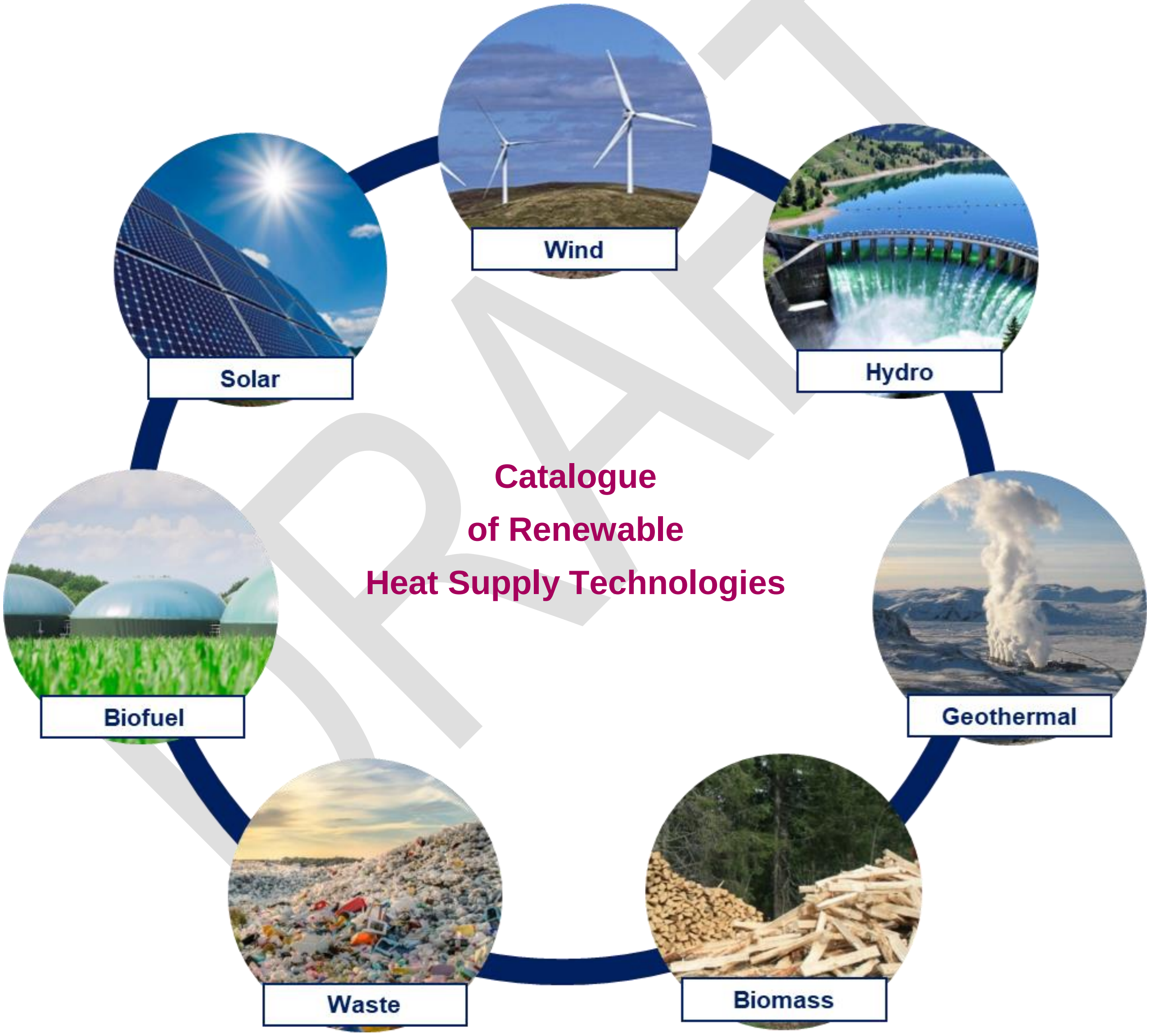
Supporting Renewable Technology Inclusive Heat Supply Legislation – Technical and Legal Consultancy. ADB. TA 6564 KAZ



Catalogue of Renewable Heat Supply Technologies

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DATA SHEETS

LIST OF ABBREVIATIONS

ADB	Asian Development Bank
BFB	Bubbling Fluidized Bed
CAPEX	Capital Expenditure
CFB	Circulating Fluidized Bed
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon dioxide
COP	Coefficient of Performance
CTF	Clean Technology Fund
DC	District Cooling
DH	District Heating
EBRD	European Bank for Reconstruction and Development
EPC	Engineering, Procurement and Construction
ESP	Electrostatic precipitator
FB	Fluidized Bed
FGT	Flue Gas Treatment
FID	Final Investment Decision
GJ	Giga Joule
GoK	Government of Kazakhstan
GW	Giga Watt
HHV	High Heating Value
HOP	Heat Only Plant
JECF	Japan - EBRD Cooperation Fund
KazREFF	Kazakhstan Renewable Energy Financing Facility
kW	Kilo Watt
LHV	Low Heating Value
MW	Mega Watt
MWh	Megawatt hour
N2O	Nitrous oxide
NOX	Nitrous Oxides
O&M	Operation and Maintenance
PV	Photovoltaic
SCADA	Supervisory control and data acquisition

SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulfur dioxide
UN	United Nation
UNDP	United Nation Developement Program
WtE	Waste-to-Energy

1 INTRODUCTION

The Republic of Kazakhstan has embarked on the energy transition from the fossil-based energy generation to renewable energy generation.

Coal is the dominant source of energy in Kazakhstan, accounting for 64.7% of total projected generation and 74.0% of thermal generation in 2019.

The GoK is seeking to diversify Kazakhstan's energy mix and the National Green Growth Plan envisages the following (optimistic) breakdown by 2030: 49.0% coal, 21.0% gas, 10.0% hydropower and 8.0% nuclear, alongside a sizeable renewables element.

The present report describe renewable heat technologies[1], which potentially could be introduced in Kazakhstan´s heating sector.

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[1] The general information on technology description and data is based on information collected from Energistyrelsen | (ens.dk)

2 RENEWABLE ENERGY - STATUS AND POTENTIAL IN KAZAKHSTAN

There is enormous potential for renewable energy in Kazakhstan, particularly from wind and small hydropower plants.

The Republic of Kazakhstan has the potential to generate 10 times as much power as it currently needs from wind energy alone. But renewable energy accounts for just 0.6 percent of all power installations. Of that, 95 percent comes from small hydropower projects.

The main barriers to investment in renewable energy are relatively high financing costs and an absence of uniform feed-in tariffs for electricity from renewable sources. The amount and duration of renewable energy feed-in tariffs are separately evaluated for each project, based on feasibility studies and project-specific generation costs. Power from wind, solar, biomass and water up to 35 MW, plus geothermal sources, are eligible for the feed-in tariff. Transmission companies are required to purchase the energy of renewable energy producers.

Kazakhstan is a party to the UN Framework Convention on Climate Change (1995) and ratified the Kyoto Protocol in 2009. Kazakhstan has committed to reduce greenhouse gas emissions. Having more renewable energy in the energy balance of Kazakhstan is one of the most effective mechanisms to reduce harmful effects of the energy sector and to diversify the national power generation capacity.

To help Kazakhstan meet its goals for renewable energy generation, the European Bank for Reconstruction and Development (EBRD) is launching the Kazakhstan Renewable Energy Financing Facility (KazREFF). The KazREFF aims to provide development support and debt finance to renewable energy projects which meet required commercial, technical and environmental criteria. Renewable energy technologies supported will include solar, wind, small hydropower, geothermal, biomass, and biogas. The Facility comprises an amount of up to $US50 million for financing projects together with up to $US20 million of concessional finance from Clean Technology Fund (CTF), and the technical assistance funded by the Japanese government through the Japan - EBRD Cooperation Fund (JECF).

In 2019, Kazakhstan launched 21 renewable energy facilities. The amount of green energy doubled over three years. In 2017, stations with renewable energy sources generated more than one billion kWh. In 2019, this indicator grew to nearly 2.5 billion kWh. As of 2020, there are 97 operating renewable energy facilities in Kazakhstan with over half of the renewable power generated by solar power plants.

2.1 HYDROPOWER

Small hydropower plants are the most rapidly developing areas of use of renewable energy in the country. Thus, in the period from 2007 to 2010 the Almaty region introduced five small hydropower plants with a total installed capacity of 20 MW. One of the important areas of energy efficiency of Kazakhstan's economy is construction of hydroelectric power plants on small rivers operating without retaining dams.

Hydropower accounts for approximately 13% percent of Kazakhstan's total generating capacity delivering around 7.78 TWh from 15 large (450 MW) hydropower station with a total capacity of 2.248 GW. Large hydropower plants comprise the Bukhtyrma (750 MW), Shulbinsk (702MW) and Ust-Kamenogorsk (315 MW) plants on the Irtysh River, the Kapshagai (364 MW) plant on the Ili River, the Moinak (300 MW) plant on the Charyn Rriver and the Shardarinskaya (104MW) plant on the Syrdarya River. Small (1–10 MW) and medium-scale (10–50 MW) hydropower projects have become more popular because of their low cost, reliability and apparent environmental friendliness. There are seven small hydropower plants (<10 MW), with a total installed capacity of 78 MW and an estimated potential of 13 TWh, spanning east and south Kazakhstan, Zhambyl and Almaty provinces.

According to the experts, provided the smaller hydropower stations are installed, about 8 billion kWh can produced per year and this is more than enough to meet the demand that is now satisfied through imports from Central Asia.

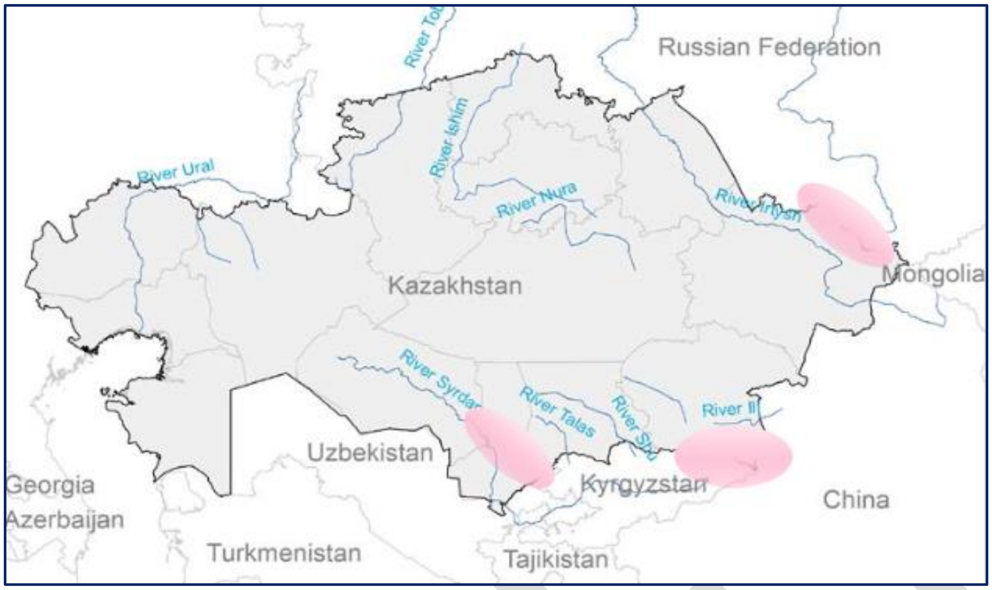

Figure 1: Potential regions for Hydropower plants

2.2 SOLAR ENERGY

Kazakhstan has areas with high insolation that could be suitable for solar power, particularly in the south of the country, receiving between 2200h and 3000h of sunlight per year, which equals 1200–1700 kW/m2 annually.

Both concentrated solar thermal and solar photovoltaic (PV) have potential. There is a 2 MW solar PV plant near Almaty and six solar PV plants are currently under construction in the Zhambyl province of southern Kazakhstan with a combined capacity of 300 MW.

In addition to solar PV, concentrated solar thermal is advantageous given it does not require water for operation so can be used in desert and semi-desert areas, the materials (steel, glass and concrete) are domestically produced in Kazakhstan and readily available, and solar thermal plants store energy in the form of heat, which is far more efficient than the batteries used in PV systems and allows electricity to be produced on demand, even after the sun has set, enabling both base and peak loads to be met.

There are no current plans to install a concentrated solar thermal plant although the government plans to create 1.04 GW of renewable energy capacity by 2020. The South-Kazakhstan, Kyzylorda oblast and the Aral region are the most suitable locations to build solar power plants.

The most significant project in this field, implemented in 2002 in Kazakhstan and financed by the UN, was to install 50 prism solar power plants with capacity of 100 liters of water each, and 50 solar stills, using the water from the Syr Darya river to provide the residents of two villages in the Aral region for drinking water and heating.

In particular, according to the Plan of Activities for Alternative and Renewable Energy in Kazakhstan, it is planned to put into operation about 28 solar energy projects until the end of 2020 with total installed capacity of 713.5 MW.

The European Bank for Reconstruction and Development (EBRD) financed two solar parks in Kazakhstan. The first one, 50 MW Burnoye Solar 1, was established in April 2014. The second one, known as Burnoye Solar 2, is also 50 MW and will be located in the Zhambyl region.

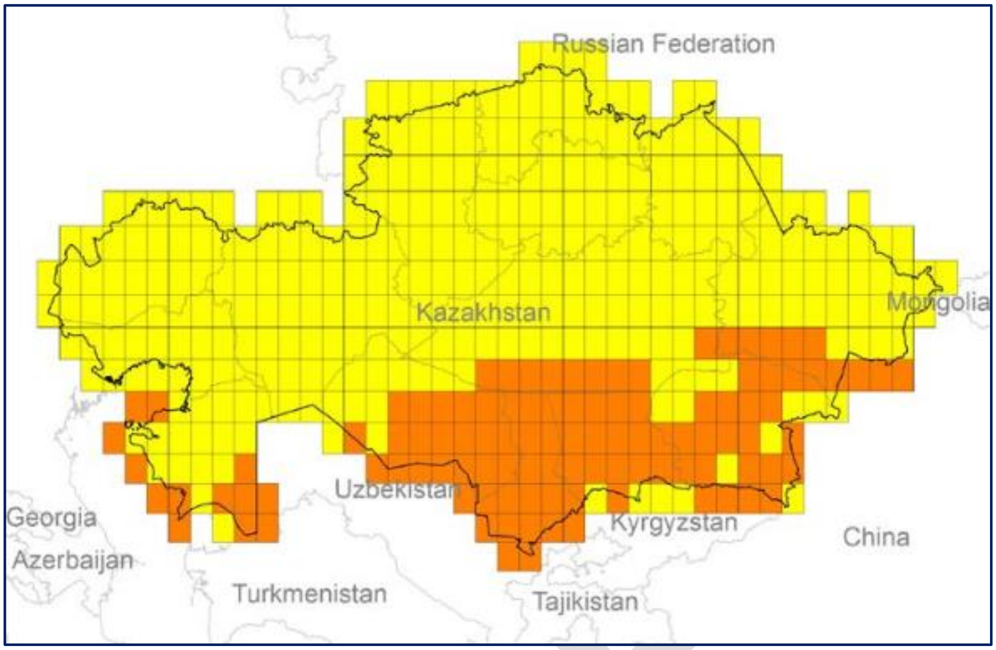

Figure 2: Potential regions for Solar power plants

2.3 WIND ENERGY

Kazakhstan's steppe geography makes it suitable for wind energy applications and the estimated potential of wind energy that can be economically developed is about 760 GW. About 50% of Kazakhstan's territory has average wind speeds suitable for energy generation (4–6 m/s) with the strongest potential in the Caspian Sea, central and northern regions.

The most promising individual sites are in the Almaty region in the Dzungar (Dzungarian) Gates, 600 km northeast of Almaty close to the Xinjiang border and the Chylyk Corridor 100 km east of Almaty. Wind potentials of 525 Wm2 in the Dzungar Gates and 240 Wm2 in the Chylyk corridor have been estimated with power production from wind turbines potentially achieving 4,400 kW/h/MW and 3,200 kW/h/MW respectively.

Currently, the Ministry of Industry and New Technologies selected 10 sites to build large wind power plants (WPP) with total capacity of 1,000 MW with a view to commercial production of electricity in the amount of 2-3 billion kWh. Currently only one wind energy plant is operating in Kazakhstan; the Kordai wind power plant with 1,500 kW capacity was launched in December 2011 in Zhambyl region.

One of Kazakhstan's power companies, Samruk-Energy JSC, was recently awarded a $94 million loan from the Eurasian Development Bank to build Kazakhstan's largest wind farm. The project will produce 172 million kilowatt/hours of electrical energy per year, save more than 60 million tons of coal, and reduce emissions of greenhouse gases.

The first wind generator production plant in the post-Soviet region is set to be constructed in Kazakhstan's Aktobe. This project, with a cost of MUS$95.3, is expected to create 500 jobs.

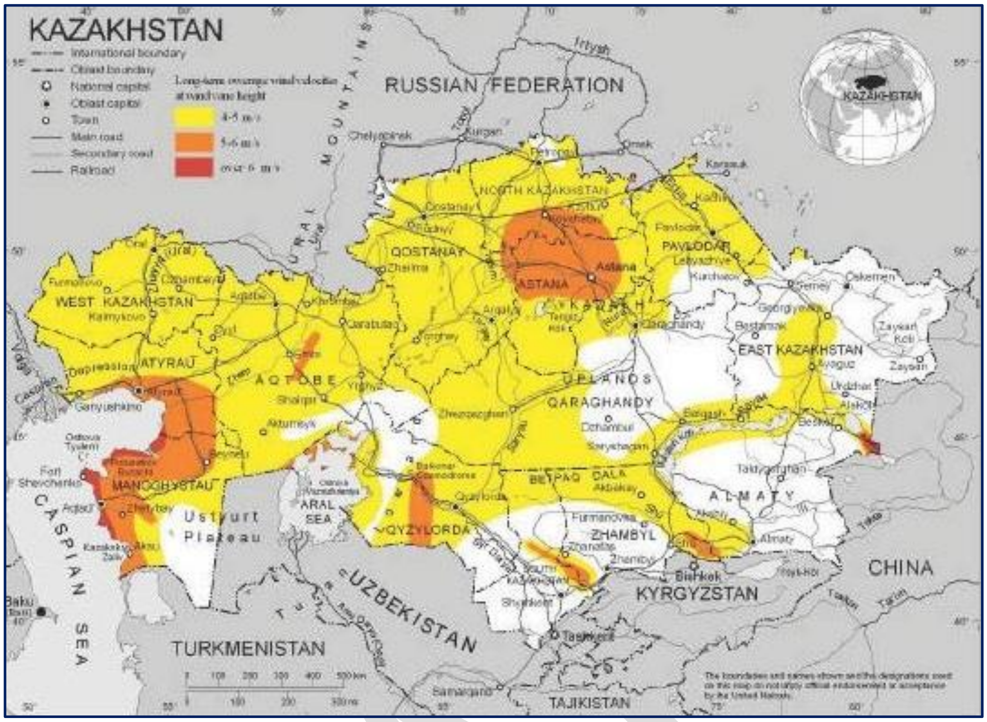

Figure 3: Potential regions for Wind power plants

2.4 BIOENERGY

Kazakhstan has 76.5 Mha agricultural land, 10 Mha forest and 185 Mha steppe grasslands providing abundant biomass wastes and residues, which have the potential to generate and arrange of bioenergy services.

Kazakhstan produces and exports crops such as wheat (winter and spring), rye (winter), maize (for grain), barley (winter and spring), oats, millet, buckwheat, rice and pulses, with an average grain yield of 17.5 – 20 Mt, which equates to roughly 12 – 14 Mt of biomass wastes. Biomass wastes are currently poorly exploited and only ~10% of the total volume of the residues issued, mostly as a feed additive for livestock. The proportion of rural households using biomass cook stoves for cooking and heating is currently unknown.

Organic wastes are also a potential source of energy and at least 400,000 households are known to keep cattle, horses and sheep. It has been estimated that electricity generation potential in Kazakhstan from biomass is 35 billion kWh per year and heat generation potential is 44 million Gcal per year.

Various external funding agencies (UNDP, GEF, HIVOS Foundation) have supported the development of biogas initiatives including the Biogas Training Centre at the Eco-museum in Karanga (2002–2003) and the ‘Azure Flame’ Central Kazakhstan Biogas Education Centre (2004–2005). However, despite this promotion there is only one large scale biogas unit currently in operation in the country which is a 360 kWe biogas plant run at Vostok village in the Kostanai region. The Vostok biogas unit consists of two 2,400 m3 digesters operating with a feedstock of 40 t/day of cow, sheep and camel manure, grain residues and 1t/day of slaughterhouse waste. The plant was installed in 2011 by Karaman-K Ltd. and Zorg Biogas with an aim of delivering 3 million kWh of electricity annually.

Another potential area is the use of biogas, which is produced from the waste of farms and poultry factories. Kazakhstan has a significant number of livestock and poultry. Methane production potential of the waste in cattle is more than 85 thousand tons.

Potential methane production from waste-water communal services is about 3 million tons.

3 GUIDELINES

3.1 INTRODUCTION TO TECHNOLOGY SHEETS

Each technology is described by a separate technology sheet, following the same format as explained below.

3.2 QUALITATIVE DESCRIPTION

The qualitative description give the key characteristics of the technology. Typical paragraphs are:

3.2.1 Brief technology description

Very brief description for non-engineers on how the technology works and for which purpose.

3.2.2 Input

The main raw materials, primarily fuels, consumed by the technology.

3.2.3 Output

The forms of generated energy, i.e. electricity, heat, bio-ethanol etc.

3.2.4 Typical capacities

The stated capacities are for a single 'plant' (e.g. a single wind turbine or a single heat pump).

3.2.5 Space requirement

Space requirement is expressed in 1,000 m^2 per MW. The value presented only refers to the area occupied by the facilities needed to produce energy.

3.2.6 Regulation ability

In particular relevant for electricity generating technologies, i.e. how fast they can respond to demand changes.

3.2.7 Advantages/disadvantages

Specific advantages and disadvantages relative to equivalent technologies.

3.2.8 Environment

Particular environmental characteristics are mentioned, e.g. special emissions or the main ecological footprints.

3.3 QUANTITATIVE DESCRIPTION

To enable comparative analyses between different technologies it is imperative that data are actually comparable: All cost data are stated in fixed 2020 prices excluding value added taxes (VAT) and other taxes.

The information given in the tables relate to the development status of the technology at the point of Final Investment Decision (FID) in the given year (2020). FID is assumed to be taken when financing of a project is secured and all permits are at hand. The year of commissioning will depend on the construction time of the individual technologies.

A typical table of quantitative data is shown below, containing all parameters used to describe the specific technologies. The table consists of a generic part, which is identical for groups of similar technologies (thermal power plants, non-thermal power plants and heat generation technologies) and a technology specific part, containing information, which is only relevant for the specific technology. The generic part is made to allow for easy comparison of technologies.

Each cell in the table contains only one number, which is the central estimate for the market standard technology, i.e. no range indications.

An example of the table for heat generation technologies are presented below:

Table 1: Data table example

Technology	
Energy / technical data	
Heat generation capacity for one unit (MW)	
Total efficiency, net (%), name plate	
Total efficiency , net (%), annual average	
Auxiliary electricity consumption (% of heat gen)	
Forced outage (%)	
Planned outage (weeks per year)	
Technical lifetime (years)	
Construction time (years)	
Regulation ability	
Primary regulation (% per 30 seconds)	
Secondary regulation (% per minute)	
Minimum load (% of full load)	
Warm start-up time (hours)	
Cold start-up time (hours)	
Environment	
SO_2 (g per GJ fuel)	
NO_X (g per GJ fuel)	
CH_4 (g per GJ fuel)	
N_2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MW)	
Fixed O&M ($US/MW/year)	
Variable O&M ($US/MWh)	

3.4 ENERGY / TECHNICAL DATA

3.4.1 Heat generating capacity for one unit

The capacity, preferably a typical capacity (not maximum capacity), is stated for a single unit, capable of producing energy e.g. a single wind turbine (not a wind farm).

In the case of a modular technology such PV or solar heating, a typical size of a solar power plant based on the historical installations or the market standard is chosen as a unit. Different sizes may be specified in separated tables, e.g. Small PV, Medium PV, Large PV.

The capacity is given as net generation capacity in continuous operation, i.e. gross capacity (output from generator) minus own consumption (house load), equal to capacity delivered to the grid.

The unit MW is used both for electric generation capacity and heat production capacity. While this is not in accordance with thermodynamic formalism, it makes comparisons easier and provides a more intuitive link between capacities, production and full load hours.

It should be stressed that data in the table is based on the typical capacity. When deviations from the typical capacity are made, economy of scale effects need to be considered inside the range of typical sizes. The capacity range should be stated in the notes.

3.4.2 Energy efficiencies

Efficiencies for all thermal plants (both electric, heat and combined heat and power) are expressed in percent at lower calorific heat value (lower heating value) at ambient conditions in Kazakhstan, considering an average air temperature of approximately xx °C.

The electric efficiency of thermal power plants equals the total delivery of electricity to the grid divided by the fuel consumption. Two efficiencies are stated: the nameplate efficiency as stated by the supplier and the expected typical annual efficiency.

For heat only technologies, the total efficiency equals the heat delivered to the district heating grid divided by the fuel consumption. The auxiliary electricity consumption is not included in the efficiency, but stated separately in percentage of heat generation capacity (i.e. MW auxiliary/MW heat).

The energy supplied by the heat source for heat pumps (both electric and absorption) is not counted as input energy. The temperatures of the heat source are specified in the specific technology chapters.

The expected typical annual efficiency takes into account a typical number of start-ups and shut-downs and is based on the assumed full load hours stated in the table below.

Table 2: Assumed number of full load hours

	FULL LOAD HOURS (ELECTRICITY)	FULL LOAD HOURS (HEAT)
Municipal Solid Waste / biogas stand alone	**8,000**	**8,000**
Boilers		**4,000**
Geothermal heat and Heat Pumps		**6000**
Electric boilers		**500**

The energy efficiency for intermittent technologies (e.g. PV and wind) is expressed as capacity factor. The capacity factor is calculated as the annual production divided by the maximum potential annual production. The maximum potential annual production is calculated assuming the plant has been operating at full load for the entire year, i.e. 8,760 hours /year.

3.4.3 Auxiliary electricity consumption

For heat-only technologies the consumption of electricity for auxiliary equipment such as pumps, ventilation systems, etc. is stated separately in percentage of heat generation capacity (i.e. MW auxiliary/MW heat).

For heat pumps, internal consumption is considered part of the efficiency (coefficient of performance, COP), while other electricity demand for external pumping, e.g. ground water pumping, is stated under auxiliary electricity consumption.

For CHP generation, auxiliary consumption is not stated separately but included in the net efficiency and for non-thermal plants, as a reduction in the number of full load hours.

3.4.4 Cogeneration values

The C_b coefficient (back-pressure coefficient) is defined as the maximum power generating capacity in back-pressure mode divided by the maximum heat capacity.

The C_v-value for an extraction steam turbine is defined as the loss of electricity production, when the heat production is increased one unit at constant fuel input.

Values for C_b and C_v are given – unless otherwise stated – at 100^{O}C forward temperature and 50^{O}C return temperature for the district heating system. For supercritical steam turbines the values should also be given at $80/40^{O}$C.

3.4.5 Average annual full load hours

The average annual capacity factor mentioned above describes the average annual net generation divided by the theoretical maximum annual net generation if the plant were operating at full capacity for 8,760 hours per year. The equivalent full load hours per year is determined by multiplying the capacity factor by 8,760 hours, the total number of hours in a year.

Full load hours vary largely depending on the location and the technology

3.4.6 Forced and planned outage

Forced outage is defined as number of weighted forced outage hours divided by the sum of forced outage hours and operation hours, multiplied by 100. The weighted forced outage hours are the hours caused by unplanned outages, weighted according to how much capacity was out.

Forced outage is given in percent, while planned outage is given in weeks per year.

The availability is determined as 1 minus (weighted forced outage hours + planned outage hours) / 8,760; possibly in percent.

3.4.7 Technical lifetime

The technical lifetime is the expected time for which an energy plant can be operated within, or acceptably close to, its original performance specifications, provided that normal operation and maintenance takes place. During this lifetime, some performance parameters may degrade gradually but still stay within acceptable limits. For instance, power plant efficiencies often decrease slightly (few percent) over the years, and O&M costs increase due to wear and degradation of components and systems. At the end of the technical lifetime, the frequency of unforeseen operational problems and risk of breakdowns is expected to lead to unacceptably low availability and/or high O&M costs. At this time, the plant is decommissioned or undergoes a lifetime extension, which implies a major renovation of components and systems as required to make the plant suitable for a new period of continued operation.

The technical lifetime stated in this catalogue is a theoretical value inherent to each technology, based on experience. As stated earlier, the thermal technologies producing electricity and/or heat are in general assumed to be designed for operated for approximately 4,000 - 5,000 full loads hours annually. The expected technical lifetime takes into account a typical number of start-ups and shut-downs (an indication of the number of start-ups and shut-downs is given in the financial data description, under Start-up costs).

In real life, specific plants of similar technology may operate for shorter or longer times. The strategy for operation and maintenance, e.g. the number of operation hours, start-ups, and the reinvestments made over the years, will largely influence the actual lifetime.

3.4.8 Construction time

Time from final investment decision (FID) until commissioning completed (start of commercial operation), expressed in years.

3.5 REGULATION ABILITY

Five parameters describe the electricity regulation capability of the technologies:

A. Primary regulation (% per 30 seconds): frequency control
B. Secondary regulation (% per minute): balancing power
C. Minimum load (percent of full load).
D. Warm start-up time, (hours)
E. Cold start-up time, (hours)

For several technologies, these parameters are not relevant, e.g. if the technology is regulated instantly in on/off-mode.

Parameters A and B are spinning reserves; i.e. the ability to regulate when the technology is already in operation.

Parameter D. The warm start-up time used for boiler technologies is defined as the time it takes to reach operating temperatures and pressure and start production from a state where the water temperature in the evaporator is above 100^{0}C, which means that the boiler is pressurized.

Parameter E. The cold start-up time used for boiler technologies is defined as the time it takes to reach operating temperature and pressure and start production from a state were the boiler is at ambient temperature and pressure

3.6 ENVIRONMENT

All plants are assumed to be designed to comply with the regulation that is currently in place in Kazakhstan.

The emissions below are stated in mass per GJ of fuel at the lower heating value.

CO_2 emissions are not stated, as these depend on fuel, not the technology.

SO_x: emissions are calculated based on the following sulphur content of fuels:

	Peat	Straw	Wood- fuel	Waste	Biogas
Sulphur (kg/GJ)	0.24	0.20	0.00	0.27	0.00

NO_x . NO_x equals NO_2 + NO, where NO is converted to NO_2 in weight-equivalents.

Greenhouse gas emissions include CH_4 and N_2O in grams per GJ fuel.

Particles includes the fine particle matters (PM 2.5). The value is given in grams per GJ of fuel.

3.7 FINANCIAL DATA

Financial data are all in $US, fixed prices, price-level 2020.

3.7.1 Investment costs

The investment cost is also called the Engineering, Procurement and Construction (EPC) price or the overnight cost. Infrastructure and connection costs, i.e. electricity, fuel and water connections inside the premises of a plant, are also included.

The investment cost is reported on a normalized basis, i.e. cost per MW. The specific investment cost is the total investment cost divided by the capacity stated in the table, i.e. the capacity as seen from the grid, whether electricity or district heat. For electricity generating technologies, incl. combined heat and power generation, the denominator is the electric capacity.

The investment cost of extraction steam turbines, which can be operated in condensation mode, is stated as cost per MW-condensation mode capacity.

Where possible, the investment cost is divided on equipment cost and installation cost. Equipment cost covers the components and machinery including environmental facilities, whereas installation cost covers engineering, civil works, buildings, grid connection, installation and commissioning of equipment.

The rent of land is not included but may be assessed based on the space requirements, if specified in the qualitative description.

The owners' predevelopment costs (administration, consultancy, project management, site preparation, approvals by authorities) and interest during construction are not included. The costs to dismantle decommissioned plants are also not included. Decommissioning costs may be offset by the residual value of the assets.

Cost of grid expansion

The costs of grid expansion from adding a new electricity generator or a new large consumer (e.g. an electric boiler or heat pump) to the grid are not included in the presented data.

3.7.2 Operation and maintenance (O&M) costs

The fixed share of O&M is calculated as cost per generating capacity per year ($US/MW/year), where the generating capacity is the one defined at the beginning of this chapter and stated in the tables. It includes all costs, which are independent of how many hours the plant is operated, e.g. administration, operational staff, payments for O&M service agreements, network or system charges, property tax, and insurance. Any necessary reinvestments to keep the plant operating within the technical lifetime are also included, whereas reinvestments to extend the life are excluded. Reinvestments are discounted at 4 % annual discount rate in real terms. The cost of reinvestments to extend the lifetime of the plants may be mentioned in a note if data are available.

The variable O&M costs ($US/MWh) include consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, spare parts and output related repair and maintenance (however not costs covered by guarantees and insurances).

Planned and unplanned maintenance costs may fall under fixed costs (e.g. scheduled yearly maintenance works) or variable costs (e.g. works depending on actual operating time), and are split accordingly.

Fuel costs are not included.

Auxiliary electricity consumption is included for heat only technologies. The electricity price applied is specified in the notes for each technology, together with the share of O&M costs due to auxiliary consumption. This enables corrections from the users with own electricity price figures. The electricity price does not include taxes.

It should be noticed that O&M costs often develop over time. The stated O&M costs are therefore average costs during the entire lifetime.

3.8 DEFINITIONS

The steam process in a CHP (co-generation of heat and power) plant can be of different types:

1. **Condensation**: All steam flows all the way through the steam turbine and is fed into a condenser, which is cooled by water at ambient temperature. A condensing steam turbine produces only electricity, no heat.

2. **Back-pressure**: All steam flows all the way through the steam turbine and is fed into a condenser, which is cooled by the return stream from a district heating network or an industrial process heating network. The condensation takes place at elevated temperatures enabling utilization of the produced heat. A back-pressure turbine produces electricity and heat, at an almost constant ratio.
3. **Extraction**: Works in the same way as condensation, but steam can be extracted from the turbine to produce heat (equivalent to back-pressure). This enables flexible operation where the electricity to heat ratio may be varied.

4 COMPARISON OF FINANCIAL KEY FIGURES

This chapter presents the financial key figures for all technologies, i.e. specific investment costs and operation and maintenance costs. Data intervals in the technology sheets have here been shortened to medium values.

All data are in constant 2020 price level.

Table 3: Key financial figures - Different technologies for generation of District Heating

Technology	Nominal inv. M$US/ MW	Fixed O&M $US/ MW/yr	Variable O&M $US/ MWh
Rebuilding coal power plants to biomass			
Coal to wood pellets existing boiler	0.61	4,054	0.44
Coal to wood chips new boiler	1.94	35,695	1.33
Coal to wood chips exisitng boiler, extraction plant	1.94	17,152	1.82
Coal to wood chips existing boiler, back pressure plant	-	35,695	1.33
Waste-to-Energy CHP Plant			
Small Waste to Energy CHP, Backpressure turbine, 35 MW feed	2.86	113,014	7.14
Medium Waste to Energy CHP, Backpressure turbine, 80 MW feed	2.54	73,810	7.14
Large Waste to Energy CHP, Backpressure turbine, 220 MW feed, 40/80°C	2.21	53,119	19.36
Large Waste to Energy CHP, Backpressure turbine, 220 MW feed, 50/100°C	2.21	53,119	19.36
Waste-to-Energy HOP Plant			
Waste to Energy, DH only, 35 MW feed	2.23	99,583	9.44
Medium-scale Biomass Power Plant			
Small Wood Chips CHP, 20 MW feed	1.13	49,852	1.69
Medium Wood Chips CHP, 80 MW feed	1.27	53,724	1.57
Wood Chips CHP, large, 40/80°C return/forward temperature	1.21	34,848	1.57
Wood Chips CHP, large, 50/100°C return/forward temperature	1.21	34,848	1.57
Wood Chips CHP, large, extraction	1.33	36,542	1.34
Wood Pellets CHP, small	1.13	50,457	0.73
Wood Pellets CHP, medium	1.13	46,343	0.69
Wood Pellets CHP, large, 40/80°C return/forward temperature	0.91	25,289	0.68
Wood Pellets CHP, large, 50/100°C return/forward temperature	0.91	25,289	0.67
Wood Pellets CHP, large, extraction	1.20	29,766	0.62
Straw CHP, small	1.23	57,717	0.83
Straw CHP, medium	1.37	54,692	0.80
Straw CHP, large, 40/80°C return/forward temperature	1.29	46,585	0.80
Straw CHP, large, 50/100°C return/forward temperature	1.29	46,585	0.76

Technology	Nominal inv. M$US/ MW	Fixed O&M $US/ MW/yr	Variable O&M $US/ MWh
Wood Chips, HOP, Small	0.96	44,891	3.75
Wood Chips, HOP, Medium	0.81	58,322	3.75
Wood Chips, HOP, Large	0.61	48,037	3.75
Wood Pellets, HOP	0.87	40,051	2.40
Straw, HOP	1.09	63,404	2.64
Stirling engines			
Gasified biomass	4.60	38,720	25.41
Wind Turbines onshore			
Large	1.36	16,940	1.82
Small, $US/unit	4.60	653	-
Photovoltaic Cells, Grid-connected			
Photovoltaics, Small	1.37	15,488	-
Photovoltaics, Medium	0.97	12,584	-
Photovoltaics, Large	0.53	10,769	-
Heat Pumps			
Comp. hp, air source 1 MW	1.69	2,420	3.27
Comp. hp, air source 3 MW	1.15	2,420	2.66
Comp. hp, air source 10 MW	1.04	2,420	2.06
Comp. hp, excess heat 1 MW	1.50	2,420	3.27
Comp. hp, excess heat 3 MW	1.04	2,420	2.66
Comp. hp, excess heat 10 MW	0.81	2,420	2.06
Comp. hp, seawater 20 MW	0.58	4,840	1.45
Absorption heat pump, DH	0.73	2,420	1.09
Electric Boilers			
Electric Boilers, 400/690 V; 1-5 MW	0.18	1,295	1.09
Electric Boilers, 10/15 kV; >10 MW	0.08	1,295	1.09
Geothermal District heating			
Geothermal DH, 1,200m	3.28	27,346	6.90
Geothermal DH, 2,000m	3.48	28,919	5.57
Geothermal DH, 1,200m	1.52	13,431	2.54
Geothermal DH, 2,000m	2.53	20,933	3.63
Geoth. DH, 1, 200m, reduced DH temperature	3.27	28,072	6.66
Geoth DH, 2,000m, reduced DH temperature	3.48	29,645	5.20
Solar District Heating			
Solar District Heating (investment and costs per MWh output)	519	0.11	0.25

Table 4 – Individual Heating Installations

Technology	**Nominal inv. 1,000$US/ MW**	**Fixed O&M $US/ MW/yr**	**Variable O&M $US/ MWh**
Biomass boiler, automatic stoking			
Biomass boiler, automatic stoking, wood pellets or wood chips - One-family house, existing and energy renovated buildings.	8.2	610	0.00
Biomass boiler, automatic stoking , wood pellets or wood chips - One-family house, new buildings	8.2	606	0.00
Biomass boiler, automatic stoking , wood pellets or wood chips - Apartment complex, existing building	106.5	2,088	0.00
Biomass boiler, automatic stoking , wood pellets or wood chips - Apartment complex, new building	64.1	1,367	0.00
Biomass boiler			
Manual stoking	8.2	551	0.00
Wood stove			
Wood stove without water tank, wood logs - One-family house, existing, energy renovated and new buildings	3.0	175	0.00
Wood stove with water tank - One-family house, existing, energy renovated and new buildings	4.8	248	0.00
Electric heat pumps			
Air-to-air, existing one family house	2.1	206	0.00
Air-to-air, new one family house	1.3	196	0.00
Air-to-water, existing one family house	11.4	336	0.00
Air-to-water, new one family house	8.5	336	0.00
Air-to-water, existing apartments	170.6	1,997	0.57
Air-to-water, new apartments	85.9	1,997	0.57
Brine-to-water (ground source), existing one family house	18.2	336	0.00
Brine-to-water (ground source), new one family house	13.3	336	0.00
Brine-to-water (ground source), existing apartments	301.3	1,997	0.57
Brine-to-water (ground source), new apartments	107.7	1,997	0.57
Ventilation, new one family house	2.3	230	0.00
Ventilation, new apartments	85.9	1,392	0.57
Gas driven heat pumps			
Gas driven absorption heat pumps, existing one family house (air-to-water)	17.8	284	0.00
Gas driven absorption heat pumps, existing one family house (brine-to-water)	37.5	284	0.00
Gas driven absorption heat pumps, existing apartment complex (air-to-water)	20.6	284	0.00
Gas driven absorption heat pumps, existing apartment complex (brine-to-water)	37.5	284	0.00
Gas engine driven heat pump, existing apartment complex (air-to-water)	4.8	284	0.00

Technology	Nominal inv. 1,000$US/ MW	Fixed O&M $US/ MW/yr	Variable O&M $US/ MWh
Gas engine driven heat pump, existing apartment complex (brine-to-water)	21.8	284	0.00
Gas driven adsorption heat pumps , existing one family house (brine-to-water)	15.7	284	0.00
Solar heating			
Solar heating system - One-family house, existing building	4.6	82	0.00
Solar heating system - One-family house, Energy renovated	4.1	82	0.00
Solar heating system - One-family house, new building	2.9	82	0.00
Solar heating system - Apartment complex, existing building	98.0	469	0.00
Solar heating system - Apartment complex, existing building	89.5	469	0.00
Electric heating			
Electric heating - One-family house, new building	3.5	29	0.00
Electric heating - Apartment complex, new building	124.6	59	0.00

Table 5 – Industrial Process Heat

Technology	Nominal inv. M$US/ MW	Fixed O&M $US/ MW/yr	Variable O&M $US/ MWh
High temperature heat pumps			
High temp. hp Up to 125°C	1.05	1,174	4.0
High temp. hp Up to 150°C	1.27	1,174	4.0
Heat driven hp			
Heat driven hp 80°C	0.68	2,420	1.21

5 TECHNOLOGY SHEETS

The technology sheets have not all been completed equally. In some cases data are missing, which reflects that it has not been possible to identify sufficiently reliable sources for such data.

5.1 TECHNOLOGY SHEETS FOR GENERATION OF DISTRICT HEATING

The following technologies are included under this category:

- Rebuilding large coal power plant to biomass;
- WtE CHP and HOP plants;
- Biomass CHP and HOP plants;
- Stirling engines, gasified biomass;
- Wind Turbines onshore;
- Photovoltaics;
- Heat pumps;
- Electric Boilers;
- Geothermal district heating; and
- Solar District Heating.

5.2 TECHNOLOGY SHEETS FOR INDIVIDUAL HEATING INSTALLATIONS

The following technologies are included under this category:

- Biomass boiler, automatic stoking;
- Biomass boiler, manual stoking;
- Wood stove;
- Electric heat pumps;
- Gas driven heat pumps; and
- Solar heating.

5.3 TECHNOLOGY SHEETS FOR INDUSTRIAL PROCESS HEAT

The following technologies are included under this category:

- High temperature heat pump; and
- Heat driven heat pump

Rebuilding large coal power plant to biomass

Brief technology description

Existing coal power plants may be rebuilt for biomass combustion, mainly in order to reduce CO_2 emissions without discarding existing generating capacity. The conversion to biomass in existing pulverized coal fired power plants may be done partly by co-firing a fraction of biomass together with the coal, or by converting the plant fully to biomass. The data and descriptions in this chapter only consider the **full conversion options**.

The power plants for rebuilding are assumed to be of age approximately 25 years meaning that a life time extension will be necessary in any case. Thus, the expected costs of lifetime extension are included for those parts of the plant that remain in operation after the rebuilding. It is further assumed that the rebuilt power plant will have a technical life time of 15 years, i.e. the O&M costs will cover the necessary refurbishments in this period.

The necessary works and associated costs for life time extension and rebuilding of existing power plants will in any case vary over a large span since the original power plants are all unique in terms of technical design and condition.

Coal power plants can be modified for biomass in a number of ways. Here the following three concepts are considered:

a) Wood pellets, existing boiler
b) Wood chips, new boiler
c) Wood chips, existing boiler

These options will determine the requirements for the necessary technical modifications and replacements of the fuel handling equipment, boiler systems etc. of the plants.

a) Wood pellets

The easiest and cheapest (concerning the investment costs) solution is to convert the fuel from coal to wood pellets, which is a fuel with the most similar characteristics to coal, meaning that the same boiler can be used.

The figure below shows a principle sketch of the plant and which elements are expected to be added, replaced, or refurbished. Among these are:

- New storage silos and transport systems for the pellets;
- Coal mills, to be modified and with extended capacity due to lower calorific value;
- Larger fans for pneumatic transport systems;
- New burners;
- Boiler modifications , e.g. soot blowers to avoid deposits; and
- Other life time extensions, as relevant.

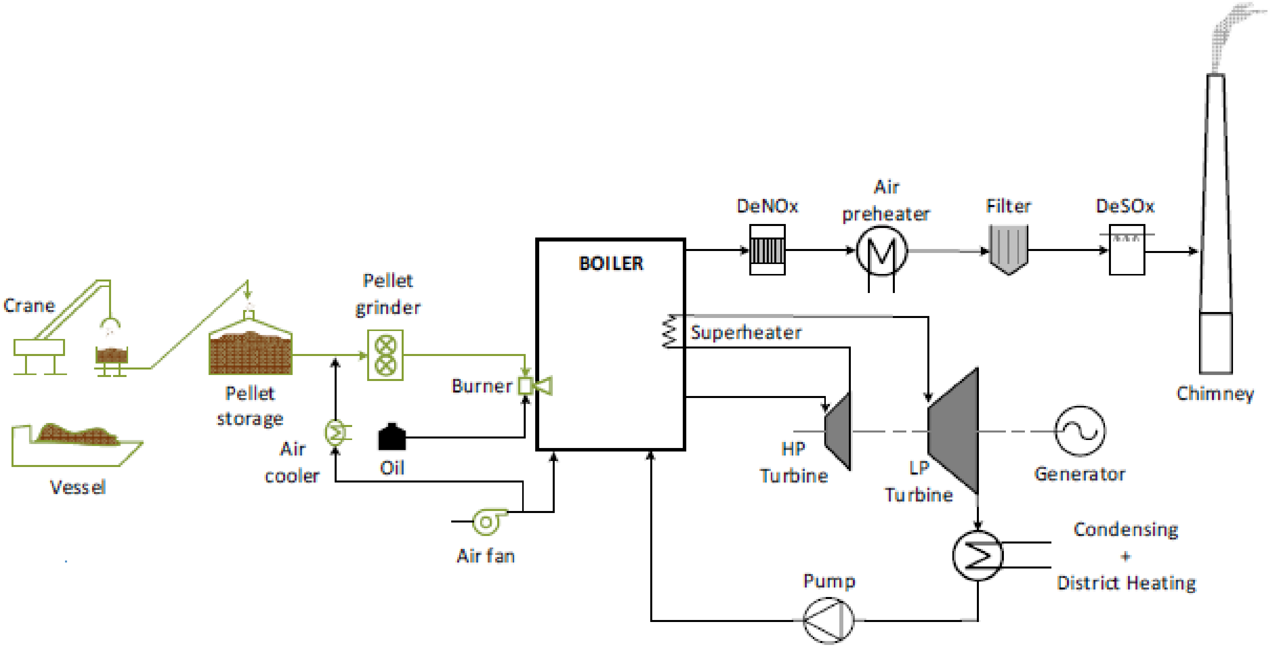

Figure 4: Sketch of CHP plant converted to firing with wood pellets. The green elements indicate the equipment that needs to be added, replaced or refurbished.

b) Wood chips, new boiler

Conversion of the fuel type from coal to wood chips requires major changes and is more time consuming and costly than conversion to pellets. However, this could be counterbalanced by a lower fuel price. One option for converting to wood chips is to install an entire new boiler.

The need for boiler replacement is due to the inability of the coal dust fired boiler to be adapted to the larger and inhomogeneous wood chips.

The figure below shows a principle sketch of the plant and which elements are expected to be added, replaced or refurbished. Among these are:

- New storage and transport systems for the wood chips
- New CFB boiler and air fans
- New high pressure turbine due to lower steam pressure. CFB boiler can also be made as super critical with high steam parameters
- New flue gas system, filters and condensation scrubber and probably also SCR
- Other life time extensions, as relevant

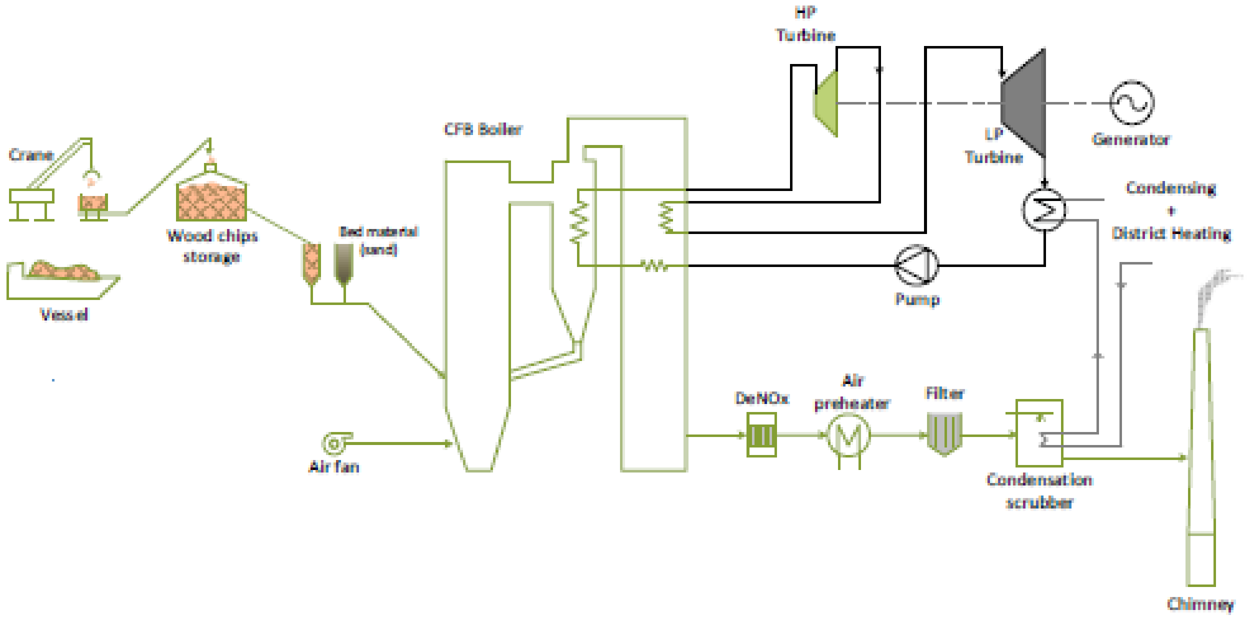

Figure 5: Sketch of CHP plant converted to firing with wood chips with a new CFB boiler. The green elements indicate the equipment that needs to be added, replaced or refurbished.

c) Wood chips, existing boiler

Another option for converting to wood chips is to reuse the existing boiler but install a plant for processing the chips into dry and fine grained matter, i.e. comparable to the fuel obtained by grinding wood pellets.

Thus, the existing boilers, flue gas systems, and steam systems can be kept in operation with minor modifications done in connection with the life time extension.

Due to the large fuel volumes the storage and preparation plant may constitute a considerable extension of the existing plant.

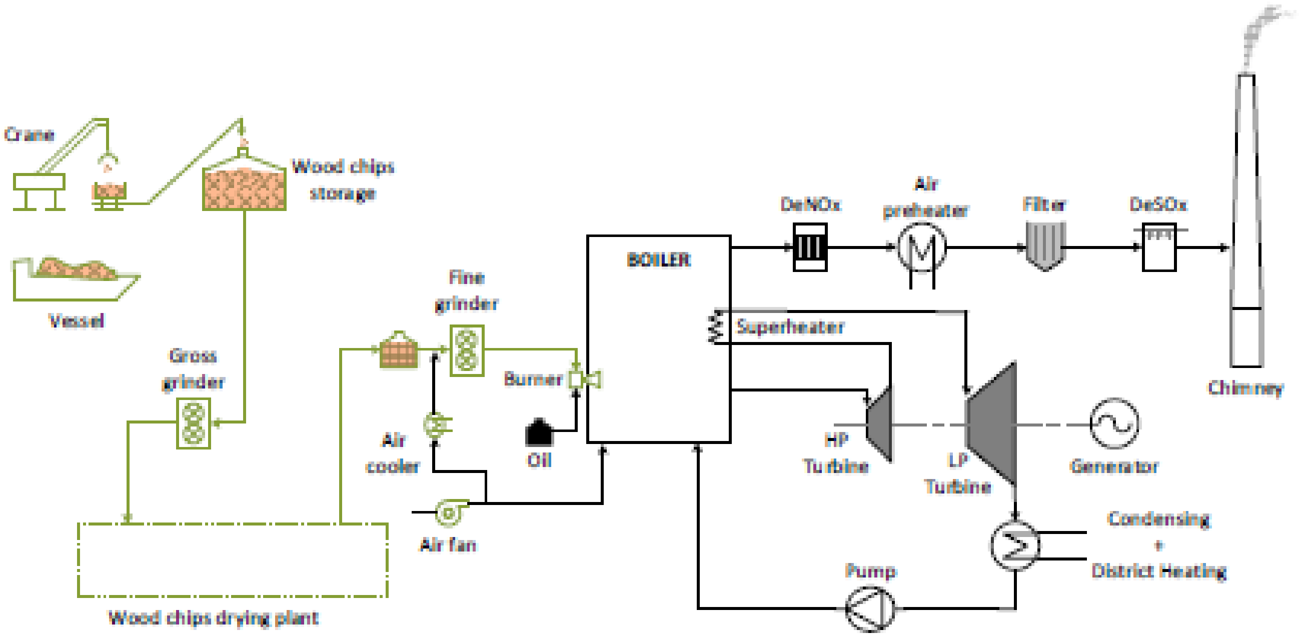

Figure 6: Sketch of CHP plant converted to firing with wood chips with its exiting boiler. The green elements indicate the equipment that needs to be added, replaced or refurbished.

As an alternative to converting the wood chips into pulverized fuel quality the boiler can be modified by installing a grate below the boiler. In such case the heat input on the grate is typically smaller than the original heat input and the plant is down rated accordingly.

Input

Primary fuels are biomass in the form of either a) dried and compressed wood pellets, or b) and c) Wood chips.

Output

The output is electricity and heat for use in district heating systems.

Typical capacities

The capacity range considered is in the range of 200-400 MW_e.

Regulation ability

The regulation abilities will in most cases not change much, in case existing boilers of coal fired plants are rebuilt to biomass firing.

Advantages / disadvantages

In general, rebuilding of coal fired power plants to biomass combustion is a relatively fast and cost effective way to reduce the use of fossil fuels (coal). Compared to building entire new units, investments are likely to be significantly lower. Also, the outage periods is likely to be shorter than if an entire new plant should be built at the same location as the one that is assumed rebuild. However, in case of building a new boiler and HP turbine, the advantage in time may not be significant.

One of the disadvantages is that the performance data will be more or less locked by those of the old plant, for instance the efficiencies will depend largely on the allowable steam temperature and pressure.

The original plants may be 20 - 30 years old and therefore not fully live up to the standards of present technology regarding efficiencies etc. Compared to coal, the chemistry of wood combustion causes increased challenges with ash and slag formation and corrosion in the boiler. This makes it necessary to reduce the boiler and steam temperature slightly, and thereby the plant's electrical efficiency is typically also lowered a few percent.

The three rebuilding options have various advantages and disadvantages compared to each other. The use of pre-fabricated wood pellets offers a quick solution for rebuilding older coal power plant with less investment than the other options. On the other hand, the fuel costs are higher.

Wood chips are a cheaper fuel than wood pellets. However, in case of both replacing the boiler and building a fuel drying and processing plant, the investment is higher.

When installing a new boiler for combustion of wood chips, which have a relatively high water content, a higher heat efficiency can be obtained when recovering the condensation heat from the flue gas, though with a somewhat lower electric efficiency. Still, the overall fuel efficiencies may be higher and even above 100% (LHV).

In the case of a CFB-type boiler, and possibly also with converted boilers, the steam pressure is often lower than in the original plant and therefore the high pressure turbine has to be replaced with a new one. However a number of CFB suppliers are able to offer also super critical boilers. Otherwise, the pressure drop over the high pressure turbine will condense the steam too much, and the low pressure turbine will get steam that is too "wet" and will eventually break faster than it should.

It is common to add coal ashes or coal in the combustion of biomass to prevent slag formation and corrosion in the boiler, this will most likely make the ashes unsuitable for spreading in the environment. At the same time, the recycling of the ashes for use in concrete products, which is normal practice with coal ashes, is questionable with wood ashes due to its high alkali content. The ashes from firing with coal or biomass can be used for producing synthetic gypsum.

Environment

The environmental issues when using biomass as a fuel in rebuilt coal power plants are generally similar to those of new biomass plants. Central issues are emission of particulate matter, NO_x emissions and condensate water. Existing plant configuration often results in higher cost for flue gas cleaning than for new plants.

Another environmental issue is heavy metals in ashes. The ashes from biomass combustion contain minerals that are valuable in agriculture and forestry, and may be recycled. This is subject to regulation involving chemical analysis and controlling concentrations of heavy metals. Especially the cadmium and lead concentrations in the ashes will limit the amounts that can be spread over a certain area per year.

There are several specific health and safety issues connected with the transportation, handling and storage of wood pellets and chips. These involve e.g. the risk of suffocation, self-ignition, explosion, and formation of poisonous molds in storages and transport systems.

Data sheet 01 - Wood pellets, existing boiler

Rebuilding power plants from coal to biomass, Wood pellets, existing boiler, extraction plant	
Energy / technical data	
Generating capacity for one unit (MW)	300
Electricity efficiency (condensation mode for extraction plants). net (%). name plate	NA
Electricity efficiency (condensation mode for extraction plants). net (%). annual average	NA
Cb coefficient (50°C/100°C)	NA
Cv coefficient (50°C/100°C)	NA
Forced outage (%)	NA

Rebuilding power plants from coal to biomass, Wood pellets, existing boiler, extraction plant	
Planned outage (weeks per year)	NA
Technical lifetime (years)	15
Construction time (years)	2
Space requirement (1,000m2/MW)	NA
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (degree of desulphuring. %)	NA
NO_X (g per GJ fuel)	20
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	0.61
Fixed O&M ($US/MWe/year)	4,054
Variable O&M ($US/MWhe)	0.44

Data sheet 02 - Wood chips, new boiler

Rebuilding power plants from coal to biomass, Wood chips. new boiler, extraction plant	
Energy / technical data	
Generating capacity for one unit (MW)	300
Electricity efficiency (condensation mode for extraction plants). net (%). name plate	NA
Electricity efficiency (condensation mode for extraction plants). net (%). annual average	NA
Cb coefficient (50°C/100°C)	NA
Cv coefficient (50°C/100°C)	NA
Forced outage (%)	NA
Planned outage (weeks per year)	NA
Technical lifetime (years)	15
Construction time (years)	2.5
Space requirement (1,000m2/MW)	NA
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (degree of desulphuring. %)	98
NO_X (g per GJ fuel)	24
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	8
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.94
Fixed O&M ($US/MWe/year)	35,695
Variable O&M ($US/MWhe)	1.33

Data sheet 03 - Wood chips, existing boiler, extraction plant

Rebuilding power plants from coal to biomass, Wood chips, existing boiler, extraction plant	
Energy / technical data	
Generating capacity for one unit (MW)	300
Electricity efficiency (condensation mode for extraction plants). net (%). name plate	NA
Electricity efficiency (condensation mode for extraction plants). net (%). annual average	NA
Cb coefficient (50°C/100°C)	NA
Cv coefficient (50°C/100°C)	NA
Forced outage (%)	NA
Planned outage (weeks per year)	NA
Technical lifetime (years)	15
Construction time (years)	2
Space requirement (1000m2/MW)	NA
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (degree of desulphuring. %)	98
NO_X (g per GJ fuel)	24
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	8
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.94
Fixed O&M ($US/MWe/year)	17,152
Variable O&M ($US/MWhe)	1.82

Data sheet 04 - Wood chips, existing boiler, back pressure plant

Rebuilding power plants from coal to biomass, Wood chips, conversion small coal boiler, back pressure plant	
Energy / technical data	
Generating capacity for one unit (MW)	70
Electricity efficiency (condensation mode for extraction plants). net (%). name plate	NA
Electricity efficiency (condensation mode for extraction plants). net (%). annual average	NA
Cb coefficient (50°C/100°C)	NA
Cv coefficient (50°C/100°C)	NA
Forced outage (%)	NA
Planned outage (weeks per year)	NA
Technical lifetime (years)	15
Construction time (years)	NA
Space requirement (1000m2/MW)	NA
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA

Rebuilding power plants from coal to biomass, Wood chips, conversion small coal boiler, back pressure plant	
Environment	
SO_2 (degree of desulphuring. %)	NA
NO_X (g per GJ fuel)	30
CH_4 (g per GJ fuel)	3
N_2O (g per GJ fuel)	10
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	NA
Fixed O&M ($US/MWe/year)	35,695
Variable O&M ($US/MWhe)	1.33

Introduction to Waste and Biomass plants

Due to large similarities the qualitative description of biomass and waste fired plants are presented with a common technology description. Also, the chapters describing combined heat and power (CHP) and heat only plants (HOP) for biomass and waste respectively have been merged in an effort to make the catalogue easier to read.

Brief technology description

The description includes technologies that have large similarities when used for CHP and HOP fired with biomass or waste, the latter named Waste-to-Energy (WtE) facility. The main systems are presented the figure below, illustrated by a WtE CHP facility.

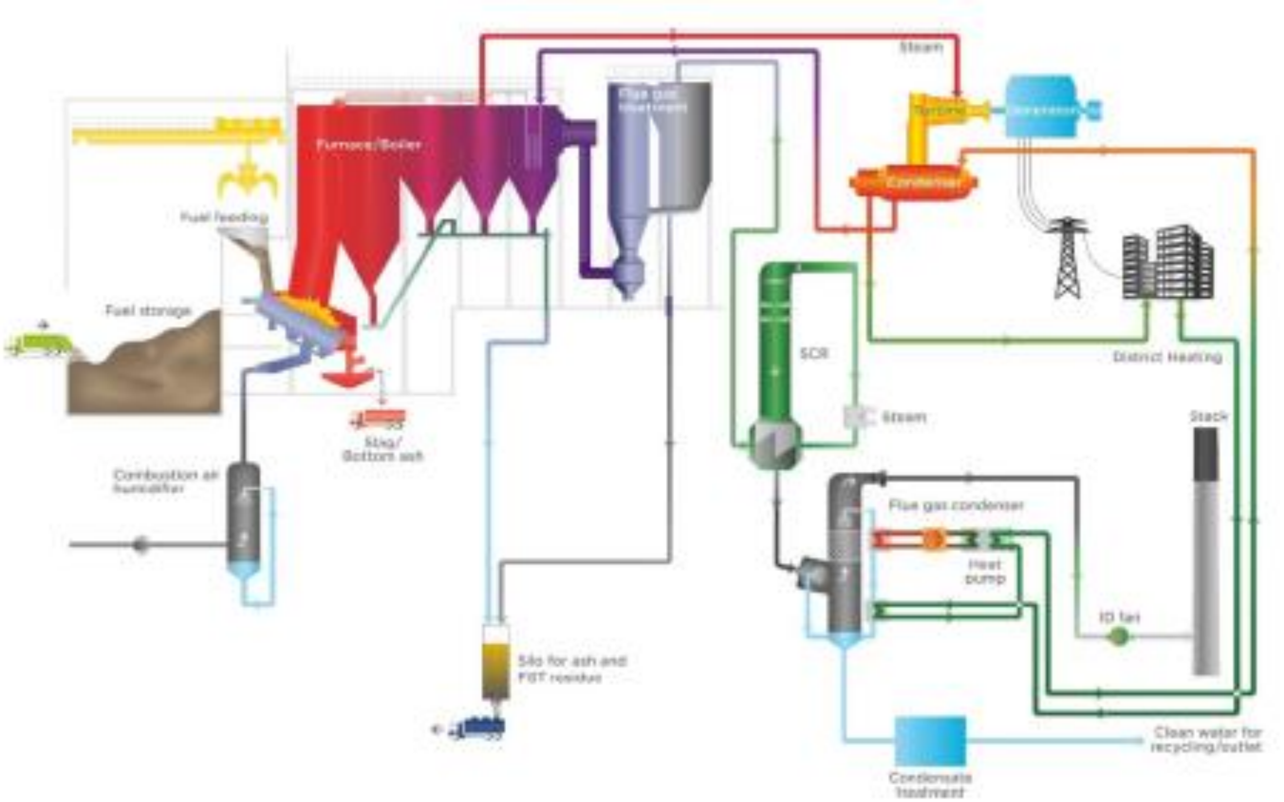

Figure 7: Main systems of a CHP (or Heat only), example WtE CHP facility.

The main systems of a biomass or waste fired CHP plant are:

- Fuel reception and storage area,
- Furnace or firing system including fuel feeding
- Steam boiler
- Steam turbine and generator,
- Flue gas treatment (FGT) system potentially including an SCR-system for NOx reduction
- Systems for handling of combustion and flue gas treatment residues
- Optional flue gas condensation system
- Optional combustion air humidification system

In case of HOP, the steam boiler is replaced with a hot water boiler, and no turbine/generator set is included.

Other main systems are in principle the same as for the CHP-plants.

Input

Wood chips, wood pellets and straw are considered for biomass plants. Other types of biomass e.g. other forest residues; sawdust and nut shells may be relevant as energy source, while different fuels set different technical requirements for the plant, these differences will not be addressed.

Waste to energy (WtE) facilities receive non-recyclable municipal solid waste (MSW), commercial waste and certain fractions of industrial waste and construction & demolition waste. It may also include refuse derived fuel (RDF). Certain types of hazardous waste may be included but dedicated hazardous waste plants are not covered here. More on fuel follows in the respective chapters on WtE and biomass.

Fuel reception and storage

The fuel is received by lorry. Storage is usually available on site for a minimum of two days full load operation.

For wood chips and wood pellets the fuel storage will typically have a capacity of 1-2 weeks. Straw is received in bales and stored in an enclosed building in order to avoid exposure to moisture; wood pellets are stored in a closed silo; wood chips may be stored outside, but often under roof to limit exposure to rain. The investment costs in the datasheets for biomass include two days' storage, only. In many cases the optimal fuel storage capacity would be larger. Therefore, specific cost of fuel storage per day in excess of 2 days is listed separately in the datasheet.

Waste is received and stored in a closed building to avoid escape of odour and it is unloaded into a dedicated bunker from where a grab brings it to the feeding hopper. The bunker would usually be sized for 4 days of operation.

Furnace

The furnace is where the fuel is injected, dried, pyrolyzed and burnt and the energy content is converted to hot flue gas for subsequent uptake in the boiler. The typical furnace technologies can be divided into:

- grate firing,
- different types of fluidized beds (FB) and
- suspension firing, where the fuel is pulverized or chopped and blown into the furnace, optionally in combination with a fossil fuel.

Grate combustion is a well-established and robust technology with regard to using different types of biomass. It can be further divided into a number of subcategories, e.g. according to EN ISO 17225-1 Solid biofuels – Fuel specifications and Classes – Part 1: General requirements.

There are examples of combined boiler technologies with both suspension- and grate firing. For geometrical reasons there is a limit to how big a grate fired plant can be constructed – of the order slightly below 200 MW thermal input.

Large FB boilers are of the type Circulating Fluid Bed (CFB) and they are typically used for CHP plants in situations where the plant size exceeds the maximum for grate firing. In particular, wood chips is an excellent fuel for FB boilers.

Alternatively, suspension firing is suitable for very large biomass power plants (substantially above 200 MW thermal input) and it requires a pulverisation of the fuel before it is fed into the furnace. Pulverisation of biomass is not an easy task but in particular pellets can be disintegrated into its finer particles using a (coal) mill. These particles are often adequate directly for combustion. Dust firing from milled wood pellets is widely used in e.g. Sweden for smaller plant down to approx. 50 MW thermal input.

WtE facilities are usually all grate fired. At WtE plants an afterburning chamber ensures that temperature and residence time requirements are met. During boiler start-up biomass or auxiliary burners in the furnace fired by oil or gas are needed to ensure heating to the required temperature. During normal operation, no auxiliary fuel is added.

Typical sizes of furnace types are shown in the following table.

Table 6: Typical sizes of furnace technologies. BFB refers to Bubbling Fluidized Bed. CFB to Circulating Fluidized Bed and grate furnace have been further divided in three subcategories.

Boiler input	**MW**	**1**	**2**	**5**	**10**	**20**	**50**	**100**	**200**	**500**	**1000**
FB	**BFB**				░	░	░	░	░	░	
	CFB				▒	▒	▒	▒	▒	▒	▒
Grate	**Travelling grate**					░	░	░	░		
	Reciprocating grates			▒	▒	▒	▒				
	Vibrating grates					▓	▓	▓	▓		
Dust fired							░	░	░	░	░

Boiler

The boiler is where the energy content of the flue gas is transferred by heat exchange to the heat media, which is usually hot water and in case of CHP, water and steam. As flue gas passes through the boiler, it is cooled, and the heat media is heated by heat exchange. In a heat only boiler, water is heated to supply the necessary district heating (DH) supply temperature, which is typically up to xx°C in Kazakhstan for distribution networks and somewhat higher, when the DH water is led to the transmission networks.

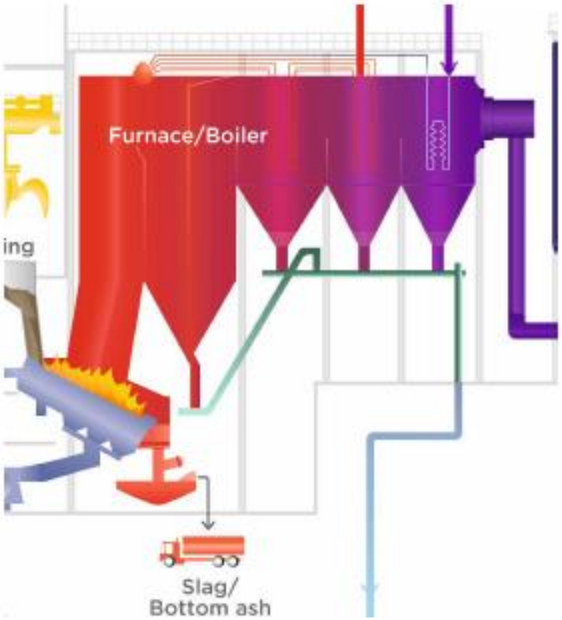

Figure 8: Furnace / Boiler system

The output from the boiler of a CHP facility is superheated steam, i.e. steam that is heated above the boiling point. The plant includes feed water pumps supplying high pressure water to the boiler, an economiser, where the input water is heated towards the boiling temperature, evaporators, where the water is evaporated to steam, a drum vessel for separation of steam and water, and super heaters, where the steam is heated above the boiling temperature. Large biomass facilities may use different boiler types.

Turbine/generator

The turbine/generator set is only included in CHP (or power only) facilities. The superheated high-pressure steam from the boiler is led to the turbine where the energy content of the steam is converted to rotation energy in the turbine. Through its connection to the generator, the rotation energy is converted to electricity.

The temperature and pressure of the steam decrease as the steam drives the rotation of the turbine blades. The low-pressure steam is extracted from the turbine to DH condensers at the pressure and temperature levels that suit the requirements of the DH network. The condensation heat is delivered to the DH network. This is different from a power-only facility where condensation happens at lower temperatures and the heat of condensation is wasted, e.g. in an air-cooled condenser. The power efficiency of a CHP facility is therefore lower than the corresponding power-only facility, but the total efficiency is much higher. Power-only facilities are not included in the present technology sheets. The turbine- and generator system of a backpressure CHP is shown in below figure.

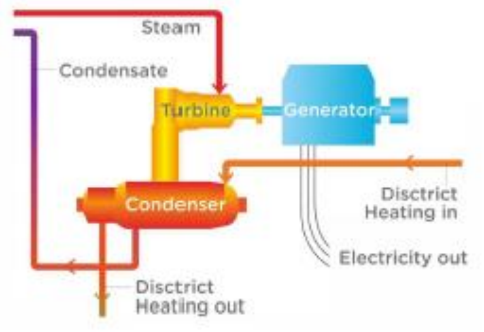

Figure 9: Turbine / generator system of backpressure CHP

A steam extraction turbine is more complex and has two heat exchangers. One of them is connected to the DH network, similar to the case for the backpressure CHP, while the other exchanges heat to the surroundings (usually large water reservoirs, e.g. sea water). The steam can be cooled in one of the heat exchangers (condensing- or backpressure mode) or in a combination of both (extraction mode).

Flue gas treatment (FGT)

The flue gas is treated to meet the emission requirements of biomass and waste, respectively. The FGT always includes a particle filter, either an electrostatic precipitator (ESP) or a bag house filter (BHF). Acid gases (HCl, SO_2 and HF) are mitigated in a dry or semi-dry process by injection of hydrated lime, for subsequent capture in a BHF, or in a wet scrubbing system. Using a wet scrubbing system reduces the amount of solid residue compared with the dry process, but effluent water must be treated before discharge to meet stringent emission levels. In WtE dioxin and mercury may be captured by injection of activated carbon.

NOx is mitigated by the SNCR or SCR process (SNCR and SCR are Selective Reduction of NOx by ammonia injection, by the respective Non-Catalytic or Catalytic process). The SNCR process works by injection of ammonia in the furnace at around 900°C. It has limited efficiency, and to meet stringent emission limit values it may be necessary to install the highly efficient catalytic SCR system. With biomass and waste an SCR system would usually be located downstream of the main FGT (tail-end) or at least downstream the particle filter to avoid that certain elements in in the flue gas deactivate the catalyst.

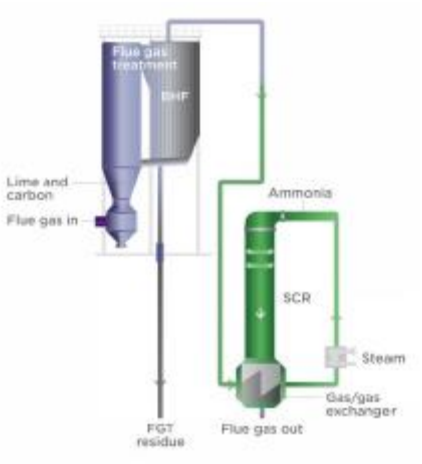

Figure 10: Flue gas treatment (dry / semi-dry) including reactor with injection of hydrated lime, a bag house filter and an SCR system with gas / gas heat exchanger, steam re-heater, ammonia injection and catalyst

Handling of solid residues

Solid residues include incombustible matter (ash) and flue gas treatment (FGT) residues. With biomass most of the ash is segregated in the boiler or particle filter and collected in a silo for disposal together with the FGT residue. In case of WtE the ash makes up 15-20% of input waste, and around 90% thereof leaves the facility as bottom ash, segregated from the furnace grate.

Flue gas condensation system

The flue gas condensation system is installed for increased heat recovery primarily through condensation of the water vapours of the flue gas. The energy efficiency could thereby be increased by more than 20%-point. Flue gas condensation is currently customary in WtE facilities and biomass fired facilities, particularly when using wood chips, waste, and similar relatively wet fuels.

Flue gas condensation may be arranged as a wet scrubbing system (see below figure) in which the scrubbing liquid is cooled by heat exchange with DH water. The relatively cold DH water cools the scrubber and it is thereby heated. When the cooled scrubbing liquid meets the warmer flue gas that has been saturated with water vapour, the vapour condenses, thereby releasing the heat of condensation. The condenser may also be arranged with flue gas running in vertical tubes exchanging heat with DH water surrounding the tubes or plate heat exchangers in the flue gas path. The flue gas condensation system may be divided into two systems. First stage is direct condensation where heat recovery happens by direct heat exchange with DH water and in the second stage condensation is assisted by heat pumps. The heat recovery by direct condensation is limited by the DH return temperature. The lower the temperature, the higher the heat recovery. The heat pump allows cooling the flue gas and condensation of water vapour to quite low temperature (20 - 30°C), corresponding to very high energy recovery at the expense of driving energy for the heat pump (typically steam or electricity).

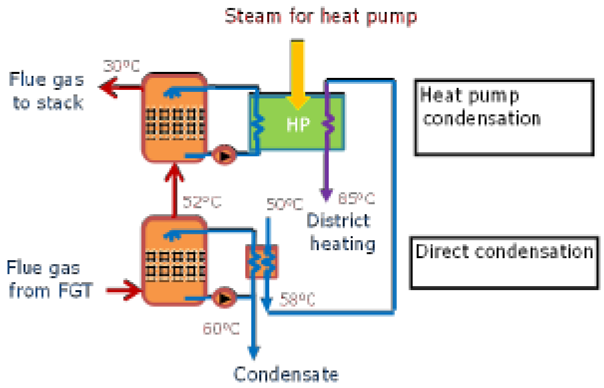

Figure 11: Flue gas condensation, direct and heat pump driven with 50°C DH return temperature, and typical WtE adiabatic scrubber temperature

In the datasheets, only direct condensation is included to the level limited by the DH return temperature of 40°C or 50°C, depending on the case. The heat pump condensation potential is listed separately (“Additional heat potential for heat pump (%)”), and not included in the listed efficiencies. Section *Total energy efficiency determination with flue gas condensation* below describes how to quantify the total efficiency for a biomass or WtE facility with flue gas condensation given a specific fuel and DH temperature.

Running the flue gas through several wet scrubbers of the flue gas condensation system contributes to reaching very low emissions of HCl, SO_2, dust, heavy metals and ammonia.

Condensate and wastewater treatment

Process waste water from a wet scrubber (if included) must be treated prior to discharge to the sewage system or the sea. In any case, stringent requirements may apply, governed for in national legislation. Treatment includes neutralisation, precipitation of heavy metal ions and filtering, and generation of a small amount of sludge.

Condensate from flue gas condensation has low content of salts and pollutants when the condensation system is located downstream the FGT-system. Condensate treatment includes reverse osmosis to yield very clean water useful for industrial applications including boiler make-up water and make-up water for the DH network. The net water production may significantly exceed the original fuel moisture content, due to water formed from hydrogen and oxygen during combustion. For relatively wet fuels the excess water may be more than 500 kg per ton of fuel input.

The excess condensate is clean, virtually salt-free water and may be used for internal purposes such as boiler make-up water, for FGT and cooling of bottom ash, effectively replacing external water supply. It may also be considered a recovered resource to be used externally for covering water losses in the district-heating network and for industrial purposes. If this is not possible, excess cleaned condensate may be discharged to the sea or the local sewage system (at a cost). The amount of excess recovered condensate is listed in the tables and included in the variable operating cost, cf. financial section. Only internal consumption for make-up water supply of steam systems is subtracted in the listed values.

Combustion air humidification system

Combustion air humidification may to some extent substitute the use of heat pump driven condensation for increased heat production. Combustion air humidification works by adding water vapour to the combustion air, thereby increasing the content of water vapour in the flue gas as it enters the flue gas condensation system, in turn increasing the heat output of the direct flue gas condensation. The energy needed to generate the water vapour input to the combustion air is recovered from the last stage of the flue gas condensation system, at the temperature level below the DH temperature. This low temperature heat, at e.g. 40°C, is used as heat source for evaporation of water in the combustion air humidification system.

The high-level effect of combustion air humidification is that the flue gas is cooled further than it is possible by heat exchange with the DH water, thereby representing an increase in energy recovery from the fuel. In the data tables it is assumed that combustion air humidification (if included) reduces the flue gas condensation temperature by 5°C and 8°C at DH return temperatures 40°C and 50°C, respectively. The system is customary in biomass fired facilities having flue gas condensation.

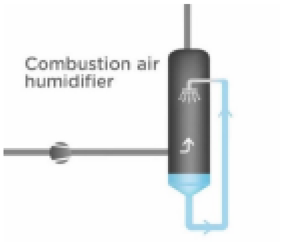

Figure 12: Combustion air humidifier, where water heated by a low-temperature source is evaporated into the combustion air flow

The energy model for the technology datasheets

Due to the technological similarities, a common model has been used to populate the sheets for biomass and waste.

The table below shows the basis plant design assumptions made for different feedstocks.

Table 7: Base assumptions for CHP plants for energy performance estimation.

Fuel	**Waste**	**Wood chips**	**Wood pellets**	**Straw**
Firing system	Grate	Grate / CFB (large)	Suspension	Grate
Live steam, CHP	425°C / 50 bar	540°C / 90 bar	560°C / 90 bar	540°C / 90 bar
Flue gas temperature after steam boiler	160°C	130°C	130°C	130°C
Excess air ratio	1.5	1.3	1.3	1.3
Boiler losses other than flue gas (% of LHV)	2%	2%	2%	2%
Turbine losses (gear/generator) (% of gross power), CHP	3%	3%	3%	3%
Flue gas condensation	Yes	Yes	Yes	Yes
Combustion air humidification	No	Yes	Yes	Yes
Flue gas cleaning type	Wet	Dry	Dry	Dry
NOx abatement (small and medium size)	SNCR	SNCR	SNCR	SNCR
NOx abatement (large facilities)	SNCR	SNCR	SCR	SCR

The total efficiency of plants with flue gas condensation is calculated assuming “direct condensation”, where the condensation heat is recovered directly with the available DH water without the use of heat pumps.

DH plants share base assumptions with the CHP plants, except that live steam parameters are not applicable, and the losses associated with a steam system and turbine/generator do not exist for these plants.

At some plants, condensation heat recovery is augmented by cooling the flue gas further, typically to 30°C using heat pumps. In the datasheets, the row “Additional heat potential for heat pump (%)” contains the additional heat that a heat pump would recover from the flue gas by cooling it further to 30°C. The so produced additional heat is the sum of this recovered amount of heat and any external driving energy (electricity or steam) supplied to drive the heat pump. The efficiencies listed in the data tables do not include the contribution from heat pump driven condensation, and the heat pump investments are not included in the listed investments.

The loss of power production caused by the steam consumption of the heat pumps is system specific and cannot be tabulated here. If electrically driven heat pumps had been used instead, the power production loss would be avoided, but instead the heat pump would consume power themselves.

Total energy efficiency determination with flue gas condensation

Flue gas condensation is a technology that can significantly increase the heat efficiency of biomass and WtE plants by recovering the heat of condensation from water vapour in the flue gases.

The heat of condensation is not included in the heating value definition of the lower heating value, LHV, which is usually used in Europe as basis for defining the energy input. Thus, total efficiencies based on LHV at plants with flue gas condensation may exceed 100%. Furthermore, the total efficiency of such plants can vary significantly for different fuels with different compositions and moisture contents when using the LHV as the basis.

For flue gas condensation the relevant heating value definition to describe the heat recovery and the total plant efficiency is the higher heating value (HHV), which takes into account the energy recovery potential from condensation. Thus, in the specific section below there is a need to make references to the HHV. The rest of the technology data sections as well as all the data tables will refer to the usual LHV only. The total HHV-based efficiency of a given plant with flue gas condensation is almost the same for any fuel, when the flue gasses are cooled, and water vapour condensed to a certain temperature. The total HHV-based efficiency with flue gas condensation depends mainly on the temperature of the DH return water, which is used to recover the low temperature heat through heat exchange.

The figure below shows the HHV-based total gross efficiency for typical biomass plants and WtE plants. This curve is generally applicable to such plants, for CHP as well as heat only configurations. Biomass plants with flue gas condensation have slightly higher HHV-based gross efficiencies because they typically operate with lower excess air ratios and have lower ash loss than WtE plants. The dashed boiler efficiency indications in in the figure show the no-condensation lower efficiency limit, which is fuel specific. Wood chips were selected for the example to give a low lower limit.

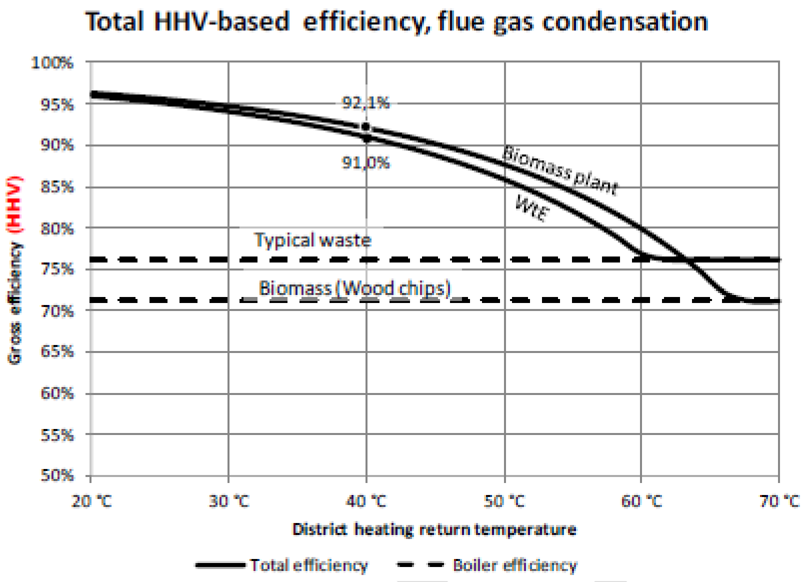

Figure 13: Total HHV-based efficiency estimate for WtE plants and biomass plants given varying DH return temperatures – or temperature of the cold media of a heat pump

The figure can be used generally with good accuracy to estimate the total efficiency (based on HHV) of a WtE or solid biomass plant equipped with flue gas condensation, based only on the available DH return temperature. The estimate is even valid for marginal efficiencies of single waste fractions such as organic waste, paper, plastics etc. The conversion to the usual LHV-based total efficiency is straight-forward. As an example, typical municipal solid waste with a LHV of 10.6 MJ/kg and a HHV of 12.2 MJ/kg treated at a plant with flue gas condensation fed with 40°C DH water would according to the figure have a total efficiency of 91.0% based on HHV. This can be calculated to the LHV-based gross total energy efficiency as: 91.0% * 12.2 MJ/kg / 10.6 MJ/kg = 104.7%. For wet organic waste with a HHV of 6.5 MJ/kg and LHV of 4.4 MJ/kg treated at the same plant, gross total energy efficiency would be 91.0%*6.5 MJ/kg / 4.4 MJ/kg = 134.9%. The table below shows examples of gross total efficiencies calculated the same way for different fuels at WtE and biomass plants connected to DH networks with return temperatures of 50°C, 40°C and 30°C.

Table 8: Gross total efficiencies for different fuels at biomass and waste fired plants with access to different DH return temperatures using flue gas condensation.

Gross total efficiencies with flue gas condensation	**Heating value**		**Total efficiency (LHV)**		
Fuel or fuel fraction	**LHV [MJ/kg]**	**HHV [MJ/kg]**	**DH 50°C**	**DH 40°C**	**DH 30°C**
WtE configuration HHV boiler efficiency			**85.8%**	**91.0%**	**94.1%**
Mixed waste 10.6 GJ/t (31% moisture)	10.6	12.2	98.8%	104.7%	108.3%
Organic waste (70% moisture)	4.4	6.5	127.3%	134.9%	139.5%
Green waste (50% moisture)	9.5	11.5	103.4%	109.6%	113.3%
Paper	11.1	12.6	97.4%	103.3%	106.8%
Plastic	35.0	37.5	91.9%	97.5%	100.8%
Biomass configuration HHV boiler efficiency			**87.7%**	**92.1%**	**94.7%**
Wood chips (50% moisture)	8.1	10.0	107.7%	113.1%	116.3%
Wood chips (40% moisture)	10.3	12.0	102.5%	107.7%	110.8%
Wood pellets (5% moisture)	17.7	19.0	94.3%	99.0%	101.9%
Straw (11% moisture)	15.0	16.4	95.8%	100.6%	103.5%

Large heat pumps can be installed to supply condenser cooling water at even lower temperatures than the DH return temperature in order to further increase the heat recovery. In these cases, the total efficiency can still be read from the above figure by replacing the DH return temperature on the x-axis by the (lower) chilled water temperature from the heat pump. The use of a heat pump to extend the flue gas condensation is considered an add-on, the feasibility of which is judged as a separate project (cf. technology sheets on heat pumps). The heat pump constitutes most of the necessary additional investment.

Even higher total efficiencies can be achieved by recovering the heat from component cooling at the plant, which is usually lost. This would require the use of heat pumps.

All efficiencies in the main data tables of all technology data sheets are given based on the usual LHV basis for the specifically assumed waste and biomass composition. Given other waste or biomass compositions, the total efficiency at plants with flue gas condensation is much more accurately estimated using the table or procedure described above with the given fuel. The power efficiency should however be taken directly from the technology data sheets, as it is not significantly affected by flue gas condensation.

Financial data

Investment

The CAPEX is based on green-field construction and the investment cost includes engineering, procurement and construction, in which a lot-based tendering approach is selected to reach a turn-key plant.

The pricing reference and distribution of cost between contract nominal price and project cost is based on tendering in relatively large lots, including a separate “civil works” lot and 3 major M&E lots, e.g. furnace/boiler, flue gas treatment and turbine/generator. There may be some minor lots to make the balance of plant. The typical “civil works” cost is 30% of total construction cost and project cost typically amounts to 15% of total construction cost (total construction cost excluding project cost).

The project cost includes:

- Owner’s organisation
- Owner’s or consultants’ fees related to procurement, and design, construction and commissioning surveillance
- Insurances
- Contingencies
- Hedging of currency exchange rates related to contracts
- Utilities connections etc. (power, water, district-heating)
- Roads, manoeuvring space and parking on site for staff and visitors
- Visitor facilities, basic to accommodate school classes and the like.
- Following are not included:
    - Land acquisition – and preparation
    - Pre-development cost
    - Approvals, environmental and others
    - Infrastructure outside site (roads, power connections, district-heating piping, sewage)
    - Financing cost other than specifically included above
    - Interest payments during construction
    - Any cost related to operation after take-over
    - Financial risk element associated with acquisition of waste (waste is assumed available)
    - Financial risk element associated with sale of heat and power (sale opportunity of power is considered available, and 100% sale of heat is considered available in the heating season, 5,000 - 6,000 h/y, but there may be limited sale in the summer)
    - Demolition of existing constructions on site
    - Site preparation such as relocation of infrastructure elements (e.g. gas-, water- and DH-piping, sewage systems, electric cables, etc.)

- Adaptions to a restricted footprint of the available site, e.g. brown-field plants and construction in proximity to cites.
- Particular architectural features and designs.
- Particular visitor facilities other than basic.

For EPC–contracts, i.e. contracts in which the entire plant includes engineering and commissioning is contracted as a turn-key project, the CAPEX is estimated as roughly unchanged or slightly higher. There could be higher cost to allow for the Contractor’s project management and assumed risk compared to a lot-based approach, but particularly at small plants this may be counteracted by savings if the Contractor has experiences with working closely together with sub-suppliers. At larger plants the owner would often prefer to procure the plant in lots to ensure control of the technical specification and execution of major subsystems and the civil works. In such cases using an EPC contract may release some additional cost. The cost also depends on the risk allocation and the details of the technical description of the tender documents.

In summary the additional cost of an EPC contract is estimated as 0-10%. This only relates to a lot-based approach compared with an EPC-contract in the construction of a plant. The plant ownership, the owner’s responsibility for the operation and the other risk elements described above must not be affected by the contracting approach.

Comparing heat-only plants (HOP) with CHP plants will show relatively large difference in investment costs expressed in $US/MW input. This is because CAPEX for CHP plants will include a steam boiler with associated high-pressure systems, steam turbine with auxiliary equipment, a generator with step-up transformer, switchyard, control system etc. and a steam turbine/generator building, which a HOP does not require.

Furthermore, when comparing investment costs expressed as $US/MW input for the same category, e.g. wood chip fired HOP, this will show a declining trend as unit size increase and the decline will typically be greatest for small plants up to say 30-40 MW fired capacity after which it will even out to an almost constant figure.

The investment costs are also influenced by legislative requirements for emission to air which will shift depending on heat input. For biomass fired plants more stringent requirements come into force when the heat input is 50 MW or higher which will require more sophisticated flue gas cleaning equipment and may also increase O&M costs.

Operation and Maintenance

O&M-costs are composed of the following components in relation to their dependence on plant production:

Variable O&M:

- Consumables (water, lubricants, oils, chemicals, additives, absorbents, etc.)
- Effluent charges for disposal of condensate from flue gas condenser
- Electricity consumption (lighting excluded as this appears as auxiliary electricity consumption)
- Temporary staff
- Other

Fixed O&M:

- Administration cost, tests (e.g. R&D, office equipment and utensils, utilities, vehicles, cleaning, etc.)
- Operating staff
- Maintenance staff
- Planned and unplanned maintenance costs (spare and wear parts, tools and scaffolding, external work force, etc.)
- Service agreements
- Property taxes
- Network and system charges
- Insurances
- Other

O&M costs are high-level estimates based on experience rather than detailed analyses of cost elements shown in above lists. As for CAPEX estimates O&M costs for a greenfield, stand-alone plant is envisaged meaning that any resources or facilities potentially shared with other units are not considered. In case of plants established as extension to existing and similar plants, where shared manning, O&M facilities and partly unmanned/remote operation are good opportunities, substantial cost reductions can be obtained, but such cases need to be analysed individually to quantify.

Fixed O&M costs are estimated with the following elements:
- fixed maintenance cost for process plant (M&E) calculated as 2% p.a. of the M&E CAPEX
- fixed maintenance cost for civil structures calculated as 1% p.a. of civil CAPEX,
- other fixed O&M costs estimated individually for all scenarios,
- fixed staff for a stand-alone plant with permanent manning of control room and including staff administrative tasks.

Variable O&M costs are estimated with the following elements:
- consumables used for the specific case,
- estimated costs for disposal of excess recovered condensate from flue gas condenser,
- other variable O&M costs for the specific case covering the rest in above list.

Excess recovered condensate is included in the data tables and included as variable operating cost at a rate of 1 $US per ton of water. The variable cost is very dependent on the opportunities available locally. It may be zero if internal or external use could be the off-taker, or if outlet to the sea (or another recipient) is possible. In case of discharge to the local public sewage system, the unit pricing is locally dependent and dependent on annual volume. It would usually be in the range 1.5-4 $US per ton of water.

WtE CHP and HOP plants

Brief technology description

WtE plants incinerate waste and produce energy. HOP's produce only heat, while CHP's also produce electricity.

Flue gas condensation technology has been used in WtE plants in Europe since 2004. It recovers the heat of condensation of the flue gas content of water vapour. The heat i.e. recovered as low temperature heat and thereby increases the energy efficiency by additional 10-25%-points for mixed waste.

Input

The fuels used in WtE plants include mainly municipal solid waste (MSW) and other combustible non-recyclable wastes. Biomass may be used mainly for starting up and closing down. In addition, Refuse Derived Fuel (RDF) may be used as fuel. Other fuels include gasoil or natural gas for burners used mainly for start-up.

The fuel, waste, is characterised by being heterogeneous having large variation in physical appearance, heating value and chemical composition. The heating value of the waste fed to the furnace is a result of controlled mixing of available waste sources fed to the bunker of the WtE facility. It is usually in the range 7-15 MJ/kg, typically averaging 10-11 MJ/kg, referring to the lower heating value, LHV.

The heating value of the waste received at the WtE plants may be affected by increased focus on recycling, which on one hand may divert organic waste with relatively low heating value and on the other hand divert plastics, paper and wood with relatively high heating value.

Output

The products from WtE CHP plants are electricity and heat as steam, hot (> 110°C) or warm (< 110°C) water.

The output from WtE HOP is hot water for district heat or low-pressure steam for industrial purposes. The energy efficiency of the WtE plant has increased over the last decade, driven by focus on combustion control, limiting the flue gas temperature at boiler exit and the excess air level, assisted by the increased use of flue gas condensation. The total energy efficiency is identical for heat and CHP plants, except that for HOP some minor heat losses in the generator and turbine gearbox of the CHP plant is avoided. The heat production from a HOP is thus identical (or slightly higher) than the sum of produced electricity and heat from an equivalent CHP plant.

In case of flue gas condensation, excess condensate (which represents up to 50% of mass input of waste) may be upgraded to high quality water useful for technical purposes such as boiler water or for covering water losses of the district-heating network.

Typical capacities

The capacity of a WtE plant is typically in the range 10 - 35 tons of waste per hour, corresponding to a thermal input of approx. 30 - 110 MW. The furnace capacity is limited to around 120 MW thermal input at the current state of development.

WtE HOPs are typically relatively small with a capacity of 5 - 15 tons of waste per hour, corresponding to a thermal input in the range 15 - 50 MW.

The initial costs for WtE CHP plants are so high that smaller plants (< 5-10 tons waste/h) are rarely financially attractive. The typical production line has a capacity of 10-35 tons waste/h. More lines are installed if required. In Scandinavia WtE plants are typically located close to larger cities with a district heating system and they are designed to treat the waste amounts produced in the vicinity. During periods where local waste generation is below the treatment capacity, it is possible to supplement with waste from other regions, including imported waste (as RDF). The size of the moving grate defines the upper limit waste mass capacity for each boiler line (approximately 40 tons waste/h).

Regulation ability

The CHP plants can be down regulated to about 70% of the nominal capacity. Below the limit the boiler may not be capable of providing adequate steam quality and compliance with the requirement of high temperature residence time of the flue gas, cf. environmental section. WtE plants are preferably operated as base load due to high initial investments and that longer term storage of some types of waste is problematic and therefore it must be incinerated continuously. This also ensures continuous district-heating supply. In order to be able to maintain a waste treatment capacity (and heat supply) during outages WtE plants are sometimes built as 2 (or more) parallel lines instead of one large unit depending on alternative disposal options of waste.

Most CHP facilities are constructed with fully flexible and fast reacting electricity production meaning that the turbine may be taken in or out of operation through the use of a turbine by-pass, which may also be used partly. When the turbine is out, the output is 100% heat for district-heating, and furnace/boiler operation continues unaffected. Turbine operation can usually be maintained down to around 15% of nameplate load.

Advantages/disadvantages

A WtE plant is not just an energy producing unit but a multi-purpose facility. Main purpose is the treatment of waste by which the waste is sterilised, and its mass and volume are greatly reduced. Compared to landfilling and anaerobic digestion the WtE prevents emissions of methane, a powerful greenhouse gas, from the waste handling.

Recovery of energy from waste is a main feature for resource recovery as part of the circular economy system for waste. It provides the opportunity of recovering resource from wastes that are not recyclable, e.g. contaminated waste, rejects from recycling operations and wastes that are too demanding to recycle.

The energy recovery process also provides the opportunities of recovering secondary raw materials from waste such as metals eventually replacing virgin metals produced from excavated metal ore. Metals (including iron, steel, aluminium and copper) are recovered from the bottom ashes. Metals contained in compound waste products that would otherwise be difficult to recycle may be recycled after the thermal treatment in the WtE facility. The remaining bottom ash is used as aggregate for road construction. Furthermore, clean water may be recovered as a result of flue gas condensation.

The disadvantage is that a polluted, corrosive flue gas is formed, requiring extensive treatment, and that the flue gas treatment generates residues usually classified as hazardous waste. The capital costs are relatively high due to the flue gas treatment system, other environmental requirements, the heterogeneous nature of the fuel and corrosive properties of the flue gas. The corrosive nature of the flue gas also limits the permissible steam data to approximately 40 - 70 bar and 400 - 440°C and hence the net power efficiency to around 20 - 30%. Due to the corrosive flue gasses the hottest parts of new boilers are often coated with expensive corrosion resistant alloys (Inconel).

The main advantage of a WtE HOP compared to a WtE CHP plant is lower investment and maintenance costs.

The main disadvantage of a WtE HOP is the lack of electricity sale and thus lower energy sales revenue and higher dependence on the sale of energy at the local heat market.

Environment

The environmental impact includes emissions to air and water, bottom ash (slag), and residues from flue gas treatment, including fly ash. Bottom ash making up around 15% of the mass input of waste is sorted to recover metals for recycling and production of aggregates for road construction.

Flue gas treatment residues and fly ash (totalling around 2 - 4% of the mass input of waste) are treated, e.g. through neutralisation with similar acid residues, and stored in a geologically stable underground deposit designed for the purpose. If the flue gas is treated by wet methods, there may also be an output of chloride containing waste water, which is treated at the plant to a purity that fulfils the requirements for discharge to the municipal sewerage system or to the sea. The discharged chloride salt substitutes deposition of a large quantity of solid residue.

On the positive side the recovered energy replaces energy produced from other resources and the emissions from this production, and recovered metals replace metals production from virgin ore.

Excess condensate from flue gas condensation may be considered a secondary raw material recycled for replacing water for technical purposes such as covering losses of district-heating networks to which the energy system is attached. The flue gas condensation system is usually located downstream of the flue gas treatment system, making the condensate low in salts and pollutants when leaving the condenser. The condensate could be treated further by electro deionization (EDI) and reverse osmosis to reach the quality required for its subsequent use or discharge to sensitive water recipients.

The air emissions from energy recovery of waste must comply with the environmental permit setting limit values on a range of pollutants including dust, CO, total organic carbon (TOC), HCl, SO_2, HF, NO_x, heavy metals and dioxins/furans.

Energy recovery also involves the generation of climate-relevant emissions of which mainly CO_2, and N_2O may be contributors. Methane, CH_4, is not emitted in in any significant amount. It is destroyed in the combustion process and its potential emission included under the restrictive limit value of TOC.

Waste is a mixture of CO_2 neutral biomass and products of fossil origin, which are mostly plastics. The CO_2-emission from energy recovery of plastics is defined as fossil CO_2 emitted from the WtE-facility. Typically, 32% ±5% of the emitted CO_2 originates from fossil sources.

In general, political and economic framework conditions define the emission limits from WtE.

Technical development in deNOx-technology and gradually more stringent emission requirements are expected to lower emissions of NOx for new facilities.

The solid residues from treatment of flue gas and wastewater are normally classified as hazardous wastes and they need usually to be treated before placed in an underground storage for hazardous waste.

Data sheets for WtE plants

The total efficiency of plants with flue gas condensation is calculated assuming “direct condensation”, where the condensation heat is recovered directly with the available DH water without the use of heat pumps.

Condensation heat recovery can be augmented by cooling the flue gas further, typically to 30°C using heat pumps. In the datasheets, the row “Additional heat potential for heat pump (%)” contains the additional heat that a heat pump would recover from the flue gas by cooling it further to 30°C. The so produced additional heat is the sum of this recovered amount of heat and any external driving energy (electricity or steam) supplied to drive the heat pump.

Data sheet 05 - WtE CHP, small

Small Waste to Energy CHP, Backpressure turbine, 35 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	8.0
Electricity efficiency, net (%), name plate	22.7
Electricity efficiency, net (%), annual average	21.6
Auxiliary electricity consumption (% of thermal input)	2.9
Cb coefficient (40°C/80°C)	0.29

Small Waste to Energy CHP, Backpressure turbine, 35 MW feed	
Cv coefficient (40°C/80°C)	1
Forced outage (%)	1
Planned outage (weeks per year)	3.3
Technical lifetime (years)	25
Construction time (years)	2.5
Space requirement (1000 m2/MWe)	2.5
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10
Minimum load (% of full load)	20
Warm start-up time (hours)	0.5
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphuring, %)	99.8
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	0.1
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	2.86
Fixed O&M ($US/MWe/year)	113,014
Variable O&M ($US/MWh_e)	7.14

Data sheet 06 - WtE CHP, medium

Medium Waste to Energy CHP, Backpressure turbine, 80 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	18.6
Electricity efficiency, net (%), name plate	23.3
Electricity efficiency, net (%), annual average	22.1
Auxiliary electricity consumption (% of thermal input)	2.9
Cb coefficient (40°C/80°C)	0.30
Cv coefficient (40°C/80°C)	1
Forced outage (%)	1.0
Planned outage (weeks per year)	2.9
Technical lifetime (years)	25
Construction time (years)	2.5
Space requirement (1000 m2/MWe)	1.6
Regulation ability	
Primary regulation (% per 30 seconds)	5.0
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	20.0
Warm start-up time (hours)	0.5
Cold start-up time (hours)	2.0
Environment	
SO2 (degree of desulphuring, %)	99.8
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	0.1
N2O (g per GJ fuel)	1.0
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	2.54
Fixed O&M ($US/MWe/year)	73,810

Medium Waste to Energy CHP, Backpressure turbine, 80 MW feed	
Variable O&M ($US/MWh_e)	7.14

Data sheet 07 - WtE CHP, large, 40/80°C return/forward temperature

Large Waste to Energy CHP, Backpressure turbine, 220 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	51.8
Electricity efficiency, net (%), name plate	23.5
Electricity efficiency, net (%), annual average	22.4
Auxiliary electricity consumption (% of thermal input)	2.9
Cb coefficient (40°C/80°C)	0.30
Cv coefficient (40°C/80°C)	1
Forced outage (%)	1.0
Planned outage (weeks per year)	2.4
Technical lifetime (years)	25
Construction time (years)	3.0
Space requirement (1000 m2/MWe)	0.8
Regulation ability	
Primary regulation (% per 30 seconds)	5.0
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	20.0
Warm start-up time (hours)	0.5
Cold start-up time (hours)	2.0
Environment	
SO2 (degree of desulphuring, %)	99.8
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	0.1
N2O (g per GJ fuel)	1.0
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	2.21
Fixed O&M ($US/MWe/year)	53,119
Variable O&M ($US/MWh_e)	19.36

Data sheet 08 - WtE CHP, large, 50/100°C return/forward temperature

Large Waste to Energy CHP, Backpressure turbine, 220 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	46.8
Electricity efficiency, net (%), name plate	21.3
Electricity efficiency, net (%), annual average	20.2
Auxiliary electricity consumption (% of thermal input)	3.0
Cb coefficient (40°C/80°C)	0.28
Cv coefficient (40°C/80°C)	1
Forced outage (%)	1.0
Planned outage (weeks per year)	2.4
Technical lifetime (years)	25
Construction time (years)	3.0
Space requirement (1000 m2/MWe)	0.9
Regulation ability	
Primary regulation (% per 30 seconds)	5.0
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	20.0

Large Waste to Energy CHP, Backpressure turbine, 220 MW feed	
Warm start-up time (hours)	0.5
Cold start-up time (hours)	2.0
Environment	
SO2 (degree of desulphuring, %)	99.8
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	0.1
N2O (g per GJ fuel)	1.0
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	2.21
Fixed O&M ($US/MWe/year)	53,119
Variable O&M ($US/MWh_e)	19.36

Data sheet 09 - Waste, HOP

Waste to Energy, DH only, 35 MW feed	
Energy/technical data	
Heat generating capacity for one unit (MW)	36.9
Total heat efficiency, net (%), ref. LHV, name plate	105.6
Total heat efficiency , net (%), ref. LHV, annual average	105.6
Auxiliary electricity consumption (% of heat gen)	2.6
Forced outage (%)	1
Planned outage (weeks per year)	2.9
Technical lifetime (years)	25
Construction time (years)	2
Space requirement (1000 m2/MWe)	0.54
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	1
Minimum load (% of full load)	70
Warm start-up time (hours)	8
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	99.8
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	0.1
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWth)	2.23
Fixed O&M ($US/MWth/year)	99,583
Variable O&M ($US/MWh_heat output)	9.44

Biomass CHP and HOP plants

Brief technology description

Energy conversion in CHP or HOP (Heat Only Plant) of biomass is the combustion of wood-chips from forestry and/or from wood industry, wood pellets or straw. The main technical differences between the two are the electricity production, which is produced in a CHP but not a HOP, and the resulting necessary operating temperatures.

The typical implementation is combustion in a biomass boiler feeding a steam turbine. The energy output from the boiler is either hot water to be used directly for district heating or it could be (high pressure) steam to be expanded through a turbine. The turbine is either a backpressure – or an extraction turbine.

In the backpressure turbine, the expansion ends in the district heat condensers at a pressure at app. 0.4 bara, in the extraction unit the expansion is extended to the lowest possible pressure app. 0.025 bara, which is provided by a water-cooled condenser. The extraction unit is capable of running both in backpressure and condensing mode as well as every combination in between.

Application of flue gas condensation for further energy recovery is customary at biomass fired boilers using feedstock with high moisture content, e.g. wood chip, except at small plants below 1 - 2 $MW_{th\ input}$ due to the additional capital and O&M costs. Plants without flue gas condensation are typically designed for other biomass fuels with less than 30% moisture content.

Flue gas condensation is however available also for straw firing. The flue gas condensation may raise the efficiency with around 10%-points according to model calculations (at 40°C DH return temperature), representing advances in condensation efficiency and return temperature compared with previous indications of 5-10%.

Straw-fired boilers are normally equipped with a bag filter for flue gas cleaning. Electro filters do not work as efficiently with straw firing as they do with wood firing due to deposits formed by salts in the straw.

Straw fired plants should be equipped with heat accumulation tanks due to their disability to produce at less than 40% of full load, as described under the section “Regulation ability”.

ORC plant

An alternative type of plant is the Organic Rankine Cycle plants (ORC plants). In this the (biomass-) boiler is used for heating (no evaporation) thermal oil to slightly above 300°C. This heated oil transfers the heat to an ORC plant which is similar to a steam cycle but it uses a refrigerant instead of water as working media.

The reason for an interest in ORC plants is that such equipment is delivered in standardized complete modules at an attractive price and in combination with ‘a boiler’ that only is used for heating oil, the investment is relatively modest.

The ORC technology is a waste heat recovery technology developed for low temperature and low-pressure power generation. The ORC unit is a factory assembled module – this makes them less flexible but cheap. This may make it financially attractive to build small scale CHP facilities. The ‘Rankine’ part indicates that it is a technology with similarities to water-steam (Rankine) based systems. The main difference being the use of a media i.e. a refrigerant or silicone oil (an organic compound that can burn but does not explode) with thermodynamic properties that makes it more adequate than water for low temperature power generation.

Input

The fuel input to biomass plants can in general be described as biomass; e.g. residues from wood industries, wood chips (from forestry), straw and energy crops. Combustion can in general be applied for biomass feedstock with average moisture contents up to 60% for wood chips and up to 25% for straw dependent on combustion technology. The three types of biomass feedstock considered here are: Wood chips, wood pellets and straw. They are in several ways very different (humidity, granularity, ash content and composition, grindability, and density).

Sometimes it is possible to change fuel at a plant from one type of biomass to another, but it should be explicitly guaranteed by the supplier of the plant. Below is a broad description of biomass fuels.

Wood (particularly in the form of chips) is usually the most favorable biomass for combustion due to its low content of ash, nitrogen and alkaline metals, however typically with 45 % moisture for chips and below 10% for pellets. Herbaceous biomass like straw, miscanthus and other annual/fast growing crops have higher contents of K, N, Cl, S etc. that lead to higher primary emissions of NO_x and particulates, increased ash generation, corrosion rates and slag deposits.

Forest residues are typically delivered as wood chips. Forest residues may also be delivered as pellets. During pellet production the fuel is dried to moisture content below 10%. Further to this there seems to be a growing interest for utilizing other types of surplus biomass from industrial productions like Vinery, olive oil production, sugar production, and more.

Wood chips are wood pieces of 5-50 mm in the fibre direction, longer twigs (slivers), and a fine fraction (fines). The quality description is based on three types of wood chips: Fine, coarse, and extra coarse. The names refer to the size distribution only, not to the quality. Fine particles as well as thin, long fibres may cause problems (in case the boiler is using grate firing). In the table below can be seen some typical (commercial) requirements for wood chips.

Table 9: General terms and commercial requirements for wood chips

Name	Withhold on sieve	Share w%
Fines	<3 mm	<12
Small	3 < X < 8 mm	<25
Coarse	8 < X < 16 mm	No requirement
Extra coarse	16 < X < 45 mm	No requirement
Over size	45 < X < 63 mm	< 3
Over long 10	> 63 mm	< 6
Over long 20	100-200 mm long	< 1.5

Note: Typical sizes in a sample (refer also to EN ISO 17225-1)

Ash concentrations must not exceed 2% on dry basis.

Wood chips with high moisture content will often be mixed with dry wood chips. Smaller units use grate firing technology when firing wood chips, while some larger units uses a Circulating Fluidized Bed (CFB) or Bubbling Fluidized Bed (BFB) boiler technology.

Other possible fuels are chipped energy crops (e.g. willow and poplar) and chipped park and garden waste. The fuel quality must be in focus. Small particles must be avoided as well as long thin pieces. High moisture content of e.g. willow will increase the level of CO and Particles, so either the willow must be low in moisture content or it must be mixed with other fuels. Willow is known to take up Cadmium from the soil and thus increasing the concentrations in ash. The amount of cadmium uptake is depending on where the willow is grown. Poplar has been found to give problems in the boiler like “popcorn” in a combustion test. Chipped Park and garden waste must be of a good quality with low content of non-combustible materials, because of risks of blocking the grate. Difficult biomass residues are therefore often utilized in WtE facilities having available capacity.

Wood pellets are made from wood chips, sawdust, wood shavings and other residues from sawmills and other wood manufacturers. Pellets are produced in several types and grades as fuels for electric power plants and DH (low grade), and residential homes (high grade). Pellets are extremely dense (up to the double of the density of the basic material) and can be produced with a low humidity content (below 5% for high grade products) that allows easy handling (incl. long-term storage) and to be burned with high combustion efficiencies. When humidified, pellets are prone to auto-ignition. When exposed to mechanical treatment like conveyer transportation the pellets may break (or disintegrate) and release dust; this dust is highly explosive and therefore constitute a serious hazard. Plants using wood pellets or –chips must ensure the sustainability of the fuel. Both the disintegration of wood chips in hammer mills and the subsequent drying require energy and this must come from non-fossil sources (e.g. the wood itself). Wood pellets are fired in larger CHP's with modified coal burners and mills. Coal ash is generally co-fired with wood pellets by adding an amount of around 5% of the feed in order to absorb alkali metals and sulfur from the flue gas. Coal ash has a good effect on minimising the slagging and fouling tendency as well as on the SCR catalyst efficiency and lifetime.

Straw is a by-product from the growing of commercial crops, in Northern Europe primarily cereal grain, rape and other seed-producing crops. Straw is often delivered as big rectangular bales (Hesston bales), typically approx. 500 - 750 kg each, or MIDI bales (400 - 800 kg each) from storages at the farms to the DH plants etc. during the year pursuant to concluded straw delivery contracts. MIDI bales are smaller, so transportation can be with 3 layers. However, the density is higher. Not all plants have a system to handle these bales.

Output

The products from biomass CHP plants are electricity and heat as steam, hot (> 110°C) or warm (< 110°C) water as district heat.

The output from biomass HOP is hot water for district heat or low-pressure steam for industrial purposes. The total energy efficiency is identical for heat and CHP plants, except that some minor heat losses in the generator and turbine gearbox of the CHP plant are avoided. The heat production from a HOP is thus identical (or slightly higher) than the sum of produced electricity and heat from an equivalent CHP plant.

In case of flue gas condensation, excess condensate may be upgraded to high quality water useful for technical purposes such as boiler water or for covering water losses of the district-heating network.

Typical capacities

Large scale CHP: > 100 MW$_{th\ input}$ (~> 25 MW$_{e}$)

Medium scale CHP: 25 - 100 MW$_{th\ input}$ (~ 6 - 25 MW$_{e}$)

Small scale CHP: 1 – 25 MW$_{th\ input}$ (~ 0.1 - 6 MW$_{e}$)

The capacities of CHP's supplying heat to district heating systems are primarily determined by the heat demands. Most plants are equipped with a facility to by-pass the turbine temporarily to increase the heat production at the expense of losing the electricity production; the by-pass is in use more often than it was 10-20 years ago.

For biomass HOP's the typical capacities are 1 - 50 MW$_{th\ input}$.

Regulation ability

The CHP's can operate in a large range (20% to 100% for once-through suspension fired boilers). Biomass plants with drum type boilers (typical for grate fired boilers) can be operated in the range from 40 - 100% load.

The lower end of the range is defined by the ability to generate super-heated steam at the required temperature to operate the turbine and obtain reasonable electricity efficiency. For heat production only, the boiler could go to lower load. The CHP-range is likely to broaden slightly in the future, but the technology appears to have limitations.

Large plants may be designed for optional operation in pure electrical mode (condensing mode) with slightly higher electrical efficiency but without heat production. The condensing ability is mainly seen in large plants over 130 MW$_{th\ input}$ and primarily used today for large Pulverized Fuel (PF) plants.

CHP's, with and without extraction, are capable of supplying both primary and secondary load support. Though somewhat slower than coal fired PF plants of comparable sizes.

Typical wood fired HOP’s are regulated 25 - 100% of full capacity. The best technologies can be regulated 10 - 120% with fuel not exceeding 35% moisture content.

Straw fired HOP’s should not be operated below approx. 40% of full load due to emission standards. Straw fired plants should accordingly be equipped with a heat accumulating tank allowing for optimal operational conditions.

Advantages/disadvantages

Extraction units have the possibility to optimize the power-production when the market calls for it i.e. when the power prize is high. Additional power can be produced, especially in the warmer periods when the need for heat is low.

Some biomass resources, in particular straw, contain highly corrosive components such as chlorine which together with potassium forms deposits that are both corrosive and limits heat uptake. In order to avoid or reduce the risk of slagging and corrosion, boiler manufacturers have traditionally abstained from using similar steam pressure/temperatures in biomass-fired plants as in coal-fired plants. However, advances in materials and boiler design have enabled the newest plants to deliver fairly high steam data and power efficiencies. Straw fired boilers can be operated up to 540°C and wood fired boilers up to slightly above 560°C. In most cases the technical limits are somewhat above what is economically feasible. The availability of suited steam turbines might limit the steam temperature for smaller sized plants.

Space requirements

Generally, in this chapter, all the investigated biomass plants are designed and priced with a small fuel storage facility. Typically, it is sized to last for two days of full load operation. The size of the storage has for some fuels a major impact on the totally required space (area) and it also can have a serious impact on the total CAPEX; to avoid this influence the store is kept small. In order to calculate CAPEX for a different size of the store, the tables contain an entry called ‘Fuel storage specific cost in excess of 2 days (MUS/MW_{th\ input}$/storage day) for biomass fuels.

The area to be used for the buildings containing the process equipment is estimated in various ways. Very little additional area is added, say for administration, canteen, garages, work shop, etc. independent of the size of the plant. Further to this, some additional area to be used for other fuel handling, maneuvering and weighing of trucks, parking of vehicles, roads and other free area. In total, it is ensured to have a reasonable percentage of area usage.

The largest plants (wood chips and pellets) are so large that a harbor facility is most appropriate, which is a significant cost addition. This element is not included neither in space requirements nor in cost in the data tables. Other infrastructure facilities like a railroad for fuel transport are not considered.

Extraction units will, compared to backpressure units, require additional space for extra heaters, condenser and cooling-water channels and/or pipes.

Environment

The main ecological footprints from biomass combustion are persistent toxicity, climate change (GHG potential), and acidification. However, the footprints are considered small. It is, however, an area of both major concern and discussion. Further to this is also added a concern on the sustainability of using in particular wood-like biomasses for power production. It is not the intent of this catalogue to initiate such a discussion but merely to mention that biomass fuelled plants can reduce GHG emissions considerably compared to fossil fuel fired plants, but it is still discussed if it resource-wise globally is a viable long term solution.

Modern flue gas cleaning systems will typically include the following processes: DeNO$_x$ - ammonia injection (SNCR) or catalytic (SCR), SO$_2$ capture by injection of lime or the use of another SO$_2$ absorbing system, dust abatement by bag house filters.

NO_x emissions may be reduced, by about 60 - 70%, by selective non-catalytic reduction (SNCR) on wood chips fired boilers and 30-40% on straw fired boilers. NO_x emission may be reduced by 80 - 90% by selective catalyst (SCR). SNCR is a relatively low-cost solution but it is not necessarily applicable for a boiler subject to large load variations and constructed with high cooling rates and super heaters in the area most suitable for ammonia injection. The SCR solution requires installation of a catalyst which can be either a high temperature location near or in the boiler (downstream a particle filter) or it could be a much more expensive tail-end solution requiring re-heat of the flue gas. For fuels with high alkali-metal concentrations (mainly potassium) tail end solution is preferred to avoid poisoning of the catalyst that could quickly reduce its activity, however some plants with high-dust SCR can utilize these fuels provided they are mixed with other fuels with low alkali metal content.

Due to the cost of the catalyst SCR is used mainly at large facilities. NO_x emission limit values are also lower for large facilities, giving further incentive to use SCR. SCR is rarely used in HOP because of their relatively small size, and their ability to reach below the NO_x emission limit values without using SCR.

The limit values for NO_x emissions are expected to be gradually tightened over time in the future. The technology in terms of combustion control, boiler design and improvements in the SNCR technology may relieve the need of SCR, but the application of SCR is nonetheless expected to increase in the future.

This is reflected in the datasheets by adding the cost of a tail-end $DeNO_x$ to the medium (and larger) plants at a certain point in the future. Application of SCR in the respective scenarios appears from the notes.

Desulfurization is not a big issue for wood firing because of the low sulfur content in the fuel. A typical sulfur content in wood is 0.04 g/GJ (dry basis) which has been used in the tables, and the generated SO_2 is to a large extent taken together with the ash and other pollutants (e.g. HCl and mercury) by particle filters in combination with flue gas condensation. On that basis it is expected that most plants yield a very low SO_2 emission of up to 2 g/GJ. Plants will be built without wet-scrubbers which have the sole purpose of cleaning the flue gas, because they are not needed for fulfilling environmental requirements. In addition, the scrubbers would barely generate any gypsum due to the low sulfur content. If the plant does not include a flue gas condenser, the sulfur dioxide is expected to be captured in the bag filter, in a dry process, when injecting a small amount of hydrated lime. In a plant with a flue gas condenser the majority of sulfur dioxide will be captured here. The flue gas condenser can act as a wet scrubber when adding lime or sodium hydroxide to the circulating water.

Future plants above a certain capacity are required to have monitoring of air emissions of mercury, Hg.

Generally, Hg is not a problem in straw fired units since Hg is oxidized by the chlorine in fuel and captured in the bag filter. Wood fired units might have a challenge with Hg if fired with woodchips from certain regions and only cleaning the flue gases with an electrostatic precipitator, ESP.

Biomass units produce 4 (four) sorts of residues: Flue gas, fly ash, bottom ash and possibly condensate from flue gas condensation.

All bottom ash and most fly ash from straw firing is recycled to farmland as a fertilizer.

Often ash from wood firing is deposited in landfills and some bottom ash is used as fertilizer. Research is ongoing on how to meet environmental acceptance limits for recycling the ash to forests. Bottom ash with relatively high content of cadmium cannot be used as fertilizer. Coal ash, if used as an additive, will make it impossible to use the ash as fertilizer, but opens the possibility to be used as coal ash in cement and concrete production.

The condensate water from wood firing is usually treated to remove heavy metals, particularly cadmium, so that its content reaches 3 milligrams per m^3, or the level required for its discharge, which is usually the local municipal sewage system. The treatment may involve pH-adjustment, addition of polymers and flocculants and the use of belt filters for separation of the generated sludge. The treatment residue (sludge) must be deposited in a safe landfill.

Condensate from straw-firing may be clean enough to be expelled without cleaning, since almost all cadmium is withheld with the fly ash in the bag filter.

Data sheets for biomass plants

Data for biomass plants is presented in the following. First, data for the CHP's is presented.

Large backpressure units are shown with two different temperature sets (return- and forward temperature of the district heating network):

- 40/80°C – corresponding to a plant connected to the distribution network
- 50/100°C – corresponding to a plant connected to the transmission network

Furthermore, data for large extraction plants fuelled by wood chips and wood pellets is presented. Lastly, data for HOP plants is shown.

The total efficiency of plants with flue gas condensation is calculated assuming "direct condensation", where the condensation heat is recovered directly with the available DH water without the use of heat pumps.

Condensation heat recovery can be augmented by cooling the flue gas further, typically to 30°C using heat pumps. In the datasheets, the row "Additional heat potential for heat pump (%)" contains the additional heat that a heat pump would recover from the flue gas by cooling it further to 30°C. The so produced additional heat is the sum of this recovered amount of heat and any external driving energy (electricity or steam) supplied to drive the heat pump.

Data sheet 10 - Wood Chips CHP, small

Small Wood Chips CHP, 20 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	2.9
Electricity efficiency, net (%), name plate	14.7
Electricity efficiency, net (%), annual average	13.9
Auxiliary electricity consumption (% of thermal input)	2.7
Cb coefficient (40°C/80°C)	0.15
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	1
Space requirement (1000 m2/MWe)	0.7
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10
Minimum load (% of full load)	20
Warm start-up time (hours)	0.25
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	10
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.13

Small Wood Chips CHP, 20 MW feed	
Fixed O&M ($US/MWe/year)	49,852
Variable O&M ($US/MWh_e)	1.69

Data sheet 11 - Wood Chips CHP, medium

Medium Wood Chips CHP, 80 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	23.8
Electricity efficiency, net (%), name plate	29.7
Electricity efficiency, net (%), annual average	28.2
Auxiliary electricity consumption (% of thermal input)	3.0
Cb coefficient (40°C/80°C)	0.37
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	2.5
Space requirement (1000 m2/MWe)	0.21
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	4
Minimum load (% of full load)	20
Warm start-up time (hours)	2
Cold start-up time (hours)	8
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	2
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.27
Fixed O&M ($US/MWe/year)	53,724
Variable O&M ($US/MWh_e)	1.57

Data sheet 12 - Wood Chips CHP, large, 40/80°C return/forward temperature

Large Wood Chips CHP, 600 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	182.6
Electricity efficiency, net (%), name plate	30.4
Electricity efficiency, net (%), annual average	28.9
Auxiliary electricity consumption (% of thermal input)	2.9
Cb coefficient (40°C/80°C)	0.37
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.08
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4

Large Wood Chips CHP, 600 MW feed	
Minimum load (% of full load)	45
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	20
CH4 (g per GJ fuel)	2
N2O (g per GJ fuel)	8
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.21
Fixed O&M ($US/MWe/year)	34,848
Variable O&M ($US/MWh_e)	1.57

Data sheet 13 - Wood Chips CHP, large, 50/100°C return/forward temperature

Large Wood Chips CHP, 600 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	169.8
Electricity efficiency, net (%), name plate	28.3
Electricity efficiency, net (%), annual average	26.9
Auxiliary electricity consumption (% of thermal input)	3.0
Cb coefficient (50°C/100°C)	0.35
Cv coefficient (50°C/100°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.09
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4
Minimum load (% of full load)	45
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	20
CH4 (g per GJ fuel)	2
N2O (g per GJ fuel)	8
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.21
Fixed O&M ($US/MWe/year)	34,848
Variable O&M ($US/MWh_e)	1.57

Data sheet 14 - Wood Chips CHP, large, extraction

Large Wood Chips CHP, 600 MW feed, Extraction	
Energy/technical data	
Generating capacity for one unit (MWe)	257.7
Electricity efficiency, net (%), name plate	43
Electricity efficiency, net (%), annual average	40.8

Large Wood Chips CHP, 600 MW feed, Extraction	
Cb coefficient (50°C/100°C)	0.44
Cv coefficient (50°C/100°C)	0.14
Forced outage (%)	3
Planned outage (weeks per year)	3
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.06
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4
Minimum load (% of full load)	45
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	97.5
NOX (g per GJ fuel)	30
CH4 (g per GJ fuel)	3
N2O (g per GJ fuel)	10
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.33
Fixed O&M ($US/MWe/year)	36,542
Variable O&M ($US/MWh_e)	1.34

Data sheet 15 - Wood Pellets CHP, small

Small Wood Pellets CHP, 20 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	3.1
Electricity efficiency, net (%), name plate	15.4
Electricity efficiency, net (%), annual average	14.6
Auxiliary electricity consumption (% of thermal input)	2.3
Cb coefficient (40°C/80°C)	0.18
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	1
Space requirement (1000 m2/MWe)	0.5
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10
Minimum load (% of full load)	20
Warm start-up time (hours)	0.25
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	98.3
NOX (g per GJ fuel)	50
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.13

Small Wood Pellets CHP, 20 MW feed	
Fixed O&M ($US/MWe/year)	50,457
Variable O&M ($US/MWh_e)	0.73

Data sheet 16 - Wood Pellets CHP, medium

Medium Wood Pellets CHP, 80 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	24.7
Electricity efficiency, net (%), name plate	30.8
Electricity efficiency, net (%), annual average	29.3
Auxiliary electricity consumption (% of thermal input)	2.5
Cb coefficient (40°C/80°C)	0.46
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	2.5
Space requirement (1000 m2/MWe)	0.18
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10
Minimum load (% of full load)	15
Warm start-up time (hours)	0.25
Cold start-up time (hours)	8
Environment	
SO2 (degree of desulphuring, %)	98.3
NOX (g per GJ fuel)	50
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.13
Fixed O&M ($US/MWe/year)	46,343
Variable O&M ($US/MWh_e)	0.69

Data sheet 17 - Wood Pellets CHP, large, 40/80°C return/forward temperature

Large Wood Pellets CHP, 800 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	268.1
Electricity efficiency, net (%), name plate	33.5
Electricity efficiency, net (%), annual average	31.8
Auxiliary electricity consumption (% of thermal input)	3.3
Cb coefficient (40°C/80°C)	0.51
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.06
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4

Large Wood Pellets CHP, 800 MW feed	
Minimum load (% of full load)	15
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	98.3
NOX (g per GJ fuel)	20
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	0.91
Fixed O&M ($US/MWe/year)	25,289
Variable O&M ($US/MWh_e)	0.68

Data sheet 18 - Wood Pellets CHP, large, 50/100°C return/forward temperature

Large Wood Pellets CHP, 800 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	253.4
Electricity efficiency, net (%), name plate	31.7
Electricity efficiency, net (%), annual average	30.1
Auxiliary electricity consumption (% of thermal input)	3.3
Cb coefficient (50°C/100°C)	0.49
Cv coefficient (50°C/100°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.06
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4
Minimum load (% of full load)	15
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	98.3
NOX (g per GJ fuel)	20
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	0.91
Fixed O&M ($US/MWe/year)	25,289
Variable O&M ($US/MWh_e)	0.67

Data sheet 19 - Wood Pellets CHP, large, extraction

Large Wood Pellets CHP, 800 MW feed, Extraction	
Energy/technical data	
Generating capacity for one unit (MWe)	357.6
Electricity efficiency, net (%), name plate	44.7
Electricity efficiency, net (%), annual average	42.5

Large Wood Pellets CHP, 800 MW feed, Extraction	
Cb coefficient (50°C/100°C)	0.59
Cv coefficient (50°C/100°C)	0.17
Forced outage (%)	3
Planned outage (weeks per year)	3
Technical lifetime (years)	25
Construction time (years)	5
Space requirement (1000 m2/MWe)	0.04
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4
Minimum load (% of full load)	15
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Environment	
SO2 (degree of desulphuring, %)	97.5
NOX (g per GJ fuel)	20
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.20
Fixed O&M ($US/MWe/year)	29,766
Variable O&M ($US/MWh_e)	0.62

Data sheet 20 - Straw CHP, small

Small Straw CHP, 20 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	3.0
Electricity efficiency, net (%), name plate	15.2
Electricity efficiency, net (%), annual average	14.5
Auxiliary electricity consumption (% of thermal input)	2.4
Cb coefficient (40°C/80°C)	0.18
Cv coefficient (40°C/80°C)	1
Forced outage (%)	4
Planned outage (weeks per year)	4.0
Technical lifetime (years)	25
Construction time (years)	1
Space requirement (1000 m2/MWe)	1.0
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10
Minimum load (% of full load)	50
Warm start-up time (hours)	0.25
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	96.4
NOX (g per GJ fuel)	70
CH4 (g per GJ fuel)	11
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.23

Small Straw CHP, 20 MW feed	
Fixed O&M ($US/MWe/year)	57,717
Variable O&M ($US/MWh_e)	0.83

Data sheet 21 - Straw CHP, medium

Medium Straw CHP, 80 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	25.3
Electricity efficiency, net (%), name plate	31.6
Electricity efficiency, net (%), annual average	30.0
Auxiliary electricity consumption (% of thermal input)	2.8
Cb coefficient (40°C/80°C)	0.46
Cv coefficient (40°C/80°C)	1
Forced outage (%)	4
Planned outage (weeks per year)	4.0
Technical lifetime (years)	25
Construction time (years)	2.5
Space requirement (1000 m2/MWe)	0.3
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	4
Minimum load (% of full load)	40
Warm start-up time (hours)	2
Cold start-up time (hours)	8
Environment	
SO2 (degree of desulphuring, %)	96.4
NOX (g per GJ fuel)	70
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.37
Fixed O&M ($US/MWe/year)	54,692
Variable O&M ($US/MWh_e)	0.80

Data sheet 22 - Straw CHP, large, 40/80°C return/forward temperature

Large Straw CHP, 132 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	41.6
Electricity efficiency, net (%), name plate	31.5
Electricity efficiency, net (%), annual average	29.9
Auxiliary electricity consumption (% of thermal input)	2.8
Cb coefficient (40°C/80°C)	0.45
Cv coefficient (40°C/80°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	3
Space requirement (1000 m2/MWe)	0.2
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4

Large Straw CHP, 132 MW feed	
Minimum load (% of full load)	40
Warm start-up time (hours)	2
Cold start-up time (hours)	8
Environment	
SO2 (degree of desulphuring, %)	96.4
NOX (g per GJ fuel)	30
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.29
Fixed O&M ($US/MWe/year)	46,585
Variable O&M ($US/MWh_e)	0.80

Data sheet 23 - Straw CHP, large, 50/100°C return/forward temperature

Large Straw CHP, 132 MW feed	
Energy/technical data	
Generating capacity for one unit (MWe)	39.0
Electricity efficiency, net (%), name plate	29.5
Electricity efficiency, net (%), annual average	28.1
Auxiliary electricity consumption (% of thermal input)	2.9
Cb coefficient (50°C/100°C)	0.43
Cv coefficient (50°C/100°C)	1
Forced outage (%)	3
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25
Construction time (years)	3
Space requirement (1000 m2/MWe)	0.3
Regulation ability	
Primary regulation (% per 30 seconds)	2
Secondary regulation (% per minute)	4
Minimum load (% of full load)	40
Warm start-up time (hours)	2
Cold start-up time (hours)	8
Environment	
SO2 (degree of desulphuring, %)	96.4
NOX (g per GJ fuel)	30
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWe)	1.29
Fixed O&M ($US/MWe/year)	46,585
Variable O&M ($US/MWh_e)	0.76

Data sheet 24 - Wood Chips, HOP, Small

Wood Chips, DH-Small, 6 MW feed	
Energy/technical data	
Heat generation capacity for one unit (MW)	6.8
Total efficiency, net (%), name plate	114.0
Total efficiency, net (%), annual average	114.0

Wood Chips, DH-Small, 6 MW feed	
Auxiliary electricity consumption (% of heat gen)	2.2
Forced outage (%)	3.0
Planned outage (weeks per year)	2.0
Technical lifetime (years)	25.0
Construction time (years)	1.0
Space requirement (1000 m2/MWth heat output)	0.2
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	20
Warm start-up time (hours)	0.3
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	11
N2O (g per GJ fuel)	3
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWth - heat output)	0.96
Fixed O&M ($US/MWth/year), heat output	44,891
Variable O&M ($US/MWh) heat output	3.75

Data sheet 25 - Wood Chips, HOP, Medium

Wood Chips, DH-Medium, 45 MW feed	
Energy/technical data	
Heat generation capacity for one unit (MW)	51.6
Total efficiency, net (%), name plate	114.8
Total efficiency, net (%), annual average	114.8
Auxiliary electricity consumption (% of heat gen)	2.2
Forced outage (%)	3.0
Planned outage (weeks per year)	2.0
Technical lifetime (years)	25.0
Construction time (years)	2.0
Space requirement (1000 m2/MWth heat output)	0.06
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	40
Warm start-up time (hours)	2.0
Cold start-up time (hours)	8.0
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	11
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWth - heat output)	0.81
Fixed O&M ($US/MWth/year), heat output	58,322
Variable O&M ($US/MWh) heat output	3.75

Data sheet 26 - Wood Chips, HOP, Large

Wood Chips, DH-Large, 90 MW feed	
Energy/technical data	
Heat generation capacity for one unit (MW)	103.4
Total efficiency, net (%), name plate	114.9
Total efficiency, net (%), annual average	114.9
Auxiliary electricity consumption (% of heat gen)	2.2
Forced outage (%)	3.0
Planned outage (weeks per year)	2.0
Technical lifetime (years)	25.0
Construction time (years)	2.5
Space requirement (1000 m2/MWth heat output)	0.05
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	40
Warm start-up time (hours)	2.0
Cold start-up time (hours)	8.0
Environment	
SO2 (degree of desulphuring, %)	98.0
NOX (g per GJ fuel)	60
CH4 (g per GJ fuel)	2
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWth - heat output)	0.61
Fixed O&M ($US/MWth/year), heat output	48,037
Variable O&M ($US/MWh) heat output	3.75

Data sheet 27 - Wood Pellets, HOP

Wood Pellets, DH only, 6 MW feed	
Energy/technical data	
Heat generation capacity for one unit (MW)	6.1
Total efficiency, net (%), name plate	101.4
Total efficiency, net (%), annual average	101.4
Auxiliary electricity consumption (% of heat gen)	2.1
Forced outage (%)	3.0
Planned outage (weeks per year)	3.0
Technical lifetime (years)	25.0
Construction time (years)	1.0
Space requirement (1000 m2/MWth heat output)	0.2
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	40.0
Warm start-up time (hours)	0.3
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	98.3
NOX (g per GJ fuel)	50
CH4 (g per GJ fuel)	0
N2O (g per GJ fuel)	1
Particles (g per GJ fuel)	0.3

Wood Pellets, DH only, 6 MW feed	
Financial data	
Nominal investment (M$US/MWth - heat output)	0.87
Fixed O&M ($US/MWth/year), heat output	40,051
Variable O&M ($US/MWh) heat output	2.40

Data sheet 28 - Straw, HOP

Small Straw, DH only, 6 MW feed	
Energy/technical data	
Heat generation capacity for one unit (MW)	6.2
Total efficiency, net (%), name plate	103.2
Total efficiency, net (%), annual average	103.2
Auxiliary electricity consumption (% of heat gen)	2.1
Forced outage (%)	4.0
Planned outage (weeks per year)	4.0
Technical lifetime (years)	25.0
Construction time (years)	1.0
Space requirement (1000 m2/MWth heat output)	0.2
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	10.0
Minimum load (% of full load)	50.0
Warm start-up time (hours)	0.3
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphuring, %)	96.4
NOX (g per GJ fuel)	70
CH4 (g per GJ fuel)	11
N2O (g per GJ fuel)	3
Particles (g per GJ fuel)	0.3
Financial data	
Nominal investment (M$US/MWth - heat output)	1.09
Fixed O&M ($US/MWth/year), heat output	63,404
Variable O&M ($US/MWh) heat output	2.64

Stirling engines, gasified biomass

This chapter has been moved here from the previous Technology Data Catalogue for Electricity and district heating production from May 2012. Therefore, the text and data sheets do not follow the same guidelines as the remainder of the catalogue.

Brief technology description

A Stirling engine is driven by temperature differences created by external heating and cooling sources. One part of the engine is permanently hot, while another part of the engine is permanently cold.

The engine is filled with a working gas, typically Hydrogen or Helium, and pressurized. This working gas is moved between the hot and the cold side of the engine by a mechanical system comprising of a displacement piston coupled to a working piston. When the working gas is heated in the hot side of the engine, it expands and pushes the working piston. When the working piston moves, the displacement piston then forces the working gas to the cold side of the engine, where it cools and contracts.

In the biomass-gasifier solution developed by the company Stirling DK, the engine is Helium-filled, heated by biomass combustion flue gasses, and cooled by cooling water.

Specifically, a solid biomass fuel is converted into producer gas, which is led to one or more combustion chambers, each coupled to a Stirling engine. The gas is ignited in the combustion chamber(s), and the flue gases are heating the Stirling engine(s), which is driving an electricity generator.

Input

Wood chips, industrial wood residues, demolition wood and energy crops can be used. Also, it is expected that more exotic fuel types, such as coconut shells and olive stones, can be used. Requirements to moisture content and size of the fuel are depending on the design of the gasifier.

The Stirling engines can also be fuelled by natural gas and mineral oil.

Output

Electricity and heat.

The electricity efficiency, when using wood chips, is around 18%.

Typical capacities

The electric output of one Stirling engine is 35 kW. For plants with several engines, one common gasifier is used.

Regulation ability

The heat load can be changed from 10 to 100 % and vice versa within a few minutes. The electrical output can not be regulated quickly.

Advantages/disadvantages

The main advantage of the Stirling engine is that it can generate power using residues from forestry and agriculture, which typically have a very low economic value. In addition, emission levels are very low. Finally, the service requirement of a Stirling engine is very low compared to otto- and diesel-engines.

The main disadvantage is a relatively high capital cost compared to otto- and diesel-engines.

Stirling engines are therefore ideally used for base load generation with many annual operating hours, preferable 6 - 8,000 hours/year.

Environment

A highly controlled gasification process together with the continuous combustion process secure much lower air emissions than otto- and diesel-engines.

Data sheet 29 - Stirling engine, gasified biomass

Stirling engine, fired by gasified biomass	
Energy/technical data	
Generating capacity electric, (kW)	40
Generating capacity heat, (kJ7s)	120
Electrical efficiency (%)	22
Time for warm-up (hours)	1
Forced outage (%)	2
Planned outage (weeks per year)	3
Technical lifetime (years)	15
Construction time (years)	0.3
Environment	
SO2 (degree of desulphuring, %)	0
NOX (ppm)	100
CH4 (ppm)	0
N2O (ppm)	0
Financial data	
Specific investment costs (($US/MW)	4.6
Fixed O&M ($US/MW/year)	38,720
Variable O&M ($US/MWh)	25.41

Wind Turbines onshore

Brief technology description

The typical large onshore wind turbine being installed today is a horizontal-axis, three bladed, upwind, grid connected turbine using active pitch, variable speed and yaw control to optimize generation at varying wind speeds.

Wind turbines work by capturing the kinetic energy in the wind with the rotor blades and transferring it to the drive shaft. The drive shaft is connected either to a speed-increasing gearbox coupled with a medium- or high-speed generator, or to a low-speed, direct-drive generator. The generator converts the rotational energy of the shaft into electrical energy. In modern wind turbines, the pitch of the rotor blades is controlled to maximize power production at low wind speeds, and to maintain a constant power output and limit the mechanical stress and loads on the turbine at high wind speeds. A general description of the turbine technology and electrical system, using a geared turbine as an example, can be seen in below figure.

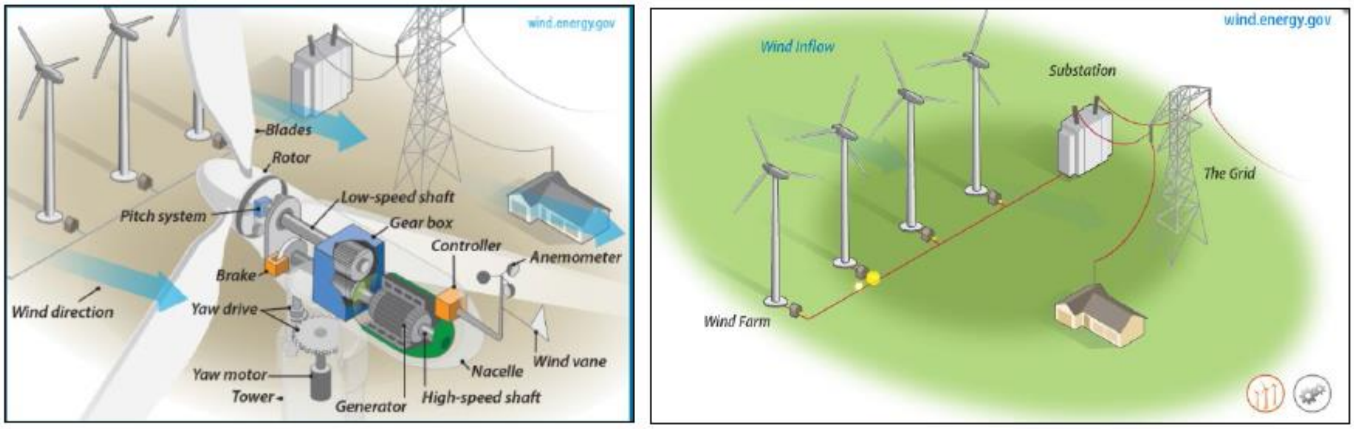

Figure 14: General turbine technology and electrical system

Wind turbines are designed to operate within a wind speed range which is bounded by a low “cut-in” wind speed and a high “cut-out” wind speed. When the wind speed is below the cut-in speed the energy in the wind is too low to be utilized. When the wind reaches the cut-in speed, the turbine begins to operate and produce electricity. As the wind speed increases, the power output of the turbine increases, and at a certain wind speed the turbine reaches its rated power. At higher wind speeds, the blade pitch is controlled to maintain the rated power output. When the wind speed reaches the cut-out speed, the turbine is shut down or operated in a reduced power mode to prevent mechanical damage.

Onshore wind turbines can be installed as single turbines, clusters or in larger wind farms.

Commercial wind turbines are operated unattended and are monitored and controlled by a supervisory control and data acquisition (SCADA) system.

Input

Input is wind.

Cut-in wind speed: 3 – 4 m/s.

Rated power generation wind speed: 10-12 m/s, depending on the specific power (defined as the ratio of the rated power to the swept rotor area).

Cut-out or transition to reduced power operation at wind speed: 25 m/s.

In the future, it is expected that manufacturers will apply a soft cut-out for high wind speeds (indicated with dashed red curve in below figure) resulting in a final cut-out wind speed around 30 m/s.

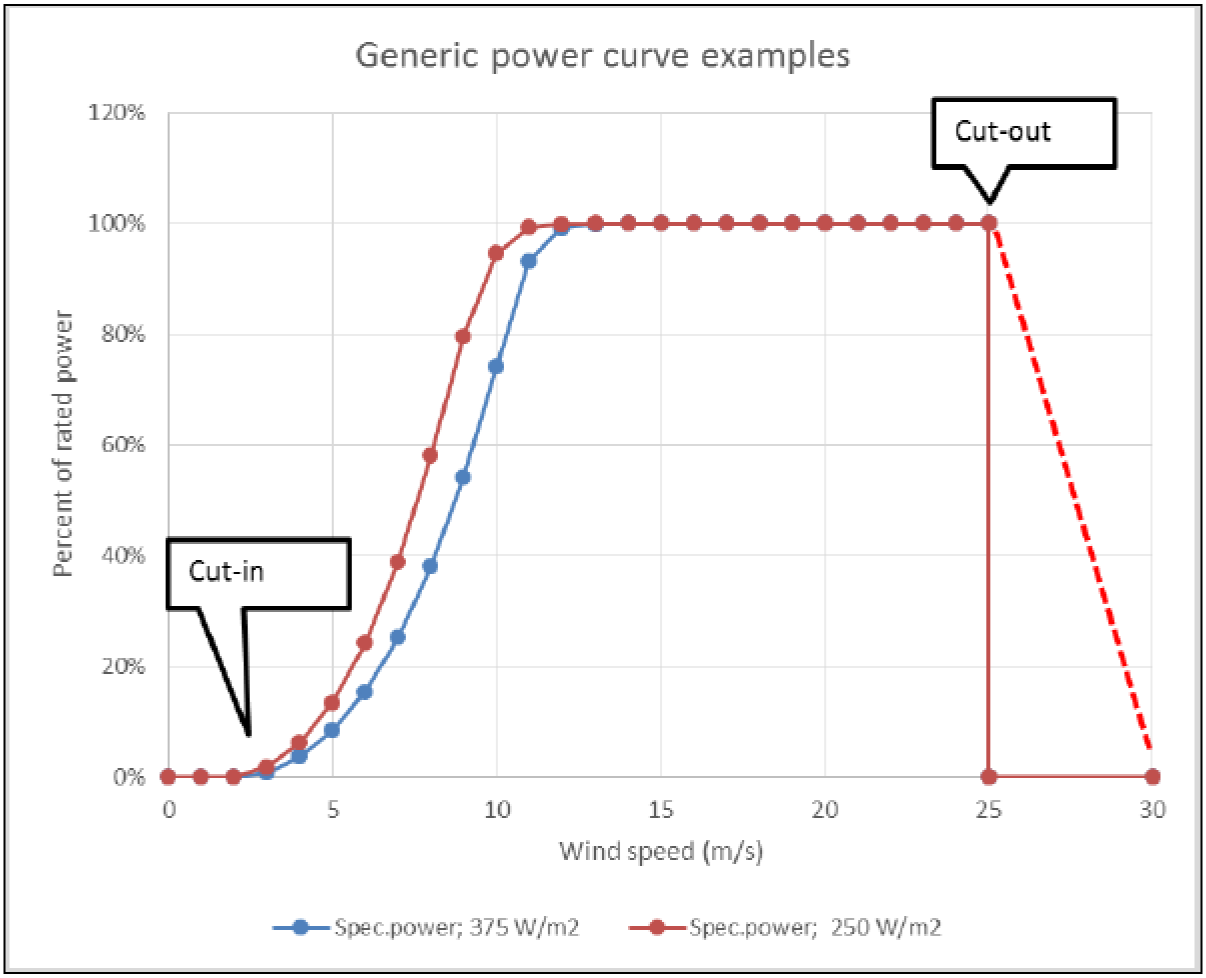

Figure 15: Turbine power curves. Specific power values refer to e.g. 3 MW with 124m rotor diameter (250 W/m2) and 3 MW with 101 m rotor diameter (375 W/m2)

The power in the wind is given by the formula P = ½*rho*A*u^3, where rho is the air density, A the swept area and u the wind speed. To calculate the net power output from a wind turbine, the result must be multiplied by C_p (Coefficient of power). C_p varies with wind speed and has a maximum of around 45%, which is typically reached at ~8 m/s, depending on the specific power.

Output

The output is electricity.

The annual energy output of a wind turbine is strongly dependent on the average wind speed at the turbine location. The average wind speed depends on the geographical location, the hub height, and the surface roughness. Hills and mountains also affect the wind flow. Also, local obstacles like forest and for small turbines buildings and hedges reduce the wind speed like wakes from neighbor turbines reduces.

The surface roughness is normally classified according to the following table:

Table 10: Description of classification of surface roughness

Roughness class	Roughness length[2] (m)	Description
0	0.0002	Water
1	0.03	Open farmland
2	0.1	Partly open farmland with some settlements and trees
3	0.4	Forest, cities, farmland with many windbreaks

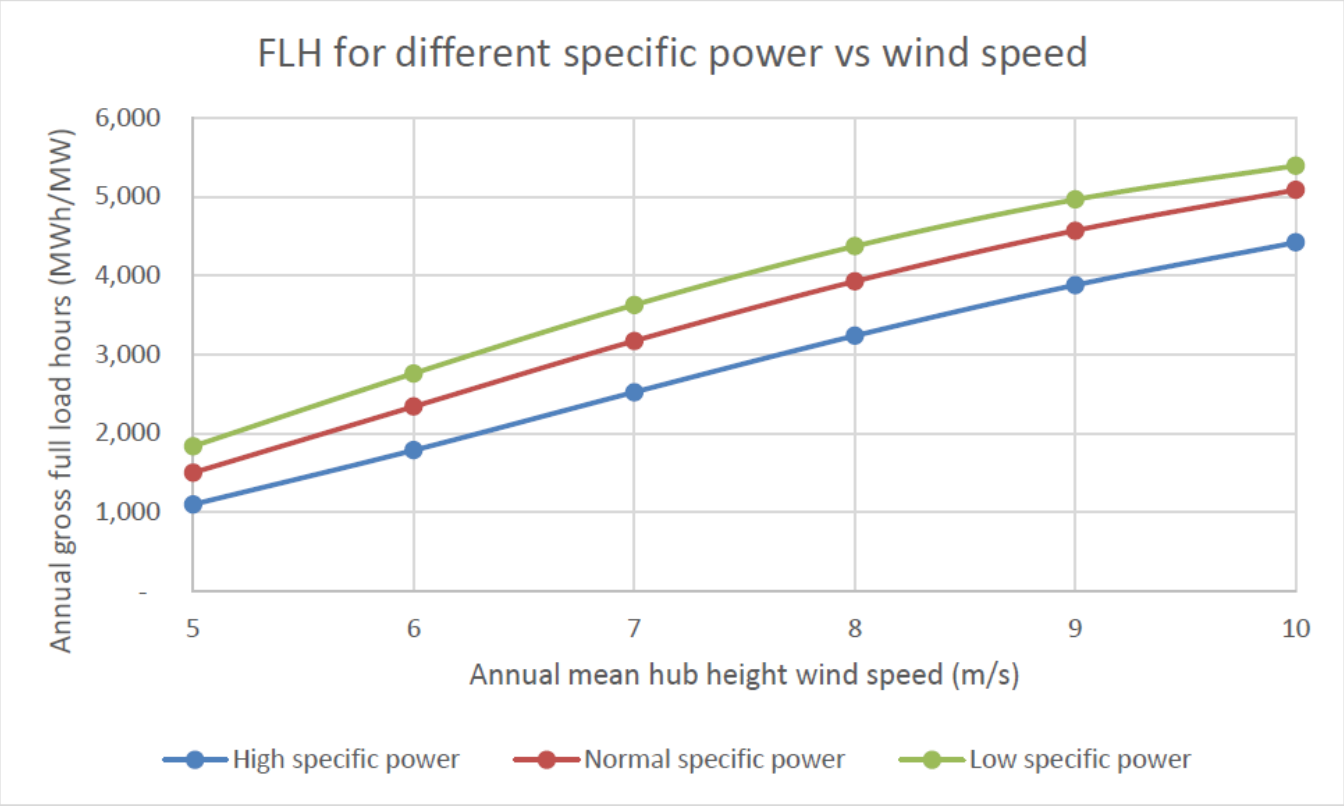

Figure 16: Annual full load hours as a function of mean wind speed at hub height. The examples in the figure are 3 MW with 90m rotor diameter, specific powers are 472 W/m2 called "high specific power" and 3.3 MW turbines with 112 m and 126 m rotor diameters, specific powers are 335 W/m2 called "medium specific power" and 265 W/m2 called "low specific power".

The above figure illustrates the importance of the annual mean wind speed as well as the specific power for the annual energy production (AEP). It is seen that the increase in AEP is almost linear with mean wind speed in the range from 6 m/s to 9 m/s. Future turbines are expected to have even lower specific power than the "low" example in above figure.

Typical capacities and development statistics

Onshore wind turbines can be categorized according to nameplate capacity. At the present time new installations are in the range of 2 to 6 MW. Another category is domestic wind turbines which is micro and small wind turbine in the range of 1 - 25 kW.

Two primary design parameters define the overall production capacity of a wind turbine. At lower wind speeds, the electricity production is a function of the swept area of the turbine rotor. At higher wind

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[2] The roughness length is the height above ground level, where average wind speed is 0. The wind speed variation with height is governed by the roughness length.

speeds, the power rating of the generator defines the power output. The interrelationship between the mechanical and electrical characteristics and their costs determines the optimal turbine design for a given site.

The size of wind turbines has increased steadily over the years. Larger generators, larger hub heights and larger rotors have all contributed to increase the electricity generation from wind turbines. Lower specific capacity (increasing the size of the rotor area more than proportionally to the increase in generator rating) improves the capacity factor (energy production per generator capacity), since power output at wind speeds below rated power is directly proportional to the swept area of the rotor. Furthermore, the larger hub heights of larger turbines provide higher wind resources in general.

The average rated power of new onshore wind turbines has increased by a factor of three since year 2000 (see figure below). Although project developers consider larger turbines to be the most attractive, the increase in rated power is not constant, partly because some older projects with smaller turbines have been expanded with more (small) turbines, and partly because some projects are established with smaller turbines than the “optimal” size due to lack of space.

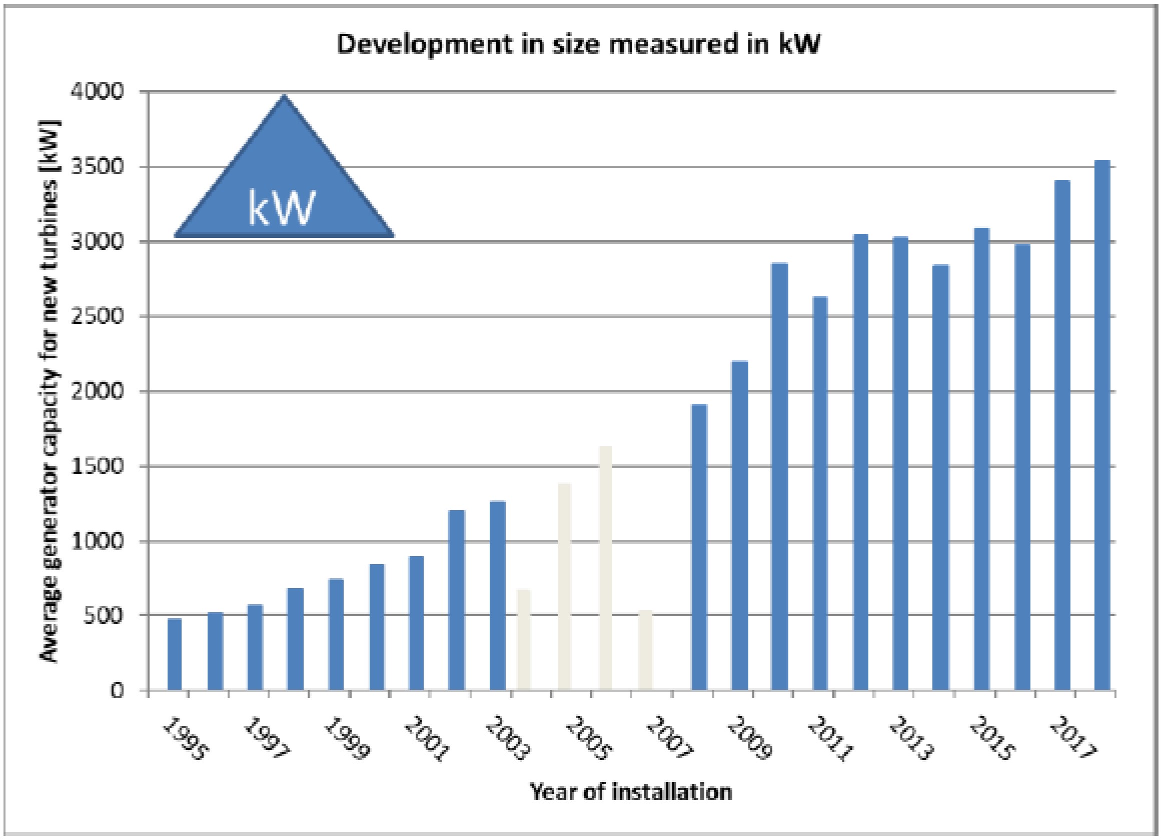

Figure 17: Average generator capacity for new turbines (rated power > 25 kW)

In the same period the rotor diameters and hub heights have also increased as illustrated in figure 18 and figure 19.

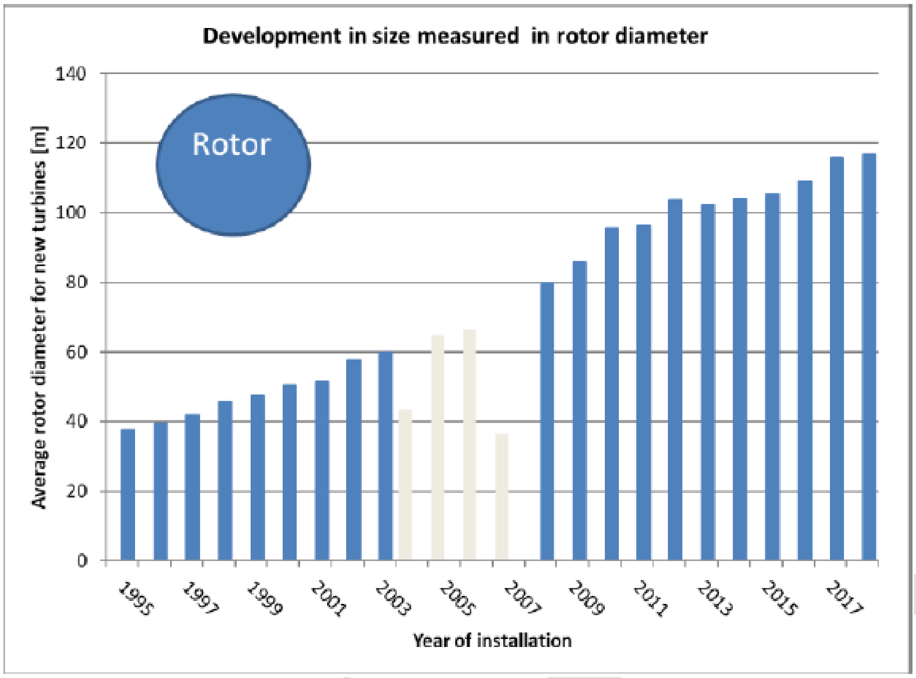

Figure 18: Average rotor diameter for new turbines (rated power > 25 kW)

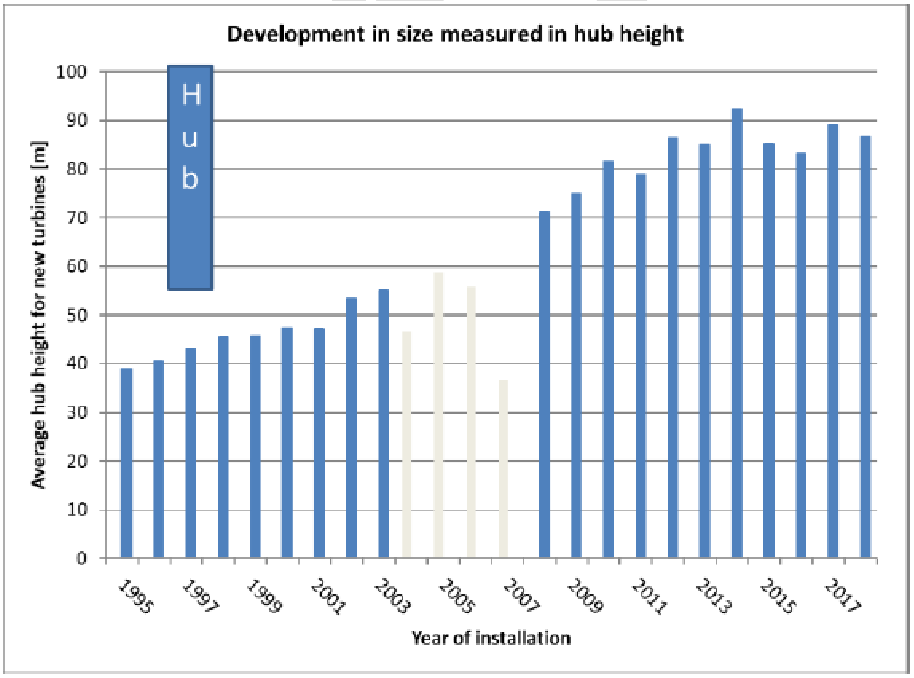

Figure 19: Average hub height for new turbines (rated power > 25 kW)

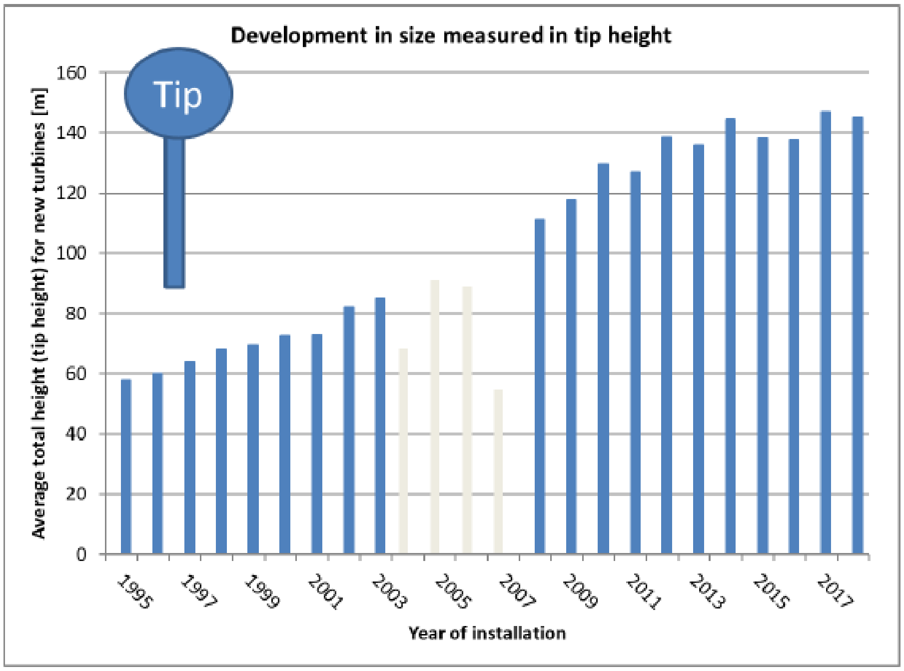

Figure 20: Average tip height for new turbines (rated power > 25 kW)

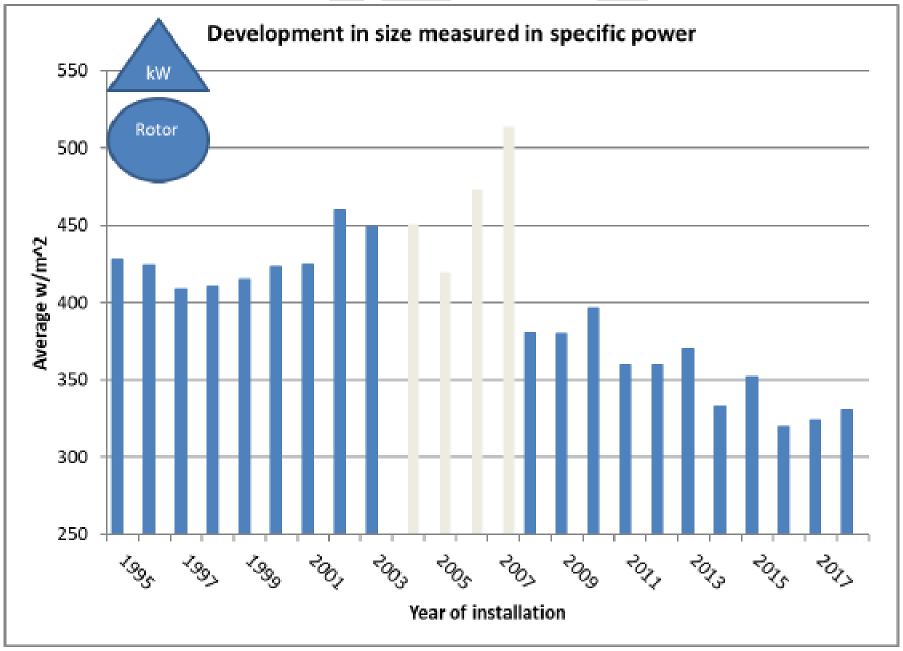

Figure 21: Average specific power for new turbines (rated power > 25 kW)

Regulation ability

Electricity from wind turbines is highly variable because it depends on the actual wind resource available. Therefore, the regulation capability depends on the weather situation. In periods with calm winds (wind speed less than 4 - 6 m/s) wind turbines cannot offer regulation, with the possible exception of voltage regulation.

With sufficient wind resource available (wind speed higher than 4 - 6 m/s and lower than 25 - 30 m/s) wind turbines can always provide down regulation, and in many cases also up regulation, provided the turbine is running in power-curtailed mode (i.e. with an output which is deliberately set below the possible power based on the available wind).

In general, a wind turbine will run at maximum power according to the power curve and up regulation is only possible if the turbine is operated at a power level below the power actually available. This mode of operation is technically possible and, in many countries, turbines are required to have this feature. However, it is rarely used, since the system operator will typically be required to compensate the owner for the reduced revenue.

Wind turbine generation can be regulated down quickly, and this feature is regularly used for grid balancing. The start-up time from no production to full operation depends on the wind resource available.

Advantages/disadvantages

Advantages:

- No emissions to air from operation
- No emission of greenhouse gasses from operation
- Stable and predictable costs due to low operating costs and no fuel costs
- Modular technology allows for capacity to be expanded according to demand avoiding overbuilds and stranded costs
- Short lead time compared to most alternative technologies

Disadvantages:

- High capital investment costs
- Variable energy resource
- Moderate contribution to capacity compared to thermal power plants
- Need for regulating power
- Visual impact and noise

Environment

Wind energy is a clean energy source. The main environmental concerns are visual impact, flickering from rapid shifts between shadow and light when turbine is between sun and settlement, noise and the risk of bat or bird-collisions.

The visual impact of wind turbines is an issue that creates some controversy, especially since onshore wind turbines have become larger.

Flickering is generally managed through a combination of prediction tools and turbine control. Turbines may in some cases need to be shut down for brief periods when flickering effect could occur at neighboring residences.

Noise is generally dealt with in the planning phase. Allowable sound emission levels are calculated on the basis of allowable sound pressure levels at neighbors. In some cases, it is necessary to operate turbines at reduced rotational speed and/or less aggressive pitch setting in order to meet the noise requirements. Noise reduced operation may cause a reduction in annual energy production of 5 - 10%. Despite meeting the required noise emission levels turbines sometimes give rise to noise complaints from neighbors.

The risk of bird collisions has been of concern in many countries due to the proximity of wind turbines to bird migration routes. In general, it turns out that birds are able to navigate around turbines, and studies report low overall bird mortality but with some regional variations.

The environmental impact from the manufacturing of wind turbines is moderate and is in line with the impact of other normal industrial production.

The energy payback time of an onshore wind turbine is in several studies calculated to be in the order of 3 - 9 months.

Life-cycle assessment (LCA) studies of wind farms have concluded that environmental impacts come from three main sources:

- bulk waste from the tower and foundations, even though a high percentage of the steel is recycled
- hazardous waste from components in the nacelle
- greenhouse gases (e.g. CO_2 from steel manufacturing and solvents from surface coatings)

Domestic wind turbines (micro wind or small-wind turbines)

Domestic wind turbines are micro-wind or small-wind turbines with a capacity up to 25 kW.

The capacity factor of small wind turbines varies a lot dependent on the local conditions. The turbines are often located close to buildings and trees, which will reduce the annual production from the turbines. The specific power will as for the larger turbines have an impact on the capacity factor and so have the relative low hub height.

Quantitative description

The following datasheet shows the technical, environmental and financial data for the specific technology.

Data sheet 30 - Onshore Wind Turbines plants

20 Large wind turbines on land	
Energy/technical data	
Generating capacity for one unit (MW)	4.2
Average annual full-load hours	3,400
Forced outage (%)	2.5%
Planned outage (%)	0.3%
Technical lifetime (years)	27
Construction time (years)	1.5
Space requirement (1000m2/MW)	---
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Financial data	
Nominal investment (M$US/MW)	1.36
Fixed O&M ($US/MW/year)	16,940
Variable O&M ($US/MWh)	1,82

Data sheet 31 - Onshore Small Wind Turbines

Small wind turbines, grid connected (< 25 kW)	
Energy/technical data	
Generating capacity for one unit (MW)	0.005
Average annual full-load hours	1,600
Forced outage (%)	3%
Planned outage (%)	0,3%
Technical lifetime (years)	20
Construction time (years)	1
Space requirement (1000m2/MW)	0,8
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Financial data	
Nominal investment (M$US/MW)	4.6

Small wind turbines, grid connected (< 25 kW)	
Fixed O&M ($US/unit/year)	653
Variable O&M ($US/MWh)	---

Photovoltaics

Brief technology description

A solar cell is a semiconductor component that generates electricity when exposed to solar irradiation. For practical reasons several solar cells are typically interconnected and laminated to (or deposited on) a glass pane in order to obtain a mechanical ridged and weathering protected solar module. The photovoltaic (PV) modules are typically 1.6 – 2.1 m^2 in size and have a power density in the range 160 - 220 W_p pr. m^2. They are sold with a product warranty of typically ten to twelve years, a power warranty of minimum 25 years and an expected lifetime of more than 30 - 35 years depending on the type of cells and encapsulation method.

PV modules are characterised according to the type of absorber material used:

- Crystalline silicon (c-Si); the most widely used substrate material is made from purified solar-grade polysilicon feedstock and come in the form of mono- or multicrystalline silicon *wafers*. Monocrystalline solar cells are made from wafers sliced from a high purity monocrystalline silicon cylinder-shaped ingot while multicrystalline solar cells are made of wafers sliced from square blocks of casted silicon where the monocrystalline grains are in the range of 5 - 50 mm in size. Silicon based solar cell technology is expected to dominate the world market for decades due to significant cost and performance advantages.

- Thin film solar cells, where the semiconducting absorber layer can be an made of materials like amorphous/microcrystalline silicon (a-Si/µc-Si), Cadmium telluride (CdTe) or Copper Indium Gallium (di) Selenide (CIGS), are deposited on the solar module glass cover in a micrometre thin layer. Tandem junction and triple junction thin film modules are commercially available. In these modules several layers are deposited on top of each other in order to increase the efficiency.

- Monolithic III-V solar cells, that are made from compounds of group III and group V elements (Ga, As, In and P), are often deposited on a Ge substrate. These materials can be used to manufacture highly efficient multi-junction solar cells that are mainly used for space applications or in Concentrated PhotoVoltaic (CPV) systems. CPV mainly utilises the direct beam component of the solar irradiation, which is not decisive under Danish conditions. Dye-Sensitized solar Cells (DSC) and Polymer/Organic Solar Cells; are emerging technologies where significant research activities are among others currently addressing efficiency and lifetime issues. These cells are currently not considered candidates for grid-connected systems.

- Perovskite material PV cells; Perovskite solar cells are in principle a DSC cell with an organo-metal salt applied as the absorber material. Perovskites can also be used as an absorber in modified (hybrid) organic/polymer solar cells. The potential to apply perovskite solar cells in a multi-stacked cell on e.g. a traditional c-Si device provides interesting opportunities. Perovskite-based solar cells have, under lab conditions, shown a remarkable progress over the years when rated with respect to efficiency. The perovskites potential is, however, paired with serious concerns related to their toxicity. The best perovskite absorbers contain soluble organic lead compounds that are toxic and environmentally hazardous at a level that calls for extraordinary precautions. Therefore, the perovskite’s health and environmental impact shall be analysed before they eventually are considered as a viable absorber material in solar cells. Furthermore, challenges in industrial scale manufacturing are presently not solved. It is currently uncertain when this type of PV cells will be commercially available.

In addition to PV modules, a grid connected PV system also includes Balance of System (BOS) consisting of a mounting (fixed tilt or tracking) system, dc-to-ac inverter (central or string), cables, monitoring/surveillance equipment and for utility scale PV power plants also transformers and park controller.

Crystal growth method

The multi-crystalline casting method has been the dominating crystallisation technology since the early 2000’s due to the flexibility in utilisation of any kind of purified silicon no matter form and residual contamination. The relative global production shares for each wafer type are shown in below figure.

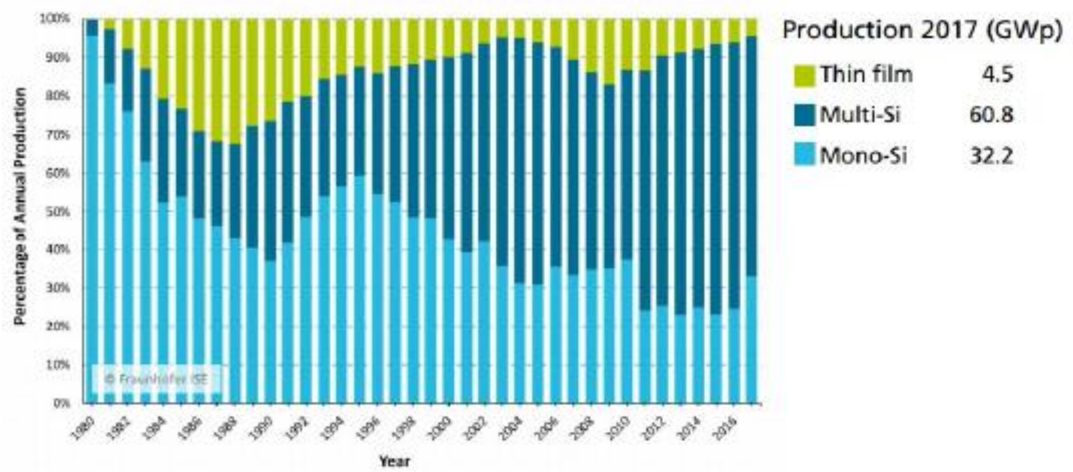

Figure 22: Historical market shares of different cell technologies

However, the mono-crystalline growth solution is now expected again to become the dominating solution and already in 2018 reached market parity with the traditional Multi-Si solution. All major PV companies are now in the process of converting to a full mono-crystalline focus by adding only new manufacturing capacity based on Mono-solutions.

Already in 2021, 80% of the global solar marked are expected to be based on mono-crystalline products.

In addition, other macro-trends are foreseeable to change the landscape of silicon products over the next few years, as both larger wafer sizes (166 x 166 mm) and n-type products are expected to become mainstream. These developments however are happening so fast, that current market reports and statistics have not yet captured this development.

Wafer slicing method

The active silicon substrate that constitutes the solar cell is sliced from the ingot or block with a wire-saw. Since the technology was invented in the 1990’es, hard silicon carbide particles in a slurry of glycol have been the preferred version. However during the last few years, this solution has almost entirely been replaced by diamond coated wires and regular cooling water. This method has demonstrated to be cheaper in operation, as it eliminates the slurry recycling operation, provides a potential to cut thinner wafers and provides a wafer surface better suited for post-cleaning structuring into micro-pyramids or other anti-reflecting surface properties by etching.

Solar cell architecture

Whereas the main cell technologies until a few years ago were based on the screen printed Al-BSF (sintered aluminum paste based back surface field) solar cells, which represent a very old, reliable and versatile solar cell architecture adaptable for both mono- and multicrystalline wafers, other concepts, which already were developed in the 1980’s, have recently been introduced into large scale manufacturing. Most dominating is the PERC (Passivated Emitter and Rear Cell) architecture, where an extra processing step has been added to reduce carrier recombination at the surface by “passivating” these surfaces (typically by a nanometer thin layer of silicon dioxide, aluminium-oxide or (oxy-)nitrides). Also alternative architectures like PERT (passivated emitter rear totally diffused), HJT (Heterojunction Technology) or TopCON (Tunnel Oxide Passivated Contact) are also now being introduced in GW-sized manufacturing facilities all due to the higher efficiency potential that can be obtained (up to 24 - 25% as compared to the Al-BSF maximum around 20 - 21%).

Solar module

The encapsulation of cells into a PV module has undergone several changes over the last few years. Whereas the front protection is still made by a 2.5 – 3.2 mm thick antireflective coated toughened glass, more and more modules have the tedlar backsheet polymer replaced by another glass pane, whereby a more mechanically rigid and better-protected structure is obtained. This also opens for an optional elimination of the aluminium frame. Additionally, more transparent encapsulation materials known as polyolefins are now in use and anti-soiling surface coatings have been introduced.

Bifacial PV-panels and half-cut cells

On top of the above listed upgrades and improvements in other manufacturing steps, yet another technology change has been introduced and found fast acceptance in the market, namely the opportunity to utilize solar energy that reaches the cell from both sides of the PV module. This is yet a further advantage of the PERC solar cell, as the backside does not block the light from entering the silicon bulk absorber (in contrast to the Al-BSF cell, where opaque aluminum covers the whole cell backside).

In addition to the bifaciality module types, also the half-cut cells technology have gained significant market attraction and demonstrated a large potential over a very short time. Whereas all ingot, wafer and cell manufacturing processes remain unchanged, the square cells are simply cut into two equally sized half cells and then placed next to each other in the PV panel that now contains 144 half-cut cells in contrast to the previous 72 cell module type for utility scale systems.

Roof top systems usually apply smaller panels containing 60 cell modules with then makes 120 half-cut cells.

Although the overall area of the module hereby increases a little due to the additional amount of cell-to-cell spacing, the overall module power uplift of approximately 5 W_p most often outweighs this disadvantage in module area efficiency.

Silicon-based bifacial modules global market shares are expected to reach a 60% market share in 2029 globally, shown in below figure, due to generation gains at a low additional cost. For utility scale systems, it is reasonable to believe that bifacial modules become the preferred technology within 2024.

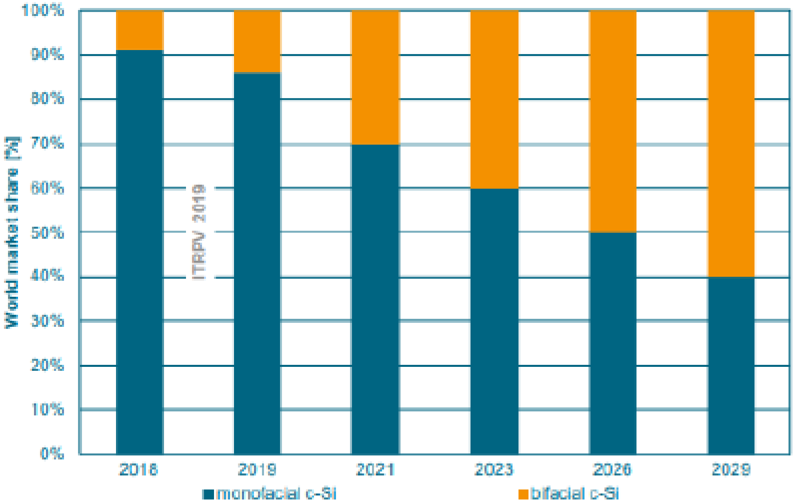

Figure 23: Silicon-based mono- and bifacial global market shares

He figure below shows the functional principle of a bifacial solar panel against a monofacial module.

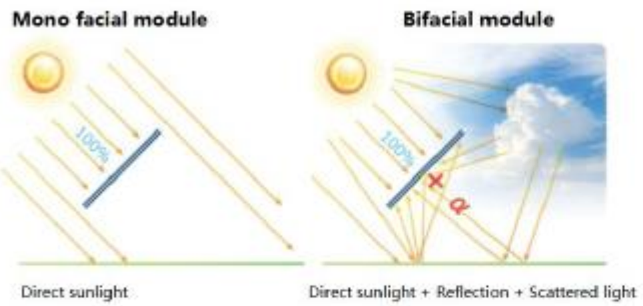

Figure 24: Bifacial module structure

Whereas most commercial power prediction software only assume a small uplift of 4% in energy production due the this bifaciality, other studies indicate that this uplift may be in the range of 6% to 8% when compared to monofacial-panel PV panels with the same cell type. The specific gain is dependent on a wide range of factors such as height of panel installation, ground albedo, avoidance of backside shadowing by the sub-structure, inclination, geographical location, weather conditions etc. Note that the relative contribution of the bifacial cells is higher in cloudy weather due to a higher share of diffuse sky radiation.

Utility scale PV with tracking system

In Southern Europe single axis tracker systems have become the new standard.

Single axis tracking

Single axis tracking systems allow rotation of the PV-panels around a single axis. This can either be around the horizontal or tilted axis. This is realized by having an electric motor connected to the panel along with a control system. In countries located on the northern hemisphere it is most customary to install long vertical single axis systems that allow rotation from facing east to west during the day, shown in below figure.

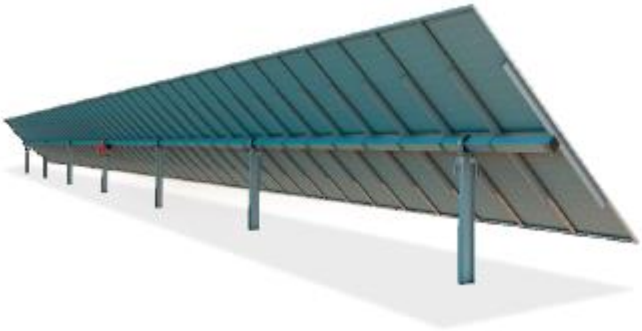

Figure 25: Single axis tracking system on the vertical axis

Dual axis tracking

Dual axis tracking systems allow rotation of the PV-panels both horizontally and vertically. It has two respective motors for rotation on each axis. This allows for the minimization of the incidence angle between the sun and the solar panel, which in turn maximizes the generation. However, the mounting structure can only support a fewer number of modules (usually limited to 10 kW_p per tracker structure) and two motors are required, causing the investments cost to be significantly higher than single-tracker plants. For that reason, it is uncommon to apply dual axis tracker technology for utility scale PV plants, unless a version of CPV that can only utilize the direct (beam) component in the daylight is installed. An illustration of a dual axis tracker is shown in below figure.

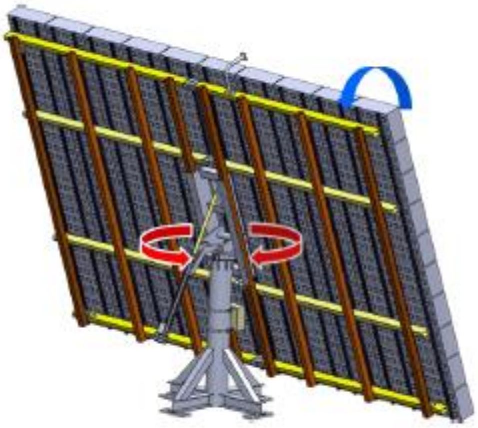

Figure 26: Generic dual PV system

1.5 axis tracking

A 1.5 axis tracking system is a fusion of the single and dual axis system because the system can partly operate on both axes. The 1.5 axis system only has one motor for rotation on both axes and requires a panel structure, which does not allow an inclination angle below 30 degrees. This results in a similar generation with respect to the dual axis system in seasons with a high solar elevation angle as well as a low seasonal angle difference. However, the generation is reduced with respect to the dual axis system if the sun's elevation angle is below 30 degrees, which is the case for most of Europe in winter. Because the tracking system only needs one motor, the investment costs are lower relative to the dual axis tracking system. Still like the dual axis tracking system, the mounting structure can only support a few modules, making the technology less relevant for large utility scale PV plants. An example of a PV 1.5 axis tracking system is shown in below figure.

Figure 27: Helioslite 1.5 tracking system

Performance of tracking systems

PV panels with any kind of tracking system will have an increased power generation with respect to fixed mount systems. This additional performance ability for tracking systems depends on geographical location, type of PV-module, type of control system, time horizon for measurements and inclination angle applied.

The production pattern of single axis trackers is slightly different to fixed systems as they have an increased generation in the early and late daylight hours while having a decreased peak in the middle of the day. In general, the generation pattern is more beneficial for the power system as the output is usually less fluctuating throughout the day.

PV module power (capacity)

The energy generation capacity (power) of a solar module depends on the intensity of the irradiation the module receives, incidence angle, spectral distribution of the solar radiation as well as module temperature. For practical reasons the module power is therefore referenced to a set of laboratory Standard Test Conditions (STC) which corresponds to an irradiation of 1000 W/m^2 with an AM 1.5 spectral distribution perpendicular to the module surface and a cell temperature of 25°C. This STC capacity is referred to as the peak capacity P_p [kW$_p$].

Losses and corrections

As the actual operating conditions will always be different from Standard Test Conditions, the average capacity of the module over the year will therefore differ from the peak capacity. The capacity of the solar module is reduced compared to the P_p value when the actual cell temperature is higher than 25°C, when the irradiation received is collected at an angle different from normal direct irradiation and when the irradiation is lower than 1000 W/m^2. Besides, some of the electricity generated from the solar modules is lost in the rest of the system, e.g. in the DC-to-AC inverter(s), cables, combiner boxes and for larger PV power plants also in the transformer. The power generation from a PV installation with a peak capacity P_p can be calculated as:

$$Energy = P_p * Global\ Horizontal\ Irradiation * Transposition\ Factor * Performance\ Ratio$$

For practical reasons, the various losses are often compiled into a single factor, called the performance ratio, which describes all energy losses in the system as compared to the reference where all irradiation is received under Standard Test Conditions. In addition to light reflection when penetrating the glass and cell surface, non-STC corrections, as well as inverter- and transformer losses, the performance ratio also includes lost production due to soiling of the panels, electrical mismatch loss between modules, cable loss etc. The uplift from bifaciality is typically included in the performance ratio or presented separately.

Inverter capacity and sizing factor

The capacity of the inverter, also known as the rated power, defines the upper limit for power that can be delivered from the plant and defines the plant capacity, P [W$_{AC}$]. The relationship (P_p/P) between the peak capacity P_p [W$_{DC}$] and the plant capacity P is called the sizing factor. A high sizing factor leads to curtailment of production in peak hours, but at the same time reduces cost for inverters and grid connection. The sizing factor is optimised differently whether the limiting factor of the installation is; availability of area, availability of grid connection, subsidy scheme, imposed constraints on the allowed nominal power, daily self-consumption profile, fixed physical orientation or tilt angle of the modules etc. The range for the sizing factor is generally within 1.0 to 1.35 globally.

Wear and degradation

In general, a PV installation is very robust and only requires a minimum of component replacement over the course of its lifetime. The inverter typically needs to be replaced every 10 - 15 years. For the PV module only limited physical degradation will occur. It is common to assign a constant yearly degradation rate of 0.3 – 0.5 % per year to the overall production output of the installation.

This degradation rate does not represent an actual physical mechanism, but rather reflect general failure rates following ordinary reliability theory with an initial high (compared to later) but rapidly decreasing “infant mortality” followed by a low rate of constant failures and with an increasing failure rate towards the end-of-life of the various products.

Failures in the PV system is typically related to soldering, cell crack or hot spots, yellowing or delamination of the encapsulant foil, junction box failures, loose cables, hailstorm and lightning. Degradation is difficult to assess on a project level, as the magnitude of degradation easily can be offset or overwhelmed by other factors influencing the individual system’s efficiency.

Input

Solar radiation is the input of a PV panel. The irradiation, which the module receives, depends on the solar energy resource potential at the location, including shading conditions and the orientation of the module.

Output

All PV modules generate direct current (DC) electricity as an output, which then needs to be converted to alternating current (AC) by use of an inverter. Some modules (AC modules) come with an integrated inverter, which exhibits certain technical advantages, such as better modularity in installation, more flexibility in installation orientation of individual modules (standard string inverters require all modules in an electrical string to be installed in the same orientation), more shade resistance, easy shutdown in case of fire thus being safer, and simple AC-electrical work to be performed directly at the panel on the roof. However, these integrated inverters are more costly and therefore they are typically only applied in residential PV modules.

The power generation depends on:
- The amount of solar irradiation received in the plane of the module (see above).
- Installed module generation capacity.
- Losses related to the installation site (soiling and shade).
- Losses related to the conversion from sunlight to electricity.
- Losses related to conversion from DC to AC electricity in the inverter.
- Grid connection and transformer losses.
- Cable length and cross section, and overall quality of components.

Typical capacities

PV systems are available from a few Watts to Gigawatt sizes but in this context, only PV systems from a few hundred Watt to a few hundred MW are relevant.

PV systems are inherently modular with varying typical module size with respect to residential, commercial and utility scale use. A typical module unit size is between 250 and 300 W_p for residential purposes whereas utility scale size is between 350 W_p and 430 W_p, but can be up to 500 W_p.

The size of a typical *residential* installation is normally between 4 and 6 kW_p corresponding to an area of 25-40 m^2 for c-Si modules. Residential PV installations are often optimised for a high degree of self-consumption, with an inverter sizing factor of 1.0 – 1.2, but may also deliver surplus power to the outer radials of the distribution grid. To increase self-consumption residential PV's can be combined with a small sized battery to absorb peak generation.

Commercial and Industrial PV systems are typically installed on residential, office or public buildings, and range typically from 50 to 500 kW_p in size. Such systems are often designed to fill the available roof area but also for a high degree of self-consumption. They will typically have a sizing factor around 1.1 – 1.2 and may deliver non-self-consumed power to a transformer in the low voltage distribution grid.

Utility scale systems or PV power plants will normally be ground mounted and typically range in size from 0.5 MW and beyond. They are typically operated by independent power producers that by use of transformers deliver power to the medium voltage grid. The sizing factor is typically around 1.25.

Space requirement

The module area needed to deliver 1 kW_p of peak generation capacity can be calculated as 1 /η_{mod}, and equals 5.3 m^2 by today's standard PV modules. For modules on tilted roofs, 1 m^2 of roof area is needed per m^2 of module area.

Modules on flat roofs and modules on ground will typically need more roof and land area than the area of the modules itself, in order to avoid too much shadowing from the other modules. The table below shows typical ratios of the area of the module to the ground surface required for the installation, so-called ground coverage ratios. For residential installations, the table shows the ratio between module area and roof area (assuming tilted roof installation).

Table 11: Ground coverage ratio and installed power density for different PV segments

	Residential	Commercial	Utility
Ground coverage ratio	1.0	0.8	0.4

Regulation ability

The generation from a PV system reflects the yearly and daily variation in solar irradiation. When connecting PV systems to the grid, a set of grid codes describing required functionality and communication protocol as set by the TSO and DSO must be respected. The detailed technical requirements depend on the system size and do not impose any specific technical demand that cannot be fulfilled by any modern PV inverter. For systems above 125 kW, a park controller which interfaces the grid operator is required to ensure system level remote control of all individual inverters, which then enables the system to deliver ancillary grid services like frequency response, reactive power, variable voltage output, or power fault ride-through functionality to the grid. PV plants may also provide down-regulation if generating or up-regulation if not generating at maximum capacity. However, currently most installed PV systems supply the full amount of available energy to the consumer/grid.

Advantages/disadvantages

Advantages:

- PV does not use any fuel or other consumable.
- PV is noiseless (except for fan-noise from inverters and transformers).
- Power is produced in the daytime when demand is high.
- PV complements wind power as the generic seasonal/daily generation profile is different.
- PV offers grid-stabilisation features.
- PV modules have a long lifetime of more than 30 years and PV modules can be recycled.
- PV systems are modular and easy to install.
- Operation & Maintenance (O&M) of PV plants is simple and limited as there are no moving parts, with the exception of tracker systems, and no wear and tear. Inverters need only be replaced once or twice during the operational life of the installation.
- Large PV power plants can be installed on land that otherwise are of no commercial use (landfills, areas of restricted access or chemically polluted areas).
- PV systems integrated in buildings require no incremental ground space, and the electrical inter-connection is readably available at no or small additional cost.

Disadvantages:

- PV systems have high upfront costs and a low capacity factor.
- Aesthetic concerns may limit the use of PV in certain urban environments and in the open space when the visual impact is unacceptable.
- PV installations can only provide ancillary services in specific situations as generation usually follows the daily and yearly variations in solar irradiation.
- Materials abundancy (In, Ga, Te) is of concern for large-scale deployment of some thin-film technologies (CIGS, CdTe).
- Some thin-film technologies do contain small amounts of toxic cadmium and arsenic.
- The best perovskite absorbers contain soluble organic lead compounds, which are toxic and environmentally hazardous at a level that calls for extraordinary precautions.
- PV systems are quite area intensive as the MW_p/ha factor is quite low, typically around 0.5 - 0.8 MW_p/ha depending on scale and application.

Environment

The environmental impacts from manufacturing, installing and operating of PV systems are limited.

Thin film modules may contain small amounts of cadmium and arsenic, but all PV modules as well as inverters are covered by the European Union “Waste from Electrical and Electronic Equipment" (WEEE) directive, whereby appropriate treatment of the products by end-of-life is organised.

The energy payback time (EPBT) is dependent on multiple factors such as PV technology type, type of manufacturer and geographical location. The current average EPBT of a typical crystalline silicon PV system in Europe is 1 year.

Generally, the multicrystalline cells have a slightly lower EPBT relative to monocrystalline since the process of making multicrystalline cells is less energy-intensive as crystal purity is prioritized for monocrystalline cells.

Quantitative description

As the boundary for both cost and performance data in the catalogue is the delivered energy to the electricity grid, all the values presented in the datasheets are referring to the AC grid connection capacity, if not stated specifically or unless stated otherwise. However, due to the strong correlation of many cost elements to the peak power (except for inverters and AC electrical connection) and relevance in the PV sector, the financial data is also presented explicitly as per DC peak power in the bottom of the datasheets.

Note that previous versions of the catalogue in contrast have explicitly stated both subscripts for either AC power or DC peak power in the datasheet for utility scale plants.

Data sheet 32 - Photovoltaic, small residential systems

Photovoltaics: Small residential systems	
Input	
Global horizontal irradiance (kWh/m2/y)	1,068
Energy/technical data	
Typical capacity for one installation (kW)(plant capacity)	6
Typical peak capacity for one installation at STC (kWp)	6.3
Energy/technical data - system design	
DC/AC sizing factor (Wp/W)	1.05
Transposition Factor for fixed tilt system	1.10
Performance ratio (meassure of combined losses)	0.84
PV module conversion efficiency (%)	19%
Availability (%)	100%
Technical lifetime of total system (years)	35
Inverter lifetime (years)	15
Output	
Full-load hours (kWh/kW)	1,043
Peak power full-load hours (kWh/kWp)	993
Financial data	
Specific investment, total system (M$US/MW)	1.37
Fixed O&M ($US/MWp/y)	15,488

Data sheet 33 - Photovoltaic, medium sized commercial systems

Photovoltaics: Medium sized commercial systems	
Input	
Global horizontal irradiance (kWh/m2/y)	1,068
Energy/technical data	

Photovoltaics: Medium sized commercial systems	
Typical capacity for one installation (kW)(plant capacity)	100
Typical peak capacity for one installation at STC (kWp)	110
Energy/technical data - system design	
DC/AC sizing factor (Wp/W)	1.1
Transposition Factor for fixed tilt system	1.1
Performance ratio (meassure of combined losses)	0.87
PV module conversion efficiency (%)	19.0%
Availability (%)	100%
Technical lifetime of total system (years)	35
Inverter lifetime (years)	15
Output	
Full-load hours (kWh/kW)	1,129
Peak power full-load hours (kWh/kWp)	1,027
Financial data	
Specific investment, total system (M$US/MW)	0.97
Fixed O&M ($US/MW/year)	12,584

Data sheet 34 - Photovoltaic, large scale utility systems

Photovoltaics: LARGE scale utility systems	
Energy/technical data	
Generating capacity for one unit (MW)	8.0
Average annual full-load hours (MWh/MW)	1,647
Forced outage (%)	0%
Planned outage (%)	0%
Technical lifetime (years)	40
Construction time (years)	0.5
Space requirement (1000m2/MW)	20
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Financial data	
Nominal investment (M$US/MW)	0.53
Fixed O&M ($US/MW/year)	10,769

Heat pumps

Brief technology description

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature level to a higher temperature level. Heat pumps draw heat from a heat source (input heat) and convert the heat to a higher temperature (output heat) through a closed process; either compression type heat pumps (using electricity or fuels) or absorption heat pumps (using heat; e.g. steam, hot water or oil). There exist many different variations of heat pumps that can overall be divided as below (or combinations):

- Compression heat pumps, using electricity
- Compression heat pumps, using a combustion engine
- Absorption heat pumps, direct fired/indirect fired

An important point regarding heat pumps is the ability to "produce" both heating and cooling. When applied with the primary purpose of cooling, the cooling demand defines the capacity. When installed for cooling the heat pump will typically be the only cooling source, whereas when installed for heating it will in many cases be in combination with other sources that can provide the heat energy (e.g. at a district heating (DH) plant). However, the primary purpose of the heat pumps in the technology catalogue is heating. In this chapter the unit MW is referring to the heat output (also MJ/s) unless otherwise noted.

Heat pumps can utilize several different heat sources. Due to recent development in heat pump utilization at DH plants, this chapter primarily focuses on compression heat pumps utilizing air, industrial excess heat and seawater at existing power plants.

Heat pumps are utilized for industrial processes, individual space heating and district heat production. Heat pumps are typically installed as a supplement to existing heat production plants meaning that coproduction is possible. Large scale heat pumps are often designed with a capacity equivalent to half of the peak heat demand due to high specific investment costs. This enables a heat pump to generate 85 to 90 % of the annual heat demand as a base load unit, where peak load or back up units complement at peak load.

The application of large heat pumps in DH systems may influence the development of the heat pumps globally – both the technology itself and the application.

The focus of this chapter is the most relevant applications in DH systems at the moment (2020). These are:

- Compression heat pumps utilizing ambient air (1, 3 and 10 MW)
- Compression heat pumps utilizing industrial excess heat (1, 3 and 10 MW)
- Compression heat pumps utilizing seawater (20 MW)
- Absorption heat pumps (12 MW)

Other applications are possible as well.

The implementation of compression heat pumps utilizing ambient air is currently accelerating rapidly. Where possible industrial excess heat can be utilized to decrease the energy consumption and compression heat pumps utilizing seawater are expected to be implemented at larger central DH systems in the near future.

Regarding regulatory approvals and contracts, air source heat pumps are the simplest and fastest type to install, as these do not require the involvement of external partners.

Heat pumps utilizing excess heat may yield lower heat production cost as the higher source temperature results in high coefficient of performance (COP). Removal of excess heat can also be beneficial for factories since it can reduce energy or water consumption at cooling towers etc. Heat pump systems are primarily relevant for processes with high energy consumption and many operation hours.

Excess heat is typically utilized by connecting existing cooling systems to a heat pump meaning that it removes heat from cooling water or glycol and replaces operation of chillers or cooling towers. Heat pump systems for such applications are relatively simple to install and the main obstacle is often the distance between the cooling water and the DH system. In most cases the heat pump is connected in series or parallel to the existing cooling systems and the reliability of the cooling system is thereby increased. The heat pump covers the base load of the cooling demand whereas the existing cooling plants will be backup or peak load units thus increasing the safety of operation. It is important to assess the simultaneity of the cooling and heating demand. Often cooling demand is largest during summer, whereas heating demand is largest during winter. In some cases excess heat may be released at higher temperatures that allows direct heat exchange, which should be done before using a heat pump for further cooling. This is beyond the scope of this chapter.

For drying processes, most of the surplus heat leaves through moist ventilation air, and there is therefore no direct cooling demand. In such applications excess heat can be recovered by cooling and dehumidifying the ventilation air as it leaves the process. This requires cooling surfaces at the exhaust from the ventilation system, which is typically more complex than a heat pump utilizing excess heat from cooling water.

Compression heat pumps

For compression heat pumps, the heat output is usually 3 to 5 times the utilized electricity input (or drive energy). This relation is referred to as the coefficient of performance (COP). The practically attainable COP depends on the efficiency of the specific heat pump (Lorenz efficiency, which should not be mistaken for Lorenz COP), the temperature of the heat source and sink and the temperature difference between heat source and sink. The energy flow is illustrated in the Sankey diagram in Figure 1.

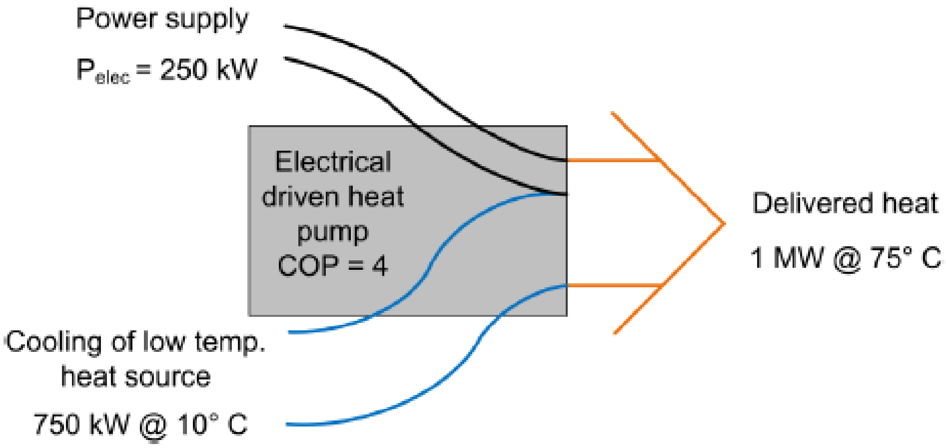

Figure 28: The electric power consumption of 250 kW enables the heat pump to utilize 750 kW from a low temperature source at 10°C. Thus delivering 1 MW at 75°C (COP is 4)

A general heat pump cycle is shown in below figure. For a heat pump that delivers DH, the source could be ambient air or a cooling stream from an industrial process, while the sink could be a flow of the DH return water, at e.g. 40 °C being heated to a higher temperature. The evaporator and condenser are heat exchangers that allows heat exchange, while separating the refrigerant from the source- and sink liquids.

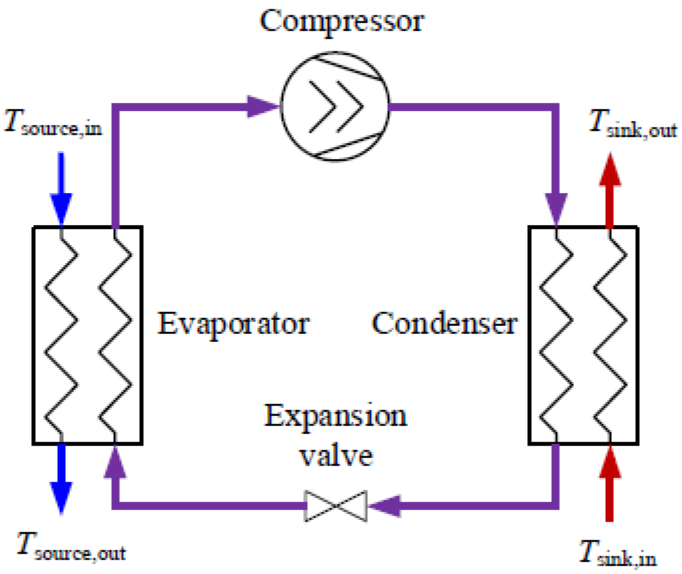

Figure 29: Sketch of the heat pump cycle with components. The Lorenz COP is the theoretical maximum.

COP calculation

The theoretical COP can be calculated as the “Carnot COP” or “Lorenz COP” which relates mechanical work to temperature differences in power generation, refrigeration and heat pump technology. Carnot regards a single refrigeration cycle with one condenser and one evaporator and relates mechanical work to the temperature difference between the condenser and evaporator. The Lorenz calculation method is preferable for “stepped” Carnot cycles, where heating and/or cooling is done in several steps, which is the case for DH, with a temperature increase of 30 - 50 K. With such high temperature increases, a heat pump system typically includes several condensers in series meaning that the system consists of several Rankine cycles. The Lorenz cycle is preferable to Carnot in this context, as this includes more steps in the cycle. The equation for Lorenz COP is shown in the equation below.

$$\mathrm{COP}_{\mathrm{Lorenz}} = \frac{T_{\mathrm{lm,sink}}}{T_{\mathrm{lm,sink}} - T_{\mathrm{lm,source}}} \quad , \qquad \text{where} \quad T_{\mathrm{lm}} = \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{\ln\left(\frac{T_{\mathrm{in}}}{T_{\mathrm{out}}}\right)}$$

Where T_{lm} is the log mean temperature of the source- and sink heat exchangers. Temperatures should be inserted as an absolute temperature, e.g. Kelvin.

Accordingly, a heat pump that heats water from 45 to 85°C (DH) and cools a source from 20 to 15°C (cooling water from a factory), will have a Lorenz COP of 7.2. In practice though, the COP will be lower due to mechanical and thermal losses, typically around 40 - 60 % of the theoretical COP. The relation between practically attainable and theoretical COP, given in the equation below, depends on component efficiencies, heat exchangers, refrigerants and more.

$$\mathrm{COP}_{real} = \mathrm{COP}_{\mathrm{Lorenz}} \cdot \eta_{\mathrm{Lorenz}}$$

All COP-values stated in this chapter are practically attainable values if nothing else is stated.

The figure below shows the dependency between COP and source temperature for two systems with different sink temperature requirements ($T_{sink,in}$ and $T_{sink,out}$), i.e. the figure shows practically attainable COP-values and how this is influenced by the source and sink temperatures. The values are calculated with a heat source that is cooled 5°C – e.g. a heat source of $T_{source,in} = 30$°C is cooled to $T_{source,out} = 25$°C.

In this example the Lorenz efficiency is fixed at 50%. Increasing the cooling of the heat source (lower $T_{source,out}$) will lead to a lower COP, but a higher output capacity, since more energy is moved.

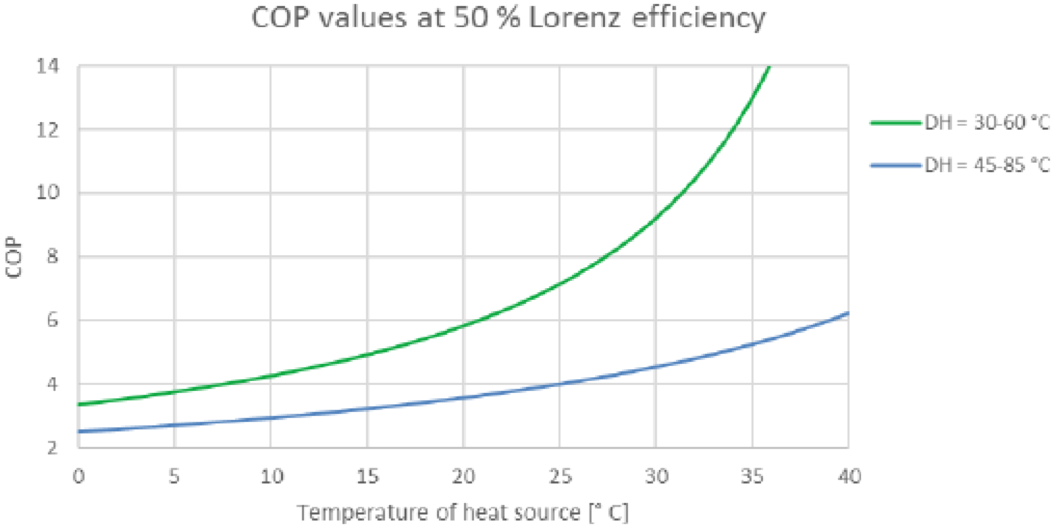

Figure 30: Practically attainable COP values of compression heat pumps with varying heat source temperatures at two different sink requirements

As the figure shows, temperatures of both sink and source have great influence on the COP of a compression heat pumps. This is also regardless of the efficiency of the heat pump itself. It follows that heat pumps are most suited for low DH temperatures combined with high temperature sources. The output heat capacity is also affected by the temperatures, especially the source temperature. This is a result of a lower evaporating pressure, meaning that the refrigerant gas is less dense at low temperatures. The figure below, shows the cooling capacity of a specific compressor with a swept volume of 1,000 m^3/h.

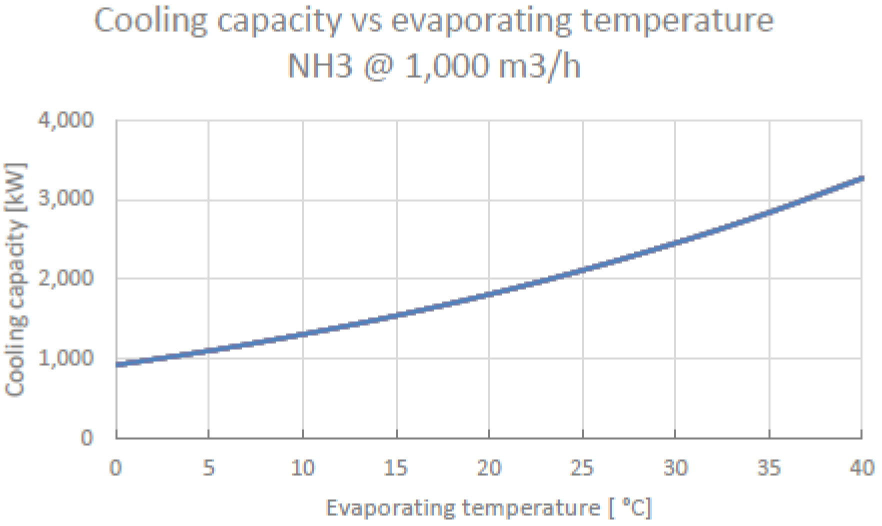

Figure 31: Cooling capacity of a specific compressor dependent on evaporating temperature

Therefore, the heat capacity of heat pumps utilizing ambient heat sources is usually greatest during summer. The figure shows the performance of a specific compressor at certain DH temperatures and serves only as an example. The relation can differ dependent on the specific design. For assessments it is thus important to notice capacity deviations for the specific plants considered, as well as variations in temperatures.

Additional information for compression heat pumps

The most relevant heat sources for heat pumps are at the moment ambient air, industrial excess heat and seawater.

Air source heat pumps can be more complex to operate than other types, where the heat source is based on water or glycol. It is important to be particularly thorough regarding design and dimensioning of the air coolers, where leaves, dust or frost can block the airflow. Furthermore, wrong placing or inadequate space around the coolers can cause short-circuits of the cooled air. In this case already cooled air will return to the cooling surface reducing the flow of fresh and “warm” air.

All in all, the design and dimensioning of cooling surfaces have great impact on the performance of air source heat pumps, decreasing both heat capacity and COP of the heat pump when designed inadequately.

Defrosting is also important to address properly. Frost should be detected precisely and dynamic defrosting only be provided when needed. Earlier air source heat pumps stopped heat production entirely while defrosting, whereas newer plants continue at reduced or full capacity while defrosting.

Earlier plants were estimated to use 2-2.5 % of the annual heat production to defrost the cooling surfaces. This has been reduced to around 1 % for recently installed smaller plants using secondary circuits, whereas larger plants using refrigerant directly in the air coolers utilize excess heat in the refrigerant to provide defrost without reducing the heat production.

Absorption heat pumps

In absorption heat pumps, high temperature heat is used to regenerate a refrigerant that can evaporate at a low temperature level and hereby utilize low grade energy. Energy from both drive heat and the low temperature heat source is delivered at a temperature in between to the sink. In theory 1 kJ of heat can regenerate around 1 kJ of refrigerant meaning that an absorption heat pump has a theoretical maximum COP of 2. Due to losses in the system the practically attainable COP is around 1.7.

For absorption heat pumps, COP is not affected by temperature levels. Certain temperature differences are required to have the process going, but as long as these are met the COP will be around 1.7 and are not affected by further temperature increase of the drive energy. The different temperature levels in both drive energy, heat source and DH affect each other meaning that a certain DH temperature is only possible, with and appropriate heat source and/or certain temperature level of the drive energy. This is important to consider, as these boundaries can the technology in some applications.

The energy flow is illustrated in the Sankey diagram in below figure:

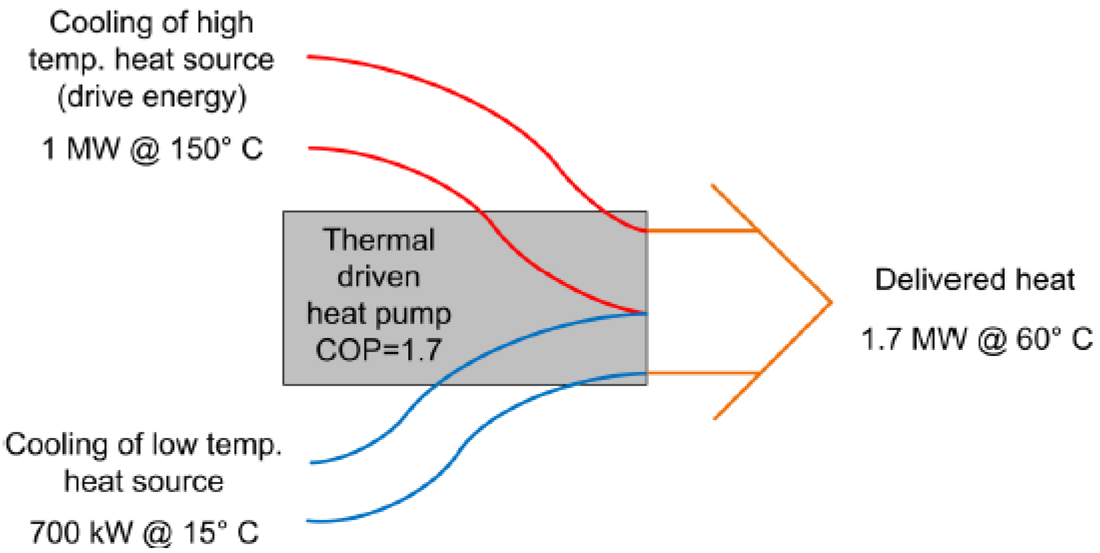

Figure 32: The high temperature drive energy of 1 MW enables the heat pump to utilize 700 kW from a low temperature heat source at 15 °C. Thus delivering 1.7 MW at 60 °C (COP is 1.7).

Two-stage versions are available for particularly high driving temperatures. In two-stage absorption heat pumps, the drive energy is used twice enabling the heat pump to utilize almost twice as much low-grade energy. The practically attainable COP of two-stage systems is typically 2.3.

Input

Heat pumps require drive energy and a heat source.

Drive energy for compression heat pumps is mechanical energy, typically provided by electricity in an electric compressor, but engines consuming fuel or biogas can also be used.

Drive energy for absorption heat pumps is heat; e.g. steam, hot water or flue gas. It also consumes a minor amount of electricity.

Heat sources can be ambient air, surface water or groundwater, ground (soil) or surplus heat from industries. Typical Kazakhstan temperatures are xx°C as ambient air temperatures and xx°C as groundwater temperature, whereas excess heat from industrial processes has much higher temperatures – sometimes enabling direct heat recovery. In some cases, the input heat is delivered through a secondary water or glycol circuit, but for optimum performance the heat source should be connected directly to the evaporator of the heat pump.

Plants utilizing ground water and surface water from lakes or streams could be investigated for other plants. Though, these energy sources often conflict with other interests as domestic water supply and/or environmental aspects, which typically results in very time consuming regulatory approvals.

Because of this and due to lower prices of electricity, air source heat pumps is the main type installed currently as well as a few heat pumps utilizing industrial excess heat where available.

For larger central plants it is expected that seawater can be utilized in addition to fuel based combined heat and power production.

This chapter focus on ambient air, industrial excess heat and seawater (for large central plants) as heat sources for compression heat pumps, since these are considered most relevant although other types can be relevant in specific cases.

Due to technical reasons, absorption heat pumps are limited to heat sources warmer than approximately 15°C. Therefore, it is not possible to utilize ambient sources and the technology is primarily suitable for industrial excess heat and flue gas from combustion.

Output

Heat is defined as the only output in this chapter, but cooling (which is the input from the heat source) can also be regarded as a useful output. For large scale heat pumps the heat will typically be delivered to the end user through a water based DH system.

The maximum delivery temperature differs according to type (compression or absorption heat pump) and also within either type depending on the actual refrigerant, design pressure and more. The most commonly used types can reach temperatures of around 73°C, and is the focus of this chapter and data sheets. More expensive high pressure versions are available where 80°C or 90°C are needed. Special compression heat pumps can reach up to 100 - 110°C, but these are only applicable in certain applications.

Absorption heat pumps are limited to around 85 - 87 °C but the specific delivery temperature depends on the temperature of the heat source.

Typical capacities

Ammonia compressors for large scale compression heat pumps, are commercially available in capacities of up to around 10 - 12,000 m^3/h, thus providing cooling capacities of around 10 MW at an evaporating temperature of 0°C and 20 MW at 20°C. Depending on temperature requirements a heat pump system often consist of several compressor stages to reach the highest efficiency. Depending on the heat source and delivery temperature, it is expected that heat pumps of more than 25 MW will be a number of heat pump units in parallel. Mainly ammonia as refrigerant in combination with positive displacement compressors is used in heat pumps. With the introduction of low-GWP HFC's the use of turbo compressors is also possible, which could be beneficial for even larger plants.

Absorption heat pumps are available in capacities of up to around 12 MW of cooling. The heat output including drive energy will thus be around 20 MW.

Dynamic response

Regulation ability is a topic currently being investigated in several projects.

As today's market is very limited, large scale heat pumps are not constructed for very fast start/stop or load changes. Using adequate secondary water systems and control methods around the heat pump can enable most large scale heat pumps to fast starts and stops. In practice, the possibilities depends on the specific heat pump construction and system requirements as outlet temperatures, efficiencies and more will be affected from fast load changes.

Advantages/disadvantages

The table below summarizes the main advantages and disadvantages for the different types of heat pumps and applications.

Table 12: Advantages and disadvantages of heat pumps.

Type	**Compression**			**Absorption**
Heat source	**Ambient air**	**Excess heat**	**Seawater**	**Excess heat**
Advantages				
Utilization of low temperature heat sources	x	x	x	x
Coupling of electricity- and heat sector	x	x	x	
Yields higher thermal output than required driving energy (COP > 1)	x	x	x	x

Can be installed in locations with restrictions on exhaust emissions	x	x	x	
Can supply combined heating and cooling		x		
Disadvantages				
Working principle is still unfamiliar to parts of the heating industry	x	x	x	x
High COP requires low temperature difference between source and sink	x	x	x	(x)
Changes in flow or temperature of the heat source affects the performance of the heat pump (capacity and COP), which can increase the complexity of the system	x	x	x	x
High specific investment costs	x	x	x	x
May not be available during coldest periods			x	

A general advantage of heat pumps is that the heat pump is able to recycle excess heat or utilize energy from the ambient which enables utilization of heat sources otherwise left unused by conventional heat production technologies.

In energy systems where electricity plays a vital role, compression heat pumps can incorporate electricity in heating systems in an effective manner. For processes that are electrically heated, heat pumps reduce power consumption and load on the electrical grid.

Compression heat pumps that are electrically driven have no direct emissions from burning fuel, meaning that these systems can be installed in locations with restrictions on exhaust emissions.

Absorption heat pumps utilize the energy quality of high temperature heat sources where exergy is otherwise wasted when for instance a boiler is used to heat water up to 70°C or 80°C. In such applications, absorption heat pumps are able to exploit heat from the boiler at a higher temperature to recover heat from a lower temperature, thus reducing fuel consumption by approximately 40%.

Compared to traditional heating technologies, heat pumps utilize a different working principle that is still unfamiliar to parts of the heating industry.

In order to reach high COP heat pumps require low temperature differences between source and sink. Therefore, heat pumps are best suited in low temperature systems.

The heat source must be available and suitable according to the required heat demand. Changes in flow or temperature of the heat source will affect the performance of the heat pump (also heat capacity and O&M), which can increase the complexity of a heat pump system.

Compared to most of the traditional heat production systems, heat pumps in general have higher investment costs, and lower energy consumption costs.

Environment

The primary environmental impact of heat pumps stems from the drive energy consumption and depends on the fuel type and production method. Absorption heat pumps are typically applied where fuel is already burned, meaning that the absorption heat pumps does not increase fuel consumption, but simply increase the heat output of an existing energy consumption.

Greenhouse emissions from refrigerants are negligible as the legislation in some countries prevents high GWP-refrigerants in circuits with more than 10 kg of refrigerant. Therefore, heat pumps with a heat capacity of more than 60 - 80 kW use natural refrigerants or low GWP-HFC’s.

Ammonia can be dangerous to mammals and especially aquatic life forms. Therefore, ammonia systems must comply with certain safety measures regarding construction, location and operation. Other natural refrigerants are highly flammable but not environmentally harmful.

Fans and cooling surfaces for air source heat pumps produce a small amount of noise that must be considered when installing such plants. Practical experience show that this is suitably addressed by providing plenty of cooling surface to limit fan and air speed. With this approach, it is possible to install air source heat pumps close to residential areas. In general noise problems regards the compressors and noise insulation of the building (which is similar for heat pumps utilizing other heat sources than ambient air) rather than the cooling surfaces.

CO_2 heat pumps operate in the so-called trans-critical pressure range, meaning that the refrigerant has a temperature glide on the warm side while the cold side evaporate at a constant temperature. This means that CO_2 is particularly suited in applications where heat is drawn from a low temperature source by cooling it only a few degrees, while the delivered heat is provided at a temperature glide of maybe 40°C. The maximum outlet temperature of CO_2 systems is app. 90°C. In order to obtain good COP values in CO_2 systems the inlet temperature of the heated media should not be higher than app. 40°C.

Hybrid H_2O/NH_3 heat pumps combine the absorption and the vapour compression cycles, hence the name hybrid. Ammonia is used as refrigerant but absorbed by H_2O thus at reduced working pressure meaning that standard components can be used for high temperatures. The maximum temperature in systems in operation is around 90°C but it is possible to reach higher temperatures using the same components.

Hydrocarbons are primarily used in medium sized applications where either propane or isobutane is used as refrigerant. These refrigerants can be used with standard components from commercial refrigeration meaning that investment costs are kept at a low level. Propane can reach temperatures of 65°C whereas isobutene can reach temperatures of around 85°C. These refrigerants are flammable meaning that heat pumps are often delivered in a special cabinet and installed outdoors.

LiBr/Water is used in absorption heat pumps whereas ammonia/water is typically used in absorption cooling systems. Water is the refrigerant meaning that the gauge working pressure is negative. The lowest possible temperature on the source side is around 6°C while the sink temperature can be up to around 85°C. The different temperatures influence each other meaning that a low source temperature can limit the delivery temperature for the heat sink.

For higher temperature lifts, it is possible to buy absorption plants where two systems are built in to one and connected in series to increase the temperature lift.

Quantitative description

A key point regarding application of the data in the data sheets is that the COP may vary considerably depending on the specific temperature set. If the temperature levels of a project does not match the temperatures for the given data sheet, it is advised to adjust the COP according to the outlined method in the subsection describing *COP calculation* in Brief technology description.

Application of the data in the data sheets for specific calculations of a project should be evaluated according to the specific local conditions. Many factors influence performance and investment costs, and the data sheets should only be considered as estimates for average installations.

Data sheets

The following types and sizes are covered in these technology sheets:

- 1 MW Compression heat pumps using ambient air as heat source
- 3 MW Compression heat pumps using ambient air as heat source
- 10 MW Compression heat pumps using ambient air as heat source
- 1 MW Compression heat pumps using industrial excess heat as heat source*

- 3 MW Compression heat pumps using industrial excess heat as heat source*
- 10 MW Compression heat pumps using industrial excess heat as heat source*
- 20 MW Compression heat pumps using seawater as heat source
- Large single effect absorption heat pumps

*Data for excess heat is based on cooling water that is cooled from 25 to 15 °C.

The data in all sheets are based on plants that has at least 6,000 annual operating hours and operates for 15 years or more. This mean that energy consumption makes up for most of the costs considering the life cycle costs. Because of this, plants with less operating hours/years, might be designed with lower efficiencies.

Data sheet 35 - Compression heat pumps, air source, small

Air source heat pumps 1 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	1
Total efficiency, net (%), name plate	255
Total efficiency , net (%), annual average	290
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.5
Space requirements (1000m2 per MWheat)	1
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	1.69
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	3.27

Data sheet 36 - Compression heat pumps, air source, medium

Air source heat pumps 3 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	3
Total efficiency, net (%), name plate	310
Total efficiency , net (%), annual average	340
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.7
Space requirements (1000m2 per MWheat)	0.8
Regulation ability	

Air source heat pumps 3 MW	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	1.15
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	2.66

Data sheet 37 - Compression heat pumps, air source, large

Air source heat pumps 10 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	10
Total efficiency, net (%), name plate	350
Total efficiency , net (%), annual average	380
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.7
Space requirements (1000m2 per MWheat)	0.6
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	1.04
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	2.06

Data sheet 38 - Compression heat pumps, excess heat, small

Heat pumps utilizing industrial waste heat 1 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	1
Total efficiency, net (%), name plate	400
Total efficiency , net (%), annual average	410

Heat pumps utilizing industrial waste heat 1 MW	
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.5
Space requirements (1000m2 per MWheat)	0.1
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	1.50
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	3.27

Data sheet 39 - Compression heat pumps, excess heat, medium

Heat pumps utilizing industrial waste heat 3 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	3
Total efficiency, net (%), name plate	450
Total efficiency , net (%), annual average	460
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.5
Space requirements (1000m2 per MWheat)	0.05
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	1.04
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	2.66

Data sheet 40 - Compression heat pumps, excess heat, large

Heat pumps utilizing industrial waste heat 10 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	10
Total efficiency, net (%), name plate	500
Total efficiency , net (%), annual average	510
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	0.5
Space requirements (1000m2 per MWheat)	0.03
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.1
Cold start-up time (hours)	1
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Specific investment (M$US per MJ/s)	0.81
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	2.06

Data sheet 41 - Compression heat pumps, seawater

Heat pumps utilizing sea water 20 MW	
Energy/technical data	
Heat generation capacity for one unit (MJ/s)	20
Total efficiency, net (%), name plate	340
Total efficiency , net (%), annual average	370
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	1
Technical lifetime (years)	25
Construction time (years)	1
Space requirements (1000m2 per MWheat)	0.03
Regulation ability	
Primary regulation (% per 30 seconds)	5
Secondary regulation (% per minute)	10
Minimum load (% of full load)	25
Warm start-up time (hours)	0.2
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	

Heat pumps utilizing sea water 20 MW	
Financial data	
Specific investment (M$US per MJ/s)	0.58
Fixed O&M ($US/MJ/s/year)	4,840
Variable O&M ($US/MWh)	1.45

Data sheet 42 - Absorption heat pumps

Absorption heat pumps - district heating	
Energy/technical data	
Heat generation capacity for one unit (MWheat) (excluding drive energy)	12
Total efficiency, net (%), name plate	N/A
Total efficiency , net (%), annual average	170
Electricity consumption for pumps etc. (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	0
Technical lifetime (years)	25
Construction time (years)	0.5
Space requirement (1000m2 per MW)	0.01
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	10
Warm start-up time (hours)	0
Cold start-up time (hours)	0.5
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MWheat) (excluding drive energy)	0.73
Fixed O&M ($US/MWheat/year)	2,420
Variable O&M ($US/MWhheat)	1.09

Electric Boilers

Brief technology description

Electric boilers are devices in the MW size range using electricity for the production of hot water or steam for industrial or district heating purposes. They are usually installed as peak load units in the same way as an oil or gas boilers. Hence, the following description of electric boilers is based on an operation strategy, aiming at approx. 500 full-load hours/year.

The conversion from electrical energy to thermal energy takes place at almost 100% efficiency. However, from an exergetical point of view, this technology should be justified by its systemic advantages. Cf. electric water heaters can be a part of the energy system facilitating utilization of wind energy and enabling efficient utilization of various heat energy sources.

Thus, the application of electric boilers in district heating systems is primarily driven by the demand for ancillary services rather than the demand for heat. Although, examples of electric boilers, that operate on the spot market can be found.

Generally, two types of electric boilers are available:

- Heating elements using electrical resistance (same principle as a hot water heater in a normal household).Typically, electrical resistance is used in smaller applications up to 1-2 MW. These electric boilers areconnected at low voltage (e.g. 400 or 690 V, depending on the voltage level at the on-site distribution board).
- Heating elements using electrode boilers. Electrode systems are used for larger applications. Electrodeboilers (larger than a few MW) are directly connected to the medium to high voltage grid at 10-15 kV(depending on the voltage in the locally available distribution grid).

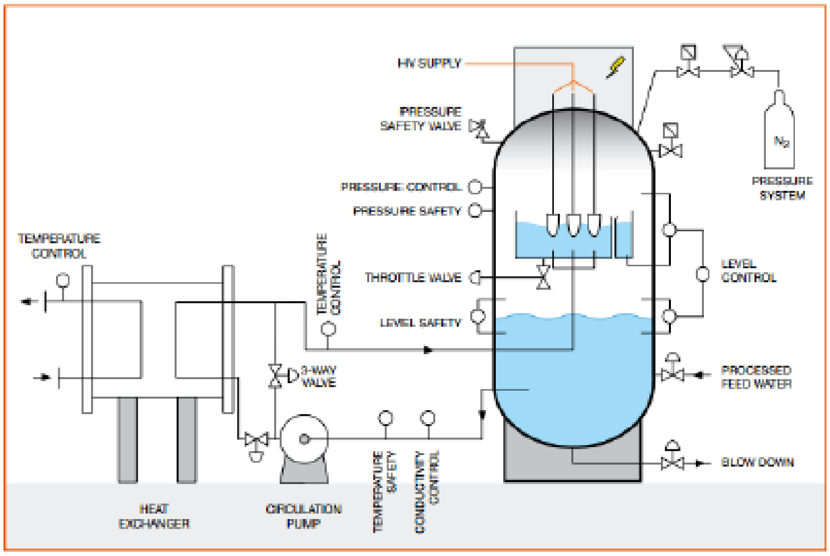

Figure 33: Schematic illustration of an electrode boiler. The heat is generated in the upper chamber through ohmic resistance between the electrodes. The boiler is pressurized with an inert gas system, e.g. nitrogen.

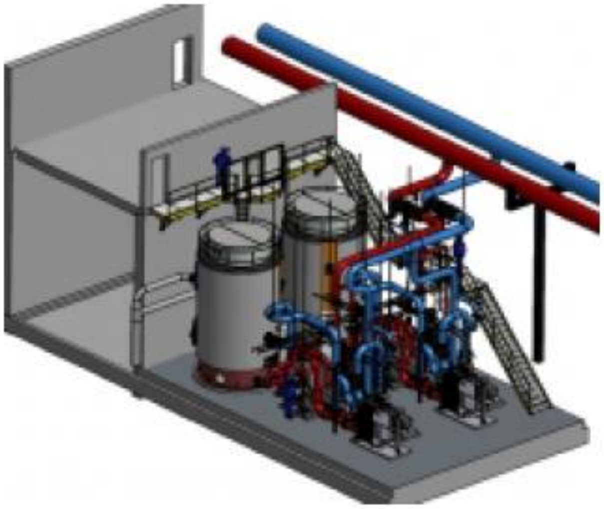

Figure 34: Illustration of 2x40 MW electric boilers installed at a power plant. The heat exchangers in front of the electric boilers transfer the heat from the water circuit in the boiler to the district heating circuit (blue/red piping).

The water in electrode boilers is heated by means of an electrode system consisting of (typically) three-phase electrodes, a neutral electrode and a water level & flow control system. When power is fed to the electrodes, the current from the phase electrodes flows directly through the water in the upper chamber, which is heated in the process. The heat production can be varied by varying the flow through the upper chamber and the power that is led through, thus enabling output to be controlled between 0 and 100%.

In a similar technology, the heat output is varied, by varying the contact area between water and electrodes, by covering the electrodes in control screens. Thus the contact area between water and electrodes can be varied by varying the water level around the electrodes.

In both technologies, there will be no high-voltage consumption in a stand-by situation, as the only stand-by consumption is due to circulation pumps, which lies in the range of 5% of full load.

Input

Electricity.

Output

Heat (hot water).

Typical capacities

Resistance-boilers are available in the span 6-5,000 kW/unit.

Electrode boilers are available in the seamless span 0 - 60 MW/unit, with typical appliances being 5 - 50 MW/unit.

Larger applications are typically a combination of multiple single units.

Space requirements

The net space requirements of electric boilers are in the range of 20 - 40 m^2/unit with a total height of approx. 5 - 6.5 m. Examples of smaller units can be found as well. Furthermore, there is a space requirement of approx. 50 - 100 m^2/appliance for heat exchangers, piping etc.

Regulation ability

Electric boilers can participate in up- and downward regulation. Modern electrode boilers have a minimal standby consumption when used as frequency-controlled reserves (down regulation). The standby consumption varies with the type of electric boiler. New electrode boilers of e.g. 12 MW have electricity consumption down to a few kW and no consumption at high voltage. Older types may have a standby consumption of 5 - 10%. The above mentioned new generation of electrode boilers operate in such a way that the voltage is kept in the boiler, without applying any power. Using this technology, the only “stand-by consumption” is related to internal pumps and electric boilers can start with close to no standby consumption. Considering the close to none standby demand, many plants chose to keep the boiler operating in standby mode in order to be able to utilize the electrode boilers immediately when necessary.

Alternatively, it is possible to offer regulating power from cold start, hence eliminating the need for a standby consumption. This is made possible ramp up times of approx. 5 minutes in cold start situations, typically being shorter than necessary to participate on e.g. the power balancing market. However, due to the above-mentioned minimal standby consumption, operation on electrode boilers in standby is very common. The load shift from 0 - 100% of nominal capacity is approx. 30 seconds.

Advantages/disadvantages

Advantages

Due to its very simple design, the electric boiler is extremely dependable and easy to maintain. The boiler has no built-in complex components, which may impede operation and maintenance. The boiler has quick startup and fast load-response. It requires no fuel feeding systems and no stack.

Disadvantages

As the input energy is electricity, the operating costs are subject to the variation in the electricity prices (market dependent) and the taxes on electricity. Electricity prices thus constitute a major part of the operation costs, without being the only factor to consider when evaluating the economy of operation.

In case electric boilers utilize power from thermal power production, exergetical losses will have to be considered in the evaluation of the total energy balance. Depending on the type of grid connection (full/limited), the availability of the electric boiler may be limited, as explained in the Brief technology description.

Environment

During operation, the electric boiler uses electricity and the environmental impact from operation depends on the origin of the electricity. Apart from the emissions, due to the consumed electricity, electric boilers have no local environmental impact.

Additional remarks

The operating costs of an electric boiler are highly dependent on the costs of electricity, i.e. the market price of electricity and currently applicable taxes and fees. Thus, heat production on electric boilers in e.g. a district heating plant can only compete with other heat production units at low electricity prices (e.g. in periods with high wind power production).

The number of full-load hours (heat) for electric boilers is assumed to be 500 according to the Guideline.

Data sheet 43 - Electrical boilers

Electric boilers, 400 or 690 V, 0.06-5 MW; 10 or 15 kV, >10 MW	
Energy/technical data	
Heat generation capacity for one unit (MW)	5
Total efficiency, net (%), name plate	99
Total efficiency , net (%), annual average	99

Electric boilers, 400 or 690 V, 0.06-5 MW; 10 or 15 kV, >10 MW	
Electricity consumption for pumps etc. (% of heat gen)	0.5
Forced outage (%)	1
Planned outage (weeks per year)	0.2
Technical lifetime (years)	20
Construction time (years)	0.5
Regulation ability	
Primary regulation (% per 30 seconds)	100
Secondary regulation (% per minute)	100
Minimum load (% of full load)	5
Warm start-up time (hours)	0.008
Cold start-up time (hours)	0.08
Financial data	
Nominal investment (M$US per MW), 400/690 V; 1-5 MW	0.18
Nominal investment (M$US per MW); 10/15 kV; >10 MW	0.08
Fixed O&M ($US/MW/year)	1,295
Variable O&M ($US/MWh)	1.09

Geothermal district heating

Brief technology description

A Geothermal district heating (DH) plant extracts heat from underground water reservoirs. Each plant consists of a number of wells and installations on the surface. Hot water (called the brine) is pumped from deep underground natural occurring reservoirs. The brine has a temperature below 100°C and the heat is extracted using a heat exchanger and possibly a heat pump. Afterwards the heat depleted brine is returned to the reservoir. The scope for this chapter is geothermal plants exploiting permeable sandstone reservoirs.

Recent definitions of geothermal energy include all heat from the ground. In the context of the technology chapter at hand, only heat production from deep wells (1,000 – 3,000 m) is described. The following section cover other uses of ground source-based heat production and storages, such as ground source heat pumps and aquifer thermal energy storage:

- Technology Data for Individual Heating Installations
- Technology Data for Energy Storage

The geothermal potential of a well can be expressed by two key factors: The temperature in the well and the permeability of the sedimentary layers found in the reservoir. On average the temperature of the reservoir increases with around 25-30°C per 1 km depth. The permeability is roughly halved for each 300 m of depth. Further, the energy yield from a well is limited by the thickness and continuity of the reservoir layer.

In the typical system, warm geothermal water is pumped to the surface from one or more production wells, where heat is extracted via heat exchangers and possibly a heat pump and the heat depleted brine pumped back into the source reservoir via one or more injection wells to maintain the pressure. The figure below shows a system with two wells, a so-called doublet system. As shown, a certain lateral spacing in the reservoir between production and reinjection wells is necessary. This can be obtained with deviated well trajectories (as the figure shows) or, from a drilling point of view simpler, with vertical wells and a horizontal transmission pipe on the surface.

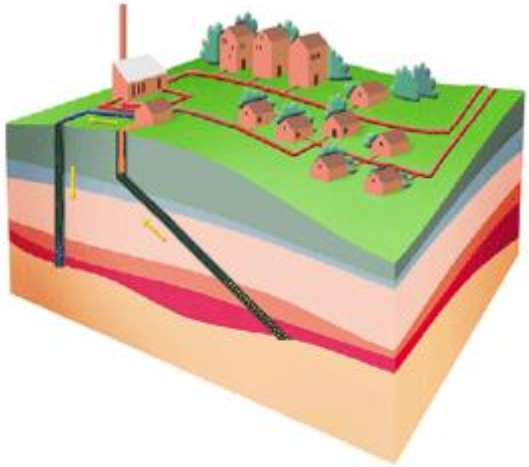

Figure 35: The principle of a doublet system geothermal plant producing to a DH system

Heat from deep reservoirs can be utilized directly through a heat exchanger, if the demanded temperature is lower than the temperature of the reservoir. Typically, heat pumps are applied to meet the demand temperature, as geothermal resources in most cases are not sufficiently hot to utilize the heat directly. Likewise, use of heat pumps increases production capacity by cooling the brine before reinjection. The geothermal water has a high content of salt - often 10 - 20% (weight - %) - and various other minerals.

Geothermal District Heating

A key parameter in the design phase of a geothermal DH plant is the set of temperatures (supply/return) in the connected DH grid. As the temperature of the geothermal well is usually insufficient, it is often boosted using a heat pump. The efficiency of the heat pumps increases with lower temperature differences between heat source and heat sink, so reducing the DH supply temperature generally increases the feasibility of geothermal DH.

Another important factor regarding the operation phase is the pumping costs. The use of deeper reservoirs with higher temperatures will generally also increase pumping costs, due to lower permeability generally expected for deeper reservoirs.

The return temperature of the DH system is also crucial, possibly enabling direct heat exchange with the geothermal water for a part of the energy thereby increasing the overall system efficiency.

However, there are examples of projects, where the ambition is to achieve the required supply temperature without the use of heat pumps. Avoiding heat pumps is a trade-off. While it does omit the investments in the heat pumps, the direct use of geothermal energy would also require deeper wells and increased pumping – both of which increase overall costs.

Combining Geothermal Wells with Heat Pumps

Increasing the supply temperature with heat pumps implies a higher reduction of the return temperature of the geothermal water before it is pumped back to the reservoir via the injection well, resulting in an increased heat extraction from the geothermal water. However, the possibility for this depends on the chemistry of the water. Hence, applications with heat pumps could increase the efficiency by extracting more heat energy from the geothermal water but also increase the risk of clogging of the injection well.

The figure below presents a simplified illustration of a possible application of geothermal energy for DH. Part of the geothermal heat (46) is used for direct heating of the return water from the DH network, while the remainder (54) is used as heat source for an absorption heat pump. The COP of the heat pump is approx. 1.7. Thus, the total heat output of the system equals the geothermal input plus the drive energy: 100 + 76 = 176 and the COP of the total system is approx. 2.1 * (176 / (76+8)).

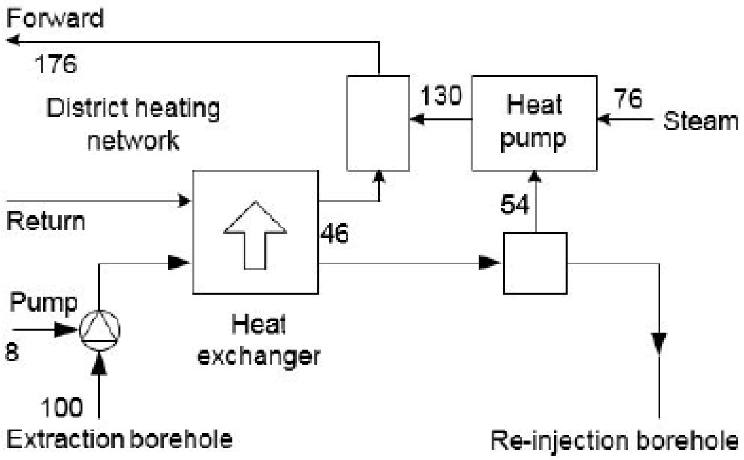

Figure 36: Example of a geothermal system with an absorption heat pump. The numbers indicate the energy flows relative to the extracted amount of geothermal heat from the reservoir, which is set 100 energy units. The heat pump COP is 1.7 and the total efficiency of the system is approximately 2.1.

The thermal energy to drive the absorption heat pump (76 energy units) may be delivered by a DH plant (e.g. biomass boiler or waste incineration plant), usually at 120 - 150°C.

Electricity consumption for the geothermal circulation pumps is normally 2 - 10% of the heat extracted from the geothermal water, but the exact number depends on a range of factors, e.g. the depth and properties of the reservoir, and the cooling of the geothermal water.

In all cases the energy used for the electrical submersible pump will to some extent be recovered as heat in the geothermal water. However, as a rough estimate, the heat losses in the well will correspond to the energy used for pumping, and thus 100 energy units are assumed available for DH.

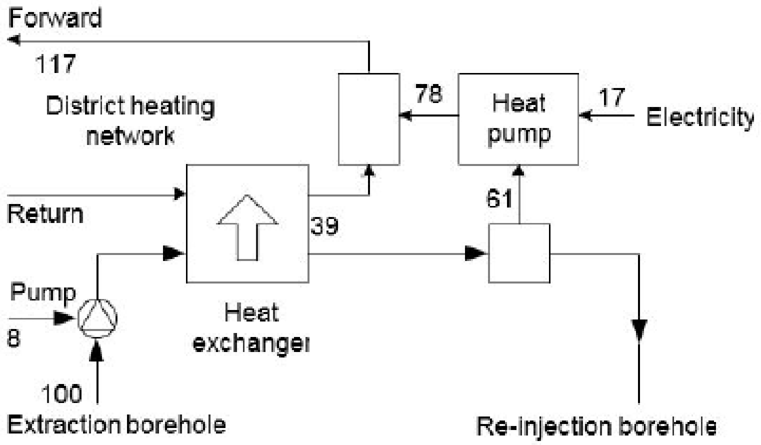

Figure 37: Example of a system with an electric heat pump. The COP of the electric heat pump is approximately 4.6 and the total efficiency (COP) of the system is approximately 4.7.

As shown in the above figure, electric heat pumps can extract relatively more geothermal energy than absorption heat pumps as their drive energy constitute a smaller part of the heat output.
Note that the auxiliary energy in the above cases is included in the total efficiency.

Input

Heat from brine (saline water) from underground reservoirs.

Indirectly, in order to increase the temperature to the appropriate level in the DH systems, electricity or thermal energy is needed in heat pumps, cf. the above section regarding technology-combinations of geothermal wells and heat pumps. The thermal energy may be supplied as steam or high-pressure hot water, through combustion of (bio-)fuels or as excess heat.

Electricity for submersible and reinjection pumps.

Output

Heat for DH.

Typical capacities

5-20 MW per plant (1-3 production wells and 2-6 injection wells) without heat storage.

Regulation ability

The geothermal flow should, as a rule, be operated continuously. However, in combination with electrical heat pumps, up- and down-regulating services can be provided. Up-regulation by turning off heat pumps (reducing the electricity consumption) and down-regulation by increasing the power consumption (and hence output) of the heat pumps. In this case, the operation can be varied 20 - 100%. The flexibility can also be obtained by applying a heat storage. This is, however, only relevant to a limited extent, since the geothermal production is primarily base load and, in general, will be operated as such.

Advantages/disadvantages

Advantages:

- Low costs in operational phase and low variable costs
- Renewable energy source and environmentally friendly technology with low or no direct CO_2 emission
- High operation stability and long lifetime
- Potential for combination with other production technologies and heat storage
- Limited area requirement
- No noise
- No direct emissions
- Local resource – security of supply
- Stable long-term production costs, once in operation

Disadvantages:

- A high geological risk persists until the first well has been drilled and the reservoir has been tested
- High investment costs
- Extensive project period for development and construction
- Needs access to a heat sink with a corresponding base load or a long-term storage
- The best reservoirs are not always located near cities (can partly be addressed through transmission pipes)

Environment

Utilization of geothermal energy does not result in any local emissions. The largest challenge is handling of geothermal water on the surface. At start up, the loop is opened to save on filter capacity and for the first few hours the water is led to a recipient, if possible. Noise during the construction phase is an issue. Drilling is typically on-going 24 hours a day for a 3 month period.

Indirectly, in case of application of thermally driven heat pumps, there may be environmental considerations, related to the energy source/fuel used to drive the heat pump. Correspondingly, when electric heat pumps are chosen, there may be emissions related to electricity consumption.

Quantitative description

The heat generation costs for geothermal energy depend primarily on geological data (depth, thickness, permeability and temperature) and the heat system (heat demand, duration curve and forward/return temperatures)..

For the context of this catalogue, six different scenarios for geothermal DH are described, varying by the factors:

- heat pump type (absorption or electrically driven),
- reservoir depth with anticipated temperature (1,200m / 44°C and 2000m / 68°C)
- supply and return temperature in the connected DH-grid (80/40°C and 70/35°C)

Thus, scenarios 1 and 2 describe possible plant designs for DH plants with a supply temperature of 80°C and a return temperature of 40°C. In scenario 3.a and 3.b, a system with a supply temperature of 70°C and 35°C return is presumed. Scenarios 3.a and 3.b are primarily to be used to evaluate the effect of temperature decreases on the secondary side, when comparing 1.a with 3.a and 1.b with 3.b respectively. The assumption in the given scenarios are collected in below table.

Table 13: Scenario-overview for described combinations of geothermal reservoir, heat pumps and DH temperatures

	Heat pump type		Reservoir temp. (°C)		Reservoir depth	DH temp. (°C)	
Scenario	Electric	Absorption	T_{res}	T_{reinj}	m	T_{supply}	T_{return}
1.a	X		44	17	1,200	80 / 40	
1.b			68	33	2,000		
2.a		X	44	17	1,200		
2.b			68	33	2,000		
3.a	X		44	17	1,200	70 / 35	
3.b			68	33	2,000		

Energy data

The corresponding energy production data and need for auxiliary energy input has been assessed based on design and operating experiences from above mentioned reference plants:

- Production wells:
  - 2 production wells
  - Specific flow: 160 m^3/hour/well
  - Total flow: 320 m^3/hour/plant

- Reinjection wells:
  - 4 reinjection wells
  - Specific flow: 80 m^3/hour/well
  - Total flow: 320 m^3/hour/plant

For the a-scenarios (1,200 m reservoir depth) this results in 9.4 $MWth_{geothermal}$ heat and for the b-scenarios (2,000 m reservoir depth) 12.2 $MWth_{geothermal}$ heat.

The thermal effect in the datasheet is stated as heat source from the geothermal reservoir at the given amount of wells with a given flow and a given temperature (th_{geo}) and the energy added as drive energy for a heat pump (th_{HP}; electricity for electrical compressor heat pumps or net heat from a boiler for absorption heat pumps).

If the reservoir temperature exceeds the return temperature of the connected DH grid by more than 4 K (assumed loss of a heat exchanger), direct heat exchange is assumed to cover as much as possible of the heat production. The remaining geothermal heat is presumed to function as heat source for a heat pump.

For electrical heat pumps the efficiency (COP factor) is calculated using a publicly available tool with a Lorenz efficiency of 50%.

Table 14: Key energy data cf. the technology data sheets

	Heat pump type		DH temp. °C)	Thermal power, total	Thermal power, geothermal	Thermal power, heat pumps	Electricity consumption for pumps etc.
Scenario	El.	Abs.	T_{supply} / T_{return}	(MW)	(MW)	(MW)	(kWh_{el} / kWh_{geoth}
1.a	X		80 / 40	11.4	9.4	2	0.05
1.b				13.2	12.2	1	0.08
2.a		X		22.9	9.4	13.4	0.05
2.b				17.7	12.2	5.5	0.08
3.a	X		70 / 35	10.9	9.4	1.5	0.05
3.b				12.7	12.2	0.5	0.08

The total efficiency for a geothermal plant is calculated as the total heat output divided by the energy input, i.e. the energy input for both heat pumps and auxiliary electricity. The energy consumption for submersible and circulation pumps is assumed in case of reservoir depth 1,200 m to be 0.05 kWh_{el}/kWh_{geoth} and for reservoir depth 2,000 m to be 0.08 kWh_{el}/kWh_{geoth} as the pumping requirement increases with lower permeability generally expected for deeper reservoirs.

Financial data

The stated cost and performance data cover the geothermal plant itself as well as investments in heat pumps. The cost of the compression heat pump is assumed to be 0.67 M$USMW and 0.56 M$US/MW for absorption heat pumps. The actual COP factors for electric heat pumps have been calculated, using a publicly available tool.

The boundary for the financial data is outlined in below figure. In case of absorption heat pumps the technology to generate the drive energy input is not included. This input can by sourced from existing or new boilers or other technologies that can supply the heat at a sufficiently high temperature. However, as the drive heat is defined as an input it is also included in the output.

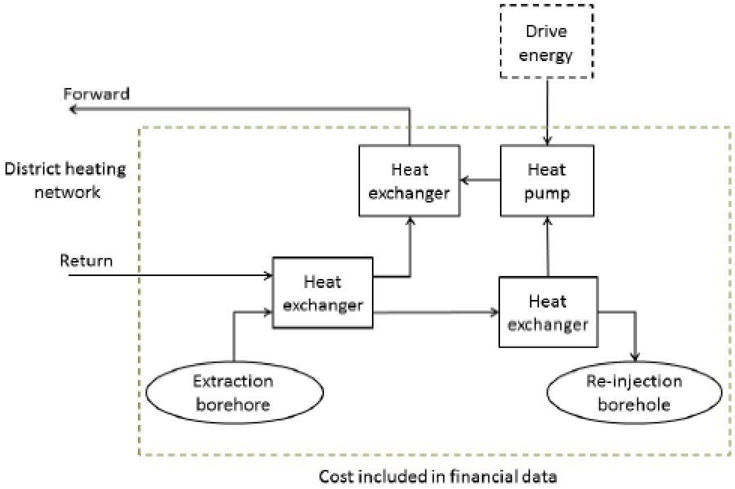

Figure 38: Boundary for financial data in data sheets

The financial data are given based on the total heat capacity (output) delivered by the geothermal plant to the DH system. However, the data is presented so that it becomes transparent which shares of costs relate to heat pumps and which to the geothermal plant itself.

The investment costs for a geothermal plant has been based on actual data from specific plants. Note that investment costs for plants with deeper wells may be considerably higher, as drilling equipment requirements, well dimensions etc. will increase. Cost for injection- and production wells are estimated to be 1,800 $US/m for 1,200 m reservoir depth and 2,000 $US/m for 2,000 m reservoir depth.

The stated costs do not include decommissioning costs.

Cost components of geothermal plant

The estimated project cost in 2020, for a 12 MW geothermal plant 1.a - 1,200 m reservoir depth with electrical heat pump, can be seen in below figure. Note that project development costs are not accounted for in the datasheets, cf. guideline. These are estimated to 1.5 - 3 M$US/site. Also, the cost differs between the scenarios/datasheets.

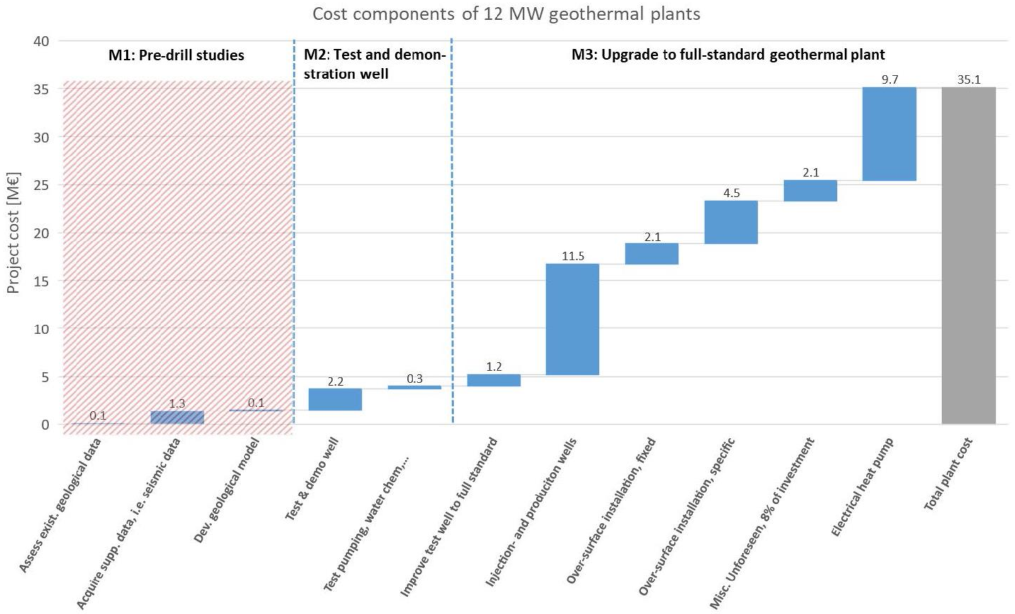

Figure 39: Cost components of a 12 MW geothermal plant 1.a - 1,200 m reservoir with electrical heat pump.

Data sheet 44 - Geothermal district heating, compression heat pump, 1,200 m

Geothermal heat-only plant with electric heat pump, 1,200m. DH temp. 80/40°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	11.4
Total efficiency, net (%) annual average	460
Auxiliary electricity consumption (% of heat gen)	4.1%
Forced outage (%)	2
Planned outage (weeks per year)	2
Technical lifetime (years)	25
Construction time (years)	4.5
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MW)	3.28
Fixed O&M ($US/MW/year)	27,346
Variable O&M ($US/MWh)	6.9

Data sheet 45 - Geothermal district heating, compression heat pump, 2,000 m

Geothermal heat-only plant with electric heat pump, 2,000m. DH temperature 80/40 °C	
Energy/technical data	
Heat generation capacity for one unit (MW)	13.1
Total efficiency, net (%) annual average	844
Auxiliary electricity consumption (% of heat gen)	6.5%
Forced outage (%)	2
Planned outage (weeks per year)	2
Technical lifetime (years)	25
Construction time (years)	4.5
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MW)	3.48
Fixed O&M ($US/MW/year)	28,919
Variable O&M ($US/MWh)	5.57

Data sheet 46 - Geothermal district heating, absorption heat pump, 1,200 m

Geothermal heat-only plant with absorption heat pump, 1,200m. DH temperature 80/40°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	13.1
Total efficiency, net (%) annual average	22.7
Auxiliary electricity consumption (% of heat gen)	165
Forced outage (%)	2.1%
Planned outage (weeks per year)	2
Technical lifetime (years)	2
Construction time (years)	25
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	

Geothermal heat-only plant with absorption heat pump, 1,200m. DH temperature 80/40°C	
Nominal investment (M$US per MW)	1.52
Fixed O&M ($US/MW/year)	13,431
Variable O&M ($US/MWh)	2.54

Data sheet 47 - Geothermal district heating, absorption heat pump, 2,000 m

Geothermal heat-only plant with absorption heat pump, 2,000m. DH temperature 80/40°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	17.6
Total efficiency, net (%) annual average	293
Auxiliary electricity consumption (% of heat gen)	4.9%
Forced outage (%)	2
Planned outage (weeks per year)	2
Technical lifetime (years)	25
Construction time (years)	4.5
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MW)	2.53
Fixed O&M ($US/MW/year)	20,933
Variable O&M ($US/MWh)	3.63

Data sheet 48 - Geothermal district heating, electric heat pump, 1,200 m, reduced DH temperature

Geothermal heat-only plant with electric heat pump, 1,200m. DH temperature 70/35°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	10.9
Total efficiency, net (%) annual average	548
Auxiliary electricity consumption (% of heat gen)	4.3%
Forced outage (%)	2
Planned outage (weeks per year)	2
Technical lifetime (years)	25
Construction time (years)	4.5
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2

Geothermal heat-only plant with electric heat pump, 1,200m. DH temperature 70/35°C	
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MW)	3.27
Fixed O&M ($US/MW/year)	28,072
Variable O&M ($US/MWh)	6.66

Data sheet 49 - Geothermal district heating, electric heat pump, 2,000 m, reduced DH temperature

Geothermal heat-only plant with electric heat pump, 2,000m. DH temperature 70/35°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	12.7
Total efficiency, net (%) annual average	1185
Auxiliary electricity consumption (% of heat gen)	6.7%
Forced outage (%)	2
Planned outage (weeks per year)	2
Technical lifetime (years)	25
Construction time (years)	4.5
Space requirement (1000m2 per MW)	5
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	20
Warm start-up time (hours)	N/A
Cold start-up time (hours)	2
Environment	
SO2 (degree of desulphurization, %)	
NOX (g per GJ fuel)	
CH4 (g per GJ fuel)	
N2O (g per GJ fuel)	
Particles (g per GJ fuel)	
Financial data	
Nominal investment (M$US per MW)	3.48
Fixed O&M ($US/MW/year)	29,645
Variable O&M ($US/MWh)	5.2

Solar District Heating

Brief technology description

Collecting energy from the sun using it to heat water is a technology, which has been in use for many years. Today, more than 580 million m^2 of solar collectors are installed around the globe, with a total installed capacity of 410 GW_{th}. Although the majority of this capacity is used for small domestic hot water systems, the fastest growth rate is for large systems (mainly for district heating).

Three different types of solar panels are produced:

- Flat Plate Collectors (FPC)
- Evacuated Tubular Collectors (ETC)
- Concentrated Solar Power (CSP)

Flat plate large module collectors are by far the most common collector type used for district heat. ETC-collectors are more efficient than flat panels at higher temperatures, but also more expensive. CSP can produce heat at high temperatures. It is possible to combine different collector types in one system; e.g. using flat plate collectors in the "cold section" of the field in order to preheat the heat transfer-fluid before evacuated tubes or CSP collectors in the "hot section".

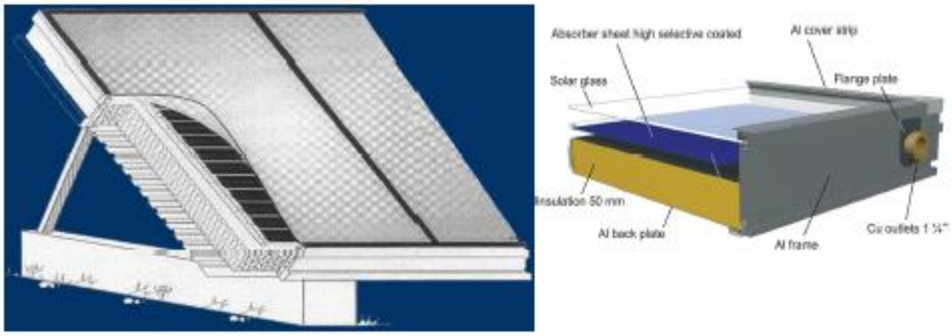

Figure 40: Basic principle of a flat plate solar collector

As shown in the figure above, the principle of flat solar panels in a district heating system is to absorb the solar energy in order to heat a fluid. Corrugated copper or aluminium-sheets serve typically as absorber, with the transfer-fluid being circulated behind these. The absorbers are surrounded by a glass layer, protecting the absorber from the surrounding environment. The back of the panel is insulated, in order to reduce heat loss, cf. figure xx below. The heat is transferred from the circulated fluid to district heating water via a heat exchanger.

For district heating systems, the collectors are typically installed on the ground in long rows connected in series. The solar heating system normally takes in the return water and heats it up to the desired forward flow temperature. All plants have the solar collectors mounted on the ground. Ground mount foundations can be concrete blocks, concrete foundations or steel foundations.

In principle, solar district heating is operating all hours of the year, but of course, the heat production depends on the solar irradiation, weather conditions, time of day and the season of the year. The seasonal variation can be compensated using a seasonal storage.

<u>Efficiency and energy yield</u>

The yield of a solar collector depends on the solar collector type and size, the solar radiation, the temperature of the collectors and the ambient temperature. The efficiency is defined by efficiency parameters. The figure below visualises the source of radiation, optical losses and thermal losses of a solar thermal system (FPC).

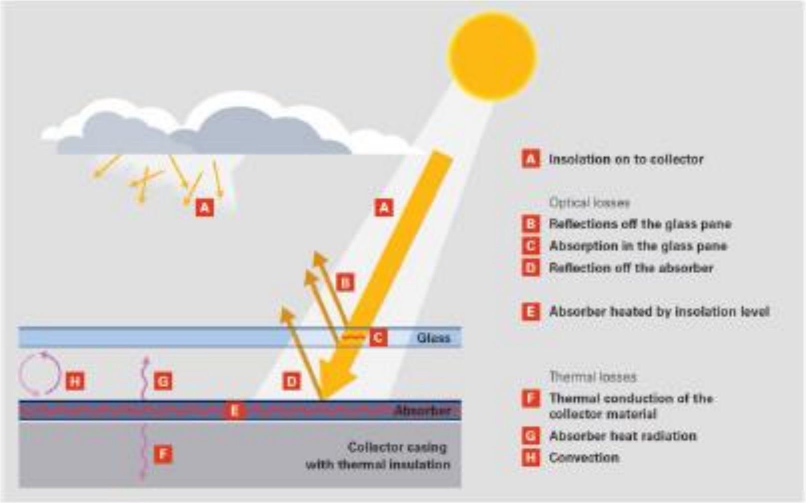

Figure 41: Example of utilisation rate of solar energy and effects influencing the efficiency

The efficiency of a FPC depends on the temperature difference between the ambient air and the average temperature of the fluids. The lower the temperature difference, the higher the efficiency. Therefore, the thermal performance at a given radiation level is higher at lower temperature differences. The efficiency depends on the flow, since this is how the temperature difference is controlled. The dependency between efficiency and temperature difference is illustrated in below figure.

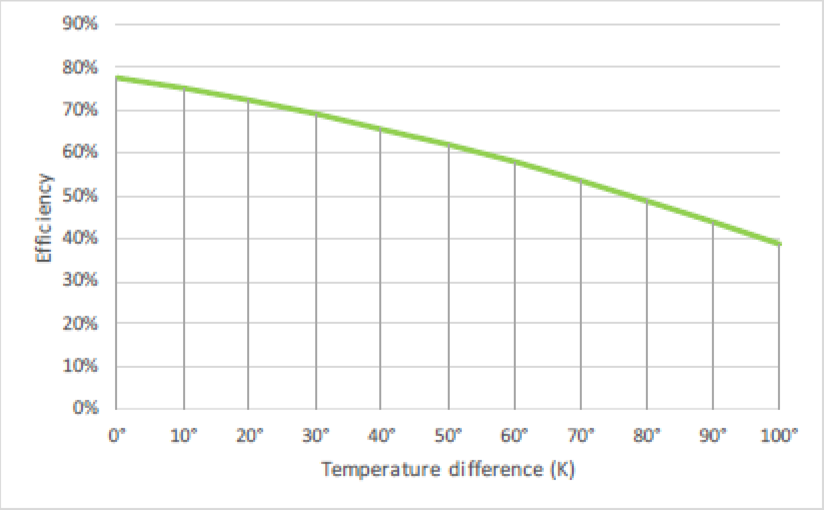

Figure 42: Efficiency as a function of temperature difference.

FPCs are typically produced in two product classes that differ by the energy efficiency of the collectors. Higher efficiencies may be achieved by applying an additional insulating layer, e.g. polymer foil or an extra layer of glass.

The specific yearly thermal output of flat plate solar collectors is around 300 -600 kWh/m^2.

<u>Application of solar thermal systems in district heating systems</u>

A solar thermal plant consists of:

- Solar collectors
- Transmission pipeline

- Tank storage
- Tank and collection tank for heat-transfer fluid (e.g. glycol/water). Circulated in the solar thermal collectors. The heat-transfer fluid is typically separated from the district heating water by a heat exchanger
- Heat exchanger, including pumps, valves etc.
- Integration of control with the existing plant

A schematic drawing of a solar thermal system integrated with a district heating grid can be seen in below figure.

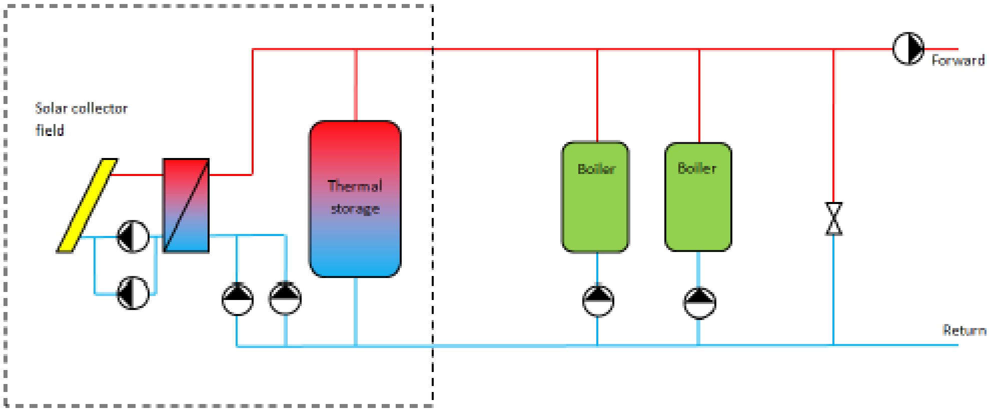

Figure 43: Schematic drawing of a possible system integration of solar district heating

When properly designed, solar collectors can work when the outside temperature is well below freezing, and they are protected from overheating on hot, sunny days.

All district heating systems equipped with solar heating utilize them as a supplement to other heat generating units, thereby ensuring that all consumers' heat demands are met, also when there is insufficient solar irradiation available.

The tilt of the collector panels can impact both annual total yield and production curve production over the year. Hence the tilt of the collector panels becomes an optimization parameter as production can be increased in the autumn at the expense of max. thermal effect and hence production during the summer (where the solar irradiation typically peaks).

Production of solar heating is taking place when the heat demand is lowest – both on daily and seasonal basis. The share of solar heating in a district heating system without heat storage is relatively low (5 - 8% of yearly heat demand). Hence, the most common application is the combination of a solar thermal system with a diurnal heat storage, which will enable approximately 20 - 25% share of solar district heating in a district heating system.

Moreover, the combination with a seasonal heat storage can increase the share of solar heating to 30 - 50% and in theory up to 100%. Hence, there is an important synergy with seasonal storage technologies.

Input

The input is solar radiation.

Outside the atmosphere of the Earth, the solar radiation is 1,367 W/m^2. The solar radiation is highest perpendicular to the solar beams.

Output

Hot water for district heating.

The thermal performance of solar heating plants is first of all influenced by the temperature level of the solar collector fluid. Besides that, the thermal performance is also influenced by the weather, the collector type, the solar collector fluid, the flow volume and the collector tilt.

Typical capacities

The typical application of solar thermal plants for district heating purposes aims at a solar share of 10 - 25% of the annual heat demand. Thus, the installed capacity varies by the plant.

Regulation ability

Regulation with regard to electricity is not relevant for solar thermal plants.

There are however other relevant regulation aspects for solar thermal collectors, e.g. the possibility to vary the flow of the absorber fluid. By varying the flow of the absorber fluid, the temperature in the plant can be regulated. This is especially important, considering the variation in intensity of solar radiation. Varying the flow secures the possibility to optimize the flow rate according to the external circumstances and desired output temperature.

Boiling of the absorber fluid can cause reduction of the corrosion protection. Ways to avoid boiling are the installation of conventional cooling towers or the scheduled and preventive cooling of stored heat by circulating water through the plant at night. The latter is applied in many plants, as it reduces the installation costs, but the cooling capacity of collectors is practically limited to FPC-technology and has decreased in recent years, due to the increased energy efficiency of collectors.

In the event that the thermal solar district heating plant is oversized compared to the available cooling capacity, the absorber fluids remains at risk of boiling.

Advantages/disadvantages

Advantages:

- Simple, robust and proven technology
- Long technical lifetime, proven at least 25 - 30 years
- Low maintenance costs, based on current plants approximately <1 US/MWh_{th}$
- Low electricity consumption required (3 - 4 kWh pr. produced MWh solar heating, primarily electricity consumption for circulation pumps)
- No continuous presence of operation personnel required during operation
- Heat production price not sensitive to variable costs of fuel, easier budgeting of the heat price, when a share of the heat price is known
- CO_2-free energy source
- High energy yield pr. occupied land-area compared to e.g. biomass, in terms of possible energy production on a given area
- Easy reestablishment of area, no or low impact on the soil from the foundations
- Approx. 98 % of a plant can be recycled after decommission
- Can be combined with heat pumps to increase yields

Disadvantages:

- Production dependent on solar radiation and weather conditions
- Summer load defines the size of the capacity in case of diurnal storage only
- High area occupation, compared to other district heating technologies like boilers or heat pumps, approximately 3 m^2 ground area for each m^2 solar panel collector, near by the district heating network – although this can be mitigated with a transmission pipeline e.g. some km, which may imply additional costs
- High initial investment pr. MW, but with a depreciation period of 15 - 20 years, the heat production cost is competitive with e.g. biomass based heat production.

Environment

No emissions related to the heat production.

Anti-freezing agents such as organic glycols are typically added to the water in the system, in order to avoid frost damages in the winter. Leakage risks can be mitigated by installing monitoring systems, monitoring e.g. pressure in the system as well as moisture in the insulation material of the pipes.

The basic components of solar thermal collectors consist of metals, insulation material, glass and the above-mentioned anti-freezing agents. Thus, most of the used materials can be recycled after decommission.

Data sheet 50 - Solar district heating

Solar District Heating	
Energy/technical data	
Typical plant size (collector area), m^2	13,000
Collector input, $kWh/m^2/year$	1,046
Collector output, $kWh/m^2/year$	473
Total efficiency , net (%), annual average	45%
Auxilary electricity consumption (share of heat gen.)	0.3%
Forced outage (%)	0.5%
Technical lifetime (years)	30
Construction time (years)	0.25
Space requirement (1,000m^2 per MWh/year)	6.3
Environment	
SO_2 (degree of desulphurization, %)	
NO_X (g per GJ fuel)	
CH_4 (g per GJ fuel)	
N_2O (g per GJ fuel)	
Financial data	
Investment cost of total solar systems excluding heat storage, \$US/MWh_{output}/year	519
Fixed O&M \$US/MWh_{output}/year/year	0.11
Variable O&M \$US/MWh_{output}	0.25

Biomass boiler, automatic stoking

Brief technology description

Wood pellets are usually applied in automatically stoking biofuel boilers, see figure below. However, some boilers, especially major ones, are also designed for firing with other types of biomass such as wood chips and grain.

The fuel is conveyed via an auger feeder from the fuel supply to the burner unit. In the burner, the combustion takes place during supply of primary and secondary air. The boiler is often a steel sheet boiler with a convection unit consisting of boiler tubes or plates.

The fuel can be supplied from an external earth storage tank, storage room or similar, or it can be supplied from an integral fuel hopper that is part of the boiler unit. Fuel is available in sacks and can be added to the silo manually, or - in case of wood pellets - the fuel can be blown into the storage tank or room.

Within automatic bio fuel boilers, there are two plant types: compact plants consisting of a boiler and a burner in the same unit, and boilers with a detachable burner. Detachable burners can be approved up to 70 kW and are exclusively applicable for stoking with pellets.

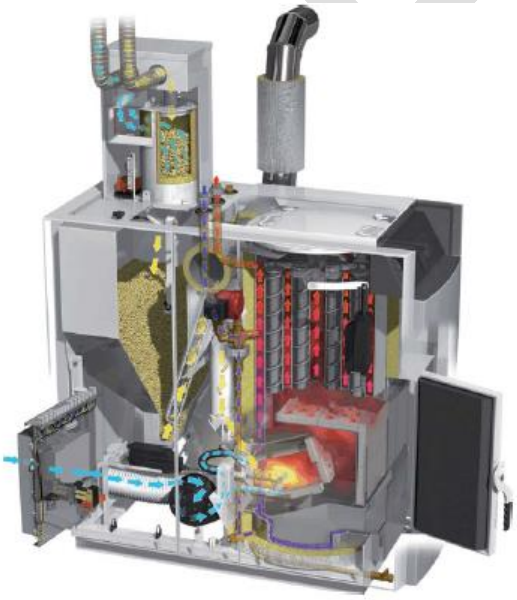

Figure 44: Biomass boiler, automatic stoking

Automatic biofuel boilers can be a stand-alone solution, but hybrid systems like solar/biomass is an attractive combination. In the summer period hot tap water is produced from the thermal solar, while the biomass heating unit covers the heating demand for hot tap water and space heating during the rest of the year.

Input

Wood pellets or wood chips. Another possible fuel depending on the boiler type is non-woody biomass such as grain. See additional remarks for detailed description of wood pellets.

Output

Heat for space heating and hot tap water.

Typical capacities

From 8 kW to 500 kW, or even larger, detachable pellet burners from 8 kW to 70 kW.

Regulation ability

All boilers can be regulated from less than 30% to 100% of full capacity, without violating emission requirements. The best technologies can be regulated from 10 to 120% of the nominal heat output stated by the manufacturer on the boiler plate.

Advantages/disadvantages

Advantages:

- The investment in a new biomass boiler is often limited if an existing oil burner must be replaced anyway.

Disadvantages:

- Biomass boilers and storage capacities require room space and an appropriate boiler room.
- For larger boilers, and also in case of firing with other types of fuels (eg. Straw or wood chips) than pellets, the labour needed for maintenance must be considered.
- Compared to district heating, gas boilers or heat pumps a considerable effort must be put into transport and handling of the fuel wood.
- Boiler and flue gas system requires regular cleaning and maintenance by the owner.

Environment

Use of high fuel quality and advanced technological combustion concepts ensure that automatic combustion systems are environmentally sound and efficient residential heating technologies. The legislation requirements have been stringent continuously and regards safety, efficiency, emission limits etc.

Data sheet 51 - Biomass boiler, automatic stoking – one-family house, existing and energy renovated building

Biomass boiler, automatic stoking, wood pellets or wood chips - One-family house, existing and energy renovated buildings.	
Energy/technical data	
Heat production capacity for one unit (kW)	10
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	82
Total efficiency, annual average, net (%)	82
Auxiliary Electricity consumption (kWh/year)	240
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	

Biomass boiler, automatic stoking, wood pellets or wood chips - One-family house, existing and energy renovated buildings.	
SO_2 (g per GJ fuel)	25
NO_X (g per GJ fuel)	70
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	4.0
Particles (g per GJ fuel)	15
Financial data	
Specific investment (1,000$US/unit)	8.2
Fixed O&M ($US/unit/year)	610
Variable O&M ($US/MWh)	0

Data sheet 52 - Biomass boiler, automatic stoking – one-family house, new buildings.

Biomass boiler, automatic stoking , wood pellets or wood chips - One-family house, new buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	10
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	78
Total efficiency, annual average, net (%)	78
Auxiliary Electricity consumption (kWh/year)	190
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_X (g per GJ fuel)	70
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	4.0
Particles (g per GJ fuel)	15
Financial data	
Specific investment (1,000$US/unit)	8.2
Fixed O&M ($US/unit/year)	606
Variable O&M ($US/MWh)	0

Data sheet 53 - Biomass boiler, automatic stoking – apartment complex, existing building

Biomass boiler, automatic stoking , wood pellets or wood chips - Apartment complex, existing building	
Energy/technical data	
Heat production capacity for one unit (kW)	400
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	85
Total efficiency, annual average, net (%)	85

Biomass boiler, automatic stoking , wood pellets or wood chips - Apartment complex, existing building	
Auxiliary Electricity consumption (kWh/year)	2,400
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_x (g per GJ fuel)	70
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	4.0
Particles (g per GJ fuel)	15
Financial data	
Specific investment (1,000$US/unit)	106.5
Fixed O&M ($US/unit/year)	2,088
Variable O&M ($US/MWh)	0

Data sheet 54 - Biomass boiler, automatic stoking – apartment complex, new building

Biomass boiler, automatic stoking , wood pellets or wood chips - Apartment complex, new building	
Energy/technical data	
Heat production capacity for one unit (kW)	160
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	85
Total efficiency, annual average, net (%)	85
Auxiliary Electricity consumption (kWh/year)	1,400
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_x (g per GJ fuel)	70
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	4.0
Particles (g per GJ fuel)	15
Financial data	
Specific investment (1,000$US/unit)	64.1
Fixed O&M ($US/unit/year)	1,367
Variable O&M ($US/MWh)	0

Biomass boiler, manual stoking

Brief technology description

Modern manually fired boilers for stoking with solid wood have downwards draught or down-draught. The principle is that the fuel is heated, dried and degasified in the combustion chamber, after which the gases are led downwards (or down in case of down-draught) through a crevice in the bottom of the combustion chamber into the chamber where the combustion takes place during supply of secondary air. This type of boiler is often provided with an air fan for supply of combustion air or a flue gas fan. Older types of boilers are up-draught boilers and do not comply with the current environmental requirements. Manual boilers should be installed with an accumulation tank of appropriate size. A buildings heat demand can be covered solely with a manual biomass boiler with a well-insulated accumulation tank.

Figure 45: Double duty wood log boiler (manual stoking) prepared for mounting of pellet burner (automatic stoking)

Input

The input is log wood of different sizes, depending on the boiler.

Output

Heat for space heating and hot tap water.

Typical capacities

Log wood boilers are available from a few kW up to 100 kW.

Regulation ability

The boilers are installed with a storage tank. A few log wood boilers have regulation abilities.

Advantages/disadvantages

Advantages:

- A biomass boiler with manual stoking is a simple and robust design.

Disadvantages:

- Compared to district heating, gas boilers or heat pumps a considerable effort must be put into transport and handling of the fuel wood.
- Boiler and flue gas system requires regular cleaning and maintenance.

Environment

Examinations show that newer boilers with accumulation tank cause considerably less pollution compared to old up-draught boilers. Legislation requirements have been stringent continuously and regards safety, efficiency, emission limits etc.

Data sheet 55 - Biomass boiler, manual stoking – one-family house, existing, new and energy renovated buildings

Biomass boiler, manual stoking, wood logs - One-family house, existing, new and energy renovated buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	30
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	0
Heat efficiency, annual average, net (%)	82
Total efficiency, annual average, net (%)	82
Auxiliary Electricity consumption (kWh/year)	240
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_X (g per GJ fuel)	70
CH_4 (g per GJ fuel)	2
N_2O (g per GJ fuel)	4
Particles (g per GJ fuel)	120
Financial data	
Specific investment (1,000$US/unit)	8.2
Fixed O&M ($US/unit/year)	551
Variable O&M ($US/MWh)	0

Wood stove

Brief technology description

A wood stove is an enclosed room heater used to heat the space in which the stove is situated. Usually, the wood stove is fired with a batch of 2-3 pieces of new firewood at a time. The firing takes place when there are no more visible yellow flames from the previous basic fire bed, and when a suitable layer of embers has been created. Modern wood stoves have up to three air inlet systems in order to achieve the best possible combustion and to ensure that the glass pane in the front door does not get sooty: primary air up through the bottom of the combustion chamber, secondary air as air wash to keep the combustion alive and to maintain the glass clean, and tertiary air in the backside of the combustion chamber for after-burning of the gases. Some stoves need to have the air inlet dampers manually adjusted in connection with each new fired batch (maximum 3-5 minutes after each charge); others are more or less self-regulating.

The chimney serves as the stove's motor, and is essential to the stove's functioning. The chimney draught sucks air through the air dampers to the combustion chamber.

Heat from wood stove is usually a supplement to other kinds of heat supply. Some stoves are assembled with a integrated boiler, and thus can be connected to the central heating system.

Figure 46: Wood stove

Input

Wood logs of different sorts like beech, birch and pine wood. The humidity should be of 12 to 20%, and the size of the wood logs depends on the stove but usually about 250 to 330 mm with a weight of 700 to 1,000 g.

Output

Space heating by convection and radiation. If the wood stove includes a water tank, it can also produce a certain amount of hot tap water.

Typical capacities

Typical capacities are 4 to 8 kW nominal output.

Regulation ability

By regulating the air dampers, the stove's heat output can be minimized or maximized within a few minutes, however, this can result in an increased emission.

Advantages/disadvantages

Advantages:

- Wood stoves are usually independent of electricity supply.
- Can supplement primary heating unit, which in turn can reduce the dependency of the primary heating supply

Disadvantages:

- Compared to district heating, gas boilers or heat pumps a considerable effort must be put into transport and handling of the fuel wood.
- High level of local emission of air pollutants e.g. particulate matter

Environment

Woodstoves emit a high level of air pollutants e.g. particulate matter at local level

Pollution from wood stoves is dependent on series of factors such as stoking conduct, the individual stove, the controlling of the combustion and chimney in relation to the surrounding topography. The chimney is the engine for the combustion and where the draft is an essential part of how much air is reaching the combustion, this can be affected by the height of the chimney, and how the surroundings e.g. other houses, hills, forests wind direction are. If the draft is not sufficient it will lead to poor combustion and more emissions. The emission from a modern wood stove is much higher than from e.g. gas, oil or biomass boilers.

Data sheet 56 - Wood stove without integrated water tank– one family house, existing and new building

Wood stove without water tank, wood logs - One-family house, existing, energy renovated and new buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	5
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	40
Expected share of hot tap water demand covered by unit (%)	0
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	70
Total efficiency, annual average, net (%)	70
Auxiliary Electricity consumption (kWh/year)	0
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_X (g per GJ fuel)	90
CH_4 (g per GJ fuel)	125
N_2O (g per GJ fuel)	4
Particles (g per GJ fuel)	40
Financial data	

Wood stove without water tank, wood logs - One-family house, existing, energy renovated and new buildings	
Specific investment (1,000$US/unit)	3.0
Fixed O&M ($US/unit/year)	174
Variable O&M ($US/MWh)	0

Data sheet 57 - Wood stove with integrated water tank– one-family house, existing, energy renovated and new building

Wood stove with water tank - One-family house, existing, energy renovated and new buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	12
Electricity generation capacity for one unit (kW)	NA
Expected share of space heating demand covered by unit (%)	45
Expected share of hot tap water demand covered by unit (%)	20
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	70
Total efficiency, annual average, net (%)	70
Auxiliary Electricity consumption (kWh/year)	140
Technical lifetime (years)	20
Regulation ability	
Primary regulation (% per 30 seconds)	NA
Secondary regulation (% per minute)	NA
Minimum load (% of full load)	NA
Warm start-up time (hours)	NA
Cold start-up time (hours)	NA
Environment	
SO_2 (g per GJ fuel)	25
NO_X (g per GJ fuel)	90
CH_4 (g per GJ fuel)	125
N_2O (g per GJ fuel)	4
Particles (g per GJ fuel)	40
Financial data	
Specific investment (1,000$US/unit)	4.8
Fixed O&M ($US/unit/year)	248
Variable O&M ($US/MWh)	0

Electric heat pumps

Brief technology description

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature level to a higher temperature level. Heat pumps draw heat from a heat source (input heat) and convert the heat to a higher temperature (output heat) through a closed process; either compression type heat pumps or “thermally driven” heat pumps.

Descriptions of the most commonly applied heat pumps are included in the same sections in order to facilitate comparison of the features of the different types of commonly applied heat pumps.

Gas heat pumps are not commonly applied, and are described in separate sections after these first sections.

Heat pumps can be categorized according to their design or operational principle as follows:

- Compressor-driven heat pumps, which can be driven by gas or electricity.
- Sorption heat pumps (split into absorption and adsorption heat pumps), which can be driven by gas, pressurized hot water or oil. They are also called “thermally driven” heat pumps.

Geothermal heat, groundwater or surface water, the sun and the air are suitable as natural sources of heat for heat pumps.

Heat pumps are differentiated by the ways used to collect heat from the heat source and ways used to distribute the heat in the house:

- Air-to-Air heat pumps draw heat from ambient air and supply heat locally through air heat exchangers. Air-to-Water heat pumps draw heat from ambient air and supply heat through a hydraulic water based heat distribution system (radiator, convectors, floor heating).
- Brine-to-Water heat pumps (“ground-source” heat pumps) are generally taking heat from the ground circulating cold brine through pipes and are distributing heat in the house via a water based system (radiator, floor heating etc.) often called “ground-source” heat pumps.
- Ventilation heat pumps draws heat from ventilation outlet air and heats up the air intake in the ventilation system, and can be either air-to-air, air-to-water or a combination of both.

Heat pumps are utilized for individual space heating, industrial processes and district heat production. Today most small heat pump systems used for individual space heating are electrically driven compression heat pumps utilizing energy from the ambient air, exhaust ventilation outlets or ground heat.

Heat pumps for water based distribution systems have a maximum outlet temperature of around 55˚C and the lower outlet temperature the higher efficiency of the heat pump, hence inlet temperature as low as 35°C is attractive. However outlet temperature around 35°C - 55°C, requires distribution system that is compliant with temperatures in this range. In many cases it is necessary to install larger radiators, floor heating and/or improve the insulation level of the building envelope.

Domestic hot water is in general preheated in a storage tank using direct electric heating as the heat capacity of heat pumps is often inadequate for heating showering water directly.

For compression heat pumps, the actual heat output is usually 3 to 5 times the drive energy (the coefficient of performance (COP)). The energy flow is illustrated in the Sankey diagram in the figure below:

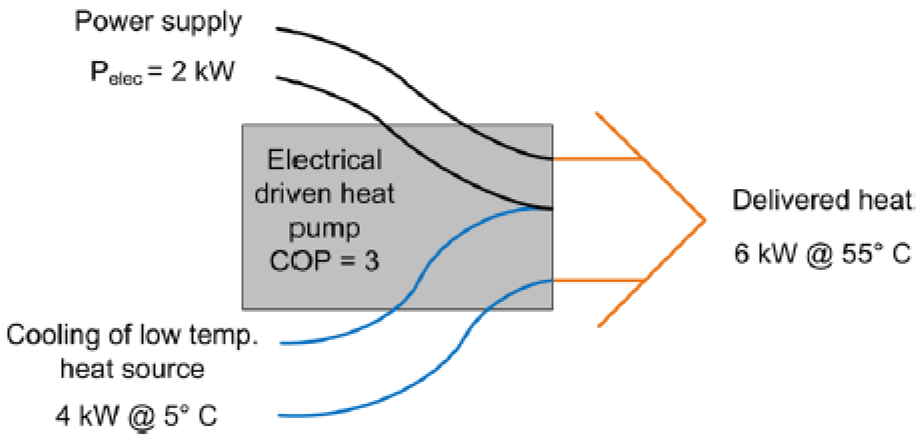

Figure 47: The electrical power consumption of 2 kW enables the heat pump to utilize 4 kW from a low temperature heat source at 5°C. Thus delivering 6 kW at 55° C (COP is 3).

The temperature difference between the temperature level of heat source and the temperature level of the heat delivered influence the COP. When the difference in temperature between the heat source and heat delivery decreases, the COP will increase and vice versa. This implies that the COP will vary e.g. according to the season – a low outdoor temperature implies a higher temperature difference, when the heat output is at the same temperature. Hence, in wintertime the COP will be less than during the summer.

Air-to-air

Air-to-air heat pumps draw heat from the ambient air and supply heat locally through an air heat exchanger. Most air-to-air heat pumps have one outdoor unit and one indoor unit and are often referred to as "split-units". This configuration means that the heat pump can only supply heat at one location in the house and that larger coverage requires an air circulation system or that the doors to adjoining rooms are open. Remaining heat demand must be covered by other sources, e.g. electrical heaters or additional air-to-air heat pumps.

Air-to-air heat pumps with more than one indoor heat exchanger (multi-split units) are also available, but only few are being installed today.

Air-to-air heat pumps will usually cover between 60% and 80% of the space heating demand. Thus requiring additional heating during the coldest periods or if the air is not circulated throughout the house. Hence air-to-air is usually installed as an auxiliary heating unit in combination as supplement to an existing primary source of heat. The existing heat source could potentially be anything, but is usually either a gas boiler or oil boiler.

Many air-to-air heat pumps are reversible meaning that they can also be used for cooling (air-condition).

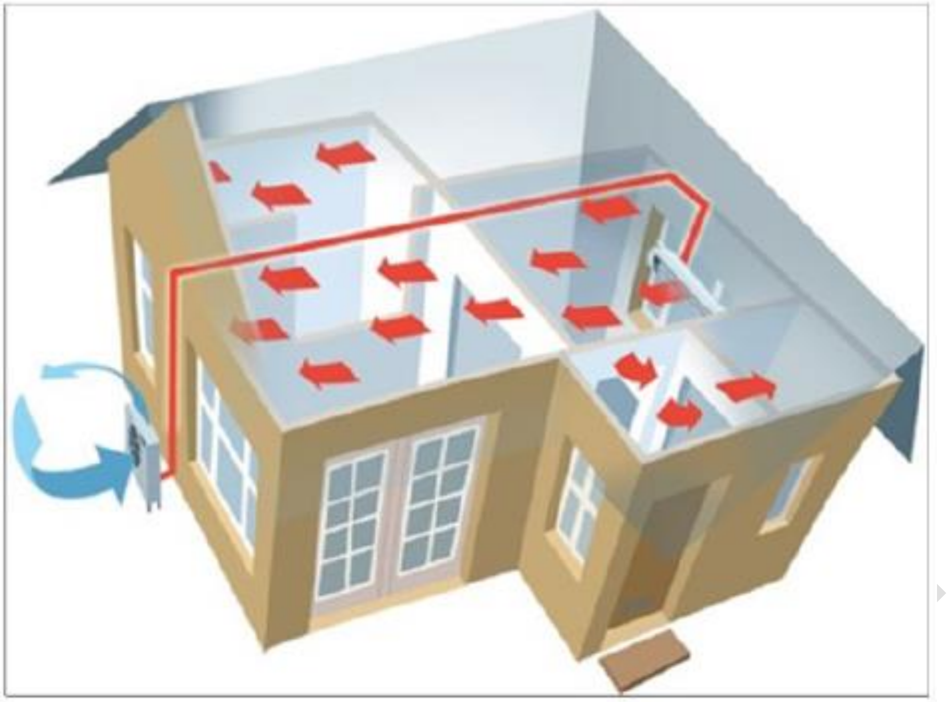

Figure 48: Air-to-air heat pump. The two units are placed according to concrete local conditions

Air-to-water heat pump

Air-to-water heat pumps draw heat from ambient air and supply heat for space heating through a water based distribution system. Air-to-water heat pumps also heat water for domestic hot water consumption and will often be equipped with an electrical heater for supplement in peak load periods, so that the unit can supply 100% of the heat demand.

Some air-to-water heat pumps are designed specifically for supplying only hot tap water. This type of air-to-water heat pump is used in a number of summer residences, especially if there is a large consumption of hot tap water.

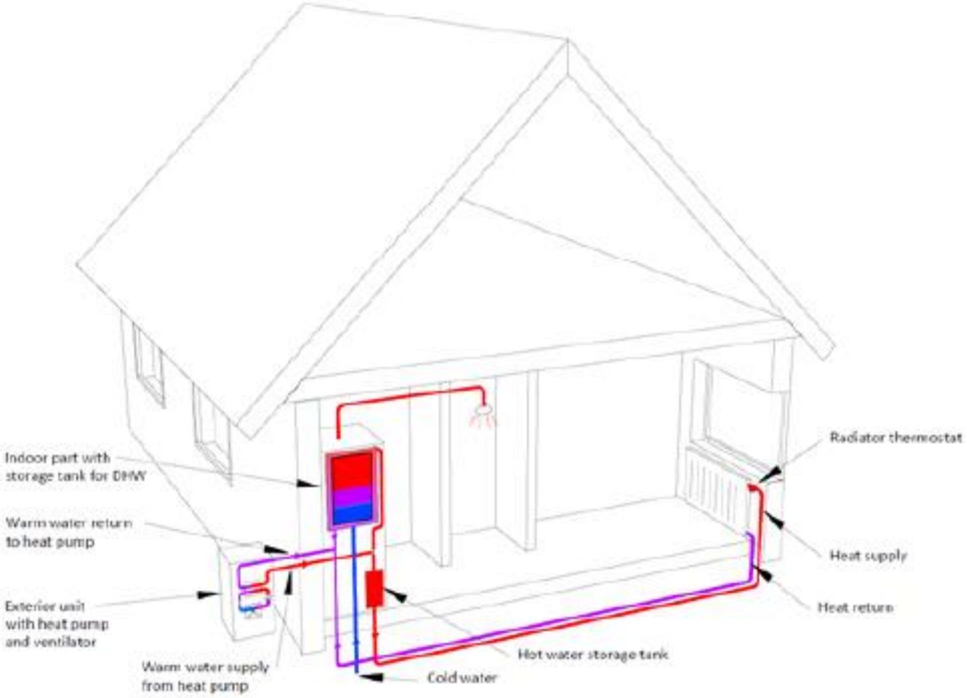

Figure 49: Air-to-water heat pump.

Brine-to-water (Ground-source) heat pump

Brine-to-water heat pumps draw heat from the ground and supply heat for space heating through a water based distribution system. Brine-to-water heat pumps also heat water for domestic hot water consumption and will often be equipped with an electrical heater for supplement in peak load periods, so that the unit can supply 100% of the heat demand.

Most ground-source heat pumps use a horizontal heat collector that consists of pipes containing anti-freeze brine, which is circulated to withdraw heat from the top soil layer.

In theory, ground sourced heat pumps will achieve a higher thermal efficiency during the heating season compared to air-to-water heat pumps. In practice, however, the difference is often small. It is possible to use vertical pipes, which can reach depths of up to 250 m. These however, have higher investment costs and are primarily used where the surface area is inadequate or unsuited for installation of horizontal pipes e.g. rocky grounds.

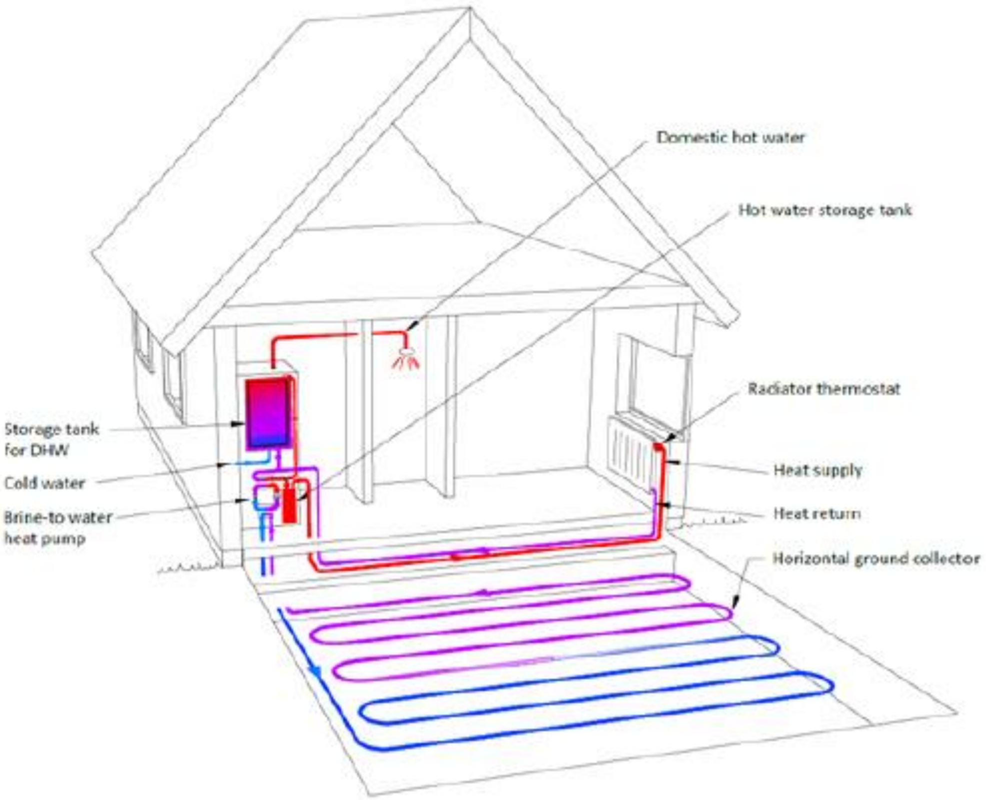

Figure 50: Ground-source heat pump (brine-to-water)

Ventilation air heat pump

Ventilation heat pumps can be either air-to-air, air-to-water or a combination of both. This type draws heat from ventilation outlet air and heats up the air intake in the ventilation system and usually domestic hot water as well. This type of heat pumps is also called exhaust air heat pumps.

The heat pump can heats the inlet air to a level providing more heat than the ventilation heat losses, and can thereby compensate for the transmission loss to some extent. Depending on the ratio between transmission heat losses and ventilation heat losses, this type of heat pump might require a supplementary heat source to cover the heat demand all year around and to make individual room regulation possible.

The system is often combined with a direct heat exchanger that will recover part of the heat from the outlet air. This means that the capacity of the heat pump is reduced, but the overall energy efficiency is increased.

Figure 51: Ventilation air heat pump

Input

Inputs for heat pumps are a heat source and drive energy.

Heat sources for individual heat pumps are primarily ambient air, ventilation outlet air or ground (soil). Typical ambient Danish temperatures are between -5°C and 18°C, while the ground temperature in a depth of 1 meter is between 2°C and 14°C (dropping to around 0°C through a winter with heat withdrawal). Other heat sources could be solar heating panels, surface water (lake or seawater).

The drive energy for individual heat pumps is electricity or gas.

Output

The output is heat for space heating as hot air or water and for some installations domestic hot water as well.

Typical capacities

The heating capacities varies between the types as for example air-to-air and ventilation heat pumps typically only heat to part of a house whereas brine to water and air to water heat pumps supply heat for the entire house including domestic hot water.

Air-to-air

Typical heating capacities for a single air-to-air heat pump are 3 - 8 kW, which will usually cover between 60% and 80% of the space heating demand. Air-to-water and brine-to-water (ground-source)

Heat pumps supplying water based systems typically ranges from approximately 4 kW up to several hundred kW heating capacity, covering the needs for both space heating and domestic hot water in both low-energy buildings and other buildings.

Water based heat pumps are normally designed to cover between 95% and 98% of the heat demand.

Ventilation

The ventilation heat pumps heating capacity range from 1.5 kW in single family houses to several hundred kW in large office buildings. In private households, the heating capacity is normally up to 3 kW. Ventilation heat pumps will usually be inadequate as the only heat source for space heating and domestic hot water production. The reason is that the exhaust ventilation air can be insufficient as the only heat source. Consequently, and depending on the ratio between transmission heat losses and ventilation heat losses, a ventilation heat pump might require a supplementary heat source during some periods.

Regulation ability

All heat pumps have on/off regulation and some are also equipped with capacity regulation, meaning that the heat pump can balance the heat production to the demand continuously down to around 20% of maximum.

Heat pumps for individual heating are able to stop immediately and a stopped heat pump is able to reach full power consumption within 1 minute.

It is important to acknowledge that varying the operation strategy of a heat pump over time has influence on the overall energy consumption and comfort levels. For heat pumps that are on/off regulated, the efficiency will drop with increasing numbers of starts and stops. Correct dimensioning and utilization of storage tanks is necessary to ensure the highest efficiencies. Heat pumps with capacity regulation have more components than on/off controlled heat pumps, which may increase the price.

The main part of air-to-air heat pumps installed today has capacity regulation. Only around 20% of the installed air-to-water and ground-source heat pumps has capacity regulation. While most heat pumps on the market today are equipped with capacity regulation, meaning that the percentage of installed heat pumps with capacity regulation will increase.

As the water based distribution systems have a higher thermal inertia on/off regulation does not affect comfort in the same way as this regulation type would on air-to-air heat pumps.

Advantages/disadvantages

The general advantage of heat pump technologies is that the primary energy consumption is reduced compared to boilers or traditional electrical heating.

Noise from air-source heat pumps can be a problem. In general the noise level is regulated by law. Additionally the EU ECO design regulation of heat pumps includes specification of maximum noise from the heat pump itself. Air-to-air heat pumps of higher quality will normally have lower noise levels though.

Air-to-air heat pumps

Advantages of the Air-to-air heat pumps are that they are simple to install in rooms and buildings with electrical heating since a water based distribution system is not necessary and the air-to-air heat pumps have a higher efficiency than direct electric heating.

And the outdoor installation only need limited outdoor space and do not need any digging in the ground. The main reasons for the large number of installed air-to-air heat pumps are low investment costs and easy installation.

A drawback of the air-to-air heat pump is that, unless it is installed as a multi-split unit, it is only able to deliver heat in a single room.

Additionally a disadvantage of air-to-air heat pumps is that the heat capacity is limited and they are unable to heat domestic water. Therefore, this type of heat pump requires a supplementary heat source.

Air-to-water heat pumps

Compared to ground-source heat pumps, air-to-water types are easier to install and does not require a large area for ground heat collectors.

Compared to air-to-air heat pumps, water based systems can deliver heat through the water based heating system in several rooms, and it is possible to regulate the heat transfer individually in each room.

Compared to ground-source heat pumps, the air-to-water heat pump is less efficient as the air temperature will be lower than the ground temperature during winter periods. Moreover, ice will build up on the outdoor heat exchanger and thereby decrease the evaporation temperature and the efficiency.

Gas hybrid air-to-water heat pumps are less expensive than standard air-to-water heat pumps, but are only applicable in areas with natural gas and have higher fuel costs due to consumption of gas.

Brine-to-water (ground- source) heat pumps

As for air-to-water heat pumps, the brine-to-water (ground-source) heat pump can deliver heat through the water based heating system in several rooms, and it is possible to regulate the heat transfer individually in each room.

Compared to air based systems, this type typically has a higher annual COP as the ground is warmer than the ambient air during the heating season.

A disadvantage is that the ground-source involves digging or other arrangements to retrieve the necessary heat. This increase investment costs compared to air based solutions but will to some extend be counterbalanced by the reduced costs of energy. A ground-source heat pump will be approximately 15% more efficient than an air-to-water heat pump.

There are no noise problems when the heat pump is running, which can make it the only possible solution in densely built areas.

Ventilation heat pumps

This heat pump is only applicable in houses with a ventilation system. In old houses with large, uncontrolled ventilation due to air infiltration, this technology will not be suitable. In new and more airtight houses ventilation systems are often applied meaning that ventilation heat pumps could be a suitable solution.

A disadvantage of ventilation heat pumps is that the heat capacity is limited by the heat that can be drawn from the exhaust air.

Environment

The environmental impact of heat pumps relates mainly to power consumption, leaking of synthetic refrigerants and noise.

The environmental impact due to the use of electricity will depend on the way the electricity is produced.

Today all heat pumps for individual heating on the Danish market use synthetic refrigerants. These are known HFC's (hydrofluorocarbons) which are fluorinated gases (F-gases), which possess a potent greenhouse effect and are covered by the Kyoto Protocol.

There are many different refrigerants based on HFCs. The most important are HFC-134a (R134a) and HFC mixtures: R404A, R410A and R407A. The most common refrigerants based on HFCs have Global Warming Potentials (GWP) of about 1,500 to 4,000 compared to CO2 which has a GWP of 1.

The national legislation in some countries bans the use of HFC's in heat pumps with more than 10 kg of refrigerant. Heat pumps for individual heating typically contain less than 2 kg's of refrigerant meaning that the ban does not affect this segment.

There are, however, some heat pumps working with natural refrigerants (including R290 – propane), but this is a minority. It is expected that there will be a transition towards natural refrigerants or other less harmful refrigerants. The European F-gas regulation from 2015 states that F-gases will be phased out towards 2030 and banned in many applications where less harmful alternatives are available, which will likely lead to an increased use of natural refrigerants in heat pumps.

Data sheets

The following data sheets are presented consecutively below in tables:

- Air-to-air, existing one family house
- Air-to-air, new one family house
- Air-to-water, existing one family house
- Air-to-water, new one family house
- Air-to-water, existing apartments
- Air-to-water, new apartments
- Brine-to-water (ground source), existing one family house
- Brine-to-water (ground source), new one family house
- Brine-to-water (ground source), existing apartments
- Brine-to-water (ground source), new apartments
- Ventilation, new one family house
- Ventilation, new apartments

Data sheet 58 - Heat pump, air-to-air – existing one-family house

Heat pump, Air-to-air, existing one family house	
Energy/technical data	
Heat production capacity for one unit (kW)	4
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	60
Expected share of hot tap water demand covered by unit (%)	0
Heat efficiency, annual average, net (%)	510
Total efficiency, annual average, net (%)	510
Auxiliary Electricity consumption (kWh/year)	0
Technical lifetime (years)	12
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	2.1
Fixed O&M ($US/unit/year)	206
Variable O&M ($US/GJ)	0

Data sheet 59 - Heat pump, air-to-air – new one-family house

Heat pump, Air-to-air, new one family house	
Energy/technical data	
Heat production capacity for one unit (kW)	2.5
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	60
Expected share of hot tap water demand covered by unit (%)	0
Heat efficiency, annual average, net (%)	490

Heat pump, Air-to-air, new one family house	
Total efficiency, annual average, net (%)	490
Auxiliary Electricity consumption (kWh/year)	0
Technical lifetime (years)	12
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	1.3
Fixed O&M ($US/unit/year)	196
Variable O&M ($US/GJ)	0

Data sheet 60 - Heat pump, air-to-water – existing one-family house

Heat pump, Air-to-water, existing one family house	
Energy/technical data	
Heat production capacity for one unit (kW)	10
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	410
Total efficiency, annual average, net (%), floor heating	400
Heat efficiency, annual average, net (%), radiators	340
Total efficiency, annual average, net (%), radiators	335
Auxiliary Electricity consumption (kWh/year)	100
Technical lifetime (years)	18
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	11.4
Fixed O&M ($US/unit/year)	336
Variable O&M ($US/MWh)	0

Data sheet 61 - Heat pump, air-to-water – new one-family house

Heat pump, Air-to-water, new one-family house	
Energy/technical data	
Heat production capacity for one unit (kW)	4
Electricity generation capacity for one unit (kW)	0

Heat pump, Air-to-water, new one-family house	
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	355
Total efficiency, annual average, net (%), floor heating	335
Heat efficiency, annual average, net (%), radiators	320
Total efficiency, annual average, net (%), radiators	305
Auxiliary Electricity consumption (kWh/year)	100
Technical lifetime (years)	18
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	8.5
Fixed O&M ($US/unit/year)	336
Variable O&M ($US/MWh)	0

Data sheet 62 - Heat pump, air-to-water – existing apartment complex

Heat pump, Air-to-water, existing apartments	
Energy/technical data	
Heat production capacity for one unit (kW)	400
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	440
Total efficiency, annual average, net (%), floor heating	420
Heat efficiency, annual average, net (%), radiators	390
Total efficiency, annual average, net (%), radiators	375
Auxiliary Electricity consumption (kWh/year)	10,000
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	50
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	170.6
Fixed O&M ($US/unit/year)	1,997
Variable O&M ($US/MWh)	0.57

Data sheet 63 - Heat pump, air-to-water – new apartment complex

Heat pump, Air-to-water, new apartments	
Energy/technical data	
Heat production capacity for one unit (kW)	160
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	450
Total efficiency, annual average, net (%), floor heating	400
Heat efficiency, annual average, net (%), radiators	430
Total efficiency, annual average, net (%), radiators	380
Auxiliary Electricity consumption (kWh/year)	10,000
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	85.9
Fixed O&M ($US/unit/year)	1,997
Variable O&M ($US/MWh)	0.57

Data sheet 64 - Heat pump, ground-source – existing one-family house

Heat pump, ground source, existing one-family house	
Energy/technical data	
Heat production capacity for one unit (kW)	10
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	450
Total efficiency, annual average, net (%), floor heating	440
Heat efficiency, annual average, net (%), radiators	380
Total efficiency, annual average, net (%), radiators	370
Auxiliary Electricity consumption (kWh/year)	100
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	18.2

Heat pump, ground source, existing one-family house	
Fixed O&M ($US/unit/year)	336
Variable O&M ($US/MWh)	0

Data sheet 65 - Heat pump, ground-source – new one-family house

Heat pump, ground source, new one-family house	
Energy/technical data	
Heat production capacity for one unit (kW)	4
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	365
Total efficiency, annual average, net (%), floor heating	345
Heat efficiency, annual average, net (%), radiators	320
Total efficiency, annual average, net (%), radiators	305
Auxiliary Electricity consumption (kWh/year)	100
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	13.3
Fixed O&M ($US/unit/year)	336
Variable O&M ($US/MWh)	0

Data sheet 66 - Heat pump, ground-source – existing apartment complex

Heat pump, Ground source, existing apartments	
Energy/technical data	
Heat production capacity for one unit (kW)	400
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	480
Total efficiency, annual average, net (%), floor heating	460
Heat efficiency, annual average, net (%), radiators	430
Total efficiency, annual average, net (%), radiators	410
Auxiliary Electricity consumption (kWh/year)	10,000
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	50
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A

Heat pump, Ground source, existing apartments	
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	301.3
Fixed O&M ($US/unit/year)	1,997
Variable O&M ($US/MWh)	0.57

Data sheet 67 - Heat pump, ground-source – new apartment complex

Heat pump, Ground source, new apartments complex	
Energy/technical data	
Heat production capacity for one unit (kW)	160
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%), floor heating	510
Total efficiency, annual average, net (%), floor heating	440
Heat efficiency, annual average, net (%), radiators	490
Total efficiency, annual average, net (%), radiators	430
Auxiliary Electricity consumption (kWh/year)	10,000
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	107.7
Fixed O&M ($US/unit/year)	1,997
Variable O&M ($US/MWh)	0.57

Data sheet 68 - Heat pump, ventilation – new one-family house

Heat pump, ventilation, new one-family house	
Energy/technical data	
Heat production capacity for one unit (kW)	2
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	80
Expected share of hot tap water demand covered by unit (%)	90
Heat efficiency, annual average, net (%)	330
Total efficiency, annual average, net (%)	325
Auxiliary Electricity consumption (kWh/year)	30
Technical lifetime (years)	15
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0

Heat pump, ventilation, new one-family house	
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	2.3
Fixed O&M ($US/unit/year)	230
Variable O&M ($US/MWh)	0

Data sheet 69 - Heat pump, ventilation – new apartment complex

Heat pump, ventilation, new apartments	
Energy/technical data	
Heat production capacity for one unit (kW)	160
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	560
Total efficiency, annual average, net (%)	540
Auxiliary Electricity consumption (kWh/year)	3,000
Technical lifetime (years)	15
Regulation ability	
Change in capacity within 1 minute (%)	100
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Specific investment (1,000 $US/unit)	85.9
Fixed O&M ($US/unit/year)	1,392
Variable O&M ($US/MWh)	0.57

Gas driven heat pumps

General qualitative description of gas driven heat pumps

The following section is an introduction to gas driven heat pumps in general and contains an introduction to the technology. This introduction is then succeeded by three sections each describing a unique heat pump technology including a data sheet for each technology.

Introduction - General Information about gas driven heat pumps

"Gas driven heat pumps" or "gas fired heat pumps" are mostly named more simply "gas heat pumps". For simplification, we have mostly also opted for this last designation in this document.

Note that there are no air-to-air gas heat pumps on the market today for residential heating, but the technology exists for gas driven engine heat pumps (Aisin, Sanyo, etc.).

In principle, all gas heat pump technologies are reversible and can also be used for cooling/air conditioning, but not all products on the market may be designed for cooling also.

Main differences to electrical heat pumps

The energy efficiency of gas heat pumps is usually expressed in percent and not in "Coefficient of Performance" (COP factor), as for the electrical heat pumps. The highest net efficiency measured for a gas heat pump in heating mode has today reached approximately 170% (COP = 1.7) (value obtained on absorption heat pump), which seems considerably lower than for electric heat pumps. One method to compare the performances of the two types of heat pump is to calculate the efficiencies based on primary energy use.

Due to the lower efficiency of gas heat pumps (compared to electric heat pumps), less energy from the outside air, ground etc. will be collected to the heat pump. Therefore, the design of gas heat pumps is different from that of electrical heat pumps (EHP). This means smaller heat exchangers for the energy source, fewer bore holes, shorter tubes in the ground. As a result, gas heat pumps have potentially lower installation costs compared to electric heat pumps. Another consequence is that gas heat pumps are less dependent on variations in the energy source temperature compared to the electric heat pumps.

Input

The input is the heat from e.g. ambient air collected by the outdoor heat exchanger or ground collector (vertical or horizontal). Gas is needed to drive the process. The heat can also be combined with other "free" energy sources like solar or waste water.

Gas heat pumps can be used with natural gas and LPG (Liquefied Petroleum Gas), but also with new "green gases" like biogas. Appliances that are certified for natural gas can cope with a large variation of natural gas specifications; including natural gas/upgraded biogas mix as long as the specifications of the mixture conform to specifications of the natural gas. Note that upgraded biogas mostly contain methane and will therefore also be able to be used directly (without mixing with natural gas = 100%).

For natural gas/hydrogen mixture, the technologies using fully premix burners (absorption and adsorption heat pumps) should be able to cope with mixtures containing up to 10 to 20% hydrogen (vol.); but no test results are available at this stage.

Output

The output is thermal energy for space heating and hot water. In case of reversible heat pumps, the output is also cooling.

Gas heat pumps can deliver water temperatures above 55°C, and so deliver domestic hot water and use lower radiator size designed for high water temperature. Note, however, the efficiency may decrease when the water temperature in the heating system increases.

Advantages/disadvantages

Advantages

- Because gas heat pumps rely less on the free renewable heat source, compared to electrical heat pumps, gas heat pumps also have a capacity that is less depending on the heat source temperature and as a results have a more constant heat delivery profile compared to electrical heat pump.
- Thus, gas heat pumps generally do not need a backup system to produce heat for low external temperatures) as they are not affected to the same extent by losing capacity with low outdoor temperatures, as electric heat pumps do.
- Another consequence is that, the ground source can be 40% smaller on average for gas heat pumps using brine-to-water (and therefore less expensive) compared to an electrical heat pump based on brine-to-water.
- Finally, most of the gas heat pumps offer the possibility of higher outlet water temperature (enabling domestic hot water and less radiators when needed);

Disadvantages

- The gas heat pump is already a mature product for the apartment block market and users with a large heat demand (shops etc.), but there are only a few market-ready appliances for the domestic sector, and there is a lack of experience (especially for the adsorption technology).
- Compared to a gas boiler, a larger installation space in the building may be necessary, especially if a wall-hung boiler is replaced by a floor-standing gas (or electrical) heat pump and heat storage unit.
- Gas heat pumps can only be installed where a natural gas grid is present or where biogas is available.

The cost of gas heat pumps and installation is much higher than the cost of a simple condensing gas boiler. As a result, the present (2020) costs are making the investment in such technology more relevant in case of high heating need/larger installation (domestic or collective) and less feasible in low-energy single-family houses.

Advantages/ Disadvantages for brine-to-water heat pump

For brine to water gas heat pumps, a disadvantage is that the ground heat source involves additional investment in piping to retrieve the necessary heat. The most common solution, which is horizontal ground collectors, needs available ground area corresponding to a maximal consumption of 40 kWh/m^2 per year where the area is the horizontal area. The investments can be counterbalanced by the reduced costs of energy. However, there is no outdoor noise problems when the heat pump is running, which can make it the only possible solution in densely built-up areas.

Advantages/ Disadvantages for air-to-water heat pump

Noise may pose a problem since the noise level has to be below 35 dB(A) on the boundary to other properties.

As for electrical heat pumps, in densely built-up areas it is sometimes not possible to install air-to-water heat pumps due to this. The air exchanger placed outside may generate other issues for some users (space available, proximity to neighbors, noise, architectural and esthetical aspects).

Finally, air-to-water heat pumps have lower efficiency compared to brine-to-water appliances.

Ground water and vertical pipes can be used instead of horizontal pipes if there is not enough available ground area. This is a more expensive solution, but is now being used more often than previously, which may lower the prices in the future.

Gas driven absorption heat pumps, air-to-water and brine-to-water

Brief technology description

Gas absorption heat pumps are the so-called “thermally driven heat pumps” using gas both as source of heat to be upgraded and as energy source to drive the heat pump process. This differentiates them from engine-driven heat pumps. The heat from gas is typically produced with a full premix burner. In the basic absorption process, ammonia is evaporated by the free energy (e.g. outside air) and flows to an absorber, where it forms a solution with water. Heat is generated and is transferred from the absorber to the heating system. The ammonia-water solution is pumped at increased pressure to the generator where heat is added through for example a gas burner. The ammonia vapour formed in the generator flows to the condenser, where it is condensed and energy is transferred to the heating system. A lean ammonia-water solution recirculates from the generator to the absorber. Liquid ammonia flows after a pressure reduction from the condenser to the evaporator where it is vaporized again. Other refrigerants are possible in the absorption process, but ammonia-water is used in heat pumps for space heating. The basic absorption cycle is shown in below figure.

The heat which the burner produces triggers various physical processes in the closed circuit of the gas heat pump - in contrast to an electric heat pump or gas engine driven heat pump, no compressor is needed.

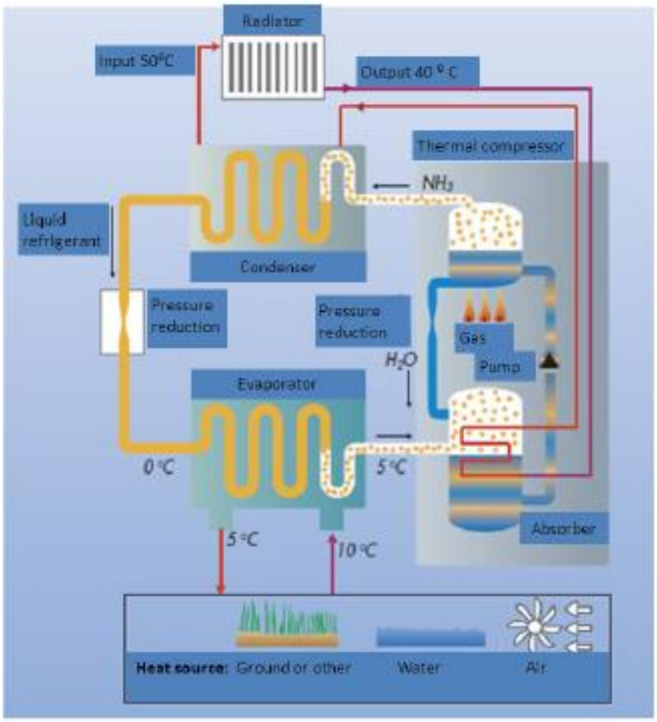

Figure 52: Operating principle for gas absorption heat pump

Typical capacities

The practical capacity range of absorption heat pumps for space heating has increased since the introduction of the Robur appliance around 2009. The limit is further lowered when absorption heat pumps, currently in field test, enter the market in 2013 - 2015. The heat pumps will then be suitable for single-family houses as well as apartment blocks. For single-family houses will the output capacity be 10 - 15 kW, and for larger heating demands in for example apartments blocks and the commercial sector, one or several 35 kW Robur heat pumps in a cascade configuration can be used. Absorption heat pumps technology could be suitable for houses with very low heat demand but, due to the present costs of the technology and installation, the market for passive houses or low-energy houses is rather limited. However, it is reported that one challenge for the technology is to further reduce the lower capacity limit.

Currently, <35 kW for a single appliance, earlier technologies of absorption heating and cooling models had up to several MW heating capacity. Larger absorption machines up to MW size that have been produced for several years are not considered to be relevant for the applications in this document and are not further described.

The above indicates the most common capacities. There are also on the market more specific technologies having their own characteristics.

Regulation ability

Different types of regulation (for the load control) exist for heat pumps. Appliances can either work in on/off mode or in modulating mode. The typical modulation range from current technologies of gas absorption heat pumps is 50 - 100%.

Advantages/disadvantages

Advantages

- The absorption gas heat pump technology is already a mature product with high efficiency.
- It is adapted for the replacement of existing boilers (minimal change of existing system) and suitable for buildings with radiators that might require higher temperatures.

Disadvantages

- There is basically only one product on the market (Robur; note that it is sold on the market under different names).

Environment

Gas absorption heat pumps use a refrigerant that is not harmful for the ozone layer, and they have an environmental advantage in this respect.

Robur gas absorption heat pump

The Robur E^3 appliances are gas-fired absorption heat pumps with modulating output and flue gas condensation. They have an output in the range of 18 – 44 kW (modulating) depending on the version of the model. The burner is a premixed burner of the same basic design as in modern condensing gas boilers. The heat pump is available in two options, as an air-to-water or ground-to-water heat pump.

Figure 53: Robur E^3 heat pump. Air-to-water (left) and ground source (right) options

Data sheets

Data sheets are elaborated for existing one-family houses and apartment complexes.
Absorption heat pumps technology could be suitable for houses with very low heat demand but, due to the present costs of the technology and installation, the market for passive houses or low-energy houses is limited. As a consequence the data for new one-house families and apartment complexes are not included in the data sheets.

Data sheet 70 - Gas driven absorption heat pump, air-to-water – existing one-family house

Air-to-water heat pump absorption gas driven, one family house, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	30
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	145
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	-
NO_X (g per GJ fuel)	10
CH_4 (g per GJ fuel)	1
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	17.8
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Data sheet 71 - Gas driven absorption heat pump, ground-source – existing one-family house

Brine-to-water (ground-source) heat pump absorption gas driven, one family house, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	30
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	145
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	-

Brine-to-water (ground-source) heat pump absorption gas driven, one family house, existing buildings	
NO_X (g per GJ fuel)	10
CH_4 (g per GJ fuel)	1
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	37.5
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Data sheet 72 - Gas driven absorption heat pump, air-to-water – existing apartment complex

Air-to-water heat pump absorption gas driven, apartment complex, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	80
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	145
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	-
NO_X (g per GJ fuel)	10
CH_4 (g per GJ fuel)	1
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	20.6
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Data sheet 73 - Gas driven absorption heat pump, ground-source – existing apartment complex

Brine-to-water (ground-source) heat pump absorption gas driven, apartment complex, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	80
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	145
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A

Brine-to-water (ground-source) heat pump absorption gas driven, apartment complex, existing buildings	
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	-
NO_X (g per GJ fuel)	10
CH_4 (g per GJ fuel)	1
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	37.5
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Gas engine driven heat pumps, air-to-water and brine-to-water

Brief technology description

A gas engine heat pump uses the same heat pump process as the electric heat pump, but the compressor is operated by a gas engine instead of an electric motor. Heat is also recovered from the engine cooling and the flue gases. In principle, any gas can be used in the gas engine. Natural gas, upgraded (or not) biogas, LPG and hydrogen are possible.

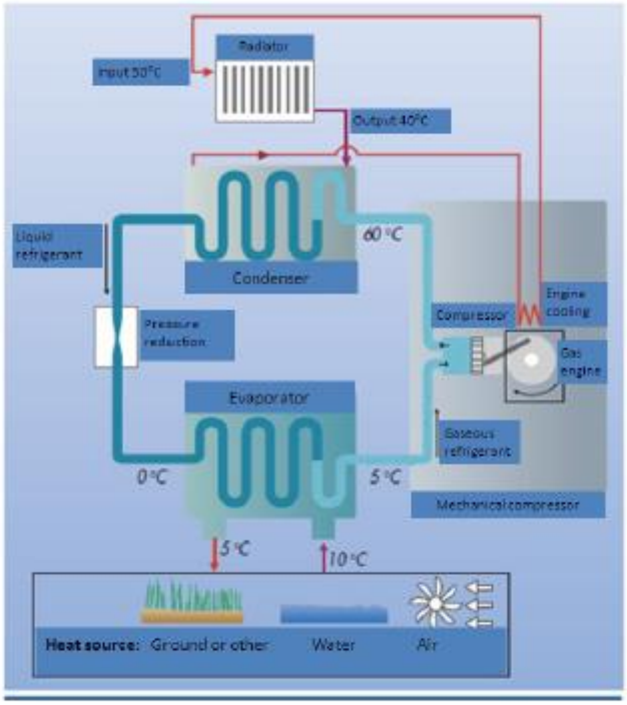

Figure 54: Operating principle for gas engine driven heat pump

Essentially, the heat pump comprises four components: the compressor, the condenser, the expansion valve and the evaporator.

In general, the gas engine driven heat pump will need an ordinary maintenance every 10,000 running hours or so.

Typical capacities

A range of capacities is available, typically from 10 kW up to a few MW heat for a single appliance. Appliances are often combined in cascade in order to obtain the needed capacity and achieve better efficiencies.

For gas engine driven heat pump, the scale ranges from a few kW to a few MW mechanical capacity. Heat pumps on the scale of MW are usually specially designed for a specific situation. The capacity range of multi-split units is 30 kW to 90 kW for heating and 20 kW to 70 kW for cooling. The technology of outdoor units based on gas engine-driven compression heat pumps is now fully mature. Outdoor units can easily be connected in cascade to achieve larger capacities (up to 1,000 kW).

Regulation ability

Different types of regulation (for the load control) exist for heat pumps. Appliances can either work in on/off mode or in modulating mode. The percentage of the maximum capacity depends on the technology and model considered.

The typical modulation ranges for gas engine driven heat pumps is approx. 30 - 100%.

Advantages/disadvantages

Advantages

- The gas engine driven gas heat pump technology is already mature.
- Gas engine heat pumps are preferable (to other gas driven heat pumps) when cooling is the main requirement because of their higher efficiency when cooling.

Disadvantages

- There are only few market-ready appliances for the domestic sector. (The appliances are mostly designed for offices, hostels, hospitals and not for the domestic sector).
- Noise from the engine may be an issue; but manufacturers (Sanyo, etc.) are making an effort to produce more silent appliances.
- The investment and maintenance cost of the product are higher than electrical heat pumps.
- The technology is not very well known by users or professionals and standards not yet ready.

Environment

Engine based heat pumps are using the same refrigerants as electrical heat pumps. The heat pumps use F-gases as refrigerants. F-gases are fluorinated gases and include HFCs, PFCs and SF6, which are potent greenhouse gases. They are covered by the Kyoto Protocol.

The HFCs (HydroFluoroCarbons) are the most important, and they are frequently used in the refrigeration industry as the working fluid in the refrigeration cycle. There are many different refrigerants based on HFCs. The most important ones are HFC-134a (R134a) and HFC mixtures: R404A, R410A and R407A. The most common refrigerants based on HFCs have Global Warming Potentials (GWP) of about 1,500 to 4,000 compared to CO2 which has a GWP of 1.

There are, however, some heat pumps working with natural refrigerants (including R290 – propane), but this is a minority. In the future, it will be possible to replace F-gases by natural refrigerants or other less harmful refrigerants.

Natural refrigerants are substances that can be found in nature's own cycle, e.g. ammonia, hydrocarbons, CO_2, water and air. None of the refrigerants in the group of natural refrigerants are perfect, and they all have technical limitations. Therefore, natural refrigerants have to be chosen with care, and one fluid cannot cover all applications.

Different types of heat pumps use the same types of refrigerants. The above description is therefore representative for all types of heat pumps.

Engine based heat pumps have higher NO_x emissions compared to thermally driven heat pumps. However, catalysts can be used to reduce the emissions.

Data sheets

Data sheets are elaborated for existing apartment complexes.

Gas heat pumps technology could be suitable for smaller houses or buildings with very low heat demand but, due to the present costs of the technology and installation, the market for low-energy houses is limited. As a consequence the data for new apartment complexes are not included in the data sheets.

Data sheet 74 - Gas-engine driven heat pump, air-to-water – existing apartment complex

Air-to-water heat pump gas-engine driven, apartment complex, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	50
Electricity generation capacity for one unit (kW)	-
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	155
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	80
CH_4 (g per GJ fuel)	5
N_2O (g per GJ fuel)	-
Particles (g per GJ fuel)	-
Financial data	
Specific investment (1 000 $US/unit)	4.8
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Data sheet 75 - Gas-engine driven heat pump, ground-source – existing apartment complex

Brine-to-water (ground-source) heat pump gas-engine driven, apartment complex, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	50
Electricity generation capacity for one unit (kW)	-
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	155
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	

Brine-to-water (ground-source) heat pump gas-engine driven, apartment complex, existing buildings	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	80
CH_4 (g per GJ fuel)	5
N_2O (g per GJ fuel)	-
Particles (g per GJ fuel)	-
Financial data	
Specific investment (1,000 $US/unit)	21.8
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Gas driven adsorption heat pumps, brine-to-water

Brief technology description

Gas adsorption (as absorption) heat pumps are part of the so-called “thermally driven heat pumps”, which use gas both for source of heat to be upgraded and energy source to drive the heat pump process. This differentiates them from engine-driven heat pumps. The heat from gas is typically produced with a full premix burner.

In adsorption processes, the water, which is mainly used as the refrigerant, evaporates, and in this process it absorbs the ambient heat. The water vapor is adsorbed on the surface of a solid substance, such as active charcoal, silica gel (glass-like silicates) or zeolite, (such as the Viessmann and Vaillant appliances). Alternative solid-sorption systems such as solid-ammonia, salt-ammonia, LiCl-H_2O are also used. Thus, heat is released at a higher temperature. Once the zeolite is saturated, the water is driven out of the zeolite again in the desorption phase. Heat from a gas burner is used for this purpose.

The adsorption heat pump process is a non-continuous regenerative and periodic process. The figure below illustrates the process. The adsorption heat pump consists of an adsorbent, a heat exchanger and a heat generator (burner). In the desorption phase, heat from the gas burner vaporizes water adsorbed in the adsorbent. The water vapor condenses in the heat exchanger, which in this phase is connected to the heating system. Heat is released during the adsorption and transferred to the heating system.

The heat which the burner produces triggers various physical processes in the closed circuit of the gas heat pump - in contrast to an electric heat pump or gas engine driven heat pump, no compressor is needed.

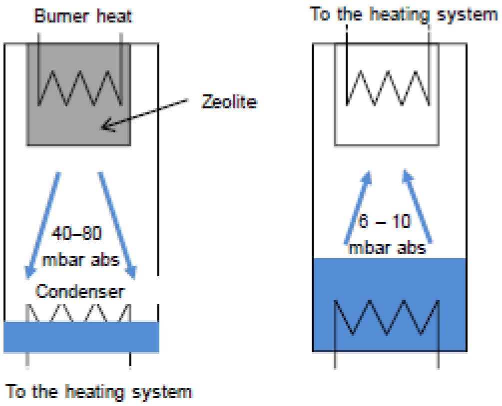

Figure 55: Sketch of the basic adsorption process, Residential gas-fired sorption heat pumps.

Typical capacities

Gas adsorption heat pumps that will come on the market are designed for the domestic market, so currently < 15 kW for a single-family house in the residential sector.

Regulation ability

Different types of regulation (for the load control) exist for heat pumps. Appliances can either work in on/off mode or in modulating mode. The modulation range for gas adsorption driven heat pumps is approx. 20 - 100%.

Advantages/disadvantages

Advantages

- Today gas adsorption driven heat pumps are designed by the gas boiler manufacturers, so the one-to-one replacement with existing gas boiler is simple and easy.
- The “package” solution will probably help the introduction on the market.
- Gas adsorption heat pumps use refrigerants with no global warming impact (ammonia/water refrigerant). Current gas adsorption heat pumps use zeolites and water.
- There are no outdoor noise problems, which makes it a possible solution in densely built-up areas.

Disadvantages

- The source energy is limited to ground or solar collectors due to the lower temperature limit of approximately 2°C. This is the reason why it is often combined with solar energy. If not, the piping must be deep enough to guarantee that this requirement is respected.
- Currently, the technology seems to have slightly lower efficiency compared to the two other gas heat pump technologies.
- The technology is very new with the disadvantages that this implies, e.g. few solutions available on the market and lack of knowledge on reliability.
- Today, the appliance is only for the domestic sector.
- The technology is not very well known by users or professionals.

Environment

Gas absorption heat pumps use a refrigerant, which is not harmful for the ozone layer, and they have an environmental advantage in this respect.

Data sheets

Data sheets are available for existing one-family houses.

Since gas adsorption heat pumps on the market are designed for the domestic single-family houses only, no data is included for apartment complexes. Additionally very limited data is available on adsorption heat pumps designed for low-energy houses, hence no data is presented on new one-family houses.

Data sheet 76 - Gas driven adsorption heat pump, ground-source – existing one-house family

Brine-to-water (ground-source) heat pump, adsorption gas driven, one family house, existing buildings	
Energy/technical data	
Heat production capacity for one unit (kW)	10
Electricity generation capacity for one unit (kW)	-
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Heat efficiency, annual average, net (%)	-
Total efficiency, annual average, net (%)	135

Brine-to-water (ground-source) heat pump, adsorption gas driven, one family house, existing buildings	
Auxiliary Electricity consumption (kWh/year)	-
Technical lifetime (years)	20
Regulation ability	
Change in capacity within 1 minute (%)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	10
CH_4 (g per GJ fuel)	1
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	15.7
Fixed O&M ($US/unit/year)	284
Variable O&M ($US/MWh)	0

Solar heating

Brief technology description

Solar energy for domestic hot water and space heating is usually based on the principle of pumping a heat transfer liquid (typically a mixture of water and propylene glycol) from an array of roof mounted solar collectors to one or more storage tanks. Solar heating for dwellings has mainly been developed for coverage of the entire hot water demand during the summer period, and to a minor degree for space heating. Because of the mismatch between demand for space heating and available solar heat, there is a need of seasonal energy storage if solar energy should be the only supply. Such storage systems are only feasible at very large scale, and therefore solar heating for single-family houses must be combined with other heating systems, e.g. gas boilers or heat pumps. Small-scale long-term storages based on heat of fusion (heat of melting – the heat used when a substance melts) are theoretically possible, but they are not on the market today.

Main components: Flat plate or vacuum tube solar collector, storage tank with heat exchangers, pump and control unit. Self-circulating systems work without pump and control.

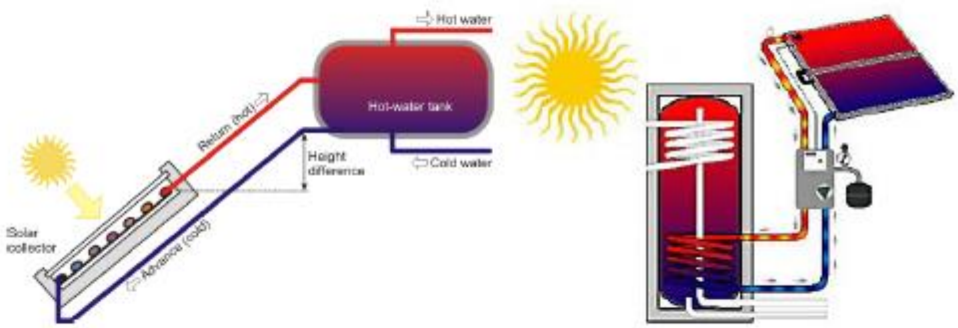

Figure 56: Small solar heating system for domestic hot water. To the left a pumped system where auxiliary heat is supplied to the upper heat exchanger coil. To the right a thermosyphon system without pump. In such a system the circulation of the heat transfer fluid is driven by natural convection rather than a mechanical pump.

Input

The primary energy input is solar radiation, of which a part can be converted to thermal energy in the absorber plate. The amount of energy reaching the solar collector depends on geographical site and orientation of the collector as well as possible shadows and ground reflectance. The only non-solar energy input to a solar heating system is the electric energy needed for the pump, controller and optional electric back-up heater. This amounts to up to 5% of the delivered energy in a typical system, not including electric backup heater.

Output

The output is thermal energy at medium temperature, typically 20 - 80°C, depending on operation conditions and collector type. Higher temperatures are possible with special double-glazed solar collectors for district or industrial heating, but they are hardly relevant for domestic hot water (DHW) and space heating. In combination with heat pumps, it is possible to use very simple and inexpensive solar collectors operating at low temperature. These are typically made of polymers without any cover or insulation. It is very important to mention that the actual performance of a solar heating system is highly dependent on the energy consumption and its distribution on time. A high consumption per m^2 collector is favourable for the efficiency, because it tends to lower the operational temperature, but it also results in a low solar fraction i.e. the part of the heating demand that is covered by the solar heating system.

Typical capacities

Traditionally, the system size is given in m_2 collector surface. For single-family homes the typical range is from 4 m^2 in case of a small DHW system to 15 m^2 for a combined space heating and DHW system. In order to compare with other technologies, IEA has estimated that 0.7 kW of nominal thermal power can be used as an equivalent to 1 m^2 collector surface.

Regulation ability

The thermal effect is largely determined by the solar irradiance and the actual operating temperature relative to ambient temperature. As the temperature increases, efficiency drops, so in a sense solar collectors are self-regulating and will stop producing heat when it reaches the so-called stagnation temperature. The regulation system in a solar heating plant can switch the available solar energy to be used for hot water or space heating and in some cases to a heat dump (typically the ground circuit in a solar/heat pump combi-system), in order to avoid boiling or temperature-induced damages. Boiling can happen in case of a power failure during periods with bright sunshine. A safety valve will open and it will be necessary to refill the system.

Advantages/disadvantages

Advantages

- No pollution during operation.
- The solar collector can be integrated in the urban environment and will then substitute a part of the building envelope.
- Large energy savings are often possible if the existing heater can be completely switched off during the summer so that standby losses can be substantially reduced.
- No dependency on fuels

Disadvantages

- Relatively expensive installation, except for large systems.
- Mismatch between heating demand and solar availability.
- Requires sufficient area on the roof with appropriate orientation
- May compete with photovoltaic systems for the same area.

Environment

A solar heating system mainly contains metals and glass that require energy in manufacturing. It is estimated that the energy payback time is 1-3 years for a well-functioning system. Almost all the materials can be recycled. The special selective surface used on most solar collectors is made in a chemical process that in some cases involves chromium. It is important that the process control is adequate to avoid any pollution from this process. The fluid used in most solar heating systems shall be disposed as low-toxic chemical waste.

Data sheet 77 - Solar heating system – one-family house, existing building

Solar heating system - One-family house, existing building	
Energy/technical data	
Heat production capacity for one unit (kW)	4.2
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	5
Expected share of hot tap water demand covered by unit (%)	65
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	NA
Total efficiency, annual average, net (%)	NA
Auxiliary Electricity consumption (kWh/year)	140
Technical lifetime (years)	25

Solar heating system - One-family house, existing building	
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	4.6
Fixed O&M ($US/unit/year)	82
Variable O&M ($US/MWh)	0

Data sheet 78 - Solar heating system – one-family house, energy renovated.

Solar heating system - One-family house, Energy renovated	
Energy/technical data	
Heat production capacity for one unit (kW)	4.2
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	10
Expected share of hot tap water demand covered by unit (%)	65
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	NA
Total efficiency, annual average, net (%)	NA
Auxiliary Electricity consumption (kWh/year)	140
Technical lifetime (years)	25
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	4.1
Fixed O&M ($US/unit/year)	82
Variable O&M ($US/MWh)	0

Data sheet 79 - Solar heating system – one-family house, new building

Solar heating system - One-family house, new building	
Energy/technical data	
Heat production capacity for one unit (kW)	4.2
Electricity generation capacity for one unit (kW)	0

Solar heating system - One-family house, new building	
Expected share of space heating demand covered by unit (%)	0
Expected share of hot tap water demand covered by unit (%)	65
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	NA
Total efficiency, annual average, net (%)	NA
Auxiliary Electricity consumption (kWh/year)	140
Technical lifetime (years)	25
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	2.9
Fixed O&M ($US/unit/year)	82
Variable O&M ($US/MWh)	0

Data sheet 80 - Solar heating system – apartment complex, existing building

Solar heating system - Apartment complex, existing building	
Energy/technical data	
Heat production capacity for one unit (kW)	140
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	0
Expected share of hot tap water demand covered by unit (%)	65
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	NA
Total efficiency, annual average, net (%)	NA
Auxiliary Electricity consumption (kWh/year)	2,800
Technical lifetime (years)	25
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	98.0
Fixed O&M ($US/unit/year)	469
Variable O&M ($US/MWh)	0

Data sheet 81 - Solar heating system – apartment complex, new building

Solar heating system - Apartment complex, existing building	
Energy/technical data	
Heat production capacity for one unit (kW)	140
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	0
Expected share of hot tap water demand covered by unit (%)	65
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	NA
Total efficiency, annual average, net (%)	NA
Auxiliary Electricity consumption (kWh/year)	2,800
Technical lifetime (years)	25
Regulation ability	
Primary regulation (% per 30 seconds)	N/A
Secondary regulation (% per minute)	N/A
Minimum load (% of full load)	N/A
Warm start-up time (hours)	N/A
Cold start-up time (hours)	N/A
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1,000 $US/unit)	89.5
Fixed O&M ($US/unit/year)	469
Variable O&M ($US/MWh)	0

Electric heating

Brief technology description

Electric radiators are mounted in each room. The bathrooms are sometimes equipped with electric floor heating systems. The hot tap water is made by a hot water tank with an electric heating coil. In case the distance to a secondary tapping point is large, more than one water heater can be installed. The radiators are equipped with internal thermostats, but more advanced systems are available, making it possible to programme a temperature schedule individually for each room. Electric heating can be a supplement or a complete system. Electric heating can be controlled by external systems, including night set back. Also remote internet control is becoming popular, particular in vacation houses. The installation will normally include a group switch per one or two rooms, making central control very simple to install.

Input

The input is electricity.

Output

The output is room heating and hot water.

Typical capacities

Typical capacities for one-family buildings and apartment complex are 5 to 400 kW.

Regulation ability

The control is very flexible and the capacity can be regulated fast from 0 to 100% and vice versa. It should be noted that the heat output is only dependent on the installed nominal power. In most cases, use of night setback or other forms of periodic heating is very efficient, as the reheating of the rooms can be very rapid. Furthermore, adding extra capacity is cheap.

Electric radiators can be built as storage heaters with some energy storage. For such radiators, electricity can be turned off for a period but heat is still emitted from the radiator. This ability can be used to e.g. fit time varying electricity tariffs in future.

Advantages/disadvantages

Advantages

- Low investment and installation costs [4]
- Very high flexibility
- Very efficient reheating after night setback
- Very precise room temperature control
- Easy possibility of remote control
- Periodic sanitation of the hot tap water is done by heating the water in the hot water tank without any loss of energy.
- Furthermore, distribution heat losses are saved compared to water based heating systems.
- It is expected that electricity will become increasingly important in the future energy supply. With increasing penetration of renewable electricity, the ability to consume electricity flexible becomes increasingly interesting. Large scale demonstration of smart grid technologies has demonstrated that households with direct electric heating are more flexible than households with heat pumps.

Disadvantages

- High energy price
- High loss of exergy when converting electricity to heat

- If widespread used, the peak load power demand can prove a challenge for both power production units and the electricity grid.
- A household or indeed an apartment complex heated by electric heating often requires reinforcement of the electricity connection compared to households heated by boilers or district heating

Environment

The environmental impact due to the use of electricity will depend on the way the electricity is produced.

Data sheet 82 - Electric heating – one-family house, new building

Electric heating - One-famely house, new building	
Energy/technical data	
Heat production capacity for one unit (kW)	3
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	100
Total efficiency, annual average, net (%)	100
Auxiliary Electricity consumption (kWh/year)	0
Technical lifetime (years)	30
Regulation ability	
Primary regulation (% per 30 seconds)	100
Secondary regulation (% per minute)	100
Minimum load (% of full load)	0
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	3.5
Fixed O&M ($US/unit/year)	29
Variable O&M ($US/MWh)	0

Data sheet 83 - Electric heating – apartment complex, new building

Electric heating - Apartment complex, new building	
Energy/technical data	
Heat production capacity for one unit (kW)	160
Electricity generation capacity for one unit (kW)	0
Expected share of space heating demand covered by unit (%)	100
Expected share of hot tap water demand covered by unit (%)	100
Electric efficiency, annual average, net (%)	NA
Heat efficiency, annual average, net (%)	100
Total efficiency, annual average, net (%)	100
Auxiliary Electricity consumption (kWh/year)	0
Technical lifetime (years)	30
Regulation ability	
Primary regulation (% per 30 seconds)	100

Electric heating - Apartment complex, new building	
Secondary regulation (% per minute)	100
Minimum load (% of full load)	0
Warm start-up time (hours)	0
Cold start-up time (hours)	0
Environment	
SO_2 (g per GJ fuel)	0
NO_X (g per GJ fuel)	0
CH_4 (g per GJ fuel)	0
N_2O (g per GJ fuel)	0
Particles (g per GJ fuel)	0
Financial data	
Specific investment (1 000 $US/unit)	124.6
Fixed O&M ($US/unit/year)	59
Variable O&M ($US/MWh)	0

High temperature heat pump

Brief technology description

Hybrid absorption/compression heat pumps (HACHP) are a new type of heat pumps being introduced to the market. The technology is not new, but advancements in compressor technology and the flux towards sustainable ways to produce process heat have resulted in this technology becoming relevant.

HACHP is one of several types of high temperature heat pumps. HACHP has been selected for this chapter based on the following reasons. HACHP can use natural refrigerant (some of the other types uses HFC). It is currently on the marked with large heating capacities, > 0.5 MW. Other types of high temperature heat pumps use natural refrigerant, but generally they currently have smaller capacities than the scope of this chapter.

The main difference between a normal vapour compression heat pumps, is that HACHPs use a zeotropic refrigerant, typically a mixture of ammonia and water. As the two fluids have different evaporation pressures, they individually evaporate and condensate at different temperatures. The zeotropic refrigerant, where the fluids are mixed, evaporates and condenses through a temperature range instead. This transforms the evaporation/condensation processes into an ab/de-sorption processes instead (hence the name), which results in an improved COP. A separate fluid loop (typical water) with a pump is also present, together with a liquid separator. A simplified setup can be seen on the figure below.

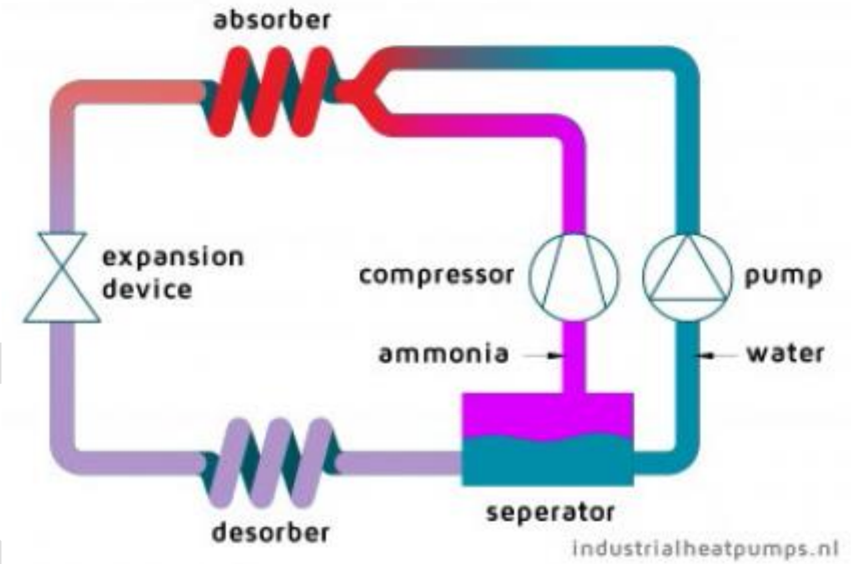

Figure 57: Simplified hybrid absorption-compression heat pump

The advantage of the HACHP compared to ordinary vapour-compression heat pumps is that the saturation temperature is increased with the zeotropic refrigerant. Industrial available compressors are currently limited to an upper pressure limit of 60 bars, at which pure ammonia – which is the most widely used refrigerant have a saturation temperature of 98°C. Combined with a minimum ΔT in the heat exchangers, this limits vapour-compression heat pumps to an upper temperature limit of ~95°C. Adding 25% water however, increases this limit to 152°C. HACHPs is thus capable of delivering heat at much higher temperatures.

HACHP can simultaneously supply cooling if temperature levels are compatible and can be used in series with conventional boilers as preliminary heating if very high temperatures are required. It is recommended to have a temperature difference between hot and cold side of less than 90°C, at higher temperature differences the COP decrease sharply.

The heat pump requires a heat source which can be either dependent or independent of other industrial processes. Using a process-dependent heat source (such as flue gas or other excess heat sources) can lead to higher efficiencies due to these being at a higher temperature level. Using non- process-dependent heat sources (such as sea/tap-water, air, geothermal) can however lead to increased flexibility due to these sources typical being independent on other processes.

As the COP of a HACHP is strongly linked to the glide[3] in temperature, processes with large temperature variations are required. For instance, pipe trace heating or other processes requiring less than 10°C in difference between the in- and outlet temperatures, will be more efficient with an ordinary vapour compression heat pump. Subsequently, having a process where a large temperature difference is required, i.e. heating water more than 10°C, will result in a HACHP being more efficient. A HACHP is hence performance wise the optimal choice when high glides can be achieved, and/or high sink temperatures are wanted.

The general interest for high temperature heat pumps is high, both in industry and academia.

The ability to replace steam generation with combustibles are driving the development and is crucial in order to reach the goals of industrial renewability, although it requires favourable ratios of the price of electricity compared to combustibles, which can limit the current business case for implementing high temperature heat pumps. It is however expected to see commercially available heat pumps producing up to 150°C steam or hot oil in the next 3-8 years.

Efficiencies

The efficiencies of heat pumps in general is strongly dependent on the temperature lift, here defined as:

$$\Delta T_{\text{Lift, process}} = \text{Sink outlet} - \text{Source inlet}$$

With the sink being the reservoir where the high temperature heat is wanted, and source being the used heat source.

The use of a zeotropic refrigerant effectively means that instead of transferring energy at a fixed temperature, the refrigerant changes temperature throughout the heat transferring process. The amount of change is defined as the *glide*. A high glide will strongly affect the efficiency of the HACHP, which can achieve very high COPs[4] at high glides. In short, this is because the process approaches the Lorenz cycle. The Lorenz cycle can be simulated by putting an infinite amount of small normal vapour compression heat pumps in series.

For instance, if a vapour compression heat pump can achieve a COP at 5 at a temperature lift of 60°C, the HACHP can achieve a maximum COP of up to 6.5 if a glide of 20°C can be reached on both the sink and source heat exchangers. In reality, the difference is a bit lower due to finite heat exchanger sizes and is of course dependable on the quality and scale of the components. Reaching the maximum COP might not always be economically feasible in real life conditions. If for instance a glide of only 5°C can be reached, the added complexity and cost associated with a hybrid heat pump might not be feasible.

Input

The primary input for this technology is electricity, which is consumed by the vapour compressor and the liquid pump.

The technology also needs a heat source. Exceeding a temperature lift of more than 90°C between heat source and heat sink (target temperature), will result in a steep decrease in the efficiency of the technology. E.g. if a target temperature is 120°C, the heat source should be minimum 30°C.

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[3] The use of a zeotropic refrigerant effectively means that instead of transferring energy at a fixed temperature, the refrigerant changes temperature throughout the heat transferring process. The amount of change is defined as the *glide*

[4] COP defined here as COP = (Heating capacity)/(Electricity consumption)

The heat source could be flue gas cooling and/or condensation. It could also be cooling of process water or waste water at elevated temperature levels or excess heat from existing chillers.

Output

This technology produces process heat up to 120°C. The heat source for the technology can also act as process cooling. Temperatures up to 98°C can be achieved when using pure Ammonia. Temperatures above 98°C can be achieved using a mixture of Ammonia and water.

Even though HACHP can produce steam given the high temperature abilities, HACHP would not operate efficiently. Given low or no temperature glide for the heat sink, as the latent phase has constant temperature.

HACHP is much better suited for high pressure hot water. High pressure hot water is typical in the temperature range 80 - 175°C, normally delivered by boilers. The HACHP then covers the heating up to 120 - 150°C and additional boiler covers the rest of the temperature lift if needed. The same field of application is evident for hot oil.

Typical capacities

The typical range of capacity for this technology is 0.5 - 5 MW_{heat} for one unit. A small temperature lift will typically result in higher capacity, due to the displacement rate and specific volume of the refrigerant.

Typical annual operation hours and load pattern

A realistic business case requires long operation hours, which is most likely to be obtained in continuous production processes. HACHP installed to deliver continuous process heat, will follow the operation hours of the facility and load pattern.

Depending on the type of heat source used, the HACHP follows ordinary heat pumps in terms of flexibility and maintenance ratios. If a steady heat source is used, the heat pump should be able to run with close to no interruptions throughout the year. Heat pumps can achieve higher COPs at part load operations due to the efficiency of the heat exchangers being increased with lower flow rates, which means that non-steady state operations are beneficial in terms of efficiency.

Regulation ability

Heat pumps, including HACHP, of this size > 0.5 MW_{heat} are often frequency controlled to operate in part-load.

Advantages/disadvantages

Advantages

- Higher efficiency than regular electric heat pumps at large temperature glides > 10 K.
- Lower vapour pressure by decreasing volatile component concentration
- Temperature levels higher than heat pump

Disadvantages

- Higher investment cost than regular heat pump
- More difficult to control than regular heat pump
- Need large temperature glide to be efficient. HACHP will not efficiently supply heat for evaporation/boiling

Environment

As the HACHP uses electricity, no direct particles or gasses are emitted doing operation. Using ammonia and water as refrigerant. Ammonia is widely used refrigerant in heat pumps and refrigeration applications. Ammonia has no ozone depletion potential (ODP = 0) and no direct greenhouse effect (GWP = 0).

Data sheet 84 - High temperature heat pumps, up to 125°C

High temperature heat pumps, up to 125°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	1.5
Total efficiency, net (%), nominel load	260
Total efficiency, net (%), annual average	255
Auxiliary electricity consumption (% of heat gen)	2
Forced outage (%)	0
Planned outage (weeks per year)	0.5
Technical lifetime (years)	20
Construction time (years)	0.6
Regulation ability	
Minimum load (% of full load)	25
Warm start-up time (hours)	0.25
Cold start-up time (hours)	1
Environment	
SO_2 (g per GJ fuel)	N/A
NO_x (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Nominal investment (M$US per MW)	1.05
Fixed O&M ($US/MJ/s/year)	1,174
Variable O&M ($US/MWh)	4.0

Data sheet 85 - High temperature heat pumps, up to 150°C

High temperature heat pumps, up to 150°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	1.5
Total efficiency, net (%), nominel load	300
Total efficiency, net (%), annual average	295
Auxiliary electricity consumption (% of heat gen)	2
Forced outage (%)	0
Planned outage (weeks per year)	0.5
Technical lifetime (years)	20
Construction time (years)	0.6
Regulation ability	
Minimum load (% of full load)	25
Warm start-up time (hours)	0.25
Cold start-up time (hours)	1
Environment	
SO_2 (g per GJ fuel)	N/A
NO_x (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A

High temperature heat pumps, up to 150°C	
Financial data	
Nominal investment (M$US per MW)	1.27
Fixed O&M ($US/MJ/s/year)	1,174
Variable O&M ($US/MWh)	4.0

Heat driven heat pump

Brief technology description

A principle of operation is depicted in Figure 1.

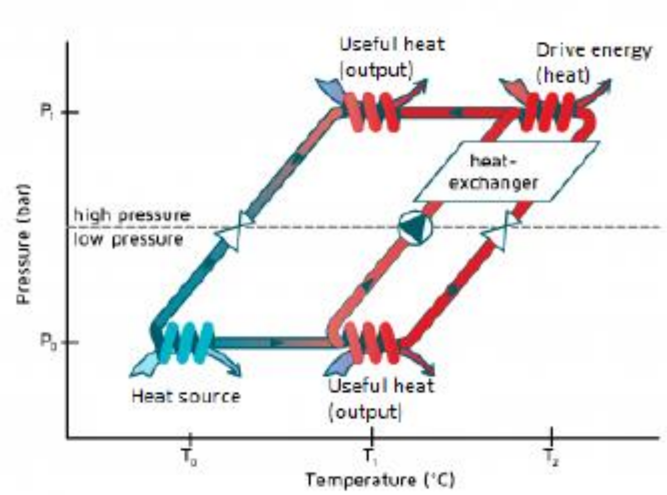

Figure 58: Principle of operation, heat driven heat pump, edited from [3]

Input

Inputs are heat source and drive energy (also heat).

The heat source can be ambient, low temperature waste heat, flue gas condensation or process cooling.

The drive energy is high temperature heat > 140°C. Most common is hot flue gas, high temperature hot water or steam, but also high temperature waste heat could be used.

Output

The main output is heat. The heat driven heat pump delivers heat up to ~80 - 85°C.

If process cooling act as heat source, process cooling will also be an output.

Typical capacities

Absorption heat pumps are available in capacities of up to around 12 MW of cooling. The heat output including drive energy will thus be around 20 MW. Due to transportation limitation, a single unit is up to 6 MW of cooling, for larger capacities unit are coupled.

Data sheet 86 - Heat driven heat pump up to 80°C

Heat driven heat pumps, up to 80°C	
Energy/technical data	
Heat generation capacity for one unit (MW)	12
Total efficiency, net (%), nominel load	170
Total efficiency, net (%), annual average	168
Auxiliary electricity consumption (% of heat gen)	1
Forced outage (%)	0
Planned outage (weeks per year)	0
Technical lifetime (years)	20
Construction time (years)	0.5

Heat driven heat pumps, up to 80°C	
Regulation ability	
Minimum load (% of full load)	N/A
Warm start-up time (hours)	0
Cold start-up time (hours)	0.5
Environment	
SO_2 (g per GJ fuel)	N/A
NO_X (g per GJ fuel)	N/A
CH_4 (g per GJ fuel)	N/A
N_2O (g per GJ fuel)	N/A
Particles (g per GJ fuel)	N/A
Financial data	
Nominal investment (M$US per MW)	0.68
Fixed O&M ($US/MJ/s/year)	2,420
Variable O&M ($US/MWh)	1.21