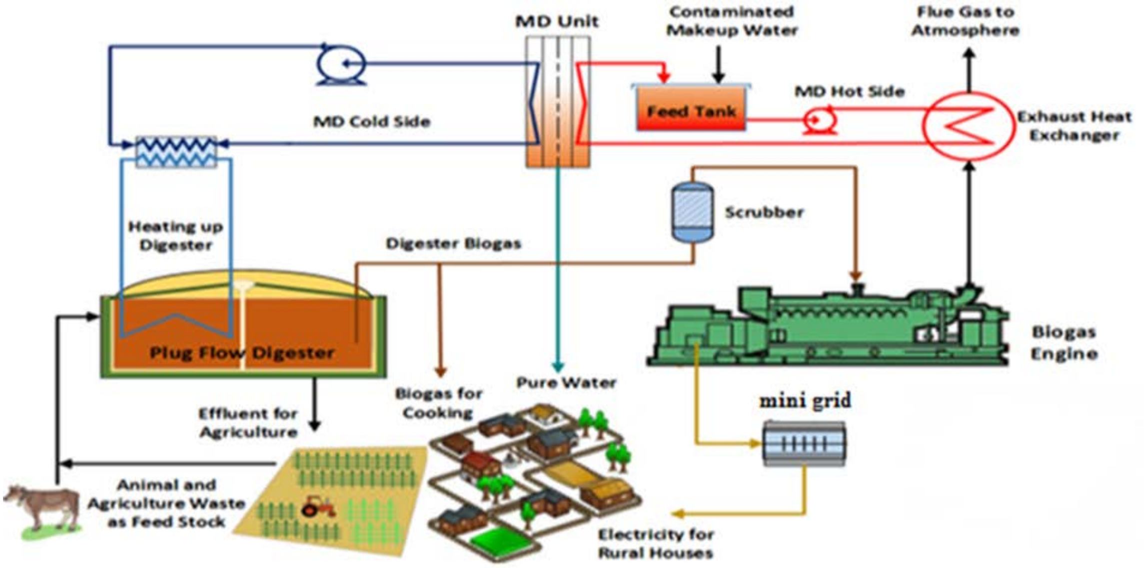

Fig. 8: Biogas based polygeneration system integration with MD [Khan and Martin, 2016]

A digester fed with animal waste and agriculture residues is considered for delivering the required amount of biogas (see Fig. 8). The digester operates at constant operating temperatures under mesophilic conditions, with gravity feed and discharge. Generated biogas from the digester is either routed to a cooking stove or is burnt in a biogas engine. Exhaust flue gas from the biogas engine passes through a heat exchanger for heating up saline/waste feedwater, which is supplied to the feed side of an MD unit. The cooling circuit of the MD unit is heat exchanged with the digester and enhances the anaerobic processes, with additional cooling provided by a surface water heat sink. Scalability of the system depends primarily on the size of the digester and engine. The set of technologies combined to supply each demand – electricity, cooking gas, pure water, and organic fertilizer – employed cow manure as the primary energy supply and contaminated groundwater the source for drinking water.

Another type of small scale polygeneration system in below;

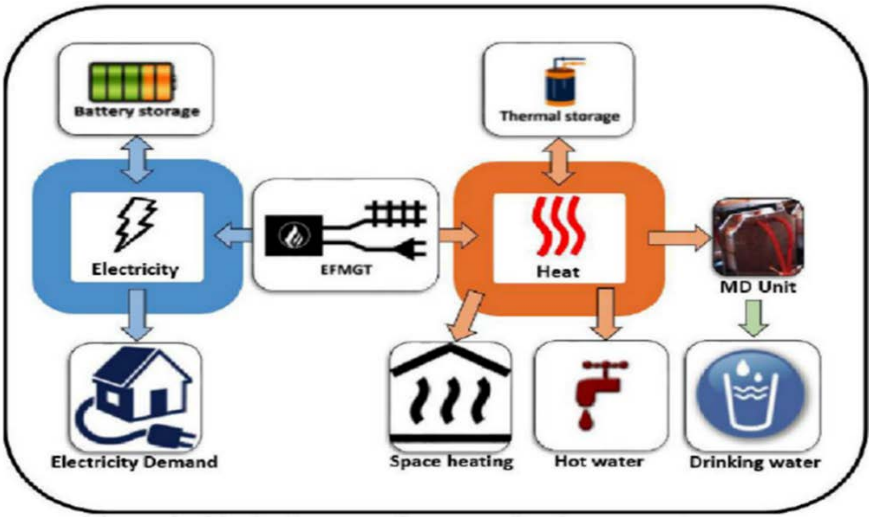

Fig. 9: Integrated polygeneration system [Rahman, 2016]

The above polygeneration system (see Fig. 9) consists of externally fired micro gas turbine unit. Electrical and thermal storage and membrane distillation unit to provide electricity, hot water and pure drinking water for standalone rural community or island.

5.2 MD integrated with district heating net

The potential configurations for membrane distillation were considered mainly based on the possibility of integrating the system with low grade temperature source such as district heating.

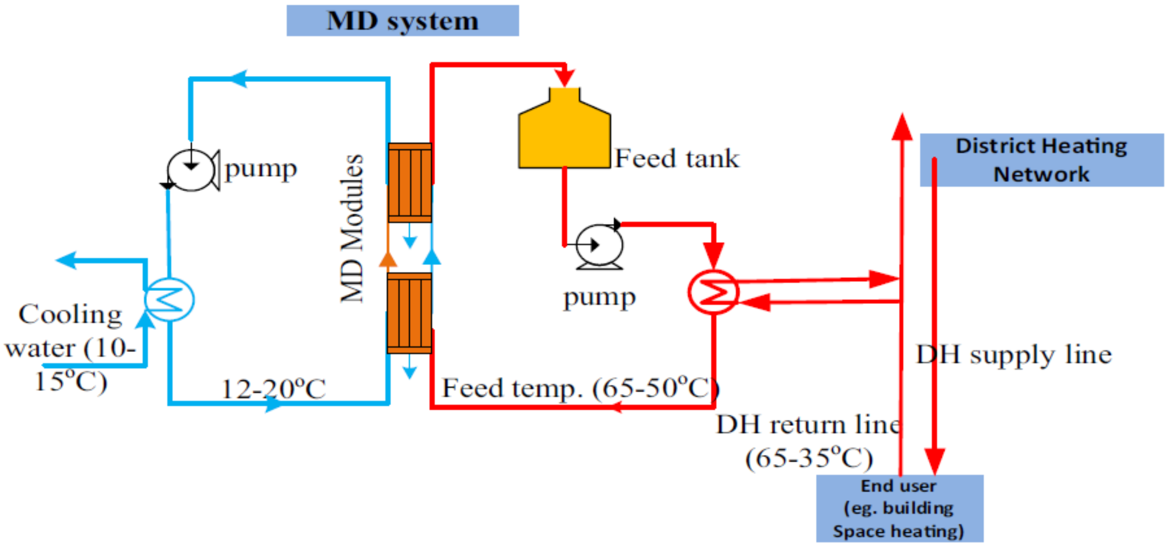

Fig. 10: Case 1 configuration where feed to the MD system heated by a DH return line [Daniel et al., 2016]

In this case, the feed to the MD is heated by the heat from a return line of a district heating network through heat exchangers. The return line from DH users generally has a temperature in the range of 65–35 °C, but the temperature could sometimes go up to 70 °C depending on the season or load from the end user side. The cooling water used in this case is an external cold tap water. The MD system for this integration is shown in Fig. 10.

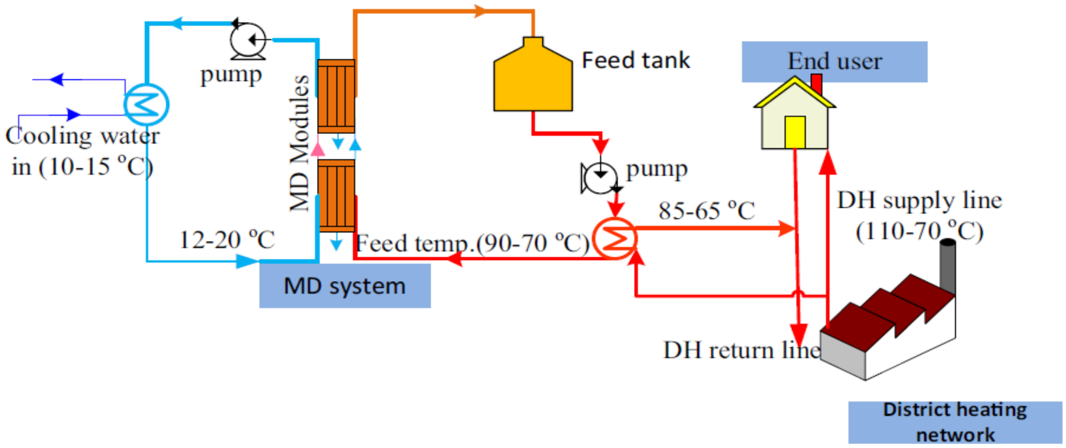

Fig. 11: Case 2 configuration where the MD system is connected to a DH supply line [Daniel et al., 2016]

In the second case of MD-DH integration, a DH supply line (110–70 ºC) is assumed to be the heat source for the MD system and external low-temperature water (tap water) is used as cooling water as shown in Fig. 11, The feed temperature can vary from about 90 to 70 ºC, depending on the heat from the district heating line.

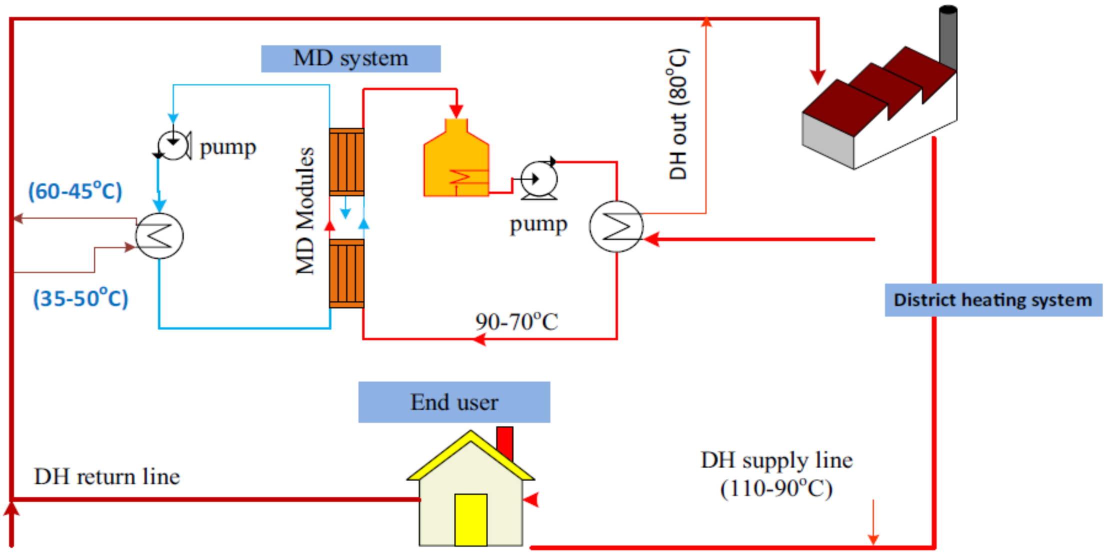

Fig. 12: Case 3 configuration with the MD system placed between DH supply and return lines [Daniel et al., 2016]

In the third case, the MD system is considered to be integrated between a high temperature (110–70 ºC) DH supply line for heating the feed and a low temperature (35–50 ºC) DH return line used as cooling water. The scheme for case 3, MD-DH integration is shown in Fig. 12, In this case, no other external cooling water source is assumed to be used. During the experiment, the temperature in the cooling loop was maintained by varying the flow rate of the external cooling water.

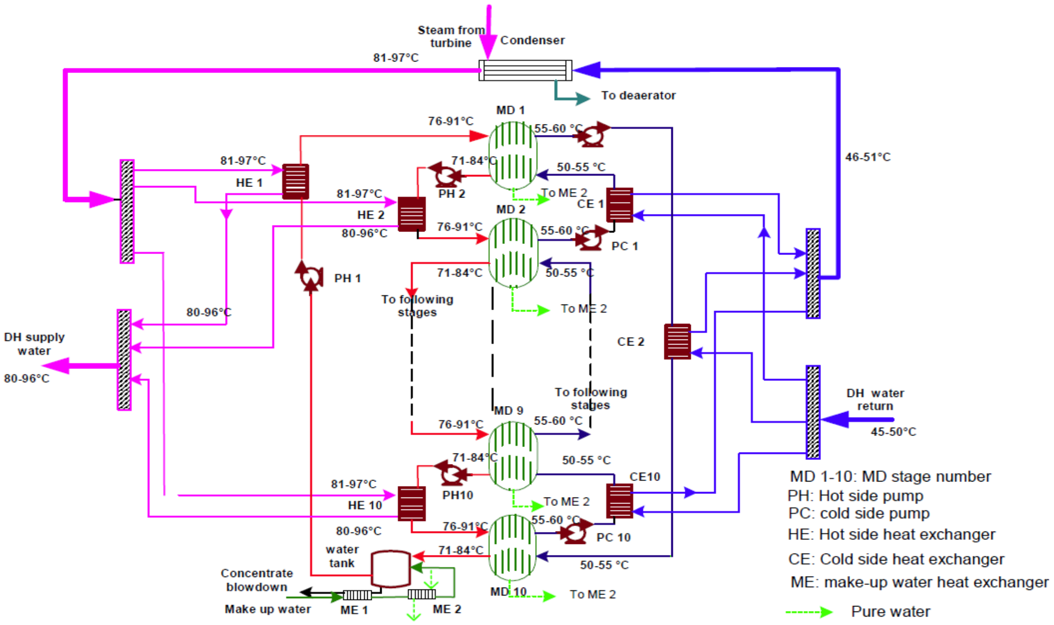

Fig. 13: Connection of fixed number of MD units with DH network [Liu and Martin, 2005]

In this Alternative, the DH return line is used for cooling of the MD units via a heat exchanger. The DH supply line is employed as the heat source for MD. The number of MD modules is calculated with winter conditions as the baseline. Pure water production is lower during the summer since DH supply temperatures are lower (presumably this is not a problem, as such plants normally reduce overall operations in the warmer months. Finally, the alternative employ heat recovery on the cooling loop, i.e. cooling is supplied by the DH return line. Thus the net thermal demand of the MD unit is determined by comparing the DH (backpressure) condenser thermal power with the baseline case where MD is not employed. The details of this alternatives are shown in Fig. 13.

5.3 MD integrated with solar thermal collector

Solar powered MD has received significant attention in recent years. The simplest system configuration involves direct solar integration. For example, Banat et al. [2007] designed and manufactured a compact solar driven, spiral-wound AGMD system with internal heat recovery to operate autonomously in arid and remote locations. A more flexible approach involves the use of thermal energy storage, as exemplified by Chafidz et al. [2014], who developed an integrated solar driven multi effect VMD system with integrated 600 L thermal store. This system was designed for operation in remote areas of Saudi Arabia with a production capacity of 100 L/day. The thermal store was shown to provide stability in operation, although drawbacks like heat losses, operational time lag, and reduction in supply temperature were observed. Kumar et al., [2016] has been analyses a solar cogeneration system with different integration strategies for potable water and domestic hot water production (see Fig. 14).

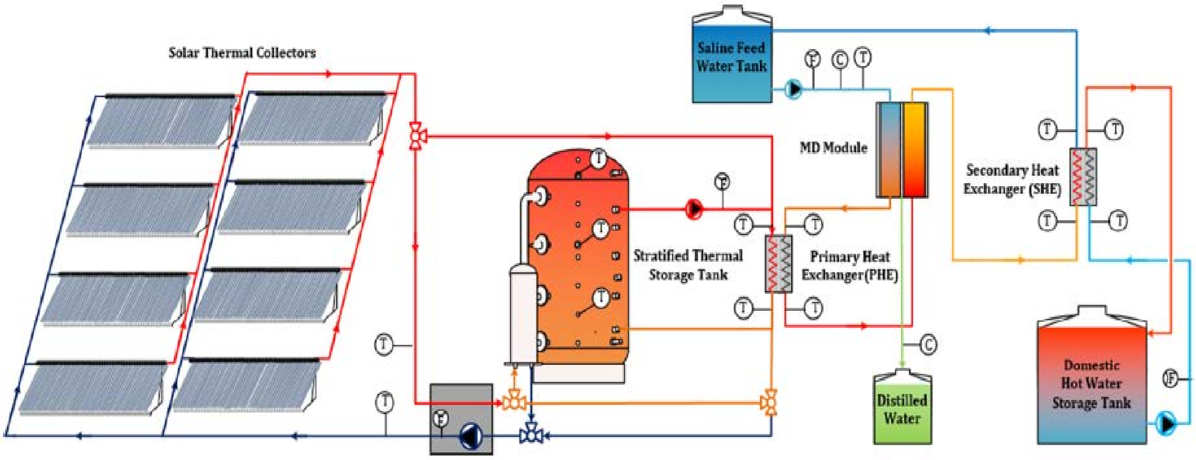

Fig. 14: Schematic of experimental setup for co-generation of pure water and domestic hot water [Kumar et al., 2016]

5.4 MD integrated with industrial waste heat

5.4.1 Cement industry

In a typical cement plant (see Fig. 15), 25% of the total energy used is electricity and 75% is thermal energy. However, the process is characterized by significant heat losses mainly by the flue gases and the ambient air stream used for cooling down the clinker. About 35% - 40% of the process heat is lost by those waste heat streams [Madloola et al., 2011]. Approximately 26% of the heat input to the system is lost by dust, clinker discharge, radiation from the kiln and preheater surfaces, and convection from the kiln and pre-heaters [Legmann, 2017; Khurana et al., 2002; Engin and Ari, 2005]. A heat recovery system could be used to increase the efficiency of the cement plant and thus lower the CO_2 emissions. Moreover, it would reduce the amount of waste heat to the environment and lower the temperature of the exhaust gases [Saneipoor et al., 2011]. Waste heat can be captured from combustion exhaust gases, heated products, or heat losses from systems [Johnson et al., 2008].

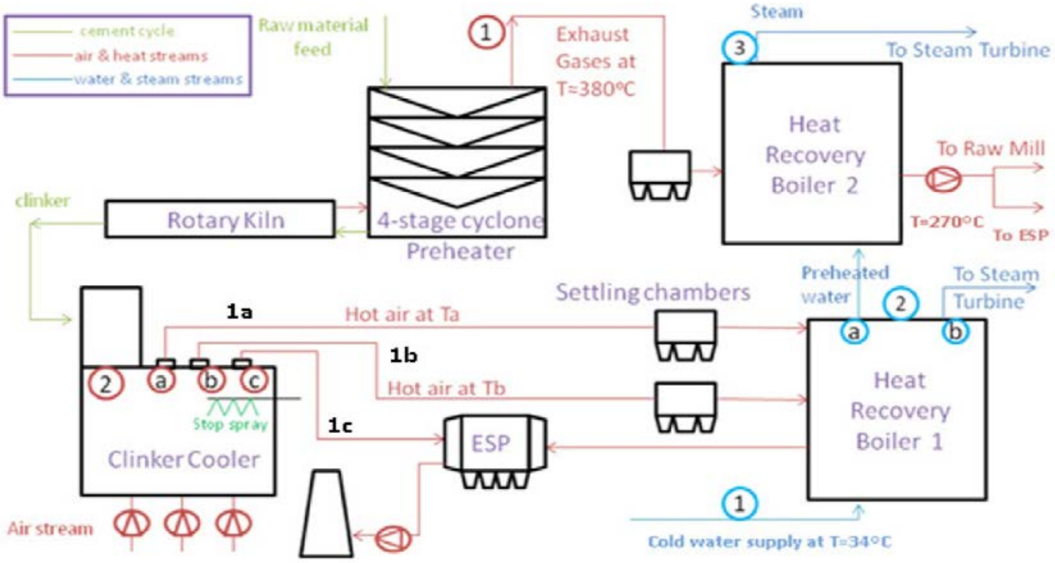

Fig. 15: Heat recovery system of a typical cement plant [Bellos, 2013]

5.4.2 Pulp and paper mill

With the growing concern for climate change and increasing energy prices, the need for energy efficiency measures has become more urgent. The Swedish pulp and paper industry (see Fig. 16), being one of the major Swedish energy users, has a potential for significant energy savings through investments in energy efficiency, such as process integration and new technology [Axelsson et al., 2006; IEA, 2004; Wising, 2003]. In Sweden, the pulp and paper industry is the largest energy consumer sector with 51% and one way of saving energy is to use industrial excess heat in a more efficient way [Jönsson et al., 2008]. There are various possibilities to recover thermal energy from steam and waste heat in the paper drying process for example recovering heat from the ventilation air of the drying section and using this heat for other purposes.

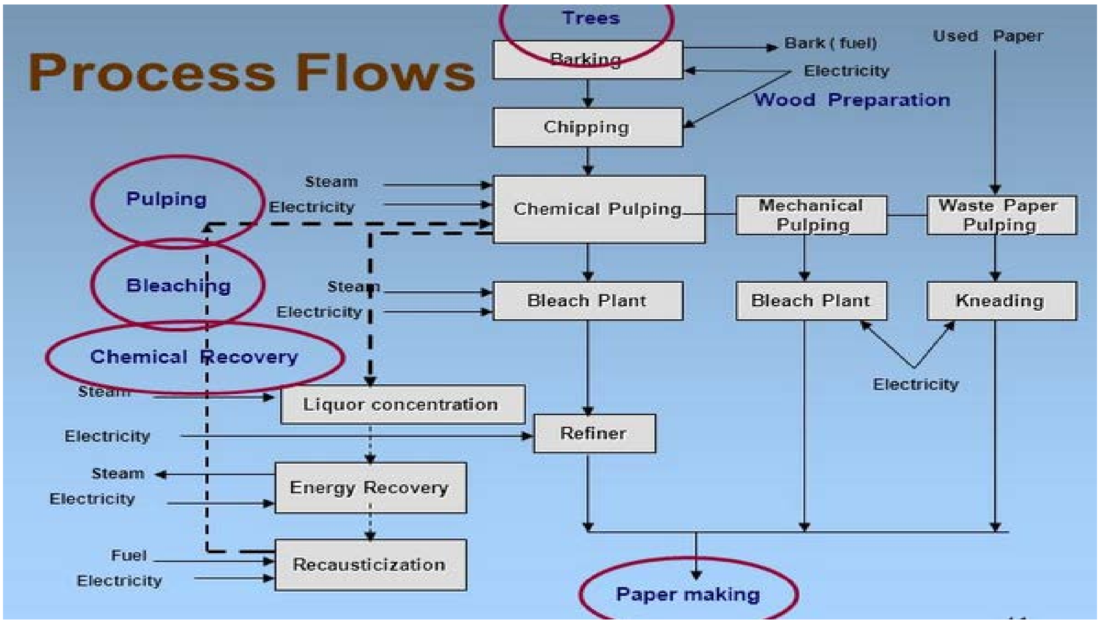

Fig. 16: Process flow diagram of pulp and paper industry [UNEP, 2005]

5.4.3 Steel industry

The iron and steel sector (see Fig. 17) comes next after pulp and paper mill with 16% energy consumption [Jönsson et al., 2008]. Waste heat recovery in by-products from the iron and steel industry in Sweden is under consideration but usage of low temperature waste heat recovery can be an alternative to quickly decrease primary energy consumption and CO_2 emissions in society.

The energy-intensive iron and steel industry often conducts production processes at high temperatures. As a consequence, large amounts of excess heat are generated (e.g. heat from hot material, hot flue gases and cooling water of low temperatures). If this excess heat were recovered and utilised, both the steel plant and the society would benefit from reduced energy costs and CO_2 emissions [Johansson and Söderström, 2013].

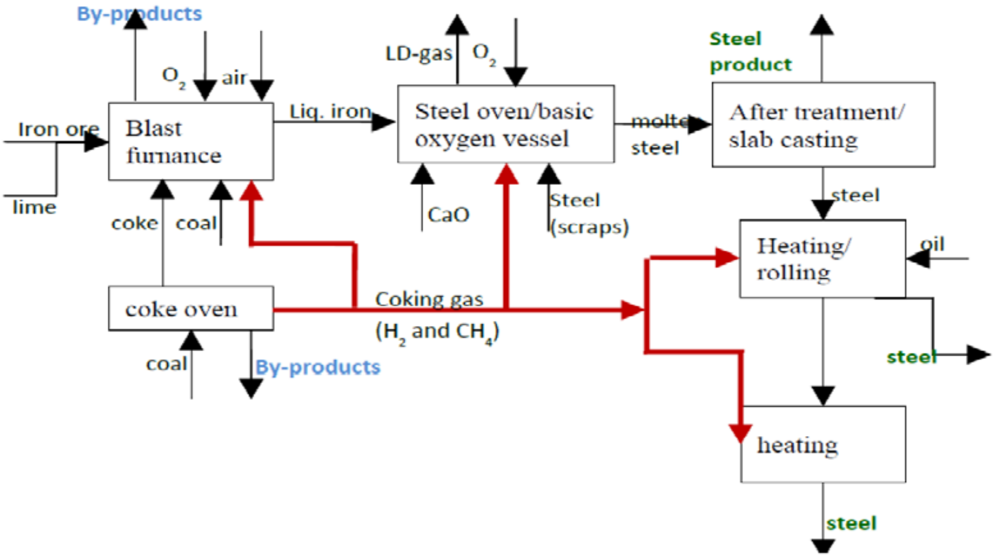

Fig. 17: SSAB Oxelösund process with potential of waste heat sources [Martin and Setterwall, 2008]

6. Potential applications of membrane distillation: Case studies in Sweden

6.1 Fresh water supply to greenhouse irrigation/farming

A dependable irrigation water supply is a vital component of any greenhouse growing operation. In the past, the quality of the water source was not a cultural issue considered by growers. They did, however, incur fertility problems that often defied explanation. Over the past 10 years, a better understanding of how water quality can impact potting media pH, soluble salts, fertility, and plant growth has made water quality a critical issue in greenhouse crop culture. Water, in terms of both quantity and quality, is crucial to the success of horticulture greenhouse production. Greenhouse production uses large volumes of water for irrigation, estimated at 2 quarts per square foot (20 L/m^2) of covered area per day [Bailey et al., 1996]. Therefore, a one-acre (0.4 ha) greenhouse uses approximately 22,000 gallons (84 kL) of water per day for irrigation purposes [Bailey et al., 1996]. As water supplies are often limited, and therefore, using low-quality irrigation water may reduce crop yields or damage the environment, soils, and aquifers. For instance, salts applied to soils via irrigation are either left in the soil to harm subsequent crop growth or are leached below the root zone to affect groundwater [Tanji & Enos, 1994]. Also, there can be long-term damage to soils and aquifers that may not be easily recoverable. Moreover, high quality water is required for a number of reasons, including the prevention of plugging of nozzles, staining of foliage and containers, excessively high substrate salt levels, and improper substrate pH [Bilderback et al., 2017]. The water source may contain essential nutrients such as iron or nitrate in high enough concentrations to justify a reduction in levels applied through a fertility program. Water may also contain harmful impurities that require corrective procedures. Water quality can be a deciding factor when choosing among sites for establishing a new greenhouse business or, where the opportunity exists, to choose among two or more water sources at a particular site [Kessler, 2005]. Ghermandi and Messalem [2009] quantified that a transformation from irrigation with brackish water to desalinated water would result in a 45% reduction in the volume of water required for crop production. This kind of change in water management could lead to a 34% saving in groundwater extracted. Moreover, the crop yield could increase by 24% when irrigated with RO permeate and 18% when irrigated with NF permeate with respect to brackish water irrigation [Ghermandi and Messalem, 2009]. The increase in yield is caused by the lower salinity level of the irrigation water applied [Quist-Jensen et al., 2015].

For irrigation purposes, the water temperature must be as close as possible to that of the plants and the layer of substrate containing the root systems. Low temperature water contributes to modify the soil temperature [Wierenga et al., 1971] which, in turn, reduces the root activity in terms of water and nutrient uptake from and to the roots (of carbohydrates and of growth metabolites, respectively). Warm water can be used advantageously to warm crops as well as supply water needs; however, water at a temperature of over 35 °C is dangerous to plants [Fao, 2013]. The optimum pH of irrigation water is commonly between 6.5 and 7.5; the minimum acceptable limit is 5.0 [Fao, 2013].

The majority of the studies conducted on wastewater applications in agriculture have focused mainly on reclaimed urban effluents. The aim of the present study is to determine the effects of secondary treated agro-wastewater on crop production performance. In particular, the objectives of the study were: (i) to evaluate the effects of the agri-wastewaters on qualitative and quantitative aspects of crops production; (ii) to assess the impact of the wastewaters on the microbiological contamination of vegetables and the microbiological soil properties.

Wastewater treatment and reuse is another opportunity to minimize the pressure on natural fresh water resources. Membrane distillation a thermally driven separation/purification technology can produce fresh safe water which not only purify low quality waste water but also keep the water temperature at certain level. The technology saves recycled water and potentially recover waste heat also.

6.2 Nutrient recovery and green fertilizer production for organic greenhouse farming

”Det är lagstadgat i Miljöbalken, 9 kapitlet, att man inte får släppa ut avloppsvatten i mark, vattenområde eller i grundvattnet. Med avloppsvatten menas även näringsrikt spillvatten från växthus” [Jordbruksverket, 2007]. The organic greenhouse production in the Sweden is limited with regard to the number of farmers, but plays an imperative role in EU organic greenhouse production. Treated wastewater not only offers an alternative water irrigation source, but also the opportunity to recycle plant nutrients [Chen et al., 2008]. Waste/drained water from agricultural production facilities such as greenhouses, dairy milking centers, and vegetable washing facilities may contain nutrients, pesticides, pathogens, and cleaning and sanitation products. This effluent, if not managed appropriately, can contaminate soil, surface water and groundwater. Greenhouse farming facilities can generate large volumes of wastewater rich in organic contaminants and nutrients, and can therefore be strong candidates for treatment processes aimed at recovery of both energy and nutrient resources. For example, during a tomato production season, about 800-1000 m^3 fresh water is supplied per 1000 m^2 of greenhouse space and out of this water about 20-25% drained off and become waste, if there is no recirculation system in the greenhouse [Månsson, 2012]. Re-circulation of the nutrient solution is environmentally beneficial and can potentially reduce water consumption by 25-30% and fertilizer usage by 30-40% [OMAFRA, 2010]. According to Jordbruksverket [2007], treated recycling water and nutrients recovery can save about 20-25% water and as well as fertilizer. The nutrient composition of the drainage water varies over the season, but is generally high in nitrogen. Considering a sustainable development of the Swedish greenhouse industry, it is therefore important to reduce the nutrient levels in the water before it is drained away. Technologies exist to collect, treat, and in some cases reuse these agricultural waste water streams. In the case of greenhouse production, leaching waters can be treated, nutrients recovered, and then re-circulated.

Fertilizer is one of the most significant on-farm input cost (ca 25%) for modern agriculture. Price instability due to a substantial increase in world demand for fertilizers, limited recourses (P and K) and costs associated with production has put financial pressure on farmers in Sweden [Batstone et al., 2009]. So, there is a need to assess nutrient resources from the Swedish agro-industrial waste streams and their potential for processing into mineral fertiliser products.

Nutrient recovery from agro-industrial wastewater could be economically beneficial, particularly when combined with energy recovery, and provides an additional revenue stream to intensive agriculture, while reducing greenhouse gas emissions, and providing a competitive, renewable fertilizer stream. Additionally, chemical fertilisers contribute to greenhouse gas emissions, fossil fuel use, use of non-renewable phosphate rock and a flow of reactive nitrogen to the biosphere, exceeding the planetary boundaries. Recycling of plant nutrients from waste and by-products from society would reduce the use of chemical fertilisers. These plant nutrient sources are also of interest for organic farming, where chemical fertilisers are not allowed.

The major concern is that the farming water that horticulture greenhouse growers recirculate comprises crop protection agents, nutrients and other constituents that do not take place naturally in the environment [TNO, 2017]. When concentrations of drained water/wastewater are too high with unwanted contaminants, the water has to be discharged or cleaned. In this circumstances, membrane distillation could be an effective option to recover the nutrients and fertilizers from the greenhouse wastewater.

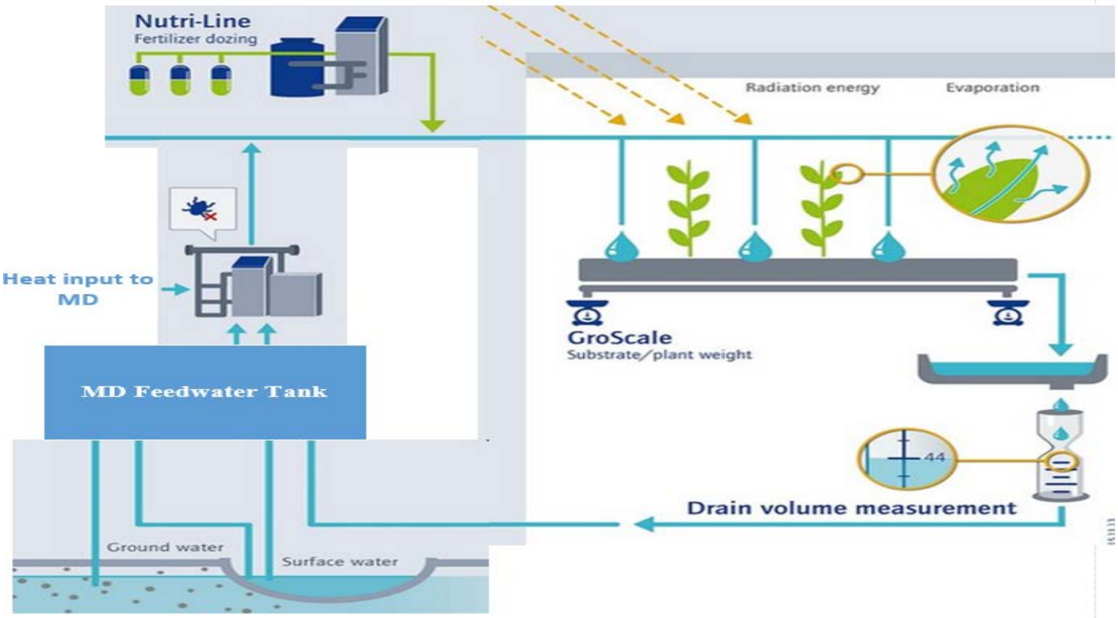

Fig. 18: MD water supply and nutrients solution in a close circulation greenhouse production

The key objectives of the project are to demonstrate waste water purification and nutrient recovery technologies at pilot scale, develop novel purification and nutrient recovery technologies, and agronomic testing of the recovered product.

The goal is to develop an efficient membrane distillation system that removes water while retaining the important nutrients. The project will calculate the energy needed to achieve varying levels of water removal. The amount of plant nutrients that may be removed along with the water will also be measured. An objective is also to investigate if it is possible to use heat from waste grey water, industrial waste heat or solar panels to power the distillation process. At the end of the project, an outline of a complete system for the removal of water will be presented.

6.3 Legionella free hot water supply to Swedish hospitals

Legionella bacteria is commonly found in water. The bacteria multiply where temperatures are between 20-45°C and nutrients are available. The bacteria are dormant below 20°C and do not survive above 60°C. Legionnaires’ disease is a potentially fatal type of pneumonia, contracted by inhaling airborne water droplets containing viable legionella bacteria [HSE, 2017].

Each year, between 100 -150 Swedes has been infected with dangerous legionella bacteria, partly driven in water systems in apartment buildings, public institutions, such as shower installations in swimming pools, sports halls, hospitals and nursing homes. Statistically 15 out of 100 infected people die of Legionnaires' disease [Boverket, 2011].

Until recently, the shower system did not have a routine for Legionella control. Previously they rinsed the shower system at night by flushing 70 ^{o}C hot water through the pipes, which would kill the bacteria but the hot water did not remove the biofilm in the pipes where bacteria grows, therefore this method is not safe [Boverket, 2004]. Growth of Legionella bacteria is reported in up to 70% of hospital water distribution systems and a water temperature of 40 to 50 ^{o}C seems ideal for Legionella colonization [Darelid et al., 2002].

Membrane distillation a thermally driven separation/purification technology can produce ultra-pure water which not only remove legionella but also keep the water temperature at safe level. The technology saves recycled water and potentially recover waste heat also. The purification system ensures that the shower water is completely free from Legionella bacteria, which otherwise poses a significant threat to patients with reduced immune system capacity, and thereby also is a major cost in preventing it from spreading.

The goal of the task force was to develop and implement prevention and control measures to minimize the risk of legionella and to control and eliminate legionella in the hospital potable water systems.

6.4 Fresh drinking water supply to Öland och Gotland islands

”Vattenfrågan har alltid varit viktig på Gotland - Water questions have always been important on Gotland” [Bastani et al., 2015]

Sweden is generally regarded as a country with good raw water sources. However, water shortage can occur in coastal areas and the archipelago, and the deficiency is becoming more pronounced due to population growth and the conversion from part-time to permanent housing. Record-low groundwater levels have been recorded on the islands of Öland and Gotland in southeastern Sweden and may lead to a severe shortage of drinking water this summer. Due to several factors, the Swedish island faces severe water shortages during the summer and is in urgent need to address this in the light of an expected growing number of people coming to Gotland [Gotlands Kommun, 2005]. In combination with a drop in the groundwater level, the island faces the challenge of historically caused run-offs of freshwater in combination with an extreme peak of visitors during the summer, when the water situation is already tensed [Gotlands Kommun, 2005; Johansson, 2003; SMGI SGU, 2017]. The regional government on Gotland has invested in a new desalination plant that it hopes will help solve the problem. On the island of Öland, trucks have shuttled water from the mainland several times a day for the past few weeks, and on the island of Gotland trucks carrying water have been running daily from the main city of Visby to different areas along the coasts. In an attempt to conserve water, the regional government on Gotland has even passed a watering ban, limiting the use of water to drinking and cooking only. A severe water shortage in the summer when the population on both Öland and Gotland often increases dramatically because of tourism.

The island Gotland is used as a case study to investigate the feasibility of various options for dealing with water shortage. Gotland was also included to identify the needs and requirements for an innovation procurement in order to solve the drinking water supply in areas of water scarcity. Finally, the study should include a market review of technology as the basis for an innovation procurement.

Integrated membrane distillation could be an alternative option to provide fresh water in this region. Waste heat from cement industries, district heating network (especially in summer) or renewable energy sources like wind, solar thermal or biomass could be sources of heat.

The aim of this project is to conduct a feasibility study for an innovation procurement of water supply technologies for areas of water scarcity, and to find opportunities for a sustainable water supply without compromising the local water resources. The focus of the study was technology for desalination and water reuse.

6.5 Water recovery using waste heat from existing power plants

Water is key input for thermal power plant. In industry it becomes more important to close water cycles. Closing water cycles and thus (internal) reuse of water relieves. Water stress on the environment and on other activities such as urban or agricultural water use. Industrial processes often need a considerable amount of fresh water [Koeman-Stein et al., 2016]. Recycled water provides a viable opportunity to supplement water supplies as well as alleviate environmental loads.

Large water consumers are cooling towers (CT) using 60–70% of the total fresh water demand in power plants [Wang et al., 2008]. In the cooling tower, water evaporates resulting in an increased concentration of salts and other contaminants. This leads to problems such as scaling and corrosion. Hence the concentrated cooling tower water is regularly discharged from the tower. This discharge is called cooling tower blowdown water (CTBD). Make-up water is added to the tower to compensate for the evaporated water and the CTBD. When the blow down water can be reused, after treatment, this will save the need for about 15% of the make-up water [Altman et al., 2012].

The fouling of boiler heat transfer surfaces can be minimized by ensuring proper boiler chemistry is maintained. Specifically be reducing the impurity levels that are suspended in boiler water. Removal of these impurities has been a problem ever since boilers started to operate. Draining then adding new water to the boiler has been the most used method to reduce these levels. These operations are known commonly in the boiler operation field as boiler blow down.

Table 1: Water quality for reuse and recycling [Veolia water, 2017]

Application for reuse and recycling water	Common quality issues	Pollutants to be removed and/or controlled
Industrial water	Dissolved solid content, iron and manganese content	TSS, Fe, Mn
Cooling make-up water	Corrosion, biological growth and scaling, disinfection in case of aerosol risk	BOD, TSS, Turbidity, silica, pathogens, legionella
Boiler make-up water	Thermal exchange limitation, steam quality reduction, scaling, corrosion	Dissolved solids, hardness, alkalinity, conductivity
Process water	pH, solids, silica, dissolved solids and chloride, pollutant concentration, bacteriology, compliance with process water specification	As appropriate to the application: pH control, dissolved solids, chloride, specific pollutant concentrations

MD systems may be a technology that can use the low temperature waste heat (below 90ºC) to treat water. By their nature, they operate at low temperature and usually low pressure. This study investigates the use of MD to recover water from typical power plants. Membrane distillation technology uses a lower amount of energy as the driving force to clean water in comparison to more traditional reverse osmosis or nanofiltration membranes.

The goal of this project was to test the feasibility of reducing the makeup water requirements for a power plant by treating non-traditional water sources (e.g., saline groundwater, boiler blow down, cooling tower blow down, condenser cooling and power plant cycle make-up water and make-up water supply in the district heating line) using power plant waste heat in conjunction with MD. The potential benefits are the production of high quality water for cooling tower and boiler makeup utilizing non-traditional water sources.

7. Waste heat driven membrane distillation for nutrients and water recovery from agri-waste/brackish/greenhouse drained water: A case study for Swedish greenhouse production

Increasing the inputs of nutrients has played an important role in increasing the supply of food to a continually growing world population. In the same time, improved supervision of all vital nutrients is required that delivers sustainable agriculture and maintains the necessary increases in food production while minimizing waste, economic loss and environmental impacts [Goulding et al., 2008]. Current fertiliser production heavily relies on the consumption of non-renewable energy and finite mineral resources. For example, the generation of ammonia from air in the Haber-Bosch process requires 35-50 MJ per kg nitrogen in the form of fossil fuel for energy supply [Desloover et al., 2012], which accounts for 2% of the world energy use. Phosphorus mining leads to a huge amount of gypsum by-products that are contaminated with heavy metals and radioactive elements [Ashley et al., 2011]. More alarming, the forecasted phosphorus production peak is approaching in 2030, with an accelerated depletion of minable phosphorus rock [Elser and Bennett, 2011]. The use of fertiliser to meet food demand also carries a heavy burden for wastewater treatment processes. Once through production and application of fertilisers results in major nutrients (nitrogen and phosphorus) being primarily found in wastewater. It is estimated that 30% of nitrogen and 16% of phosphorus in fertilisers ends up in wastewater [Rahman et al., 2014; Verstraete et al., 2009]. According to grodan [2016], careful managing of water and nutrients combined with recycling the drain water in greenhouse will assist the industry in several aspects like;

- Reduce total fertilizer input and use organic nutrients
- Save costs
- Optimize the growth of your crop
- Secure the availability of sufficient and clean irrigation water
- Secure the availability of a sufficiently wide range of plant protection products
- Protect the environment
- Comply with legislation

Water to be utilized in the agricultural sector especially in greenhouse production has to address specific quality requirements in order to obtain an optimal production rate of irrigated crops. At the same time, taking into account the huge amount of water necessary in agriculture, a proper and sustainable management of water resources together with an efficient water supply network is necessary to minimize losses, leaching and drainage (phenomena that can cause elevated concentrations of salts and nutrients in nearby soils and water bodies). Treated wastewater from greenhouse not only offers an alternative water irrigation source, but also the opportunity to recycle plant nutrients [Chen et al., 2008]. Its application might ensure the transfer of fertilizing elements, such as nitrogen (N), phosphorous (P), potassium (K+), organic matter, and meso-nutrients and micro-nutrients, into agricultural soil [WCED, 1987]. On the other hand, as the economic costs of energy and the negative externalities associated with the combustion of fossil fuels threaten the economic viability of greenhouses in cold climates there is a renewed interest in the use of industrial waste heat.

Recycling technologies offer several advantages: significant water and fertilizer savings (50%-70%), enhanced quality yields, (as the result of increasing water applications), improved availability of nutrients and more efficient flushing, which reduces ground water contamination and ecological damage in agronomic regions [Netafim, 2017].

The Swedish greenhouse industry is primarily heavily dependent on heating source (because of cold weather), water and nutrients to plants to grow a variety of vegetable crops including cucumber and tomato. The nutrient rich drainage water from these greenhouses is generally released into the local environment causing pollution concerns. This study is initiated to investigate the opportunities to use waste heat for heating, and recycling drainage water to increase water and nutrient-use efficiency of greenhouses production and reduce the environmental impact of the drainage water discharge.

7.1 Greenhouse production and membrane distillation integrated with power plants/industrial waste heat

The purpose of a greenhouse is to allow the cultivation of horticultural crops outside of their traditional climatic zones and requirements. The primary objective of a greenhouse is to produce higher yield outside the cultivation season, which is possible by maintaining the optimum temperature at every stage of the crop. For example, in Sweden greenhouses are used to provide “hot house” tomatoes essentially year round to compete against imported produce from countries with more favorable climatic conditions.

In case of greenhouse cultivation, thermal energy associated expenditures can be significant. According to De Pascale and Maggio [2005], the cost of energy used to condition greenhouse air accounts for 20% to 30% of the total production cost in Italy. In the North European countries, the energy cost can be higher than 50% of the overall production cost [Greenergy, 2008]. Canakci and Akinci [2006] analyzed the energy use pattern and the result showed that the consumption of energy for heating accounted for 54% to 62% of the total energy used in the greenhouse operation.

Large industrial factories, power generating stations and all kind of process industry all produce waste heat during different processes generally in the form of flue gases or warm water. The high or medium temperate waste heat can be used for many applications, however low temperature waste heat has a few usages or no use. Heating is one of the main costs for greenhouse especially in the cold regions like Sweden, so it is very clear that the use of waste heat for greenhouse space heating can bring economic and environmental friendly benefits both for industries and greenhouse owners.

High water quality is particularly important in organic greenhouse production in order to prevent soil salinization and ensure optimal soil biological activity. Indeed, unbalanced organic fertilizer inputs may contribute to soil salinity, while soil microbial activities responsible for nutrient mineralization, soil suppressiveness and plant health, are affected by soil pH, ions, and contaminants. Additionally, drained greenhouse wastewater nutrient recovery holds promise for more sustainable water and agricultural industries. Moreover, greenhouse drained/wastewater nutrient and/water recovery is anticipated to become a promising strategy to sustain fertiliser and food production, and at the same time, potentially bring benefits to wastewater treatment facilities [Grant et al., 2012; Guest et al., 2009; Verstraete et al., 2009]. One of recent study showed that the reclaimed of the drainage water resulted in a 33% reduction in potable water used for irrigation in cucumber production and the drained water contained 59% applied N, 25% applied P and 55% applied K and that illustrated the potential for nutrient recovery [Grewal et al., 2011].

In these above circumstances, industrial waste heat integrated with membrane distillation and greenhouse production could be an interesting combination in order to reduce costs of energy, recover the fresh water and organic fertilizer as well as save the environment.

The main requirements for the greenhouse productions are; i) Water: Access to large volumes of clean water is essential for a commercial operation, ii) Heat Supply: A heat supply is traditionally provided by natural gas (the most common method), fuel oil or coal, but can be supplied by industrial waste heat, and iii) Organic nutrients: Optimum amount of organic nutrients is necessary for proper growth crop yield.

The majority of the studies conducted on drained water applications in greenhouse production have focused mainly on reclaimed wastewater. The objective of this work was to quantify the performance of membrane distillation in terms of separation and purification efficiency and water production rate and analyze the use of thermal energy consumption in MD and commercial Swedish greenhouses. Furthermore the aim of study is to investigate how MD is perform under different operating conditions.

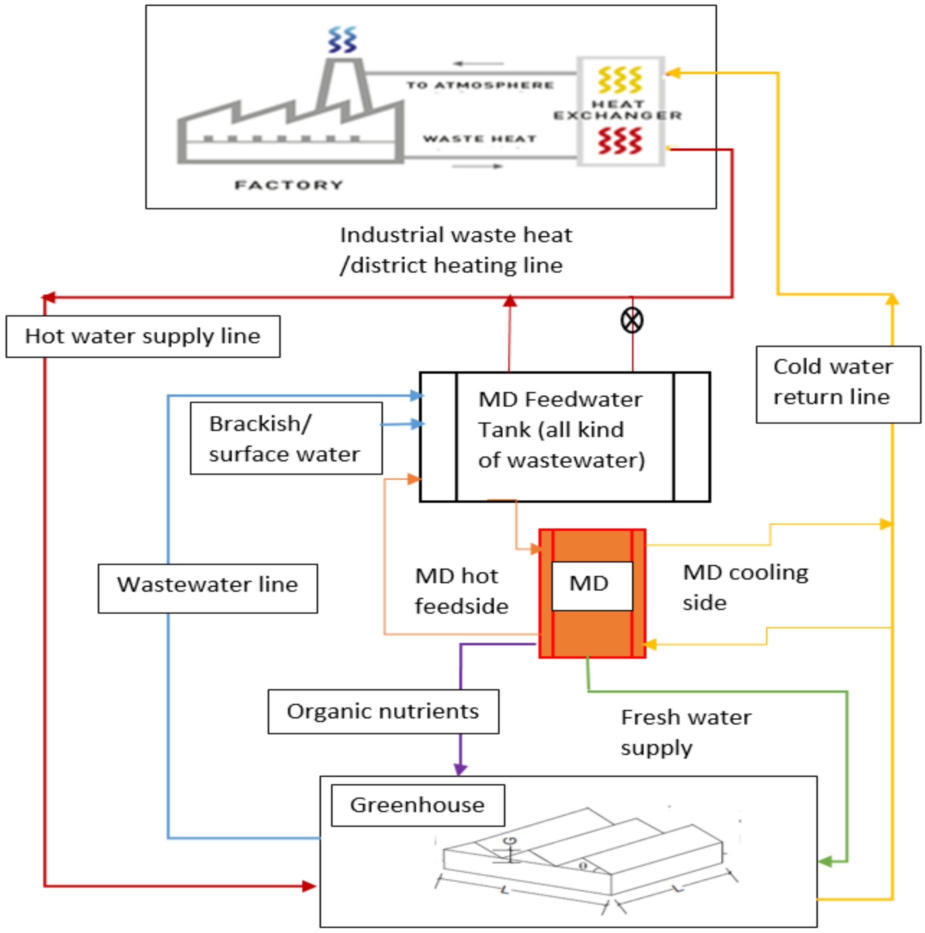

Fig. 19: Greenhouse production integrated with membrane distillation and waste heat

In the greenhouse heating system [Fig. 19], available waste heat from industry is used to heating up water and the hot water is delivered to the greenhouse for keep the inside temperature at certain level. The average temperature of the inlet water in circuit is about 82°C and of the outlet water 37°C. The heating pipes were located both below the crop beds and above the plant canopy. The integrated system consists of waste heat source, greenhouse production facility and membrane distillation unit. Part of the waste can be delivered to feedwater (drain water, surface and other source of water) in order to drive MD and the cooling side of the MD is heat exchanged with hot water return line. Scalability of the integrated system is dependent on the size of individual components and available waste heat.

7.2 Materials and Methods

For the purpose of sizing a representative greenhouse production system, a medium size plant has been considered in this investigation.

1. Greenhouse facilities:
2. Waste heat availability:
3. Field characteristics and feed preparation:
4. Water treatments and MD experimental design:
5. Mass and energy analysis of the integrated system:
6. Life cycle analysis:

7.3 Conclusions remarks

Waste heat integration of the membrane distillation with existing nutrient precipitation processes could substantially improve nutrient recovery efficiency, and diversify the nutrient product that can be extracted, even achieving a near complete wastewater nutrient recovery. The primary study reveals that there is a significant potential to save water and nutrients and protect the environment by shifting from non-reuse systems to reuse systems in greenhouses.

8. Discussion

Membrane distillation has been shown to be a promising separation/purification technology not only for water purification applications in process water production for industries, but also for recovering valuable by-products and removing pollutants from wastewater effluents. The work presented some potential applications of MD systems integrated with district heating (DH) net, CHP plants, cement and process industry networks that could be preferred over current practices in the industries.

The fluxes of membrane distillation are lower than those for NF and RO. However the energy required to get the flux by membrane distillation is mostly low grade heat and a small amount of electrical energy is required for pumping, while the flux for nanofiltration and reverse osmosis is completely driven by electrical energy.

Varying composition of nutrient-rich waste stream can pose distinctive challenges to MD in nutrient recovery [Meng et al., 2014; Tijing et al., 2015; Van der Bruggen, 2013]. The volatile organic compounds, such as volatile fatty acids that exert partial vapour pressures comparable to or higher than water are transported across the MD membrane with the water vapour, causing contamination of the permeate stream and jeopardising the quality of recovered ammonia fertiliser.

Possible implementation of MD technology in the near term would first require the resolution of a few issues. The permeate flux is relatively low comparing with the recirculation rate, which has a negative impact on the electricity consumption. To be able to overcome this problem, appropriate redesign of the module that takes in account enhancing the mass transfer and increasing the membrane area per module volume (compactness) is needed.

Wastewater streams normally include many chemicals that could potentially lead to membrane surface fouling and membrane pore wetting, is another major challenge [Shirazi & Kargari, 2015]. Hence, fouling of membranes due to other organic components in the feed affects the frequency at which they should be cleaned or replaced which affects the cost of purification. Fouling cannot be fully prevented even with optimized pre-treatment. Therefore, periodical membrane cleaning has to be performed. Qaisrani and Samhaber [2011] have evaluated different methods for fouling reduction and the enhancement of trans-membrane flux including enhanced cross-flow velocity, air bubbling, backflushing and combination of backflushing and air bubbling. Moreover, membrane scaling led to flux declines, but flux was easily restored using an acid clean. Scaling was found to be effectively managed by cleaning or the addition of anti-scalant [Camacho et al., 2013].

The AGMD module was directly integrated with solar collectors without external heat exchanger to achieve higher performance by reducing heat losses. However this integration has a disadvantage in that the solar collector should withstand seawater and requires high solar irradiation during operational hours due to absence of thermal storage [Kumar et al., 2016].

Pilot plant trials will allow for a more detailed evaluation of this technology under actual operating conditions (especially at higher temperature levels which could not be tested in the present experimental facility).

In conclusion, membrane distillation processes are promising technology for approaching water and nutrients solutions in the agricultural industry. The various techniques both as stand-alone units and in integration can address the different water qualities required by the agricultural industry according to crop selection, soil and existing water resources. Moreover, the possibility of having small and large scale plants together with centralized and decentralized systems according to the specific requirements in the given area makes membranes an interesting answer for water/and nutrients production in agriculture.

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