UTILIZATION OF EXHAUST STEAM OF WASTE TO ENERGY (WTE) POWER PLANTS FOR WATER DESALINATION

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EXECUTIVE SUMMARY

There are over one thousand waste to energy (WTE) plants operational around the world to recovery energy and generate electricity from 250 million tons of municipal solid waste (MSW) per year. The most common WTE plants are electricity-only producers and use the heat of combustion to produce steam that powers a turbine generator. To maximize electricity productivity, the exhaust steam from turbine is sent to an air or water cooled condenser, then recycled to the boiler. For a typical WTE plant of 10 t/h capacity, the gross electricity generating capacity is about 6 MWh/hour, which in the U.S. represents about 20% of the energy contained in the MSW combusted. Such plants do not make use of the energy contained in the exhaust steam from turbine.

To improve the energy efficiency of WTE plants, many European WTE plants are combined heat and power (CHP) facilities. These facilities sell the extract or exhaust steam from turbine for district heating (DH) system. A CHP WTE plant of 10 t/h capacity and 50% steam extraction can produce up to 5 MWh/hour of electricity plus 31,000-62,500 MJ/h of heat. Although 20% of electric power is sacrificed, the overall efficiency increases from 20% to at least 65% compared to the condensing WTE plants. heat recovery system, the thermal efficiency for these facilities can reach 80-90%.

However, the use of the WTE exhaust steam for district heating is limited to climates with cold winter and also by the cost of DH transmission system construction.. This thesis examines another option for utilizing the turbine exhaust steam as an energy source for thermal water desalination.

Desalination refers to processes that remove salt and other minerals from saline water to provide freshwater. Almost 16,000 desalination facilities have been built worldwide, producing over 70 million cubic meters of potable water. Water desalination uses either thermal or membrane technologies. Main technology includes electricity powered reverse osmosis (RO), steam and electricity powered multiple-effect distillation (MED) and multi-stage flash evaporation (MSF). With lower energy consumption of 1-7 kWh/m^3 and decreasing cost of 0.1-1.0 USD/m^3, membrane (RO) desalination is a preferable choice for most desalination plants and represents 60% of the installed capacity worldwide. The MSF desalination units have a relative high temperature demand, 100-130°C for feed steam and 90-120°C for operation, resulting in an higher energy consumption of 13.5-25.5 kWh/m^3 electrical equivalent and cost of 0.5-1.75 USD/m^3. The MED process can operate with low pressure (0.3-0.5 bar), low temperature (70-90°C) steam by nearly vacuum pressure condition. With lower electric consumption of 1.5-2.5 kWh/m^3 than MSF, the typical production cost of MED is around 0.7-1 USD/m^3, competitive to RO technology..

Inspired from CHP plants for DH, two power-desalination cogeneration plants were examined in this study: The St. Barth WTE-desalination cogeneration plant in

the Caribbean and the Hebei Huanghua power-desalination plant in China. With only 1.5t/h MSW capacity, the St. Barth WTE plant sells 67% of recovered energy to the MED desalination plant which produces 1350 m^3 freshwater per day. The heat consumption for potable water production is 8.6MJ/m^3 (40.6kWh/m^3). In addition, about 8.5% of the chemical energy in the MSW is transformed to electricity, sufficient for the electric consumption of both the WTE and the MED process. In brief, this plant helps St. Barth to deal with its MSW while also solving the water supply issue of the island.

The Huanghua power plant is a coal-powered plant with 2,520 MW generation capacity, located on the Pohai Gulf of China. An estimated 3,200,000-4,400,000 m^3 of freshwater is consumed annually as feed-water for the boiler units, as well as for desulfurization and other processes. Huanghua solved this massive water consumption through several coupled MED desalination units which use the turbines' exhaust steam as the heat source. These MED units produce 57,500 m^3/d of fresh water and consume 40% of the energy in the coal input. In addition to meeting its own needs, the plant also produces up to 10 million tons of freshwater for use (14,000-28,000 m^3/d) by the Port of Huanghua. With this combination of electricity and freshwater production, 90% of total energy in the coal to the plant is transferred to valuable products, resulting in an estimated saving of 500 tons per day of coal.

This study showed that the cogeneration of power and water is an ecological and economical solution, both for WTE and fossil fuel-fired power plants. Considering the benefits and requirements of WTE-desalination cogeneration plants, the most promising places for this technique are those tropical islands or gulf cities with little access to land, fuels and waters. Suitable regions include the Mediterranean Sea (Cyprus, Crete, etc.), Persian Gulf countries (Kuwait, Bahrain, Oman, etc.), Caribbean Sea islands, the Red Sea, etc. The cases of Cyprus and Union Territory of Lakshadweep (India) were analyzed. This study also included the energy and resource side benefits. However, additional cost-benefit analysis is necessary for a specific geographic area.

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1. Background

Thermal energy can be recovered from municipal solid waste (MSW) by incineration before it transports to landfilling, typically being output in the form of steam, electricity or hot water. Simultaneously the volume of waste can be reduced by up to 80%-90% with a mass reduction of 50%. According to a 2012 market report published by German environmental consultancy, ecoprog, there are 2150 thermal waste to energy (WTE) plants operational around the world with almost 250 million tons waste treatment capacity per year. In addition, 250 new waste to energy facilities with a total capacity of 70 million tons per year will be commissioned by 2016, mainly leading by the investment of China and Europe[1]. The most proven and dominant WTE technology is mass burning, or grate combustion, due to its simplicity of operation, high availability and relatively low capital cost. Of over 800 main WTE plants in the world, about 600 of them choose mass burn technology. Various types of grate are available depending on the way that the waste is fed on to the combustion grate, including horizontal grate, forward-moving grate, reverse-acting grate and roller grate[2].

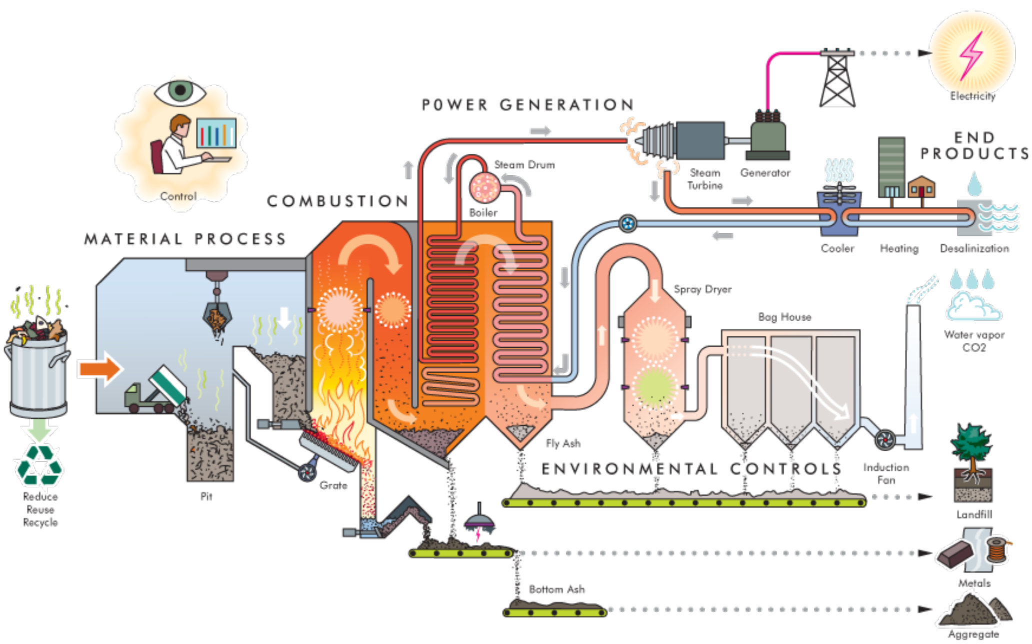


Figure 1 WTE Process and Application

With similar technologies, the utilization of energy recovered from MSW is of several different type. In the majority of countries like US and China, the most common WTE plants are electricity-only business. They use the steam produced by combustion to drive the electricity generation turbine, the exhaust steam from turbine is sent to a condenser for cooling, then recycled to boiler or injected into natural water system. It should be noted that such process makes very little use of the energy contained in the exhaust steam from turbine and losses over 60% of the energy released from the controlled combustion of MSW. Taking United States for instance, 62 of its 84 WTE plants generate electricity as their only energy product. Based on its share of market, about 11 million megawatt hours of electricity is generated in 2012 while over 20 million megawatt hours of energy from MSW lost[3]. Possible application of this part of energy, however, is finite due to the relative low pressure and temperature characters of exhaust steam. To reduce the energy losses of electricity from power generation, countries like Europe and South Korea uses energy recovered in different ways. Many of their WTE plants are heat-only facilities or combined heat and power (CHP) facilities. These facilities provide heat energy as their product in the form of steam or hot water and sells it for district heating and cooling (DHC) or for other related industrial production processes. The thermal efficiency for these facilities are typically around 80%, much higher than the electric business plants. Besides, tangible economic benefits can be achieved at the same time. Based on the success in Europe, DH is a great choice for many places to fully utilize energy in exhaust steam. However, this application restricted by the high request and cost of DH transmission system construction as well as the suitable climate condition of the area. Currently a new choice is posed by the worldwide fresh water scarcity -- using the exhaust steam as an energy source for thermal water desalination.

Water desalination refers to processes that remove some amount of salt and other minerals from saline water to provide people with needed freshwater. With limited fresh water resources (1%) and continuous growing population, the scarcity of fresh water and the need for additional water supplies are already posing major problems for more than a billion of people around the world. This issue is significantly critical in many arid regions of the world and many of them even do not have surface fresh water resources such as rivers and lakes, and many only have limited underground water resources. The World Health Organization predicts that by mid-century, four billion of us—nearly two-thirds of the world's present population—will face severe fresh water shortages. Recent advances in technology have made seawater desalination a realistic and most promising solution to supply fresh water.

In the past 45 years, the desalination industry has grown from virtually zero, to over 70 million cubic meters of treated water per day and almost 16,000 desalination facilities have been built worldwide. Up till 2012, seawater has already accounted for almost two-thirds of all feed water[4]. Stimulated by the thirst of water and abundant oil supply, the desalination market is led by Middle East, the Gulf States, with a share of 53.4%, followed by North America (17%) and Europe (10%)[5]. Technology advancement and wide adoption of desalination also causes a significant cost cut-down which in turns further accelerate the development of desalination market. The cost of desalinated water has downed to 0.45~1 US$/m^3 in 2013 compared to the 9 US$/m^3 in 1970, nearly compatible to the price of tap water in US (~0.53 US$/m^3). Consequently, transportation, energy and environmental costs have now replaced technology as the primary impediments to large-scale desalination and as the most dominated part, energy cost accounts to 30~45% of the total operative cost[6][7][8].

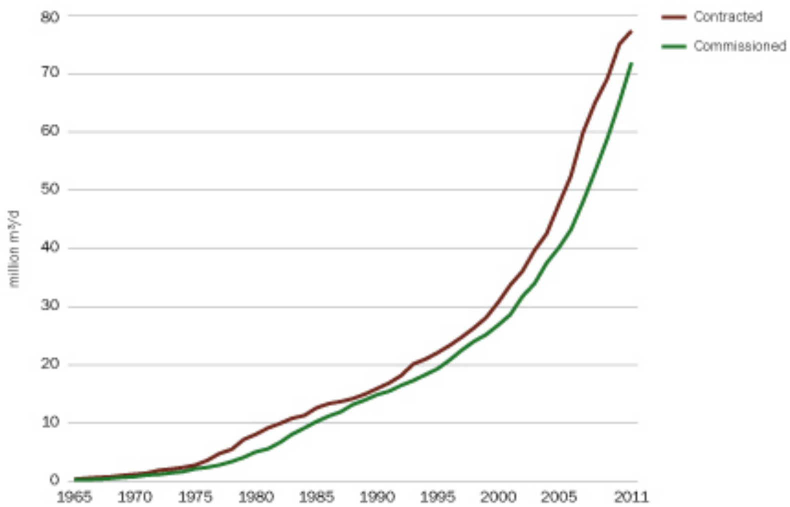


Figure 2 Cumulative contracted and commissioned desalination capacity 1965-2011[4]

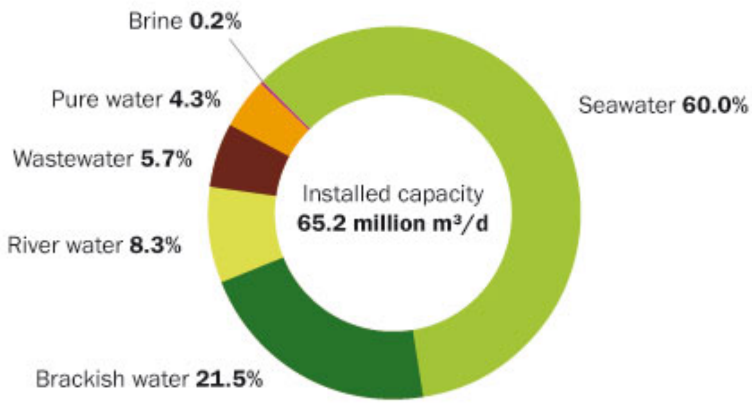


Figure 3 Total worldwide installed capacity by feedwater category[4]

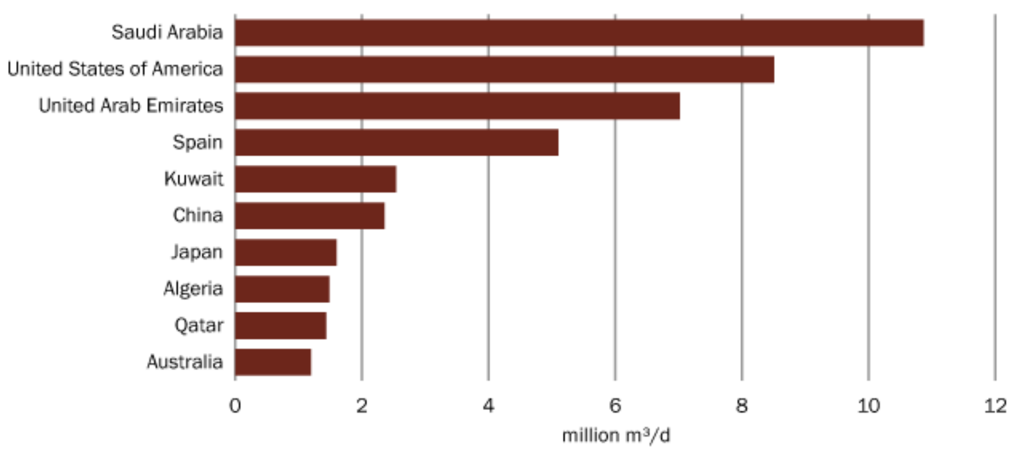


Figure 4 Top 10 countries by total installed capacity since 1945[4]

Water desalination uses either thermal or membrane technologies. Membrane technologies include reverse osmosis (RO), electrodeionisation (EDI) and electrodialysis (ED) and generally powered by electricity. Thermal technologies include multiple-effect distillation (MED) and multi-stage flash evaporation (MSF) and are powered by steam together with some electricity. As for sea water purification, all of the approaches mentioned is well developed and proved by practical production. With lower energy consumption and decreasing cost of membrane, membrane desalination is a preferable cost-effective choice for most desalination plants. It has grown rapidly since 2003, occupied 60% of the installed desalination capacity worldwide. Being more energy-intensive, the comparatively high price of steam is exceptionally believed to be the key blocker of thermal treatment development. Despite expectations of decline, however, thermal desalination also continues to grow. It may cause by the development of solar thermal technologies and its new bond to power plants. Saudia Arabia and the United Arab Emirates have led the thermal desalination market since the Gulf States access to abundant oil supplies.

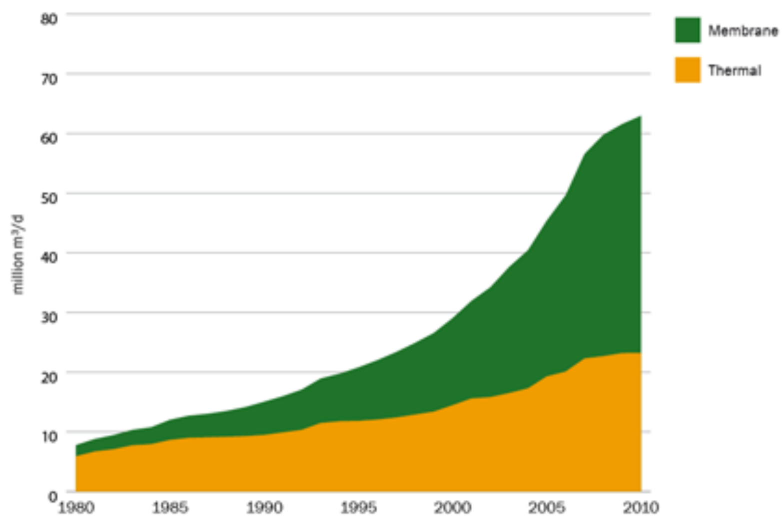


Figure 5 Installed membrane and thermal capacity, 1980-2010 (cumulative)

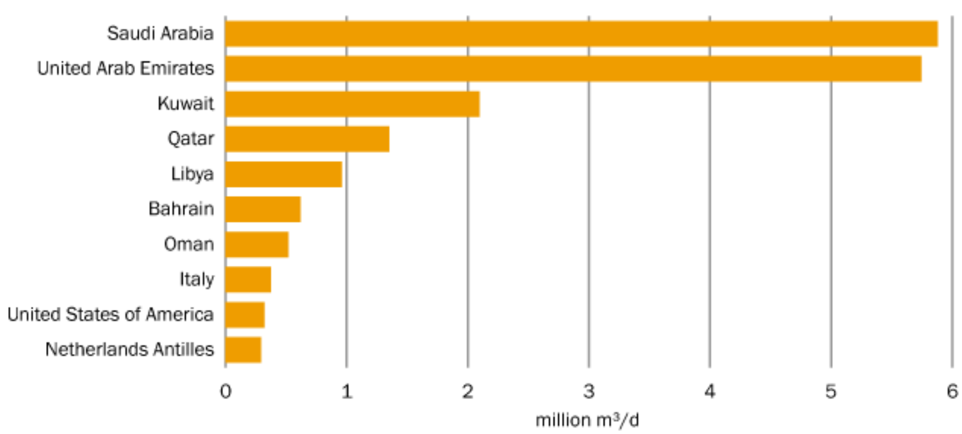


Figure 6 Top 10 countries by total installed thermal capacity since 1945

As is mentioned, some big-scale power-desalination cogeneration plants have been built recent years, mostly in Saudi Arabia area, to make use of the waste energy from nearby power plants cut down the energy cost of desalination. Similar to many traditional power plants, WTE plants also have considerable potential to be an energy supplier to thermal desalination facilities. This may highly increase the energy efficiency of WTE plants while create accountable fresh water to mitigate the water scarcity. This study aims at making an initial assessment of the possible benefits of using exhaust steam from WTE for water desalination by:

- Analyze and compare the energy flow and efficiency of existing exhaust steam treatment or application, including condensing and district heating;
- Analyze and compare the operation requirement, energy consumption and cost of most popular thermal desalination techniques;
- Case study of existing WTE-desalination plants;
- Based on the analysis above, suggest some places suitable for the development of waste-to-water cogeneration.

2. Energy Flow Analysis of Typical Exhaust Steam Utilization

2.1. Without Exhaust Steam Treatment and Utilization

2.1.1. Description of Process

WTE plant is designed to combust unrecyclable MSW and simultaneously recuperates the energy and cleans the gases generated from combustion[9]. By definition, waste incineration is carried out with surplus of air. This process releases energy and produces solid residues as well as a flue gas emitted into the atmosphere[10].

A schematic description of general incineration process is represented as Figure 7. As depicted, MSW is first discharged into and then extracted from a waste bunker by an overhead claw crane, then loaded into a feed hopper of WTE furnace and processed on a moving grate in order to achieve a correct combustion in combustion chamber[11].

The high temperature oxidation in the chamber reduces large particle MSW to ash and discharged at the lower end of the grate. Some of the ash is transported for landfilling while some can be reused in applications such as filling in the building and construction industries. To guarantee the high performance of combustion, the air is typically fed into the combustion twice. The primary air is injected from bottom of the grate, drying the MSW while provide oxygen for combustion; the secondary air is injected from top of the chamber, providing a circulate condition within the chamber as well as providing extra oxygen for unburned residuals. Additional fuels may be needed to ensure the combustion depending on the composition and heat value of MSW. The combustion product, called flue gases, then exchanges its energy with the boiler. The water in tubes within the boiler becomes superheated steam (high pressure) as heat transferred, and is sent to drive the turbine that generates electricity. Low pressure steam from the generator then exhausted for further treatment or use.

In terms of the steam turbine, it can be roughly divided into condensing turbine and non-condensing (back pressure) turbine. For a condensing steam turbine, it is operated with an exhaust pressure less than atmospheric to maximize the pressure drop through the turbine, thus greater the energy extracted from steam input (approx. 30-40% efficiency). The technology with condensing turbine will further be explained and analyzed in Chapter 2.2. The non-condensing turbine, on the contrary, is operated with an exhaust steam equal to or in excess of atmospheric pressure and is most widely used for process steam applications (refineries, district heating units, paper plants, and desalination facilities). The exhaust steam pressure can be controlled by regulating valve to suit the needs of the processes.

The flue gas cleaning system, or air pollution control (APC) system, ensures controlled emissions from WTE plants. A certain percentage of pollutant particles, however, will still be emitted into the atmosphere after treatment, depending on the composition of MSW and the type of APC system chose. The common pollutants are CO_2, N_2O, NOx, SOx and NH_3.

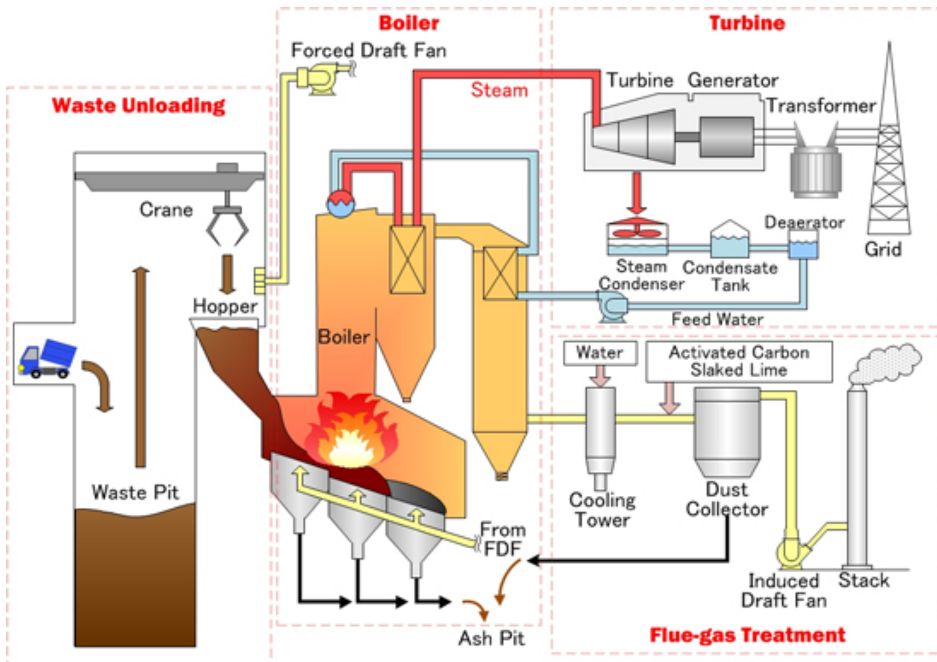


Figure 7 Schematic Description of WTE Plant

2.1.2. Thermodynamic Simulated Model of WTE Process

To assess the energy efficiency of the WTE processes mentioned above, a thermodynamic model is needed. According to the first law of thermodynamics, for an isolated system the total amount of energy is constant, that is to say the energy input equals to the energy output and energy losses. For this study, we define the WTE plant and the electricity generator unit as our study system and our main target is the flow of energy generated and used from the MSW. In this case, despite the extra fuels added to help the combustion and energy for preheating, other energy like electricity consumed by equipment operation will not be included in the calculation. This is because in most cases the electricity consumed is supplied by the plants themselves by detouring part of power generated for self-use before inject to grid. And to better analysis the energy transformation of this system, we divide the material flow into three parts:

1) Waste flow: this flow mainly indicates the flow of solid particles within the system, from MSW to bottom ash via incineration.
2) Flue gas flow: this flow mainly indicates the flow of gas phase within the system,

from the air preheated, injected into the combustion chamber, heated by incineration, exchanged with boiler and then exhausted after treatment.

3) Water flow: this flow mainly indicates the flow of water and steam within the system, injected water from outsource (municipal tap water), heated by boiler to steam, drive the turbine and then exhausted.

Certain percentage of energy will be lost due to radiation during the mass transportation and heat exchanging processes. From the three mass flow, it can be clearly clarified the input and output of energy of the simulated system:

Energy Input:
1) MSW feed;
2) Extra fuels assisting incineration (if needed);
3) Energy used for air preheating;
4) Energy used for feed water preheating.

Energy Output:
1) Electricity generated;
2) Energy remained in exhaust steam;
3) Energy remained in bottom ash;
4) Energy remained in exhausted flue gas;
5) Other energy losses during the process due to the radiation or efficiency of equipment.

To set a justified WTE system to calculate the energy flow baseline for this study, technological restrictions as well as emission and safety concerns must be taken into consideration. Steam temperature should be limited to avoid corrosion risks. In the case of mixed waste combustion, the average temperature range of combustion is between 1,000°C to 1,200°C[2] and the furnace temperature is 1,050 °C[11]. For China, the temperature is typically a lower range from 850~950 °C due to the low heat value of waste. Besides, for most APC system, the flue gases should not be cooled below 200 °C to avoid the risk of condensation of aggressive compounds[12]. Multiple researches and WTE facilities has been studied to ensure the parameter chose are logical and sensible. Operation parameters of some existing study models and WTE plants is summarized in Table 2.

According to the working data from studies, the simulated system runs as below:

1) Combustion System: The MSW (12MJ/kg, 10 t/h) is burned with grate-fired furnace and no extra fuels is added. Dry air is imposed as primary and secondary air feed and is heated to 120 °C to obtain a combustion temperature of 1100 °C. Assume the air is preheated respectively without using heat from combustion system. The amount of air is estimated to ensure a residual oxygen concentration of the flue gas equal to 7%, according to the European regulations[13]. According to the "CEWEP Energy Efficiency Report (Status 2007-2010)"[14], the mean primary air fed of 314 WTE plants is 3 m^3/kg MSW while the secondary air fed is

1.5 m^3/kg MSW without flue gas recirculation. Set the fed rate as 4 m^3/kg and 2 m^3/kg respectively for this model. With plenty supply of oxygen, assume the concentration of CO is negligible and the unburned carbon in the bottom ash is 0.5% of LHV. The thermodynamic equilibrium of combustion products is imposed after secondary air injection.

2) Heat Recovery System (Boiler and Super-heater): The water feeds to the boiler is preheated to 120 °C, 4.5 MPa to ensure certain heat efficiency. The working conditions of the Rankine cycle within boiler were fixed at a steam temperature of 400 °C and pressure of 4.0 MPa. After the radiation heat exchange with boiler, several units of super-heater and an economizer were considered corresponding to the water-wall of combustion chamber, the convective section of the evaporator, feed-water preheater as well as adjuster of flue gas temperature required by the practice of WTE facilities. Assume that the flue gas at the end of the radiant section is about 850 °C, entering the economizer at 430 °C, exhausted for treatment at about 200 °C according to the temperature requirement by semi-dry cleaning system[15]. Assume the heat transfer efficiency between water and flue gas is 95%. The treated flue gas (150 °C) is not recirculated.

3) Power Generation System: The multi-stage back-pressure steam turbine is considered for the most basic WTE model. No bleeding steams for other use with the model. According to the studies, an isentropic efficiency of 70% is imposed[16], electrical and mechanical efficiency are together set to be 95%[17]. The steam exhausts from turbine with pressure of 1MPa. Considering the electricity production of 83 electricity-only WTE plant in Europe[14], adopt a generate level of 0.45 MWh/t MSW, for the turbine.

2.1.3. Energy Flow of Simulated WTE Model

Using the model built in 2.1.2, the energy consumption and loss for each process is calculated. The principles and main formulas are:

1) The energy input from MSW:

E(MSW) = Incineration Capacity of MSW * LHV

2) The energy transaction calculation of air and water/steam is based on their heat value or enthalpy under process status; similarly, the operation status of flow can be estimated from their heat value or enthalpy:

Δ E (Process) = Mass Flow Rate * Time * [enthalpy (status 1) – enthalpy (status 2)]

E (Transfer) = Δ E (Process) * Efficiency

3) Electricity production from steam turbine:

Electricity Produce Capacity = Productivity * Incineration Capacity of MSW

= Δ E (Steam Pass Turbine) * Electrical and Mechanical Efficiency * Isentropic Efficiency

The step-by-step calculation is listed in Table 3 and the result can be briefly summarized as Table 1. Figure 8 represents the overall energy flow of simulated system based on one hour scale (10 tons of MSW combusted). With a combustion capacity of 10t/h, the plant generates 16,200 MJ electricity per hour while producing 34.6 tons of steam (1 MPa, 180 Celsius) which underlying 58% of total energy input. Despite utilization or treatment of exhaust steam, only 15% of the energy from MSW is sufficiently used (electricity and flue gas cleaning). This portion may increase in part by recirculating part of the treated flue gas to down the consumption of air pre-heating. In terms of the unavoidable energy losses, the combustion and heat transformation efficiency matters the most, attributing to nearly half of the total losses. Besides, the isentropic efficiency of steam turbine is a key factor to reducing the energy losses. Despite these energy losses, such process consumes 24,410 MJ extra energy for air and water pre-heating. Alternative energy sources can be wood, building materials or fossil fuels (coal, diesel, etc.). The large water consumption, approximately 3.5 ton per ton of MSW, also stresses the importance of exhaust steam treatment which will be discussed in later chapters.

Table 1 Energy Flow Result of Basic Simulation Model

Energy Inflow	Amount (MJ)	Percentage	Energy Outflow	Amount (MJ)	Percentage
MSW	120,000	83.10%	Gross Electricity	16,200	11.21%
Air pre-heating	8,333	5.77%	Exhaust Steam	83,681.40	57.90%
Water pre-heating	16,076.9	11.13%	Flue Gas Cleaning	5,187	3.59%
			Exhaust Flue Gas	10,776	7.46%
			Bottom Ash	150	0.10%
			Other Losses	28,537	19.74%

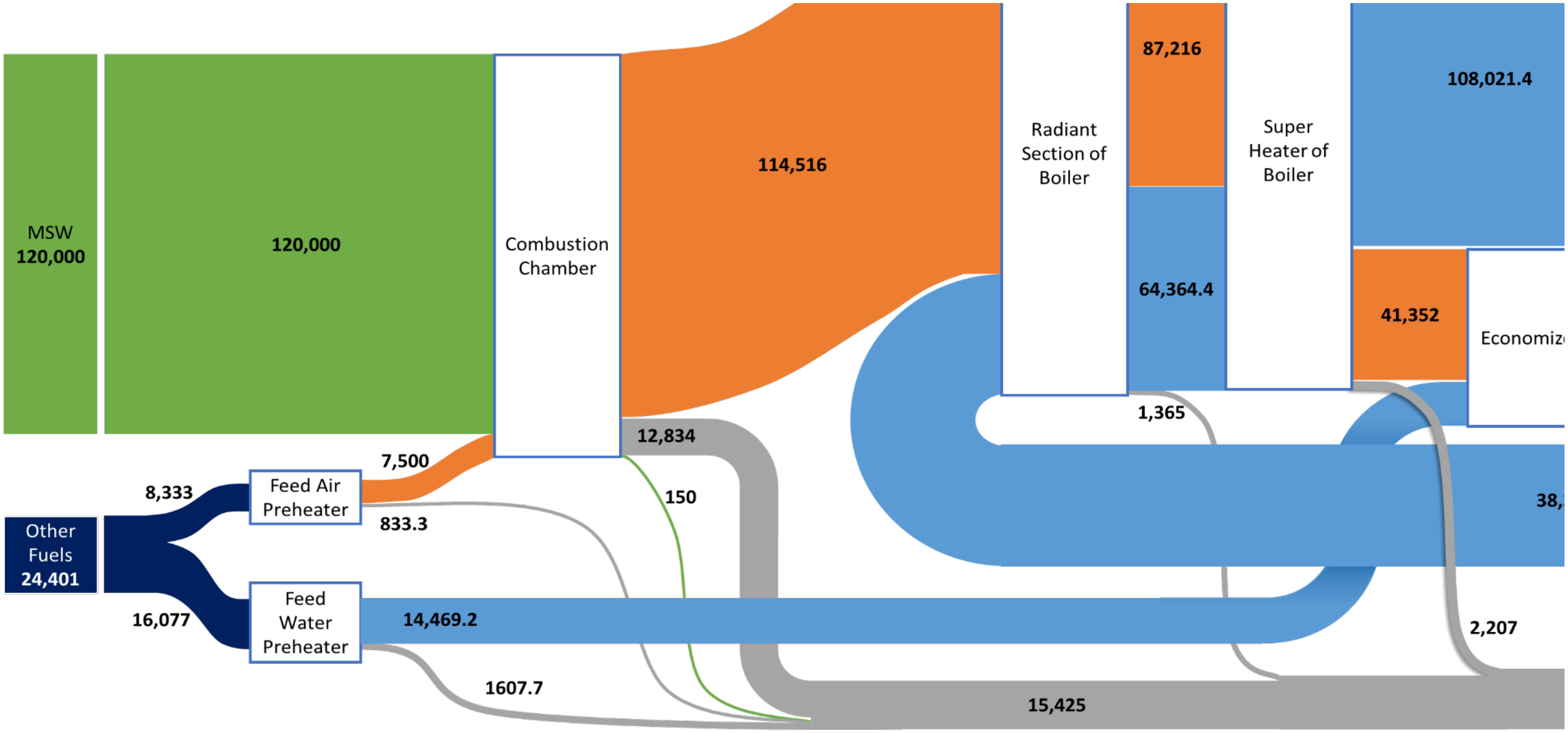


Figure 8 Energy Flow of Basic Simulated Model – Without Exhaust Steam Treatment and Utilization (Unit: MJ/h, Based

		Capacity	MSW	Added	Unburnt Carbon	y air Temp.	Flow Rate	Super-heater Inlet	Temp. Outlet	Water	Temp.	Pressu
Simulated Model Study	Representative of a number of plants in Northern Italy	65,000 ton/year	10.11 MJ/kg	Building Materials	0.8% LHV	120 °C	15.55 Nm3/s (dry, 11% O2)	Max 650 °C (Controlled by economizer)	160 °C	/	400 °C	45 b
		390,000 ton/year	10.11 MJ/kg	Building Materials	0.8% LHV	120 °C	91.93 Nm3/s	Max 650 °C	140 °C	/	440 °C	65ba
Simulated Model Study	Respects to technological restrictions related to electricity production	100,000 ton/year	9.61 MJ/kg	Biomass	/	/	/	/	/	/	400 °C	4 MI
Simulated Model Study	Fluidized bed combustor, parameters are estimated from a number of plants using FBC	56.52 t/h	10.5 MJ/kg	/	/	/	/	820-920 °C (Typically)	200 °C	/	380 °C	40 b
WTE Plant	MVA Zistersdorf WTE plant in Austria, with grate furnace	17.3 t/h	12 MJ/kg	Null	/	/	/	/	195 °C	/	405 °C	42 b
WTE Plant	IVM WTE plant in Belgium, with moveable furnace	14 t/h	10 MJ/kg	Oil (404,259 liters/y)	/	/	/	/	180 °C	/	400 °C	35 b
WTE Plant	L90 Affaldsforbrænding WTE plant in Denmark	24 t/h (180,000 t/y)	11.5 MJ/kg	Oil (315,000 liter/y)	/	/	/	/	/	130 °C	400 °C	42 b
WTE Plant	Aars Fjernvarmeværk WTE plant in Danmark	5 t/h (Line 2)	/	Null	/	/	/	/	45-55 °C (After cleaning)	/	430 °C	47 b
WTE Plant	Reno Nord line 4 in Aalborg, Denmark	20 t/h (160,000 t/y)	12 MJ/kg	/	< 0.23%	145 °C/ 125°C	/	620 °C	180 °C	/	425 °C	50 b
Study on WTE Plant	Study of efficient parameters of middle to large sized WTE plants	/	/	/	/	/	/	850-950 °C	/	/	/	/
Study on WTE Plant	Study on the effect of steam parameter towards electricity generation	750 t/d	6.22 MJ/kg	/	/	/	/	/	/	/	400 °C	4 MI
											450 °C	6.4 M
WTE Plant	WTE plant designed in Yuxi, China	200 t/d	/	/	0.5-1.5%	220 °C	/	850 °C	200 °C	140 °C, 5.0 MPa	415 °C	4.0 M
Simulated Model Study	The working conditions were imposed based on process data of many recent incineration plants in Italy and Europe.	185 t/d	15.38 MJ/kg	/	neglected	115 °C	17.5 Nm3/s, 10.6 Nm3/s	700 °C (1150 °C, 1 atm for combustion)	170 °C	120 °C, 7.0 MPa	450 °C	6.0 M

* 1 bar = 0.1 MPa

Total chemical energy in MSW	12MJ/kg * 10t/h = 120,000 MJ/h	120,000	-	-	LHV = 12 Capacity
Heating up of primary combustion air	1.25kJ/m3/°C * 4m3/kg MSW * 10t/h * (120°C - 20°C) / 90% = 5,555.6 MJ/h	5,000	555.6	90%	Heat valu Heat tran Air fed: 4
Heating up of Secondary combustion air	1.25kJ/m3/°C * 2m3/kg MSW * 10t/h * (120°C - 20°C) / 90% = 2,777.8 MJ/h	2,500	277.8	90%	Heat valu Heat tran Air fed: 2
Energy in bottom ash	0.5% * 12MJ/kg * 25% * 10t/h = 150 MJ/h	-	150	-	Unburne Mass red
Energy input in flue gas in chamber	1.4 kJ/m3/°C * 1.3 * 6m3/kg * 10t/h * (1100°C - 120°C) = 107,016 MJ/h	107,016	12,834	89.3%	Heat valu Volume c Loss = ch
Heat emit from flue gas in radiant section	1.4 kJ/m3/°C * 1.3 * 6m3/kg * 10t/h * (1100°C - 850°C) = 27,300 MJ/h	27,300	-	-	Flue gas
Heat emit from flue gas in super-heaters	1.4 kJ/m3/°C * 1.3 * 6m3/kg * 10t/h * (850°C - 430°C) = 45,864 MJ/h	45,864	-	-	Flue gas
Heat emit from flue gas in economizer	1.4 kJ/m3/°C * 1.3 * 6m3/kg * 10t/h * (430°C - 200°C) = 25,116 MJ/h	25,116	-	-	Flue gas
Energy for flue gas cleaning	1.4 kJ/m3/°C * 1.3 * 6m3/kg * 10t/h * (200°C - 150°C) = 5,460 MJ/h	5,187	273	95%	Used for Efficiency
Energy in exhaust flue gas	107,016 + 5,000 + 2,500 – 27,300 – 45,864 – 25,116 – 5,460 = 10,776 MJ/h	-	10,776		Calculate
Feed water preheating	(506.813kJ/kg – 88.144kJ/kg) * 9.6kg/s * 3600s / 1000 / 90% = 16,076.88 MJ/h	14,469.2	1,607.7	90%	Enthalpy Heat tran
Heating up of water in economizer	25,116MJ/h * 95% = 23,860.2 MJ/h	23,860.2	1,255.8	95%	Energy in Enthalpy Status of
Heating up of water in radiant section	27,300MJ/h * 95% = 25,935 MJ/h	25,935	1,365	95%	Energy in Enthalpy Status of
Heating up of water in super-heaters	(3210.87kJ/kg – 1947.65kJ/kg) * 9.6kg/s * 3600s / 1000 - 67,310.7 MJ/h = 43,657 MJ/h	43,657	2,207	95.2%	Enthalpy Loss = 45
Electricity generated	0.45MWh/t * 10t/h * 3600 = 16,200 MJ/h	16,200	852.6	95%	Producti Electrical
Energy from steam to drive the turbine	(16200MJ/h + 852.6MJ/h)/70% = 24,360.9 MJ/h	17,052.6	7,308.3	70%	Isentropi
Energy in exhaust steam	3214.37kJ/kg * 9.6kg/s * 3600s / 1000 – 24,360.9MJ/h = 86,727.7 MJ/h	86,727.7			Enthalpy Enthalpy Exhaust s
Energy in exhaust steam from the system	86,727.7 – (88.144kJ/kg * 9.6kg/s * 3600s / 1000) = 83,681.4 MJ/h	83,681.4			Calculate

2.2. Exhaust Steam Condensation

2.2.1. Condensing steam turbine

For the conventional WTE utilities, the primary type of turbine adopted is the condensing turbine. The exhaust steam from power generation turbine is directly rejected into surface condensers which maintains an almost vacuum condition at the discharge of the turbine. Operated with an exhaust pressure much lower than atmospheric one, the maximized pressure drop enlarges the energy extracted from steam input. According to the study, the effectiveness of condensing system can be quantified through the principle: the lower the pressure the greater the effects[25]. From the previous calculation, we notice that there still 60%-80% of the energy remaining in the exhaust steam. Therefore, the cooling system usually extracts heat at 2 to 4 times the rate of electric power generated and any small improvement can then lead to large fuel saving and efficiency enhancement for the plants[26]. Simultaneously, the exhaust steam is converted into pure water by condensation and can be further reused in boiler as feed water to achieve a close loop of water as well as cutting down the fresh water consumption. The surface condenser has shells and an array of tubes and can be classified as water-cooled condenser and air-cooled con denser according to the cooling medium.

For the water-cooled condenser, it can be cooled by river, lake or cooling tower water. Commonly, the cooling water flows through the tubes while the steam enters the shell side and the condensation occurs on the outside of tubes (Figure 9). Then the condensate drips down and are collected at the bottom pan of condenser called hotwell. As a small amount of air is known to leak into the shell side under nearly vacuum pressure, a relatively small air ejector is used to remove those gases from the condenser. Typically the coolant water temperature has a 10 degree rise from inlet to outlet under full load[27]. Water from natural water body (sea, lakes, rivers, etc.) is adopted for chilling in many power plants. However, the scarcity of water supply and an excessively higher environmental impact at overheating of the water tables used as heat sinks[28] withdraw the adoption of water-cooled condensers.

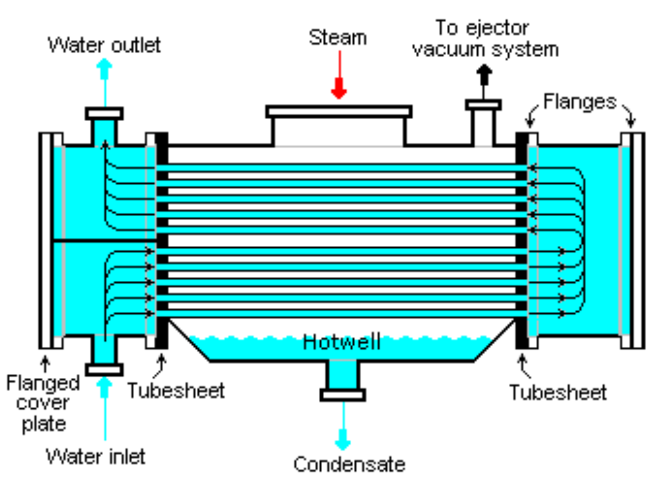


Figure 9 Water-cooled surface condenser

For the air-cooled condenser, it usually consists of an array of fanned tube modules arranged in parallel rows[29]. This kind of condenser feeds the steam through the tubes while the coolant air flowing around the tubes outside, forced by axial flow fan units located above or below (Figure 10). As a result, heat from the condensing steam is rejected to the environment via the finned tubes. The problem is that an air-cooled condenser, however, is significantly more expensive due to the high energy consumption to drive the fans. Also it cannot achieve as low the steam turbine exhaust temperature and pressure as water-cooled condenser due to the limitation of inlet air temperature, which is greatly infected by the climate condition of local environment[30][31]. The condensation temperature within the condenser is considered to be 6°C-20°C above air inlet temperature for general purposes and varies according to the ambient temperature[32]. The air temperature reaches a 20°C-30°C rise as it passes through the coils[33].

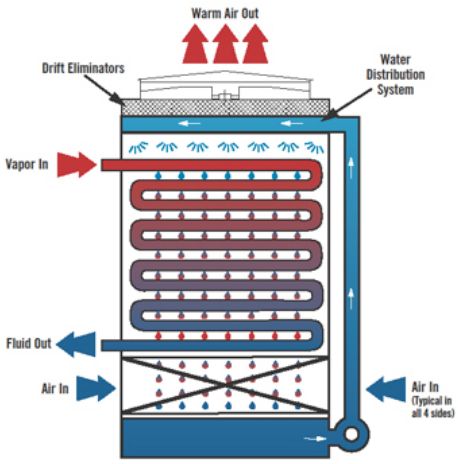


Figure 10 Air-cooled surface condenser

2.2.2. Thermodynamic Simulated Model of Condensing WTE Plant

The assumption of combustion and boiler system operating condition keeps the same as the simulation model of chapter 2.1.2. Both the water-cooled and air-cooled condensers will be studied. The differences and changes for a condensing power generation process are listed as follows:

(1) The heat removed from the exhaust steam (contains in outlet cooling water or air) will not be further used, but treated as energy losses. Assume 95% of the energy removed from exhaust steam is transformed into coolant.
(2) The cooled steam from the condenser would be recycled to the boiler, extra energy may needed for water pre-heating according to the calculation result.
(3) According to the former studies, assume the condensing pressure (exhaust steam pressure) of water-cooled condenser is 0.1MPa while 0.25MPa for the air-cooled condenser. The input coolant water (air) has a temperature of 20°C. A 10°C temperature rise is considered for the cooling water, a 20°C for the cooling air. The output temperature of cooled exhaust steam (liquid) is 60°C. No steam or water leakage is considered for this model.
(4) Considering the electricity production capacity range of 83 electricity-only WTE plant in Europe (0.075-0.873 MWh/t MSW) [14], adopt a generate level of 0.65 MWh/t MSW for the water-cooled turbine, 0.60 MWh/t for the air-cooled turbine. The multi-stage condensing steam turbine is considered and no bleeding steams for other use with the model. According to the studies, an isentropic efficiency of 80% is imposed[16], electrical and mechanical efficiency are together set to be 95%[17].

2.2.3. Discussion of Condensation Simulation Model of WTE Process

According to the modified model we built in 2.2.2, the calculation for both water-cooled and air-cooled condensation WTE system is listed in Table 5. For the condensing steam turbine system, the gross electricity generating capacity is around 22,000 MJ to 23,000 MJ, contributes to 15-17% of total energy input, 20% of the energy containing in MSW combusted. This portion can be further increased to 30% with lower extract steam pressure of 5-8kPa which is hundred times lower than our model. Compared to the basic non-condensing cycle in Chapter 2.1, 7000MJ more electricity is produced, increasing the energy efficiency by at least 5%.

No extra feed water is needed by cooling down and recycling the exhaust steam (water), thus cutting down 50% of the energy consumed by water pre-heating compared to the basic model. However, the water demand for chillers is considerable. With 10 ton/h MSW combusted capacity, the estimated water flow rate for 10 degree rise in condenser is as much as 1,629 ton per hour. Affected by the size, cooling capacity and ambient temperature of water-cooled condenser, some chiller units in market even shows larger water consumption up to 9,000 ton per hour[34] under the working capacity of simulated WTE plant model. For large scale power plants, this part of water is always taken from and emitted to nearby water bodies, causing series heat pollution effects towards the ecosystem. The injection of heat from cooling water to natural water body significantly increases its temperature, leading to the reduction of dissolved oxygen and death of aquatic animals. Also, a higher water temperature promotes the reproduction of disease-causing bacteria and virus and increases the toxicity of some chemicals (cyanide and heavy metal ions)[35].

For the air-cooled chillers, an estimation of 2,800,000 m^3/h air is needed to carry out the heat from exhaust steam. When calculate with a 162.25 kW (~585MJ/h) eight-fan air-cooling model from condenser producer FRITERM A.S. [32], 120 units with total air flow rate of 4,757,000 m^3/h is consumed for this combustion scale, together with 1109 MJ/h electric power to drive the fans.

From the discussion above, the traditional electricity-only WTE plants with condensing steam turbine more sufficiently generate power from MSW than the basic model and well used 20-30% of energy from total input. However, about two thirds of energy from MSW losses during condensation processes. The relative high environmental impacts and energy consumption also attract consideration against this inefficient operation mode.

Table 4 Energy Flow Result of Condensing Simulation Model

Energy Inflow	Amount (MJ)	Percentage	Energy Outflow (W)	Amount (MJ)	Percentage	Energy Outflow (A)	Amount (MJ)	Percentage
MSW	120,000	87.57%	Gross Electricity	23,400	16.93%	Gross Electricity	21,600	15.62%
Air pre-heating	8,333	6.08%	Refrigerant Loss	68,036	49.21%	Refrigerant Loss	70,288	50.84%
Water pre-heating	8,706	6.35%	Flue Gas Cleaning	5,187	3.75%	Flue Gas Cleaning	5,187	3.75%
			Exhaust Flue Gas	10,776	7.79%	Exhaust Flue Gas	10,776	7.79%
			Bottom Ash	150	0.11%	Bottom Ash	150	0.11%
			Other Losses	30,706	22.21%	Other Losses	30,256	21.88%

Table 5 Energy Flow Accounting of WTE Plants (For Chapter 2.2)

Process	Formula	Efficient Amount (MJ/h)	Losses (MJ/h)	Efficiency (%)	Remark
Feed water preheating	(506.813kJ/kg– 254.915kJ/kg) * 9.6kg/s * 3600s / 1000 / 90% = 9,672.9 MJ/h	8,705.6	967.3	90%	Enthalpy of water: 506.813kJ/kg (120°C, 4.5MPa), 254.915kJ/kg (60°C, 4.5MPa) Heat transfer efficiency: 90%
Electricity generated from turbine (W)	0.65MWh/t * 10t/h * 3600 = 23,400 MJ/h	23,400	1,231.6	95%	Productivity: 0.65 MWhel per ton of MSW Electrical and mechanical efficiency: 95%
Electricity generated from turbine (A)	0.60MWh/t * 10t/h * 3600 = 21,600 MJ/h	21,600	1,136.8	95%	Productivity: 0.60 MWhel per ton of MSW Electrical and mechanical efficiency: 95%
Energy from steam to drive the turbine (W)	23,400MJ/h /95%/80% = 30,789.5 MJ/h	24,631.6	6,157.9	80%	Isentropic efficiency of turbine: 80%
Energy from steam to drive the turbine (A)	21,600MJ/h /95%/80% = 28,421.0 MJ/h	22,736.8	5,684.2	80%	Isentropic efficiency of turbine: 80%
Energy in steam from turbine (W)	3214.37kJ/kg * 9.6kg/s * 3600s / 1000 – 30,789.5MJ/h = 80,299.1 MJ/h	80,299.1			Enthalpy of water: 3214.37kJ/kg (400°C, 4.0MPa) Enthalpy of exhaust steam: 2321.444 kJ/kg Exhaust steam status: 99.61 °C, 0.1 MPa
Energy in steam from turbine (A)	3214.37kJ/kg * 9.6kg/s * 3600s / 1000 – 28,421.0MJ/h = 82,667.6 MJ/h	82,667.6			Enthalpy of water: 3214.37kJ/kg (400°C, 4.0MPa) Enthalpy of exhaust steam: 2392.002 kJ/kg Exhaust steam status: 127.41 °C, 0.25 MPa
Energy in exhaust steam from condenser (W)	251.222kJ/kg * 9.6kg/s * 3600s / 1000 = 8682.2 MJ/h	8,682.2			Enthalpy of water: 251.22kJ/kg (60°C, 0.1MPa) Calculated by separate the part of energy in feed water (20 °C, 4.5 MPa)
Energy in water from condenser (A)	251.348kJ/kg * 9.6kg/s * 3600s / 1000 = 8686.6 MJ/h	8,686.6			Enthalpy of water: 251.35kJ/kg (60°C, 0.25MPa)
Energy to coolant (W)	(80,299.1 MJ – 8682.2 MJ) * 95% = 68,036.1 MJ	68,036.1	3580.8	95%	Water condition: Inlet 20°C, 2 MPa; Outlet 10°C increase. Water flow rate: 68,036.1MJ/h / (127.564 kJ/kg - 85.7984 kJ/kg) = 1629.0 ton/h
Energy to coolant (A)	(82,667.6 MJ – 8686.6 MJ) * 95% = 70,287.7 MJ	70,287.7	3699.4	95%	Air condition: 1.5 MPa, T(inlet) = 20°C, 20°C increase. Heat value of air: 1.25 kJ/m3/°C. Air flow rate: 70287.7MJ/h / 1.25 kJ/m3/°C / 20°C = 2,811,508 m3/h

* W: water-cooled condensation module; A: air cooled condensation module.

2.3. Exhaust Steam for District Heating

2.3.1. District Heating and Cogeneration WTE Plants

District Heating (DH) is defined as the distribution of thermal energy from a central heat source to its surrounding residential by steam or hot water through an insulated pipe network. The steam or hot water is then directed into buildings and circulated through heating equipment. In the case of hot water systems or newer steam systems, heat exchangers are frequently used. This successfully isolates the users from the thermal system, thus preserving the integrity of both DH system and customers. DH best suits to those areas with high population density and cold climate which help ensuring stable and competitive pricing[36]. Typically the central heat supply for DH can be from coal-fired plants, oil-fired plants or WTE plants (heat only). Another approach, called "cogeneration" or Combined Heat and Power (CHP), is applying the by-product steam of some other utilities to achieve high energy utilization efficiency. For a CHP plant, the energy efficiency can reach as high as 80% to 90%.

Currently, 221 of 314 European WTE plants sell heat as energy product; 184 of these are CHP production plants. These plants generate from 700-899 kWh of electricity and from 400 to up to 2,000 kWh of heat per ton of MSW incinerated[14]. The Danish WTE facilities obtain an average energy balance of up to 0.6 MWh electricity plus up to 2 MWh heat per ton of MSW, thus tripling the amount of total energy obtained. In United States, twenty eight of the 88 WTE plants sell steam as product and 21 cogenerate a total of about 470 MW of heat (corresponding to 1.6 million lbs of steam per hour) and 272 MW of electricity[37]. Despite the increasing of energy efficiency, there are still significant advantages to be gained from a cogeneration WTE plant for district heating: Lower GHG emission levels of WTE facilities compared to other technologies and overall fuel conservation.

As mentioned above, district heating can divided into two different modes according to the medium: steam system and hot water system. To feed a steam carried DH system, the steam bleeds has to be extracted with higher-pressure to fulfill the required pressure drop in the piping network. Extraction turbine is used in this case which has openings for extraction of a portion of the steam at some intermediate pressure, the rest of the steam is condensed, as illustrated in Figure 11. Part of electricity generating capacity is lost during cogeneration process and well depends on the pressure, flow rate and number of extractions of extracted steam. The ratio of electricity lost to heat generation ordinarily range 0.1 to 0.2 kWh of electricity per kWh of thermal energy obtained[38]. A steam pipeline system normally services consumers within 2-3 miles from the central heat source which is short and limited. Considering existing problems for steam DH system like pipeline corrosion, storage capacity, transmission distance and heat loss, it is now replaced by more efficient and economical hot water system.

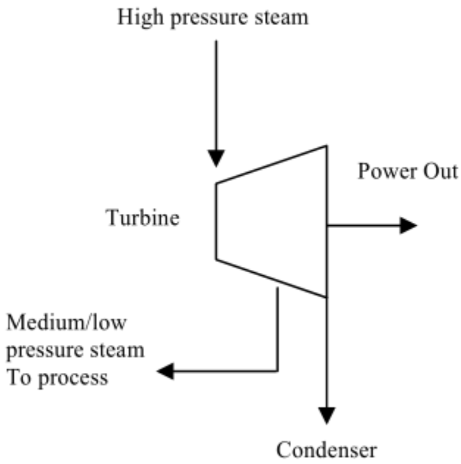


Figure 11 Extraction Steam Turbine

To supply a hot water thermal system, the WTE plants normally produce hot water by placing a heat exchanger at the back pressure turbine exhaust, transforming the energy in low pressure steam from turbine bleeds to DH system's water supply. Extraction steam turbine is adopted by some CHP facilities to heat the water in multiple stages[39]. In this case, the water flow of WTE facility is kept separating from the water network for thermal market. Simultaneously, the dropped energy level conveyed by exhaust steam remarkably reduces the loads and cost for condensation, especially for those whose coolant is not returned. The maximum supply temperatures of hot water systems are designed between 110-130 °C and return at 50-70 °C. The recommended temperatures for hot water DH supply is between 93 and 121 °C, the ratio of thermal energy extraction to electricity generation in medium scale is 2.0 to 2.5 MW thermal per MW electricity[40]. Hot water system allows the transmission of heat over longer distances up to 20 miles with relatively low heat loss between 5%-10%. The pressure within pipelines depends on the system size and ambient operating temperature, mostly varying from 9-17 bar in winter seasons. Steel is the most frequently utilized pipe material in DH systems in order to prevent groundwater damage on external pipe surfaces.

2.3.2. Thermodynamic Simulation of CHP WTE Plant

The assumption of combustion and boiler system operating condition keeps the same as the simulation model of chapter 2.1.2. According to the application ratio, choose hot water DH system for the simulated model. The supply temperature of 110 °C and return temperature of 60 °C is considered for the model, with a transmission heat loss of 5%. The pressure of hot water system is set as 10 bar (1 MPa). Three different heat exchange modes will be studied:

(1) The first model using multiple stage back pressure steam turbine without any bleeds in the middle. All the exhaust steam from turbine is directed to a heat exchanger for DH water warming, with an assumed heat transfer efficiency of 95%. Assume the outflow steam (water) status from heat exchanger is 120 °C, 0.8MPa. The outflow is recirculated in WTE plant via pump as feed water and in this case there is no need for extra feed water pre-heating. Other parameters assumptions of turbine keep the same as base model in 2.1.2.

(2) The second model using extraction/condensing steam turbine. In this model, a water-cooled condenser (95% efficiency) is considered after the steam turbine. Assume 50% of steam is extracted at 1 MPa at extraction turbine stage. Adopt a generate level of 0.43 MWh/t MSW (70% isentropic efficiency) for the turbine before extraction. Assume the exhaust steam from condensing steam turbine is under same status as Chapter 2.2 (99.61 °C, 0.1 MPa, Enthalpy of 2321.444 kJ/kg, 80% isentropic efficiency). The exhaust steam (60°C, 0.1 MPa) chilled is recirculated as feed water. A 10°C temperature rise is considered for the cooling water.

(3) The third model using extraction/back pressure steam turbine. Assume 50% of steam is extracted, 60°C and 1.3 MPa, at extraction turbine stage. Both the bleeds and exhaust steam (179.9°C, 1 MPa) are used for two-stage water heating to DH system: the first stage is done by exhaust steam while the extracted steam is used for the 2^{nd} stage, bring the DH temperature to 110°C. The condensed steam from second stage heat exchanger cascades into the first exchanger, then returned to the plant system as feed water. Adopt a 70% isentropic efficiency for both stage of turbine. To estimate the mass flow can be heated by waste steam, suppose the mixed steam (water) from exchanger has the same amount of energy as water at 1MPa, 120°C. In this occasion, no extra feed water pre-heating is considered for model three.

2.3.3. Discussion of Condensation Simulation Model of WTE Process

According to the modified model we built in 2.3.2, the calculation for three exhaust steam treatment model is listed in Table 8. When applying all the exhaust steam from back pressure turbine for DH (Model I), the WTE still generates 16,200 MJ gross electricity per hour together with approximately 62,500 MJ thermal energy. Although 7,000 MJ of electric power is sacrificed, the overall efficiency of the WTE plants increases from 21% to over 65%, thus over 70% of the energy from combusted MSW is sufficiently used. In some advanced cogeneration WTE plants of Norway and Germany, the efficiency can be even as high as 80%-90%.

Table 6 Energy Flow Result of Three DH Simulation Model

	All for DH (I)		DH + Condensing (II)		Two Stage Extraction (III)	
	Amount (MJ)	Percentage	Amount (MJ)	Percentage	Amount (MJ)	Percentage
Gross Electricity	16,200	12.60%	18,669	13.99%	12,907	10.00%
DH	62,545	48.66%	31,273	23.44%	67,010	51.94%
Water Pre-heating	0	-	4,353	-	0	-
Refrigerant Loss	-	-	33,985	25.48%	-	-
Flue Gas Cleaning	5,187	4.03%	5,187	3.89%	5,187	4.02%
Exhaust Flue Gas	10,776	8.38%	10,776	8.08%	10,776	8.35%
Bottom Ash	150	0.12%	150	0.11%	150	0.12%
Other Losses	33,686	26.21%	33,360	25.01%	32,993	25.57%
Useful	83,932	65.29%	55,129	41.32%	85,104	65.96%

Compared to traditional fossil fuels fired cogeneration power plants, considerable economic and environmental benefits can be achieved. According to European environmental policy, European power plants have to annually demonstrate a CO_2 emission allowance corresponding to their actual CO_2 emissions. The price for the second commitment period (2008 to 2012) is 22 € (23.61 USD) per ton of CO_2[41]. Assuming that 50% of the energy from fossil resources is used to supply 62,500 MJ DH demand in CHP plants, the fuel consumption, economic and environmental cost of some representative sources are listed in Table 7. Depending on the fuel type, 2-15 million dollars can be saved each year, 30 thousand tons of coal (or 5.6 million gallons of oil) consumption and more than 40 thousand tons of carbon dioxide emission can be prevented by adopting exhaust steam from a WTE plant for DH.

Table 7 Consumption and Cost of Fossil Fuels DH

Fuels	Calorific Value (kJ/kg)[42]	Amount (ton/h)	Unit Price (USD/t)	Fuel Cost (USD/h)	CO2 EF (g/kWh)[43]	CO2 Emission (ton/y)	CO2 Emission Allowance (USD/y)
Hard Coal	27,431	4.56	50.08	228.21	270	41,062.24	969,479
Oil	147,708 (kJ/gal)	846 (gal)	2.08 (USD/gal)	1,759.68	360	54,749.65	1,292,639
Waste	12,000	10	0	0	20	3,041.65	71,813

For the Condensing-DH model, it generate 18,700 MJ gross electricity with 31,300 MJ heat. Compared to the whole condensing WTE plants, it sacrifices 20% of electricity capacity to earn a 20% addition of overall efficiency. For the condensing turbine part, the productivity decreased from 0.65 MWhel to 0.14 MWhel due to the decreasing steam pressure and amount. Half of the refrigerant demand, 800 tons of water per hour, is saved as well as the energy loss during condensation. Changing the proportion of steam extracted after the turbine for DH and keeping the other steam parameters the same, the energy output and efficiency of plants is shown in Figure 12. It is clear that energy conveyed by steam for DH is much more efficiently utilized than that for driving a condensing turbine. The total energy efficiency of CHP WTE plant climbs stably, from 16% to 65%, as the extracted proportion of steam increases. Simultaneously, the water consumption and energy loss for exhaust steam condensation keeps cutting down. To reach the highest working efficiency, the plant is under the same operation status as model I we built.

For the third model, the DH system is heated by exhaust steam in two stages. Among these three models, model III generate power with highest heat-electricity ratio of 5.2. The efficiency under this operation condition is approximately 65%, nearly equals to model I. Similarly, the efficiency and power ratio may vary under different steam extract proportion and pressure.

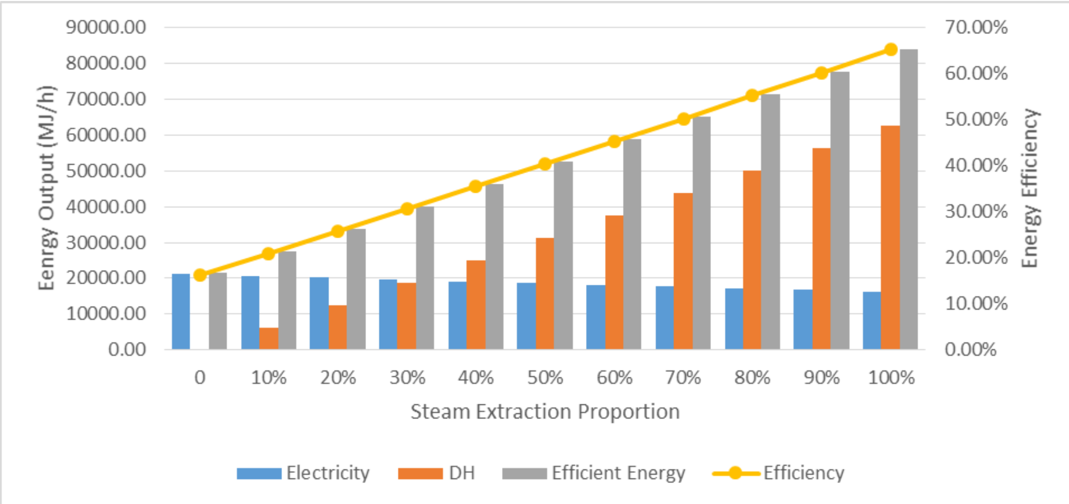


Figure 12 Energy Output for Cogeneration WTE Plants with Different Steam Extraction Ratio

From the discussion above, applying the exhaust steam as a source of DH is an energy efficient, environmental friendly and economical solution for both WTE facilities and heat consumers. More than 70% of power from MSW can be well utilized. Furthermore, the energy consumption and losses of pre-heating and condensation is avoided, and cutting down the operating expenses of the WTE plants at the same time.

Table 8 Energy Flow Accounting of WTE Plants (For Chapter 2.3)

Process	Formula	Efficient (MJ/h)	Losses (MJ/h)	Efficiency (%)	Remark
Energy from steam to DH water (I)	(2509.483kJ/kg– 504.207kJ/kg) * 9.6kg/s * 3600s / 1000 * 95% = 65,837.2 MJ/h	65,837.2	3,465.1	95%	Enthalpy of steam (hot water): 2509.483 kJ/kg (179.9°C, 1 MPa), 504.207 kJ/kg (120°C, 0.8 MPa), 461.987 kJ/kg (110°C, 1 MPa), 251.977 kJ/kg (60°C, 1 MPa); Water mass flow: 87.1 kg/s
Energy for DH (I)	65837.2MJ/h * 95% = 62545.3 MJ/h	62,545.3	3,291.9	95%	Transmission loss: 5%
Electricity generated from extraction turbine (II)	0.45MWh/t*10t/h*3600=16,200MJ/h	16,200	852.6	95%	Productivity: 0.45MWhel per ton of MSW Electrical and mechanical efficiency: 95%
Energy from steam to drive the extraction turbine (II)	(16200MJ/h + 852.6MJ/h)/70% = 24,360.9 MJ/h	17,052.6	7,308.3	70%	Isentropic efficiency of turbine: 70%
Energy from steam to drive the condensing turbine (II)	(2509.483kJ/kg– 2321.444kJ/kg) * 4.8kg/s * 3600s / 1000 = 3,249.3 MJ/h	2,599.5	649.8	80%	Isentropic efficiency of turbine: 80%
Electricity generated from condensing turbine (II)	2599.5MJ/h * 95% = 2,469.5 MJ/h	2,469.5	130.0	95%	Productivity: 0.14MWhel per ton of MSW (5 ton MSW base considering steam extraction)
Energy from steam to DH water (II)	(2509.483kJ/kg – 504.207kJ/kg) * 4.8kg/s * 3600s / 1000 * 95% = 32,918.6 MJ/h	32,918.6	1,732.6	95%	Water mass flow: 43.6 kg/s
Energy for DH (II)	32918.6MJ/h * 95% = 31272.7 MJ/h	31,272.7	1,645.9	95%	Transmission loss: 5%
Energy in exhaust steam from condenser (II)	251.222kJ/kg * 4.8kg/s * 3600s / 1000 = 4341.1 MJ/h	4,341.1			Enthalpy of water: 251.22kJ/kg (60°C, 0.1MPa)
Energy to coolant (II)	(40114.6 MJ – 4341.1 MJ) * 95% = 33,984.8 MJ	33,984.8	1,788.7	95%	Water condition: Inlet 20°C, 2 MPa; Outlet 10°C increase. Water flow rate: 33,984.8MJ/h / (127.564 kJ/kg - 85.7984 kJ/kg) = 813.7 ton/h
Energy for feed	(506.813kJ/kg–254.915kJ/kg)*4.8kg/s * 3600s / 1000 / 90% = 4836.4 MJ/h	4,352.8	483.6	90%	Enthalpy of water: 506.813kJ/kg

water preheating (II)					(120°C, 4.5MPa), 254.915kJ/kg (60°C, 4.5MPa); Heat transfer efficiency: 90%
Energy from steam to drive the extraction turbine (III)	(3214.37kJ/kg–2796.04kJ/kg)*9.6kg/s * 3600s / 1000 = 14,457.5 MJ/h	10,120.2	4,337.3	70%	Enthalpy of steam: 3214.37 kJ/kg (400°C, 4MPa), 2796.04 kJ/kg (195°C, 1.3 MPa); Isentropic efficiency of turbine: 70%
Electricity generated from extraction turbine (III)	10120.2MJ/h * 95% = 9614.2 MJ/h	9,614.2	506.0	95%	Productivity: 0.27 MWhel per ton of MSW Electrical and mechanical efficiency: 95%
Energy from steam to drive the 2nd stage turbine (III)	(2796.04kJ/kg – 2509.483kJ/kg) * 4.8kg/s * 3600s / 1000 = 4,951.7 MJ/h	3,466.2	1,485.5	70%	Isentropic efficiency of turbine: 80%
Electricity generated from 2nd stage turbine (III)	3466.2MJ/h * 95% = 2,469.5 MJ/h	3,292.9	173.3	95%	Productivity: 0.18 MWhel per ton of MSW (5 ton MSW based considering steam extraction)
Energy from steam to DH water (III)	[(2509.483kJ/kg+2796.04kJ/kg)*4.8kg/s-504.348kJ/kg*9.6kg/s]*3600s/1000*95% = 70,536.7 MJ/h	70,536.7	3,712.5	95%	Water mass flow: 93.3 kg/s
Energy for DH (III)	70536.7MJ/h * 95% = 67,009.9 MJ/h	67,009.9	3,526.8	95%	Transmission loss: 5%

* I, II, III stands for model one, two and three.

3. Main Desalination Technologies

Though our earth is a “blue marble”, a water world, but about 97.5 percent of that is undrinkable high salinity water and unfortunately two-thirds of fresh water is tucked away in frozen glaciers or otherwise unavailable for our use. As a result, more than one sixth people (1.1 billion) around world are water stressed, or do not have access to potable water. Under the current fresh water consumption rate, two-thirds of population may face water shortages by 2025. The good news is that technology advances and cost reduction in seawater desalination have made it a realistic and promising solution to fresh water supply. By 2012, desalination have already contribute for two-thirds of world feed water, more than 60 million cubic meters per day, mainly for Middle East and Gulf States. The production cost of desalination have downed to approximately 0.45-1 USD/m^3 in 2013 compared to 9 USD/m^3 in 1970. But for some developing areas, the expenses is still around 3-5 USD/m^3.

Saline water desalination can be realized essentially by either thermal processes or membrane processes. Effective integration or cogeneration of desalination and power facilities can reduce the cost of desalination and electric power production. In many countries, power demand may fluctuate from 100% in summer to 30% in winter due to air conditioning systems whereas water demand remains stable all the year round. Thermal and membrane processes are coupled in some cogeneration plants to solve the large variation between summer and winter. Current desalination market is major occupied by membrane technologies because of its lower energy consumption and decreasing cost. The most widely used is reverse osmosis (RO), accounting for 60% of the total industry. Other membrane techniques like electrodeionisation (EDI) and electrodialysis (ED) only occupy approximately 4% of total desalination capacity. With new technology keeps developing, the energy consumption of desalination have significantly reduced to as low as 3 kWh per cubic meter. However, compared to local fresh water supply techniques which consumes 0.1-1 kWh/m3, desalination is still energy-intensive and need further sustainable solutions.

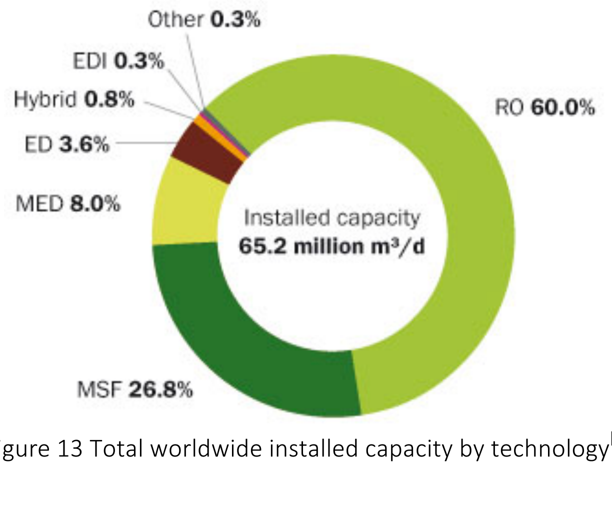


Figure 13 Total worldwide installed capacity by technology[4]

3.1. RO Desalination Techniques

1) Technical Principles

The core principle of RO desalination is a natural phenomenon, osmosis, by which water automatically passes through a semi-permeable membrane from lower salinity solution into a more concentrated solution. No heating or phase change takes place in this process. When pressure is applied to the higher salinity solution, the water will be forced to flow in a reverse direction through the semi-permeable membrane while leaving the salt behind.

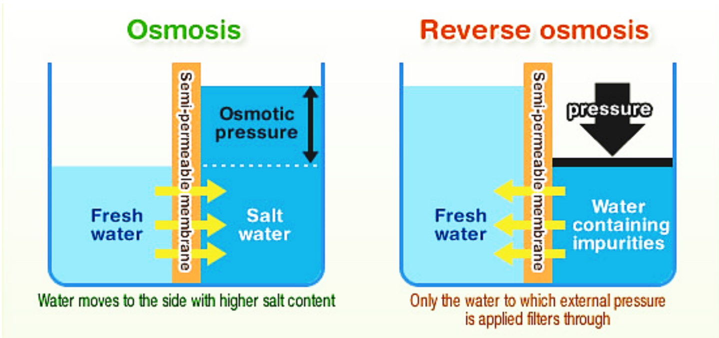


Figure 14 Mechanism of Osmosis and Reverse Osmosis

2) Technical Description

For an RO desalination plants, it essentially consists of four parts: a pretreatment system, a high pressure pump, a core membrane system and the post treatment system. In some of the plants, there is an energy recovery system between the pumps and membrane to cut down the energy demand of desalination plants.

The feed saline water is first pretreated to promise the cleanness of RO membranes surface. Therefore, suspended solids contained in feed water must be removed to prevent salt precipitation or microbial growth. Pre-treatment may involve conventional water treatment methods such as screen separation, chemical sedimentation and filtration, or advanced membrane processes like microfiltration (MF) or ultrafiltration (UF)[44]. Also, pH adjustment is sometimes required based on water characteristics.

High pressure pump section supplies the pressure needed to encourage clarified feed water flowing through membrane, typically between 55-85 bar depending on the temperature and salinity of water[45]. The normally operation pressure is 2-17 bar (30-250 psi) for slightly brackish water, 17-28 bar (250-400 psi) for brackish water and 55-82 bar (800-1200 psi) for seawater[46][47]. The high pressure pumps involve the major energy requirement of the whole RO processes, around 5-7 kWh per cubic meter treated. The recent development of more efficient energy recovery devices, pressure exchanger and energy recovery pump, realize the recovery of energy from concentrate brine flow via piston system, thus greatly reducing the overall energy consumption to approximately 1-3 kWh/m^3.

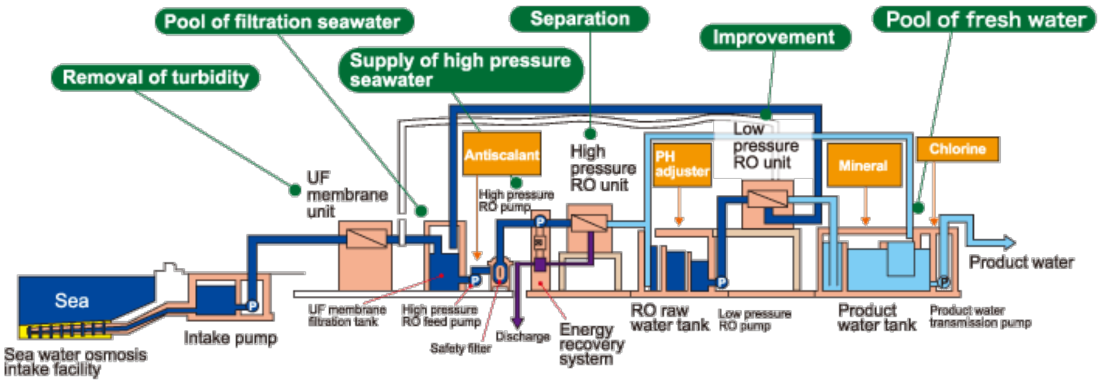


Figure 15 RO Desalination Plants

The membrane assembly consists of a pressure vessel and a semi-permeable membrane elements inside, varying from one to eight per vessel. The membrane inhibits the passage of dissolved salts while permitting water to pass by, thus dividing the feed water flow into a fresh product stream and a concentrated brine stream. However, no membrane works perfect so that there may be a small percentage of salt remaining in the product water. The most widely accepted RO membrane configuration type is Spiral wound which generally composed of cellulose acetate or of other composite polymers. Spiral wound module is actually a flat sheet of membrane wrapped around a central collecting tube. The pressurized feed water flows in spaces within the membrane envelope, purified and collected in the tube. As water purified, the remaining saline water become more concentrated, resulting in over-saturation of salts and ever-boosting energy input to overcome the natural increased osmotic pressure. In this case, certain portion of feed water is withdraw from the membrane elements. The discharged amount typically ranges from around 20 % for brackish water to 50-80% for seawater. The concentrate flow is normally just 1.5-3.5 bar (20-50 psi) less than the feed pressure while the product water runs at atmospheric pressure.

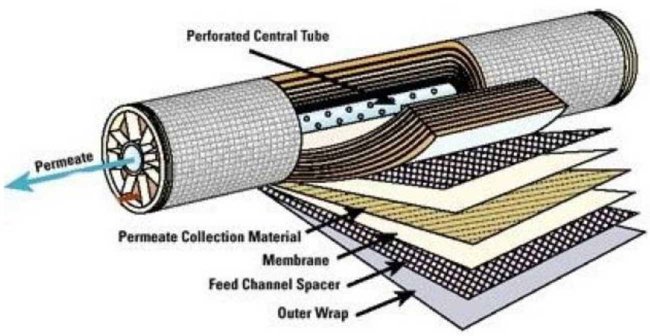


Figure 16 Spiral Wound RO Membrane[45]

The main purpose of desalinated water post-treatment is to stabilize the water and prepare it for distribution. This mainly includes re-mineralization, pH adjustment, disinfection and degasification before delivered to distribution system.

3) Production Cost

The production cost for RO desalination plants is influenced by massive factors including electricity price, labor cost, feed water quality, treatment capacity and so on[48]. According to "Courtesy of Water Desalination Report", the sea water RO desalination cost is generally within the variation of 700-1200 USD/acre-foot (0.58-1.00 USD/m^3). In United States, the brackish water RO desalination cost is about 0.10-1.05 USD/m^3. Aside from fixed capital cost, the most significant costs are typically the costs of electricity (40-55%), membrane replacement (5-10%), and labor (~5%)[49].

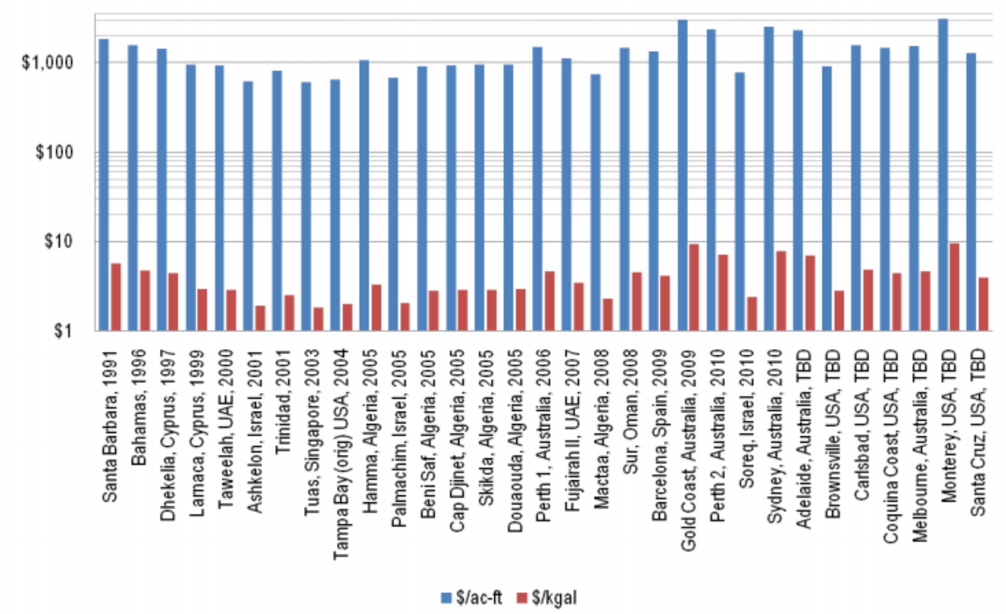


Figure 17 Annualized SWRO Cost Trends

4) Productivity and Effectiveness

Currently the RO technology can separate over 99% of salt from seawater with a productivity of 15-24 liters/m^2 membrane per day (1.7-3.3m^3/d/membrane[50]). Made of composite polyamide, the membrane for now is said to be guaranteed a 5 years life without replacement. Besides, the wounded membrane elements greatly save the space of desalination plants, resulting in a very high space/production capacity ratio, ranging from 25,000 to 60,000 liters/day/m^2[47].

5) Disadvantages

- In practice, RO technology is highly depends on a reliable energy source;
- Limited by the design of water intake and pretreatment, RO desalination plants using seawater may be interrupted by stormy weathers because of the re-suspension and increasing suspended particulate concentration;
- Even new materials is applied to strength the RO membrane, it is still very sensitive to abuse so that extra construction for feed water pretreatment is always in need;
- There are bacterial contamination risks on membrane surface, causing tastes and

odors problems on product water;

- The highly concentrated brine from RO technology must be carefully disposed to avoid hazardous environmental impacts on oceanic and underground water system.

3.2. Thermal Desalination Techniques

As its name implies, thermal desalination techniques heat up the saline water and gather pure product water mainly by distillation. Distillation is defined as a purification processes of fluid via evaporation and condensation. The condensed product of distillation is usually of single compound and free from salt due to the different evaporation point. This simple principle based thermal technologies is widely used in seawater desalination but rarely used in brackish water desalination, mainly because of its high costs involved. Solar power are now often coupled with thermal desalination facilities to cut down their cost and unrenewable energy consumptions. The two major thermal ways of desalination are Multiple Effect Distillation (MED) and Multi-Stage Flash Distillation (MSF). Depending on the availability and quality of energy on-site, MED plants sometimes fit with thermal or mechanical compressor to enhance their performance and optimize their energy requirements, called MED-TVC (Thermal Vapor Compression) and MED-MVC (Mechanical Vapor Compression). They are typically powered by steam together with some electricity. For thermal desalination processes, no special pre-treatment is required. But to protect the evaporators and pipelines, filtration is sometimes applied to remove large solid particles.

3.2.1. Multiple Effect Distillation (MED)

1) Technical Principles

The MED method is said to be the most efficient, economical and easy operating thermal desalination process, occupied approximately 28% of desalination market. It is a low temperature thermal process that collect fresh water by distillation in a sequence of vessels called effects. Each of the effect maintains a lower temperature and pressure than the previous one. Since the boiling point of water decreases with reduced pressure (Table 9), the saline water can efficiently keep evaporating in all vessels with pressure control, even under low temperature of 40°C.

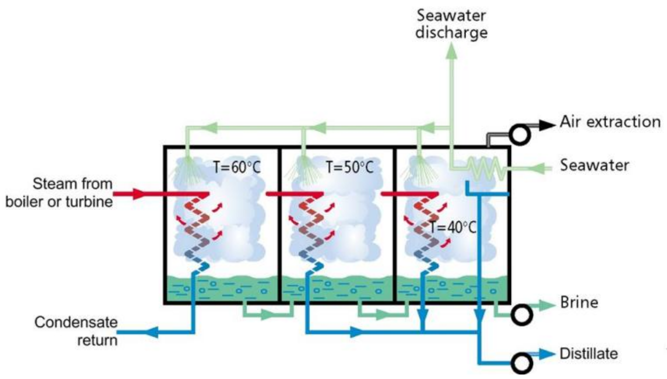
Table 9 Water Boiling Point Table

Pressure	1bar	0.47 bar	0.32 bar	0.25 bar	0.1 bar
Boiling point	100°C	80°C	70°C	65°C	45°C

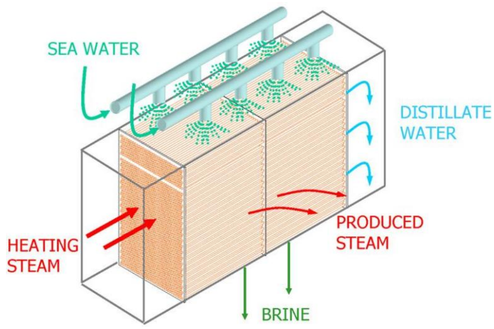
2) Process Description

The core of MED process is the MED evaporator. It consists of a serious of consecutive effects, 2-16 typically, remained at decreasing level of temperature and pressure. Figure 18 shows the schematic three-stage MED evaporator and a zoomed picture of single MED cell. Each effect contains a bundle of horizontal heat transfer tubes wherein heating steam is introduced and condensed. Feed seawater is sprayed from top of the bundle and flows downward tube-by-tube with gravity. The seawater cools the tube externally, condensing the steam inside into purified water. Simultaneously, the heat released from the inner steam flow warms up the feed water and partly evaporates it. The seawater gradually concentrates with evaporation and gives brine at the cell bottom which will then be transport to next stage. The vapor formed outside the tube is directed to flow inside tubes for next stage and used as heating source where the process repeats. In the last effect, the produced steam condenses in a conventional shell and tubes heat exchanger cooled by feed seawater. Extra condensing seawater other than sprayed feed flow is rejected back to the sea. The concentrated brine is collected cell to cell till the last one, then extracted by centrifugal pumps.

For MED desalination, only the first effect with highest pressure requires external heat source and greatly withdraw the energy consumption of this process. The heating steam of the first effect is generally low pressure condensing steam (0.3-0.5 bar, 70-90°C). Other heating media like hot water, waste energy from power plants or solar heat can also be applied for this method. To maintain the effect cells at low pressure, the seawater temperatures typically remains below 65-70°C, thus avoiding unnecessary heating and allowing a good control of scaling. Typical pressure drop across the system is 5-50kPa (less than 5kPa/stage). The more effects a process has, the higher performance ratio it generally reaches.



(a)



(b)

Figure 18 Schematic of MED Evaporator and Single Effect Unit[51]

3) Energy Consumption and Production Cost

The energy consumption of MED process is result from varies operation factors: Top Brine Temperature (TBT) known as the maximum temperature of the brine solution; Number of stages; Gain Output Ratio (GOR) known as the ratio between product water amount per unit mass of dry saturated steam supplied to the system. The typical electric power consumption of MED is 1.5-2.5kWh/m^3, the thermal energy is 60-110 kWh/m^3 corresponding to GOR value from 10 to 6. Electrical equivalent defined as the amount of electrical energy cannot be produced because of extraction of heating steam is also used to evaluate the energy consumption for the process. For MED technique, the electrical equivalent for thermal energy is 5-8.5 kWh/m^3, 6.5-11 kWh/m^3 in all. The production cost for MED technique is 0.7-1 USD/m^3 while the capital cost is 3.5-4 USD per installed gallon per day.

4) Productivity

For recent years, the unit treatment capacity of MED technology is significantly increased from 4,500 m^3/d to dramatic 45,000-68,000 m^3/d[52]. The typical working capacity of an MED unit is about 5,000-15,000 m^3/d[53].

3.2.2. MED-TVC and MED-MVC

As an enhancement of conventional low-temperature MED process, MED-TVC (Thermal Vapor Compression) and MED-MVC (Mechanical Vapor Compression) is involved in many thermal desalination facilities to optimize the performance of MED evaporators, particularly in many cogeneration plants.

The MED-TVC evaporator fitted a thermal compressor, called thermocompressor, with basic MED units to take advantage of pressure of available steam (usually 2.5-3 bar, 120-150°C) extracted from back-pressure or extraction steam turbine. The supply steam, called motive steam, is fed into thermocompressor through a nozzle. The motive steam expansion within compressor body forces the sucking out of low pressure vapor from evaporator. Both motive and suction steams are then mixed by diffusion and finally discharged with the pressure suitable for first vessel. The latent heat in last stage vapor is recycled to evaporator at the same time and becomes available again for MED desalination processes, leading to energy savings.

A higher GOR can be obtained with MED -TVC units, usually 12-15 and can even up to 17. The thermal energy can reduced to 40 kWh/m^3 with a GOR of 16 while the electric power consumption stays the same (1.5-2.5 kWh/m^3). There are also studies suggest a lower electricity consumption variation of 1-1.7 kWh/m3 for the MED-TVC process [52]. But with relative high extract steam pressure, the electrical equivalent for MED-TVC process is high, 9.5-25.5 kWh/m^3 for thermal energy, and 11-28 kWh/m^3 in all. Moreover, the recycling of part of vapor permits the evaporator running in larger scale. The typical unit productivity of MED-TVC is 10,000- 35,000 m^3/d, doubled than simple MED units.

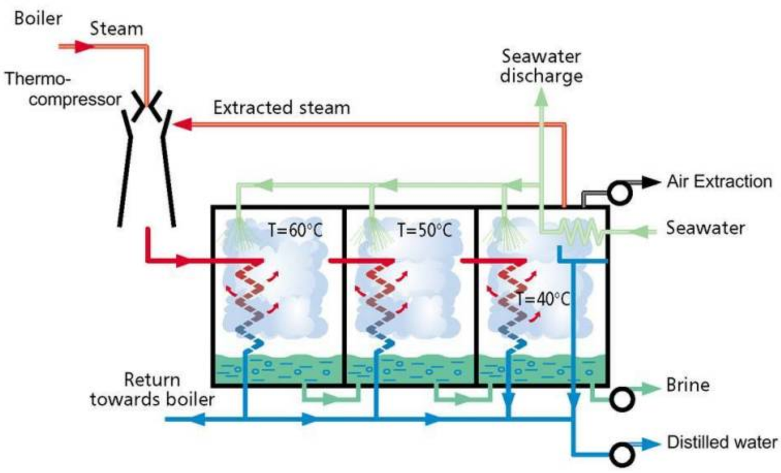


Figure 19 Schematic of MED-TVC Process[51]

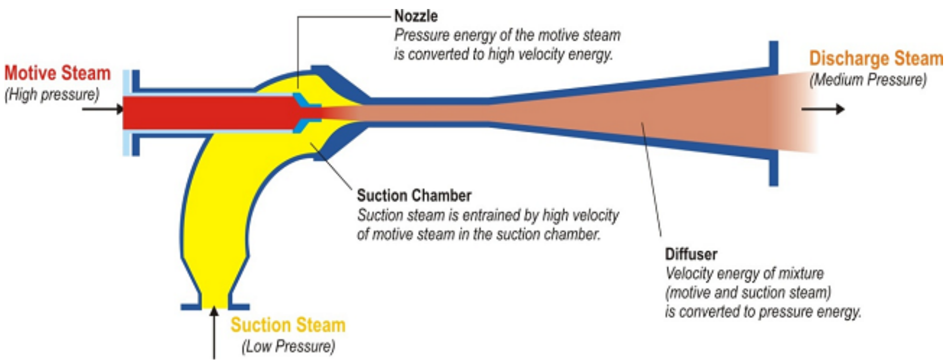


Figure 20 Schematic of Thermocompression

Unlike mainly thermal powered MED and MED-TVC processes, the MED-MVC evaporator is a MED evaporator only powered by electrical energy. All the features described for MED evaporator apply for MED-MVC process, but the vapor produced by the coldest effect is recovered to the first bundle through a mechanical compressor. The electric powered compressor brings the extract vapor to the pressure condition prevailing inside the first vessel, enabling the latent heat re-available for distillation. The heat from distillated product and discharged brine is recovered to preheat the seawater feed by two heat exchangers. Due to this high efficiency operation mode, the MED-MVC process does not calls for extra cooling stuffs other than feed seawater which makes it attractive in cooling source intensive places.

The energy input of MED-MVC typically ranges from about 18 kWh/m^3 for a single effect evaporator to around 8 kWh/m^3 for a four-cell evaporator. This is quiet similar to simple MVC process which use 7-12 kWh/m^3 electric energy generally. This process is attractive in terms of energy consumption compared to MED-TVC. However, due to the high cost of mechanical compressor, the investment is always higher than for a MED or MED-TVC plant. Another problem for this process is that the plant size greatly restricted by the capacity of available compressor on the market. For the time being, the common unit size is 100-2,500 m^3/d while the maximum possible size produce fresh water at the rate of approximately 5,000 m^3/d.

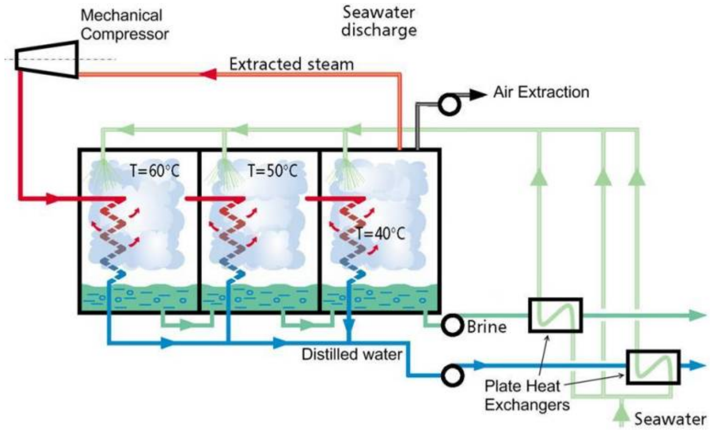


Figure 21 Schematic of MED-MVC Process[51]

3.2.3. Multi-Stage Flash (MSF) Distillation

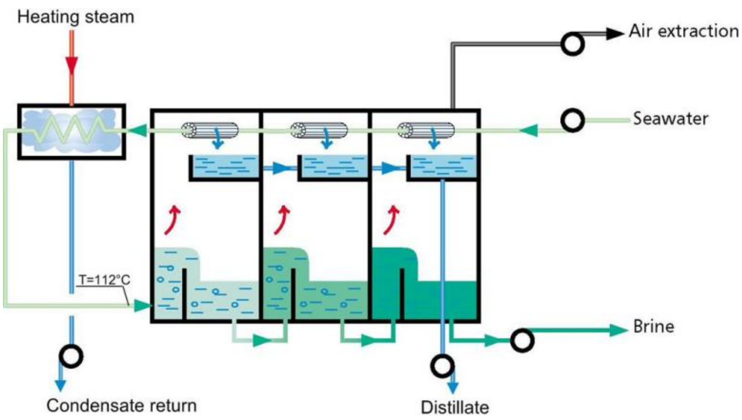
1) Technical Principles

Multi-Stage Flash (MSF) distillation is based on distillation through several or multi-stage chambers operating at progressively lower pressures. The feed seawater is pre-heated under high pressure. When the saline water is led into the first chamber, the pressure is releasing causes a rapid boiling or sudden evaporation of feed water, known as 'flashing'. This 'flashing' continues happening in each successive stage because of the reducing pressure within chambers.

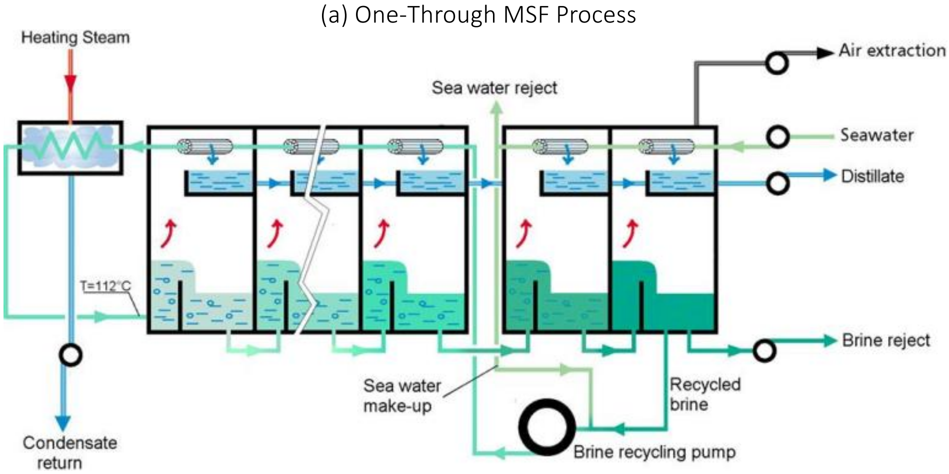
2) Process Description

The MSF process delivers feed seawater within a closed pipe passing through the flash chambers and is heated by vapor generated from flashing. The low-pressure steam (2-3.5 bar, 100-130°C) is treated as an additional heat source to warm up the seawater from tubes to the initial high temperature, typically around 110°C. TBT should be limited within 90-120°C to avoid precipitation of salt. The flashed vapor exchanges heat with feed tubes, condensed and collected as product water. The velocity of flashed vapor should not exceed 6m/s due to the entrainment of brine droplet into vapor system.

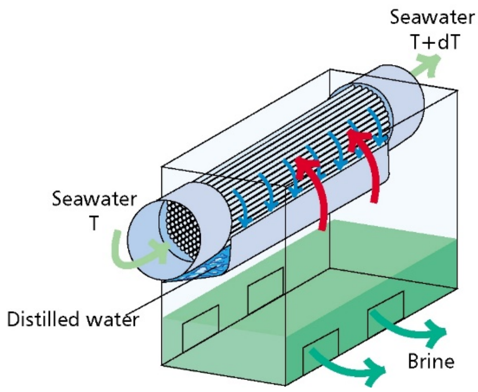
According to the brine treatment, MSF distillation has a division of 'once-through' mode or 'brine recycled' mode. For once-through design, the feed water pass through chambers once and the left brine is directly disposed. For recycled design, part of the brine is recycled and mixed with feed water to improve the recovery ratio. MSF plants are subject to corrosion caused by the turbulence of salt water unless stainless steel is used extensively.



(a) One-Through MSF Process



(b) Brine Recycled MSF Process



(c) MSF Cell

Figure 22 MSF Desalination Process and MSF Cell

3) Energy Consumption and Production Cost

The electricity mainly consumed by pumps for MSF procedure is 4-6 kWh/m^3 of distillate. The heat consumption is about 55-110 kWh/m^3 with GOR value from 12.2 to 6. With a heating steam pressure of 2-3.5 bar, the equivalent electric power for thermal supply is 0.5-19.5 kWh/$m^{3,}$ 13.5-25.5 kWh/m^3 in total. The production cost for MSF technique is 0.5-1.75 USD/m^3 [54] while the capital cost is 5.5-10 USD per installed gallon per day[55].

4) Productivity

A MSF plants evaporator unit typically contains 15-25 stages with unit capacity from 50,000 m^3/d to 70,000 m^3/d. The featured GOR of MSF process is around 8. To ensure the efficient operation of MSF process, the system should not run below 70-80% of designed capacity[56].

3.3. Comparison of Popular Desalination Technologies

The operating condition of described desalination technologies can be summarized as Table 10.

Table 10 Comparison of Characteristics of Main Desalination Technologies[53] [57]

	RO	MSF	MED	MED-TVC	MED-MVC
Typical Unit Treatment Capacity (m^3/d)	24,000	50,000-70,000	5,000-15,000	10,000-35,000	100-2,500
Feed Water Quality	Specific pre-treated	Not critical	Not critical	Not critical	Not critical
Distillate Quality (ppm TDS)	1 stage: 300 2 stage: 10-50	1-10	1-10	1-10	1-10
Steam Temperature (°C)	/	100-130	70-90	120-150	/
Steam Pressure (bar)	/	2-3.5	0.3-0.5	2.5-3	/
Operating pressure or Temperature	55-82 bar (seawater)	90-120 °C	65-70 °C	65-70 °C	65-70 °C
Thermal Power Consumption (kWh/m^3)	/	55-110	60-110	40-110	/
Electric Power Consumption (kWh/m^3)	1-7	4-6	1.5-2.5	1.5-2.5	8-18
Electrical Equivalent (kWh/m^3)	1-7	13.5-25.5	6.5-11	11-28	8-18
Production Cost (USD/m^3)	0.45-0.58	0.5-1.75	0.7-1		~1*
Capital Cost (USD/gal/d)	0.35-1.18	5.5-10	3.5-4	4.5-9.0	
Maintenance Cost	Medium	Low	Low	Low	Low

4. Case Study of Cogeneration Desalination Plant

In most cases, particularly for large desalination plants, the lowest cost and highest efficiency is obtained by coupling water production with power generation, optimizing the exhaust conditions of turbines to feed the desalination units. The large desalination plants around Arabian Sea are usually developed on such cogeneration concept. Sometimes RO units are associated to these thermal desalination processes to further optimize the practicability and feasibility of cogeneration desalination facilities, called hybrid plant[58]. This part aims to give out several case studies of existing cogeneration desalination plants to better understanding their process, productivity and energy flow details.

4.1. St. Barth WTE Desalination Cogeneration Plant

4.1.1. Background of St. Barth

Saint Barthélemy (also known as St. Barth or St. Barts) is located in the French West Indies, approximately 160 miles east of Puerto Rico and the nearer Virgin Islands and 15 miles southeast of St. Martin[59]. St Barth belongs to France and has European ambience unlike any other island in the Caribbean, with a total population of 7,237. This eight-square-mile island has hilly landscape and abound with beaches, almost completely surrounded by shallow-water reefs. Gustavia is the capital city, built at the west island around the harbor[60]. With few natural resources, the economy of St Barth is fostered by high-end tourism and duty-free luxury commerce, serving more than 200,000 visitors primarily from North America. The climate type of St Barth is tropical climate, practically no variation in temperature with two clear seasons: dry and humid. With no natural rivers and streams, fresh water resources is in short supply, especially in tourist summer season from May to November. Fresh water supply on St. Barth is mainly provided by sea water desalination, rain water collection and via water tanker import. Besides, nearly all food, energy resources and most manufactured goods are supplied by import.

Figure 23 Map of St. Barth[61]

4.1.2. Waste Management and Water Production in St. Barth

To relieve the conflict between resource shortage reality and improving energy and fresh water demands as well as to improve the waste manage system on island, St. Barth institute a recycling program for household trash in 1998[62]. A WTE-desalination facility, owned by Groupe TIRU (EDF), is then under constructed at Gustavia and put into operation in 2001.

Figure 24 WTE-Desalination Plant of St. Barth

According to the MSW management system of St. Barth, the waste is first collected at the island's waste disposal plant, located just outside Gustavia, for recyclables separation. Components like batteries and metals are generally stockpiled and sent off-island to Guadeloupe, Miami, France by barge for recycling; glass is repurposed locally to create sub-strata; trash, paper/cardboard and plastic containers are sent to the WTE plant for incineration[61]. This open-air classification process increase the combustible component percentile and partially dried the waste by sunlight, resulting in a relative high calorific value of feed MSW.


Figure 25 Combustible Waste Dried and Moved[61]

The WTE plant combusts MSW collected using a Cyclerige oscillating kiln with a capacity of 1.5 tons per hour, 9000 tons annually[2]. With 80% thermal recovery efficiency, this incineration process can produce 3 tons of steam per ton of burned MSW[63]. The electricity generated from turbine is used for the operation consumption of WTE and neighbored desalination plant, the rest of steam is sold in form of heat to power the thermal MED units provided by SIDEM[64]. Steam delivered from WTE can produce 1200-1720[2] cubic meters of potable water per day, 1350 cubic meter per day generally[63], providing 40% of the island's water demand[65]. The rest of fresh water is produced by a RO desalination plant. In 2009, the maximum production of potable water in St. Barth is 4,300 cubic meters per day comparing to an average consumption of 3,000 cubic meters per day[66]. In 2013, EDF installed two extra power generation units to the WTE facility with 16MW output in all[67].

Table 11 Operation Data of St. Barth WTE Plant

	2008	2009
MSW Combusted/ton	9,762	9,038
Heat Sold/MWh	20,666	19,876
Production Factor/ MWh/ton MSW	2.117	2.199
Average Working Hour	6508h 17.8h/d	6025h 16.5h/d

4.1.3. WTE-Desalination Plant Energy Flow Estimation

Since only very limited information is offered by St. Barth local government and device suppliers, parameter estimation is introduced for brief energy flow study. According to the WTE plant operation data in 2008 and 2009, the estimation result can be shown as Table 12. The calorific value of feed waste is estimated from sold heat, with 60%-80% energy transfer efficiency from MSW. The flue gas from kiln is used for combustion feed air pre-heating. According to the water temperature in Caribbean Sea (23-31°C), an average of 27°C is considered as feed water temperature. Losses for steam transport between two units is ignored. Other operating parameters are estimated based on previous models and heat balance equations.

Table 12 Parameter Estimation of St. Barth WTE Plant

	Estimated Range	Parameter Adopted
LHV of MSW (MJ/kg)	9.5-13.2	11.5
MSW Incineration Capacity (t/h)	1.5	1.5
Steam Generation (kg/s)	1.25	1.25
Heat Sold (MWh/t MSW)	2.1-2.2	2.15
Heat Sold (kJ/kg Steam)	2556-2628	2580
Status of Sold Steam	246°C, 15bar	246°C, 15bar
Status of Back Steam/Water	80°C, 15bar	80°C, 15bar
Average Working Hour (h/d)	16.5-17.8	17

Table 13 Operation Parameter of St. Barth Desalination Plant[51]

Desalination Technique	MED Process
Fresh Water Generation Capacity (m3/h)	913
Effect 1: Temperature, Pressure (Boiling Point)	60°C, 0.20bar (58.9°C)
Fresh Water Temperature (°C)	32
Feed Raw Water Mass Flow (kg/s)	81.25
Raw Water Temperature (°C)	27
Saline Temperature (°C)	38
Salinity of Raw Water	3.6%
Salinity of Exhaust Saline	5.0%
Density of Raw Sea Water (t/m3)	1.0238
Heat Capacity of Raw Water (kJ/kg・°C)	4.096

From the accounting result, the St. Barth WTE plant is a heat-focused facility that 67% of heat is sold for fresh water production and only 8.5% is transformed to electricity. The over-all energy efficiency of St. Barth's WTE unit is around 75%, still have space for improvement. Based on the boiler productivity data (3 ton steam per ton of MSW), the steam temperature and pressure would be really high (4.5-5MPa, 480+°C). If steam supplied at 2.58 MJ/ton (steam) status, then the feed steam would also under very high status, possibly over 150°C and returned around 80°C. Comparing to general MED units with 0.3-0.5 bar, 70-90°C steam feed, this high energy level and obvious temperature gap greatly improves the raw sea water dealing rate and accelerate the heat transfer between feed steam and raw water, while the returned hot water does not need to be pre-heated. The relative high heat transfer efficiency (~92%) also ensure the productivity of MED unit. Regardless of the electric power consumption, the heat consumption for potable water production is 8.6MJ/m3 (40.6 kWh/m3). In all, the coupled WTE and thermal desalination plants reached an impressive GOR of 17.8, higher than the world's average 8-10. Looking at several MED desalination project operated by SIDEM, this GOR data is acceptable from a typical GOR level of 14.

Table 14 Energy Flow Result of St. Barth WTE-Desalination Plant (1h Scale)

Plant	Energy Inflow	Amount (MJ)	Percentage	Energy Outflow	Amount (MJ)	Percentage
WTE Plant	MSW	17,250	100%	Gross Electricity	1,456.4	8.44%
				Desalination	11,610	67.30%
				Air pre-heating	1,125	6.52%
				WTE Loss	4,296.1	24.90%
Desalination Plant	Steam	11,610	100%	Fresh Water Production	1,711.7	14.74%
				Exhaust Saline	9,498.1	81.81%
				Other Losses	940.2	8.10%

Table 15 Energy Flow Accounting of St. Barth WTE Plants

Process	Formula	Efficient Amount (MJ/h)	Losses (MJ/h)	Efficiency (%)	Remark
Total chemical energy in MSW	11.5MJ/kg * 1.5t/h = 17,250 MJ/h	17,250	-	-	LHV = 11.5MJ/kg Capacity: 1.5t/h
Heating up of primary combustion air	1.25kJ/m3/°C * 4m3/kg MSW * 1.5t/h * (120°C - 30°C) / 90% = 750 MJ/h	675	75	90%	Heat value of air: 1.25 kJ/m3/°C Heat transfer efficiency: 90% Air fed: 4m3/kg MSW
Heating up of Secondary combustion air	1.25kJ/m3/°C * 2m3/kg MSW * 1.5t/h * (120°C - 30°C) / 90% = 375 MJ/h	337.5	37.5	90%	Heat value of air: 1.25 kJ/m3/°C Heat transfer efficiency: 90% Air fed: 2 m3/kg MSW
Energy to boiler steam	17,250MJ/h * 80% = 13,800MJ/h	13,800	3450	80%	Heat Efficiency of Chamber to Boiler: 80% Loss include heat transfer loss, bottom ash, flue gas loss
Energy Sold in Heat	2.15MWh/t MSW * 1.5t/h = 11,610MJ/h	11,610			
Energy from steam to drive the turbine	13,800-11,610 = 2,190 MJ/h	1,533	657	70%	Isentropic efficiency of turbine: 70%
Electricity generated	1,533MJ/h * 95% = 1,456.35 MJ/h	1,456.4	76.6	95%	Productivity: 0.27 MWhel per ton of MSW Electrical and mechanical efficiency: 95%
Efficient energy for fresh water production	22.75kg/s * 4.18 kJ/kg/°C * 3600s * (32°C - 27°C) = 1,711.71MJ/h	1,711.7			
Energy for raw water heating	(81.25-22.75)kg/s * 4.10 kJ/kg/°C * 3600s * (38°C - 27°C) = 9,498.06MJ/h	9,498.1			
Energy Loss for MED	11610-1711.7-9498.1 = 940.2MJ/h		940.2	91.9%	

4.2. Hebei Huanghua Power-Desalination Cogeneration Plant

4.2.1. Introduction of Huanghua Power Plant

Huanghua coal-fired power plant is the first power plant in China that coupled electricity generation with desalination units. It is owned and invested by Shenhua Group together with Hebei and Cangzhou local government, operated by Shenhua's subside Guohua Cangdong Power. The designed power generation capacity of Huanghua power plant is 6520MW, 2520MW among them is now under operation. Located near Pohai Gulf, direct sea water cooling is used for all the condensers of Huanghua power plant. Approximately 3,200,000 - 4,400,000 m^3 of freshwater is consumed annually as feed-water for the four boiler units, as well as for desulfurization and other processes. This massive water consumption requirement is completely filled through coupled desalination units of Huanghua power plant. The power-water cogeneration process achieves zero fresh water consumption and effectively converts conventional water-intensive power plant into a fresh water supplier to surrounding regions. With the completion of 3rd-stage desalination unit construction, the current production capacity of Huanghua power plant has reached 57,500 ton per day. Despite meeting the needs of self-utilization, the desalination units produce 5-10 million external tons of fresh water annually (14,000-28,000 ton/d) for the Port of Huanghua in Cangzhou, Hebei, as well as industrial users in nearby steel plants[68].

Table 16 Introduction of Huanghua Power Plant[69]

Stage of Construction	I	II	III
Year	2004-2007	2007-2009	2013
Power Generation	600MW ×2	660MW ×2	1,000MW ×4
Desalination Unit	10,000ton/d ×2	12,500ton/d	25,000ton/d
Operation Status	Under Operation	Under Operation	Incomplete
Investment (USD)	794,500,000		44,000,000

Figure 26 Guohua Cangdong Power Plant Desalination Facility (25,000t/d)

Although the equipment investment and water production costs for SWRO technique is lower, but its higher requirement in terms of seawater quality reduce its adaptability. It has no obvious advantages in investment as well as operational energy consumption when applied in northern China with relative low sea water quality[70]. Driven by the company's resource-saving strategic development needs, Shenhua Guohua select MED-TVC technology for its cogeneration of power and water. Through research, development, and application, Shenhua Guohua has proprietary of large-scale MED equipment and built up a 25,000 ton/d MED unit at Huanghua power plant.

The MED unit developed by Shenhua Guohua uses a horizontal-pipe falling film evaporator (Figure 27) [70]. The exhaust steam from power plant turbine enters the heat exchanger of first effect and condenses after releasing sensible and latent heat. The feed seawater is partially evaporated by absorbing this heat, then guided into the second effect. Such step is repeated for each sequential evaporator. When the exhaust steam has a higher temperature and pressure level, part of the evaporated vapor can be recirculated via a thermal vapor compressor to increase its pressure and transfer it to the first effect heating source, thus improving the efficiency and reducing the costs of water generation. The vapor from last effect is directed into a condenser for feed raw water pre-heating, the condensed fresh water is also collected as product. To implement efficient heat transfer, Shenhua Guohua mastered the mechanisms of vacuum heat transfer and flow with small temperature differences and multiphase through R&D.

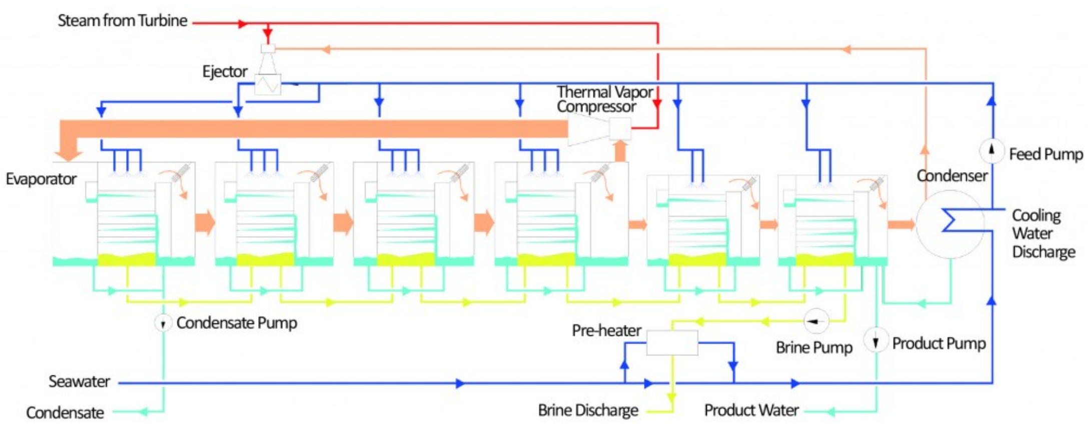


Figure 27 Schematic of Shenhua Guohua Large-scale MED Process (12,000t/d)

4.2.2 Coal-Fired Power-Water Cogeneration Energy Flow Estimation

The operation parameter of Huanghua power-desalination plant is shown in Table 17 and Table 18. In 2009, Huanghua power plant generate 9,410,000 MWh (8,950,000 MWh sold) with 2520MW installed capacity. The coal consumption level of finance is around 331g/kWh[71]. Take this generation level into considered, the effective operation time of the turbine is 3734h, 10.23h/d. The returned heat steam (water) temperature from 1st effect is typically around 140°C. Since the third stage power unit is still under construction and the 2nd stage is under eco-adjustment, only first construction stage's recent operation parameter is offered by the power plant. In this case, the estimated energy flow accounting of Huanghua power plant only takes the first construction stage into calculation.

Table 17 Huaghua Power Plant Turbine Operation Data

Stage of Construction	I	II[72]	III[73]
Equipment Manufacturer	Shanghai Electric	Shanghai Electric	Shanghai Electric
Number of Turbine	2	2	4
Generation Capacity	600MW	660MW	1,000MW (1,030max)
Feed Steam Temperature (°C)	538	566	600 (610max)
Feed Steam Pressure (bar)	167	242	250 (270max)
Feed Steam Flow Rate	1800t/h	1800t/h	~2800t/h
Steam Extraction	4 stage	4 stage	4 stage
Thermal Efficiency			45.4%
Coal Consumption	330-350g/kWh	~300g/kWh	~275g/kWh

Table 18 Operation Parameter of Huanghua Desalination Units

Stage of Construction	I[74]	II[75]	III[76]
Equipment Manufacturer	SIDEM	Shenhua Guohua	Shenhua Guohua
Desalination Technique	MED-TVC	MED-TVC	MED-TVC
Number of Effect	4	6	10
Fresh Water Generation Capacity (t/d)	10,000	12,500	25,000
Steam Supply	4^{th} extraction from 600MW×2 steam turbine	4^{th} extraction from 660MW×2 steam turbine	4^{th} extraction from 600MW×2 and 660MW×2 steam turbine
Vapor Extraction to TVC	4^{th} Effect	4^{th} Effect	7^{th} Effect
Feed Steam Flow (t/h)	50	52 (48.5 exhaust steam and 3.5 extraction vapor from effect)[77]	77
Feed Steam Pressure (bar)	3.7-5.5 (<8.0)	5.5(>3)	5.5
Work Load Feasibility	50-100%	40-110%	40-100%
Feed Steam Temperature (°C)	320 (<380)	320	320
GOR	8.33	9.67-10.2	13.5(⩾13)
Designed Raw Water Temperature (°C)	-	25(-1.5-30) 42(from condenser)	20 42(from condenser)
Salinity of Raw Water	3.6%	3.6%	3.6%
Concentration Times	1.4-1.5	-	-
Salinity of Exhaust Saline	-	-	5.11%
Electricity Consumption		0.82-1.0 kWh/t	1.0-1.2kWh/t

To improve the heat efficiency of power plant, there is a steam re-heating process between the high pressure turbine and middle pressure turbine for the 600MW steam turbine. It also has four-level steam extraction for feed water pre-heating from 35°C to 273.7°C, the extracted steam is then mixed with water supply as feed water.

Sea water is applied as condensate in the steam condenser which can be also treated as pre-heating process of sea water desalination, especially in low temperature winter seasons. The overall mass flow of raw sea water is 260,000m^3/d with temperature of 25°C. The stepped accounting processes can be shown in Table 20.

According to the accounting result (Table 19), with the heating recovery system and coupled desalination system, only 10% of total energy input lost during the process, the electricity consumption can be covered by the electricity generated from turbine. About 40% of the heat generated is removed into sea water pumping from the surrounding Pohai Gulf, cutting the plant's condensing water consumption to zero. However, merely 20% of the heat is efficiently utilized for desalination process, even including part of heat consumed by the 25,000m^3/d MED unit. During the winter season, the efficient proportion increases to around 40% due to the lower sea water temperature. Assume an overall thermal efficiency of 80% to 20,000 m^3/d coal-powered MED desalination unit, approximately 480-500 tons of coal (47,500 USD[78]) is saved every day. The reduced water production cost also guarantee the water supply and water price of surrounding local area.

Table 19 Energy Flow Result of Hunaghua Power-Desalination Plant (1h Scale)

Plant	Energy Inflow	Amount (MJ)	Percentage	Energy Outflow	Amount (MJ)	Percentage
Power Plant	Coal	11,630,016.0	77.45%	Gross Electricity	4,320,000.0	28.77%
	Electricity	216,000	1.44%	Desalination	6,290,831.5	41.89%
	Ancillary Fuel	3,169,600.8	21.11%	Air Pre-heating	1,562,623.1	10.41%
				Feed Water Pre-heating	1,289,584.5	8.59%
				Other Loss	1,552,577.7	10.34%
Desalination Plant	Exhaust Steam	6,040,352.5	96.02%	Fresh Water	32,687.6	0.52%
	Extract Steam	250,479.0	3.98%	Exhaust Saline	154,685.4	2.46%
				Raw Sea Water Pre-heating	920,186.9	14.63%
				Losses	5,183,271.6	82.39%

Table 20 Energy Flow Accounting of Huanghua Power-Desalinations Plants[79]

Process	Formula	Efficient (MJ/h)	Losses(MJ/h)	Efficiency(%)	Remark
Coal combusted in power plant	29.28MJ/kg * 331kg/MWh * 1200MW = 11,630,016MJ/h	11,630,016	-	-	LHV = 29.28MJ/kg Capacity: 331g/kWh
Energy to steam	(3398.62-1200.26)*1800*2+(3539.42 -3013.81)*1520*2= 9,511,950.4MJ/h	9,511,950.4		78.74%	Enthalpy of Steam: 3398.62kJ/kg (538°C, 167bar), 1800t/h; 1200.26kJ/kg (273.7°C, 190bar); 3013.81kJ/kg (314.4°C, 35.8bar); 3539.42kJ/kg (538°C, 33.2bar)
Energy from flue gas for air pre-heating	2118065.6*0.5 = 1,059,032.8 MJ/h	1,059,032.8	1,059,032.8	50%	
Energy from extract steam for feed water pre-heating	(3125.1*130+3013.81*150+3325.16*70 +3114.49*75+2917.08*60+2753.22*40 +600*50-1200.26*575)*2=1,899,373.1 MJ/h	1,289,584.5	125,897.6	93.37%	Enthalpy of Steam: 3125.1kJ/kg (378.5°C, 58.6bar), 130t/h; 3398.62kJ/kg (314.4°C, 35.8bar), 150t/h; 3325.16kJ/kg (432.5°C, 16.1bar), 70t/h; 3114.49kJ/kg (326.7°C, 7.4bar), 125t/h; 2917.08kJ/kg (225°C, 3 bar), 60t/h; 2753.22kJ/kg (139.5°C, 1.3bar), 40t/h; 147.538kJ/kg (35°C, 10bar)
Energy from extract steam for air pre-heating	629,487.9*0.8 = 503,590.3 MJ/h	503,590.3			
Energy from exhaust steam to raw sea water	(2612.1-146.65) * 1225 *2 = 6,040,352.5MJ/h	6,040,352.5			Enthalpy of Steam: 2612.1kJ/kg (60°C, 5.88kPa), 146.65kJ/kg (35°C, 5.88kPa)
Energy to desalination units	(3104.79-600)MJ/t*50t/h*2= 250,479MJ/h	250,479	970	99.4%	Enthalpy of Steam: 3114.49kJ/kg (326.7°C, 7.4bar); 3104.79kJ/kg (320°C, 5.5bar); The Loss indicate the transmission loss from power plant to desalination units.
Energy from steam to generate electricity	[3398.62*1800+(3539.42-3013.81)*1520 -(3125.1*130+398.62*150+3325.16*70 +3114.49*125+2917.08*60+2753.22*40) -2612.1*1225]*2 =4,686,677.3 MJ/h	4,686,677.3			Enthalpy of Steam: 3398.62kJ/kg (538°C, 167bar), 1800t/h; 2612.1kJ/kg (60°C, 5.88kPa)
Electricity generated	600MW*2 = 4,320,000 MJ/h	4,320,000	366,677.3	92.18%	
Energy for raw water pre-heating	(7350+5865)*4.096*(42-25)=920,186.88 MJ/h	920,186.9	5,120,165.6	15.23%	
	(7350+5865)*4.096*(42-0)=2,273,402.9 MJ/h	2,273,402.9	3,766,949.6	37.64%	
Energy left in fresh water and saline	5395*4.096*(32-25)+1955*4.18*(29-25) = 187,373 MJ/h	187,373	63,106	62.24%	Raw Sea Water Supply: 75000t/h; Heat Capacity of Sea Water: 4.096kJ/ (kg˙°C)

5. Locations for WTE-Desalination Plants Development

From the previous study, the cogeneration of power and water is a new ecological and economical solution. For power generation plant, it maintains the certain power generation level by adoption of condensing steam turbine, cuts down the condensing water/air consumption by adopting sea water as condensate, improves the energy efficiency and alleviates the local water scarcity by utilizing exhaust heat for desalination process. For desalination process, it greatly cuts down the fuel consumption compared to simple desalination plants and in turn reduces the cost of fresh water production. According to the study[76], for a coal powered MED desalination process, the capital cost is about US$0.87 per cubic meter fresh water produced. The steam cost (mainly coal cost) covered nearly 50% of the total cost. When extract steam or exhaust steam from power plant is adopted as desalination heat sources, the total cost of capital water production reduced to US$0.40 and US$0.19 respectively. Such environmental and economical beneficial effects will be further enlarged with WTE facilities, the sustainable waste management method.

Considering the benefits and requirements of WTE-desalination cogeneration plant, the most promising places for this technique should be:

1) Along the seaside;
2) Limited fresh water supply;
3) Limited access to fuel sources;
4) Limited land source for efficient MSW management;
5) Relative warm or high temperature with mild seasonal fluctuation.

In this case, those gulf cities and small islands is the prioritized places for the development of WTE-desalination cogeneration plants. Feasible options including areas like:

- Mediterranean: Cyprus; Crete;
- Persian Gulf - Kuwait, Bahrain, Oman, Qatar, the United Arab Emirates (UAE);
- Caribbean Sea: US - Virgin Islands, Puerto Rico; Mexico - Cancun, Yucatan;
- North Africa: Egypt - Red Sea or Sinai;
- Other regions: Kenya - Mombasa region; South East Asia – Malaysia, etc.

In accordance with listed conditions, Cyprus and Union Territory of Lakshadweep (India) are selected to do brief feasibility analysis for WTE-desalination facility development.

5.1. Cyprus

Figure 28 Map of Cyprus

Cyprus is a former British colony and became independent in 1960, capitaled in Nicosia. It is an island located in Mediterranean Sea, south of Turkey, with an overall land area of 9,241 km^2 and population of 1,189,197 (2015 est.) [59]. Cyprus has a Mediterranean climate with hot, dry summers (26-29°C in average) and cool winters (10-13°C in average). With total renewable water resource of 0.78 km3 (2011), the chronic water shortage worries Cyprus a lot. The capita water withdraws of Cyprus is 213.5m^3 per person per year (2009) and 180,000m^3 in all. This number continuously increased with boost population and tourists.

The electricity consumption of Cyprus is 4.296 billion kWh (2012 est.), all produced by local power plants. 90% of total installed capacity is from fossil fuels while the left 10% generated from renewable sources including MSW. No hydro-electric power plant is implied in Cyprus. Though has 141.6 billion cubic meters proved natural gas reserved, the continental fuel consumption of Cyprus is completely provided by import, mainly oil product and some coal and biomass[80]. The amount of refined petroleum products imported is 52,480 bbl/day (2012 est.). The total carbon dioxide emission from energy consumption in Cyprus reaches 8.801 million tons in 2012.

According to WtERT[81], Cyprus generated 754 kg of MSW per person per year: 13% recycled, 87% landfilled, 0% composted or incinerated. The composition of MSW in Cyprus is shown in Figure 29[82], 51.6% of which is recyclable and 65.6% biodegradable. Therefore there is still large for the improvement of Cyprus's waste management system and energy recovery from waste. A study of EPEM[83] estimated the amount of MSW of Cyprus that can be further utilized for energy recovery (Table 21) and analyzed the development possibility of several main energy recovery technology. Compared to pyrolysis, gasification and plasma techniques, the WTE plants with waste incineration is the most promising one, lower cost with more mature and developed technology. With new constructed incineration WTE plant, 424,400MWh energy can be recovered per year, surplus 339,500MWh annually.

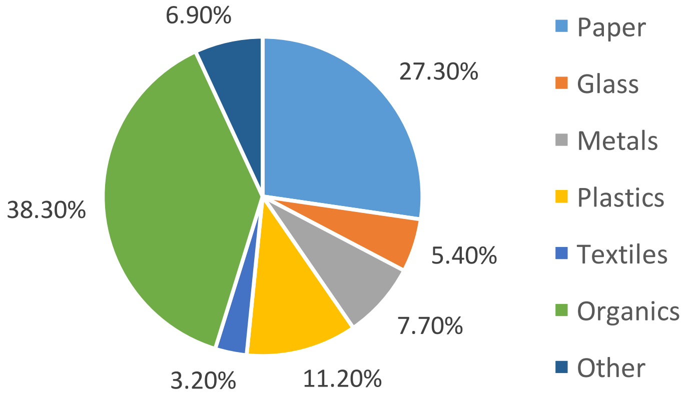


Figure 29 MSW Composition of Cyprus

Table 21 Distribution of MSW in Cyprus Can Be Utilized for Energy Recovery per Region[83]

	Annual waste quantity (tn)			
Waste type	Nicosia	Larnaka and Famagusta	Limassol	Pafos
Waste from food industry – Other organic waste	143.560	97.000	116.400	31.040
Paper and wood industrial waste	41.730	23.540	31.030	10.700
Sludge from industrial wastewater	21.060	11.880	15.660	5.400
Used oils	2.000	1.150	1.350	500
Oil residues – bilge water	0	12.500	12.500	0
Old tires	2.600	1.365	1.885	650
Sewage sludge	1.950	4.500	6.000	2.550
Products of rendering facilities	0	41.000	0	0
Animal fat	0	5.000	0	0
RDF/SRF	70.000	0	70.000	0

In terms of the desalination industry of Cyprus, the government has invested heavily in the creation of water desalination plants which currently have supplied almost 12% of total water consumption and 40-50% of domestic water. Five desalination plants is under operation while the 6th one located at Vassilikos was inaugurated recently[84]. The operational data of five existing plants can be summarized as Table 22. All of the desalination plants in Cyprus applies the RO technology for its water production process considering the limited access to fuels. The average power consumption of these RO desalination plants is 4.50kWh/m^3 or three liters of petrol per ton. Therefore, at least 800MWh (6.8% of total electricity consumption) or 3,354 liters of petrol per day (6.5% of total consumption) is consumed for the fresh water production.

Table 22 Operation Parameter of Cyprus Desalination Plants[85][86]

Name	Dhekelia Desalination Plant	Larnaca Desalination Plant	Limassol Desalination Plant[87]	Paphos Desalination Plant	Moni Mobil Desalination Plant[88]
Start of Production	April 1997	May 2001	2004	2006	2008
Fresh Water Generation Capacity (m3/d)	54,000-60,000	55,800-62,000	20,000-40,000	30,000-40,000	18,000-20,000
Service Area	Nicosia-Larnaca-Famagusta Water Supply System	Nicosia-Larnaca-Famagusta Water Supply System	Limassol	Paphos	Limassol
Desalination Technique	RO	RO	RO	RO	RO
Recovery	~50%	~50%	45%	/	44%
Selling Price (€/m3)	0.82	1.08	/	/	1.39

With boost population and tourists, the Cyprus government is still planned to enlarge its desalination capacity. Simultaneously the reducing space for waste landfilling and intensive energy accessibility calls for efficient energy recovery from MSW. Since the raw sea water temperature greatly matters the productivity of thermal desalination processes, the relative warm and dry climate condition also potentially ensure a stable productivity of coupled thermal desalination facilities. From the data above, WTE-thermal desalination cogeneration plant can possibly bring Cyprus 51,000MWh extra electricity and 85 million tons of fresh water per year which nearly equals to the installed RO desalination capacity. Besides, the water and electricity generation cost will significantly reduce from the current status due to nearly zero fuel cost. And this sustainable way will mitigate the GHG emission of the power and water generation processes, help the government to meet the carbon reduction regulations of EU.

In short, coupled WTE-desalination technology is highly recommended and well suitable for the sustainable development of Cyprus and exactly solves several most severe and troubled environmental issues at the same time. Of course, cities or countries around Mediterranean Sea with similar climate and embarrassments can take this solution into their consideration for the future construction.

5.2. UT of Lakshadweep

The Union Territory (UT) of Lakshadweep is a group of islands governed by the Union

Government of India in the Laccadive Sea, 200 to 440 km off the south western coast of India. The archipelago is formed of 12 atolls, 3 reefs and 5 submerged banks, with a total of about thirty-nine islands and islets. The main islands are Kavaratti, Agatti, Minicoy, and Amini and Kavaratti serves as the capital of the UT. The Lakshadweep region enjoys tropical climate, 25-30°C all the year round. The annual rainfall is 2,500mm, mainly in May to August[89]. The surface area of the whole Kavaratti islands is just 32 square kilometers with population of 64,429 (2011). It has 10 inhabited islands, 17 uninhabited islands[90]. The population density in the inhabited islands (2,013 persons per square km) is much above the national average of 324 while Amini has the highest density of 2,839 persons/km^2 [91].

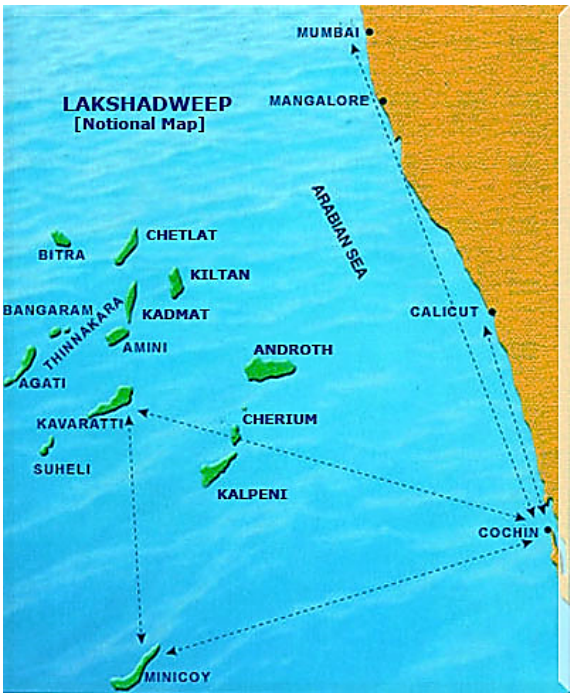


Figure 30 Map of Lakshadweep

The power supply of the UT is mainly through diesel powered generating sets located in eight inhabited islands. During 2002, the installed capacity reaches 9,837kW, generated 19,856 MWh electricity in all[92]. About 6,600,000 liters of high speed diesel (HSD) is transported from Beypore annually to provide uninterrupted power supply in the islands[93]. As an area of sun and sea, Lakshadweep ambitiously build up its renewable energy system. So far four solar photovoltaic (SPV) power plants are installed in four islands, generating 185kW of energy while a 100kW one under installation at Minicoy. According to the Union Territory Administration, 20% of its demand (1MW) is aimed to be met through solar energy[93]. Besides, an 80kW wind powered generator is installed at Kavaratti and Agatti and one 200kW capacity biomass gasifier plant was proposed to be installed at Kavaratti[94].

The absence of systematic waste management and treatment is one major issue faced Lakshadweep. The untreated domestic sewage are discharged into the sea directly without any treatment. The non-degradable solid wastes are dumped on the narrow shore line at one end of each island by the local bodies[95], or right behind each house-hold. It is estimated that about 5 tons of MSW per day is generated at

Lakshadweep in 2011 (0.382kg per day per capita[96]). In addition, bulks of plastic waste containing sand, and building materials are brought to the island from Kerala. Therefore, there is an urgent need for proper solid waste management in these tourism based islands.

None of the Lakshadweep islands have rivers or creaks but one between two large lagoons of Kavaratti is a brackish one. To make things even worse, it is revealed that the scarce fresh water resources in Lakshadweep are threatened by salinity intrusion and sewage contamination. In the absence of sewage treatment plants, about 50,000 to 100,000 liters of sewage waste is let into septic tanks or cess pools each day[91]. Around 50% of the island's population suffered from stomach, dental and skin diseases due to biological contamination of water. Considering a basic residential water consumption level of 55 liters per capita per day, 3,543,595 liters of potable water is required every day. However, the natural fresh water resource of Lakshadweep can merely offer 303,550 liters per day, left a 3,240,045 liters deficit, let along the extra water consumption of tourism and other industries.

A combined system consisting of ground water collecting wells/ponds, rainwater harvesting (RWH) tanks and desalination plants is adopted in these islands to supply the municipal fresh water. A total of 436 fresh water ponds were recorded in whole ten inhabited islands, 90 in Kalpeni Island, 75 in Amini, 54 in Agathi and 53 in Kiltan. Most of these ponds are man-made ecosystems with a dimension of 5-10 square meters and there are two big ponds of about 25 square meters at Amini and Kavaratti islands[97]. There are two community rain water harvesting system, one each at Kavaratti and Minicoy. In addition, there are more than 1,700 individual RWH tanks constructed on the roof top. Currently speaking, Lakshadweep have created infrastructures for RWH to an extent of about 11 million liters per year (~30,150 L/d). Ten RO desalination units are installed at different islands of Lakshadweep[98], providing approximately 400,000 (est.) liters of fresh water per day[99]. Besides, three desalination plants, based on the Low Temperature Thermal Desalination (LTTD) technology developed and demonstrated by the National Institute of Ocean Technology (NIOT), have been successfully built one each at Kavaratti (2005), Minicoy (2011), and Agatti (2011)[100]. The capacity of each LTTD plants is 100,000 liters per day. Six more projects are under progress at Androth, Amini, Kalpeni, Chetlat, Kadmat and Kalpeni, cost 1.25 billion Indian Rupees (18.6 million US dollars) in all[101]. The LTTD desalination plant was the sole source of drinking water free piped to every household on Lakshadweep islands.

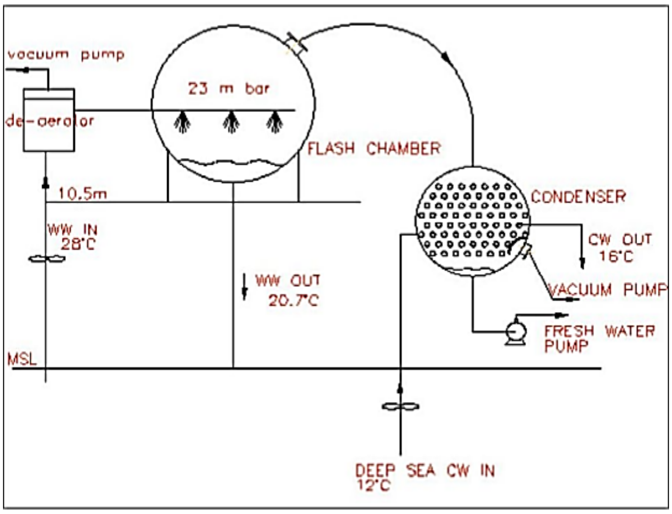


Figure 31 Schematic of LTTD process for Karavatti
(WW, Warm water; CW, Cold water)

LTTD technology is a thermal desalination method which based on pressure and temperature differential between surface sea water and deep sea water. The warmer surface sea water is evaporated at low pressures, the obtained vapor is then condensed by the colder deep sea water (Figure 31). In terms of the energy consumption of pumps, the LTTD plant consumes around 10 kWh of electrical energy per cubic meter of fresh water produced, higher than other desalination techniques. According to the cost estimates made by an independent agency for LTTD technology, the cost per liter of desalinated potable water is about 0.97 Rupee (0.01 US dollar) for island based plants[102]. Though the cost is said to be reduced with enlarged treatment scale, it still need to be further verified.

From the description above, the Lakshadweep administration need to evolve an efficient and detailed MSW management plan to protect and conserving its fragile coastal marine ecosystems. To begin with, a pilot project on solid waste disposal and collection is required. Then the WTE incineration plant or pyrolysis plant can be introduced to Lakshadweep islands to improve the MSW management and reduce fuel import. Since the desalination industry improvement and enlargement is still necessary in islands, a waste heat recovery fresh water generator project of 10,000 liters is under installation at Kavaratti Power House to provide portion of potable water and optimize diesel utilization efficiency[93]. Under such background, the coupled diesel/waste power plant and desalination plant is a promising and government favorable solution to Lakshadweep. Considering there's no big industrial business on the island, the majority of MSW is combustible for the WTE plant. Assume 80% of the solid waste (12MJ/kg) is collected for combustion, approximately 490,000kWh of electricity and 73,000m^3 (202,250 L/d) of fresh water can be generated each year, to some extent release the energy and water intensity.

In short, coupled WTE-thermal desalination technology is recommended and well suitable for the sustainable development of Lakshadweep. It economically solves the most severe water and waste issues at the same time. It also saves the space for solid waste treatment and cut the fuel import. Considering the relative low solid waste generation rate, this facility is especially suited to be constructed in dense populated island like Karawatti and Amini.

6. Conclusion

There are 2150 waste to energy (WTE) plants operational around the world to recovery energy and generate electricity from 250 million tons of municipal solid waste (MSW) per year. The most common WTE plants are electricity-only business and that use heat to produce steam and drive turbines. To maximize electricity productivity, the exhaust steam from turbine is sent to an air or water cooled condenser, then recycled to boiler or injected into natural water. For a typical WTE plant of 10 t/h capacity, the gross electricity generating capacity is around 22,000 MJ/h to 23,000 MJ/h, about 20% of the energy containing in MSW combusted. Such process makes very little use of the energy contained in the exhaust steam from turbine and losses over 50% of the energy released from the controlled combustion of MSW. In addition, an estimation of 2,800,000 m^3/h air or 4,757,000 m^3/h water is consumed under this combustion scale, together with 1,109 MJ/h electric power consumption to drive the fans. The exhaust condensate air and water also cause some thermal pollution to surrounding ecosystem.

To improve the energy efficiency of WTE plants, countries like Europe and South Korea uses energy recovered in different ways. Many of their WTE plants are combined heat and power (CHP) facilities. These facilities sacrifice part of their electricity productivity and sell the extract or exhaust steam from turbine for district heating (DH) system. Three type of turbine system may adopted for CHP plant: 1) back pressure steam turbine, all of the exhaust steam from turbine is used for DH; 2) condensing extraction steam turbine, part of steam exhaust from turbine for DH, the left exhaust steam is condensed; 3) back pressure extraction turbine, both the extract steam and exhaust steam is used for DH. Under this three situations a CHP WTE plant of 10 t/h capacity and 50% steam extraction can generates 12,900-18,700 MJ/h gross electricity and approximately 31,000-62,500 MJ/h heat. Although 20-40% of electric power is sacrificed, the overall efficiency increases from 20% to at least 65% compared to the condensing WTE plants, thus sufficiently using over 70% of the energy from MSW. According to European environmental policy's CO_2 emission allowance price and fuel price, 2-15 million dollars can be saved each year, 30 thousand tons of coal (or 5.6 million gallons of oil) consumption and more than 40 thousand tons of carbon dioxide emission can be prevented per year. With further improvement of heat recovery system, the thermal efficiency for these facilities can reach 80-90%. However, use the exhaust steam for DH is restricted by the high request and cost of DH transmission system construction as well as the suitable climate condition of the area, especially for those torrid zones. New solutions of exhaust steam utilization still need further exploration. Currently a new choice is posed by the worldwide fresh water scarcity -- using the exhaust steam as an energy source for thermal water desalination.

Desalination refers to processes that remove salt and other minerals from saline water to provide freshwater. Almost 16,000 desalination facilities have been built worldwide, producing over 70 million cubic meters of potable water and accounting for two-thirds of feed water. Water desalination uses either thermal or membrane technologies. Main technology includes electricity powered reverse osmosis (RO), steam and electricity powered multiple-effect distillation (MED) and multi-stage flash evaporation (MSF). With lower energy consumption of 1-7 kWh/m^3 and decreasing cost of 0.1-1.0 USD/m^3, membrane (RO) desalination is a preferable choice for most desalination plants occupied 60% of the installed capacity worldwide. The MSF desalination units has a relative high temperature demand, 100-130°C for feed steam and 90-120°C for operation, resulting in an higher energy consumption of 13.5-25.5 kWh/m^3 electrical equivalent and cost of 0.5-1.75 USD/m^3. The MED process can operate with low pressure (0.3-0.5 bar), low temperature (70-90°C) steam by nearly vacuum pressure condition. With lower electric consumption of 1.5-2.5 kWh/m^3 than MSF, the typical production cost of MED is around 0.7-1 USD/m^3, competitive to RO technology. Since energy cost accounts to 30-50% of total desalination cost, find an alternative thermal source lies the key of current thermal desalination techniques' development.

Inspired from CHP plants for DH, two power-desalination cogeneration plants is studied: St. Barth WTE-desalination cogeneration plant and Hebei Huanghua power-desalination cogeneration plant. With 1.5t/h MSW incineration capacity, the St. Barth WTE plant sells 67% of recovered energy for MED desalination process, generating 1350m^3 freshwater per day for domestic use. The heat consumption for potable water production is 8.6MJ/m^3 (40.6kWh/m^3) and reached an impressive GOR of 17.8. Besides, about 8.5% of energy from MSW is transformed to electricity, completely covered the electric consumption of both WTE and MED process. In brief, this plant helps St. Barth efficiently deals its MSW while solve the water supply issue of the island with negative energy input.

Huanghua power plant is a coal-powered plant with 2,520MW generation capacity located along Pohai Gulf of China. Approximately 3,200,000-4,400,000m^3 of freshwater is consumed annually as feed-water for the boiler units, as well as for desulfurization and other processes. Huanghua solved this massive water consumption through several coupled MED desalination units which applied the extraction and exhaust steam from turbine as heat source. These MED units produce 57,500 m^3/d of fresh water, consumed 40% of energy from coal input. Despite meeting the needs of self-utilization, the plant also produce 5-10 million external tons of freshwater annually (14,000-28,000 m^3/d) for the Port of Huanghua. With such combined system, 90% of total energy input transferred to valuable products, approximately 480-500 ton/d of coal (47,500 USD/d) is saved. The reduced water production cost also guarantee the water supply and water price of surrounding local area.

From the study, it can be noted that the cogeneration of power and water is an ecological and economical solution. When extract steam or exhaust steam from coal-fired power plant is adopted as desalination heat sources, the total cost of capital water production reduced from 0.87 USD to 0.40 USD and 0.19USD respectively. Such advantages will be further enlarged with WTE facilities due to the waste management profit. Considering the benefits and requirements of WTE-desalination cogeneration plant, the most promising places for this technique are those tropical islands or gulf cities with little access to land, fuels and waters.

Suitable area includes Mediterranean Sea countries (Cyprus, Crete, etc.), Persian Gulf countries (Kuwait, Bahrain, Oman, etc.), Caribbean Sea islands, Red Sea area and so on. In specification, the situation of Cyprus and Union Territory of Lakshadweep (India) are analyzed and improved the immediacy and necessity of such integrate solution to this area. This study only carried out the energy and resource side beneficial analysis, further cost-benefit analysis is needed to approve the economical accessibility of this solution.

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