# Technology Data for
# Electricity and Heat Generating Plants

**March 2005**

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# INTRODUCTION

The Danish Energy Authority and the two Danish electricity transmission and system operators, Elkraft System and Eltra, initiated updating of current technology catalogues in 2003. The first updated catalogue was published in March 2004. This report presents the results of the second phase of updating.

The primary objective has been to establish a uniform, commonly accepted and up-to-date basis for energy planning activities, such as future outlooks, evaluations of security of supply and environmental impacts, climate change evaluations, and technical and economic analyses.

The catalogue may furthermore be used as reference for evaluations of the development perspectives for the numerous technologies available for energy generation in relation to the programming of funding schemes for research, development and demonstration of emerging technologies.

It has finally been the intention to offer the catalogue for the international audience, as a contribution to similar initiates aiming at forming a public and concerted knowledge base for international analyses and negotiations.

A guiding principle for developing the catalogue has been to primarily rely on well-documented and public information, secondarily on invited expert advice. Since many experts are reluctant in estimating future quantitative performance data, the data tables are not complete, in the sense that most data tables show several blank spaces. This approach has been chosen in order to achieve data, which to some extent are equivalently reliable, rather than to risk a largely incoherent data set including unfounded guesses.

# INTRODUCTION IN DANISH

Energistyrelsen, Elkraft System og Eltra startede i 2002 en fælles opdatering af eksisterende teknologikataloger på energiområdet.

Senest blev der i forbindelse med Danmarks Energifremtider og Energi 21 i 1995-96 udgivet en række baggrundsrapporter, herunder "Teknologidata for el- og varmeproduktionsanlæg" og "Teknologidata for vedvarende energianlæg" – del 1 og 2.

Et hovedformål med at opdatere teknologikataloget er at sikre et ensartet, alment accepteret og aktuelt grundlag for planlægningsarbejdet og vurderinger af forsyningssikkerhed, beredskab, miljø og markedsudvikling hos bl.a. de systemansvarlige selskaber og Energistyrelsen. Dette omfatter for eksempel fremskrivninger, scenarieanalyser og teknisk-økonomiske analyser.

Desuden vil teknologikataloget være et nyttigt redskab til at vurdere udviklingsmulighederne for energisektorens mange teknologier til brug for tilrettelæggelsen af støtteprogrammer for energiforskning- og udvikling. Tilsvarende afspejler kataloget resultaterne af den energirelaterede forskning og udvikling. Også behovet for planlægning og vurdering af klima-projekter har aktualiseret nødvendigheden af et opdateret databeredskab.

Teknologikataloget vil endelig kunne anvendes i såvel nordisk som internationalt perspektiv. Det vil derudover kunne bruges som et led i en systematisk international videns-opbygning og -udveksling, ligesom kataloget kan benyttes som dansk udspil til teknologiske forudsætninger for internationale analyser og forhandlinger. Af disse grunde er dette katalog som noget nyt udarbejdet på engelsk.

Det første opdaterede katalog udkom i marts 2004, indeholdende 18 teknologier. Nærværende katalog består af en opdatering af de hidtidige 18 teknologier samt en udvidelse med yderligere 9 teknologier. For begge katalogers vedkommende har arbejdet været gennemført i tre faser:
1. Rambøll udarbejder førsteudkast af samtlige teknologiblade.
2. Interne eksperter hos Energistyrelsen, Elkraft System og Eltra kommenterer teknologibladene.
3. En række eksterne eksperter (primært danske; leverandører af energianlæg, energiselskaber og videncentre) inviteres til at kommentere og bidrage til færdiggørelse af teknologibladene.

Den 18. september 2004 afholdt Energistyrelsen en større workshop, hvor udkastet til teknologikatalog blev præsenteret og diskuteret.

# 1. GUIDELINES AND MANUAL

## 1. Introduction

This document serves two objectives:
1. To guide authors of technology sheets in selecting the right data.
2. To assist readers in interpreting the data.

## 2. Qualitative description

One to three pages giving key characteristics of the technology. Typical paragraphs are as described below. When drafting new technology sheets, it is recommended to review existing technology sheets for inspiration.

**Brief technology description**

**Input**

**Output**

**Typical capacities**
Shall be stated for a single 'engine' (e.g. a single wind turbine, not or wind farm, or a single gas turbine, not a power plant consisting of a multitude of gas turbines)

**Regulation ability**

**Advantages/disadvantages**
Specific advantages and disadvantages relative to equivalent technologies. Generic advantages are ignored; e.g. renewable energy technologies mitigate climate risk and enhance security of supply.

**Life cycle assessment**
Typically, a LCA cannot be described in a few words, since a multitude of parameters are involved. For the present purpose, two primary perspectives have been chosen.

Firstly, the total emission of greenhouse gasses during up to four major activities are stated per MWh electricity generated:
Total $CO_2$-equivalent emissions: Operation xx kg/MWh, construction and decommissioning yy kg/MWh, fuel procurement (incl. fuel transport) zz kg/MWh, and residues uu kg/MWh.

For technologies generating electricity and heat, the challenge is how to allocate the environmental impacts to the two products. Therefore, two methods are applied:
- Allocation according to energy content: Electricity and heat are energetically equal in value, so that emissions are allocated according to how much electricity and heat is generated.

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- Allocation according to energy quality (exergy): Electricity is a higher quality energy carrier than heat. As a simple rule-of-thump 1 MWh heat equals 0.15 MWh electricity. Then emissions are allocated according to how much electric exergy and heat exergy is generated.

Example: A typical large-scale coal-fired cogeneration plant generates equal amounts of electricity and heat. To generate one MWh of electricity and one MWh of heat, the total $CO_2$ emission comes to 760 kg. Allocation according to energy contents gives a 50-50 split; whereby the $CO_2$ emission per MWh electricity becomes 380 kg/MWh. Allocation according to energy quality gives a 50-7.5 split (the exergy content of 50 MWh district heat is 7.5 MWh); whereby the $CO_2$ emission per MWh electricity becomes 661 kg/MWh.

Allocation by energy content or by exergy are two possible allocation models. Other models are available, for example allocation by economic value, allocation by fuel substitution compared to reference plant technologies or allocation according to consumer preference, i.e. "willingness-to-buy".

Secondly, the main ecological footprints may be stated. These cannot be used to compare technologies. For example, photovoltaic cells have few and small footprints, one of the major ones being radioactive waste. However, this does not mean that there is more radioactive waste from solar electricity than coal-fired electricity. It only means that radioactive waste is one footprint from photovoltaic cells which its more important than other footprints from the same technology.

Finally, a third LCA parameter may be the energy pay back time or energy self-depreciation time; i.e. the time required by the technology for the production of energy equal to the amount of energy that was consumed during the production of the technology

**Research and development**

**Examples of best available technology**

**Special remarks**

**References**

# 3. Quantitative description

To enable comparative analyses between different technologies it is imperative that data are actually comparable. As an example, economic data should be stated in the same price level. Also it should be clear, what is meant by generating capacity (gross or net?).

It is essential that data be given for the same years. Year 2004 is the base for the present status of the technology (best available technology commissioned in 2004), whereas data for expectations to future developments shall be given at years 2010-2015 and 2020-2030 (intervals have been chosen to reflect the uncertainties in forecasting). However, in the very initial phase of the project it has proven instrumental to refer to existing technology catalogues, which have used other years.

Overleaf is shown a gross datasheet, containing all parameters that may be used to describe the specific technologies. This datasheet should not be regarded rigidly. For most technologies, the datasheet must be adjusted to suit the specific characteristics. As an example, the start-up fuel consumption does not make sense for a wind turbine.

Gross datasheet:

| Technology | | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | | | | |
| Total efficiency (%) net | | | | |
| Electricity efficiency (%) net - 100% load | | | | |
| 75% load | | | | |
| 50% load | | | | |
| Start-up fuel consumption (GJ) | | | | |
| Time for varm start-up (hours) | | | | |
| Cb coefficient (40$^{o}$C/80$^{o}$C) | | | | |
| (50$^{o}$C/100$^{o}$C) | | | | |
| Cv coefficient (40$^{o}$C/80$^{o}$C) | | | | |
| (50$^{o}$C/100$^{o}$C) | | | | |
| Forced outage (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | | | | |
| Construction time (years) | | | | |
| **Environment** (Fuel: name, LHV in MJ/kg, and sulphor content) | | | | |
| $SO_2$ (kg per GJ fuel) | | | | |
| $SO_2$ (degree of desulphoring, %) | | | | |
| $NO_X$ (kg per GJ fuel) | | | | |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| Ashes (kg per GJ fuel) | | | | |
| Other residuals (kg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) | | | | |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1
2

**Remarks:**
A

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## 3.1. Technology

Examples of (systematic) headlines:
- Gas turbines, combined cycle
- Gas turbines, single cycle
- Steam turbine, grate fired biomass, industry
- Wind turbines, offshore


## 3.2. Energy/technical data

**Generating capacity for one unit**

The capacity, preferably a typical capacity (not maximum capacity) , shall be stated for a single 'engine' (e.g. a single wind turbine, not or wind farm, or a single gas turbine, not a power plant consisting of a multitude of gas turbines).

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.


**Energy efficiencies**

The total efficiency equals the total delivery of electricity plus heat at the fence (i.e. excluded own consumption) divided by the fuel consumption. The efficiency is stated in per cent at ambient conditions; air 15 $^{o}$C and water 10 $^{o}$C.

The electricity efficiency equals the total delivery of electricity to the grid divided by the fuel consumption. The efficiency is stated in per cent.

The efficiencies are determined at full load (100%), continuous operation. If the efficiencies vary much at part load, numbers should be presented at e.g. 50%, 75% and 100% load.

**Start-up**

The warm start-up time – used for boiler technologies – is defined as a start, where the water temperature in the evaporator is above 100 $^{o}$C, which means that the boiler is pressurized.

**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 difference between the power capacities in full condensation mode and in full backpressure mode (at equal maximum boiler capacity) divided by the maximum heat capacity.

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.

**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 per cent, while planned outage is given in weeks per year.

The availability is determined as 1 minus (weighted forced outage hours + planned outage hours) / 8760; possible in per cent.

**Construction time**

Period from financial closure – i.e. financing secured and all permits are at hand - until commissioning completed (start of commercial operation).


## 3.3. Environment

State the type of fuel.

In general, all emissions data should be in agreement with current of planned future EU emission standards. It is important that the financial data reflect this condition.

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

SOx: kg per GJ fuel. The sulphur content of the fuel should also be given; in the same line as the headline 'Environment'. For technologies, where de-sulphuring equipment is employed (typically large power plants), the degree of desulphuring (%) should be stated as well.

NOx: kg per GJ fuel. NOx equals $NO_2$ + NO, where NO is converted to $NO_2$ in weight-equivalents. For technologies, where de-NOx equipment is employed (typically large power plants), this shall be mentioned in the remarks.

Greenhouse gasses: $CH_4$ and $N_2O$ in tonnes per GJ fuel. Unburned hydrocarbons (UHC) should be included, either as a separate number (kg/GJ) or converted to $CH_4$-equivalent

Particles: mg per GJ fuel.


## 3.4. Financial data

Financial data are all in Euro (€), fixed prices, price-level 2002.

Several data originate in Danish references. For those data a fixed exchange ratio of 7.50 DKK per € has been used.

To inflate prices to 2002 level, the price index for machinery, tools and transport equipment has been employed (by the Danish national statistical bureau):

| 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|------|------|------|------|------|------|------|------|
| 106.8 | 108.0 | 109.7 | 111.2 | 112.3 | 114.4 | 114.8 | 115.1 |

**Specific investment**

The total investment cost is divided by the net electric capacity to arrive at the specific investment.

The investment cost shall include all physical equipment, but not land and transaction costs, e.g. administration, insurance, consultancy, project management, approvals by authorities, and interest during construction.

The cost to dismantle decommissioned plants is not included in the tables. However, such costs can be included in the text part.

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

**Operation and maintenance (O&M) costs**

Fixed O&M (€/MW/year):
The fixed share of O&M includes all costs, which are independent of how the plant is operated, e.g. administration, operational staff, property tax, insurance, and payments for O&M service agreements. Re-investments within the stated lifetime are also included.

The variable O&M costs (€/MWh) include consumption of auxiliary materials (water, lubricants, fuel additives), spare parts, and repairs (however not costs covered by guarantees and insurance).

Fuel costs are not included. Own electricity consumption is only included for heat only technologies. However, electricity consumption is not included in O&M for heat pumps.

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

## 3.5. Regulation ability

The regulation is described by three parameters:
   A. Fast reserve, MW per 15 minutes.
   B. Regulation speed, MW per second
   C. Minimum load, per cent of full load

For several technologies, these parameters do not make sense, 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.

# 4. Explanations

## 4.1. Vocabulary

A steam process can be of different nature:
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**: Same as condensation, but the steam pressure (and temperature) in the condenser is higher, so that the temperature of the coolant becomes sufficiently high to be used for industrial processes or district heating. A back-pressure turbine produces electricity and heat, at an almost constant ratio.
3. **Extraction**: Same as condensation, but steam can be extracted from the turbine to produce heat (equivalent to back-pressure). Very flexible, no fixed ratio between electricity and heat.

## 4.2. Symbols

All data in the datasheets are referenced by a number in the utmost right column, referring to source specifics below the table. The following separators are used:

| | |
|---|---|
| ; (semicolon) | separation between the three time horizons (2004, 2010-15, and 2020-30 |
| / (forward slash) | separation between sources with different data |
| + (plus) | agreement between sources on same data |

# 2. COMPARISON OF FINANCIAL KEY FIGURES

The following pages show the financial key figures for all technologies, i.e. specific investment costs and operation and maintenance costs. All data are in constant 2002 price level.

| 2004 | | Specific investment | Total O&M | | Fixed O&M | Variable O&M |
|---|---|---|---|---|---|---|
| | | (M€/MW) | % of inv. | €/MWh | €/MW/yr | €/MWh |
| **Electricity generation, thermal processes** | | | | | | |
| 01 | Advanced pulverized coal power plant | 1.1 | | | 16000 | 1.8 |
| 02 | CO2 sequestration and storage | | | | | |
| 03 | Large-scale biomass power plant | | | | | |
| | 100% biomass | 1.3 | | | 25000 | 2.7 |
| | co-firing 80% coal + 20% biomass | 1.2 | | | 22000 | 3 |
| 04 | Re-powering of steam turbines | | | | | |
| 05 | Waste-to-energy Combined Heat and Power | 6.8 | | | 272000 | 25 |
| 06 | Gas turbines single cycle | | | | | |
| | Large, 40-125 MW | 0.44-0.53 | | | 6700-8000 | 2-3 |
| | Medium, 5-40 MW | 0.57-0.86 | | | 8000 | 2.5-8 |
| | Mini, 0.1 - 5 MW | 1.1-1.7 | | >7 | | |
| | Micro, 0.003 - 0.010 MW | 1.2-1.8 | | 10-15 | | |
| 07 | Gas turbines combine cycle | | | | | |
| | Large, 100-400 MW | 0.35-0.70 | | | 14000 | 1.5 |
| | Small, 10-100 MW | 0.57-0.83 | | | 10000 | 2.0-3.5 |
| 08 | Gas engines | | | | | |
| | Spark ignition, large, 1-5 MW | 0.8-1.2 | | 6-9 | | |
| | Spark ignition, micro, 0.001-0.020 MW | 2.9 | | 13-27 | | |
| | Dual fuel, 0.5-16 MW | 0.9 | | 10 | | |
| 09 | Small-scale biomass cogeneration | | | | | |
| | Wood chips, 0.6-4.3 MW | 4.2-5.7 | 3-4 | | | |
| | Straw, 8-10 MW | 4.3-5.5 | 4 | | | |
| 10 | Gasifiers, biomass, staged gasification | 3.5 | | | 150000 | 15 |
| 11 | Gasifiers, biomass, updraft | 4.0 | | | 150000 | 15 |
| 12 | Micro combined heat and power systems | | | | | |
| | Gas turbine, 3-10 kW | 1.2-1.8 | | 5-10 | | |
| | Gas engine, 1-20 kW | 2.9 | | 13-27 | | |
| 13 | Centralised biogas plants | | | | | |
| | 300 tonnes/day waste input | 5.5 | | 30 | | |
| | 550 tonnes/day waste input | 3.9 | | 25 | | |
| | 800 tonnes/day waste input | 3.2 | | 26 | | |
| **Electricity generation, renewable energy except biomass** | | | | | | |
| 20 | Wind turbines on land | 0.80-0.85 | | 9 | | |
| 21 | Wind turbines, offshore | 1.5-1.7 | | 10-16 | | |
| 22 | Photovoltaic cells, grid-connected systems | 4.9 | ~1 | | | |
| 23 | Wave power | 2.5-4 | | - | | |
| **Electricity generation, fuel cells** | | | | | | |
| 30 | Solid oxide fuel cells | - | | - | | |
| 31 | Proton exchange membrane fuel cells | 10 | | 50 | | |
| **Electricity storage** | | | | | | |
| 40 | Pumped hydro storage | 0.5 | | | 10000 | - |
| 41 | Compressed air energy storage | | | | | |
| | 10 MW | 0.67 | | | 20000 | - |
| | 300 MW | 0.36 | | | 11000 | - |
| 42 | Electrolysis and hydrogen storage | | | | | |
| 43 | Batteries | | | | | |
| | Vanadium Redox (VRB) | - | | | - | - |
| | Sodium Sulphur (NAS) | - | | | - | - |
| **Heat generation** | | | | | | |
| 50 | Heat pumps | | | | | |
| | Very large, 50-100 MJ/s | 0.6-1.5 | | | 1000-3000 | 0 |
| | Very large, 50-100 MJ/s (hot) | 0.8-1.7 | | | 1000-3000 | 0 |
| | Large, 0.025-1.5 MJ/s (hot) | 0.6-1.1 | | | 1000-4500 | 0 |
| | Medium, 0.2-1.5 MJ/s | 0.6-1.1 | | | 3000-6000 | 0 |
| | Small, 0.001-0.025 MJ/s | 1.0-2.5 | | | 5000-10000 | 0 |
| 51 | District heating boilers, wood-chips fired | 0.25-0.6 | | | 15000-25000 | 0 |
| 52 | District heating boilers, gas fired | 0.05-0.1 | | | 1000-5000 | 0 |
| 53 | Geothermal energy | 1.1 | | 3.2 | - | - |
| 54 | Waste-to-energy District Heating | 1.0 | | | 49000 | 5.1 |

| 2010 - 2015 | | Specific investment | Total O&M | | Fixed O&M | Variable O&M |
|---|---|---|---|---|---|---|
| | | (M€/MW) | % of inv. | €/MWh | €/MW/yr | €/MWh |
| **Electricity generation, thermal processes** | | | | | | |
| 01 | Advanced pulverized coal power plant | 1.2 | | | 16000 | 1.8 |
| 02 | CO2 sequestration and storage | | | | | |
| 03 | Large-scale biomass power plant | | | | | |
| | 100% biomass | 1.3 | | | 25000 | 2.7 |
| | co-firing 80% coal + 20% biomass | 1.2 | | | 22000 | 3 |
| 04 | Re-powering of steam turbines | | | | | |
| 05 | Waste-to-energy Combined Heat and Power | 5.5 | | | 220000 | 21 |
| 06 | Gas turbines single cycle | | | | | |
| | Large, 40-125 MW | 0.44-0.53 | | | 6700-8000 | 2-3 |
| | Medium, 5-40 MW | 0.57-0.86 | | | 8000 | 2.5-4 |
| | Mini, 0.1 - 5 MW | 0.8-1.7 | | 1.4 | | |
| | Micro, 0.003 - 0.010 MW | 0.8-1.4 | | 8-12 | | |
| 07 | Gas turbines combine cycle | | | | | |
| | Large, 100-400 MW | 0.4-0.7 | | | 11000-14000 | 1.5 |
| | Small, 10-100 MW | 0.57-0.83 | | | 10000 | 2.0-3.5 |
| 08 | Gas engines | | | | | |
| | Spark ignition, large, 1-5 MW | 0.8-1.2 | | 6-9 | | |
| | Spark ignition, micro, 0.001-0.020 MW | | | | | |
| | Dual fuel, 0.5-16 MW | 0.9 | | 7-10 | | |
| 09 | Small-scale biomass cogeneration | | | | | |
| | Wood chips, 0.6-4.3 MW | 3.4-4.7 | 3-4 | | | |
| | Straw, 8-10 MW | 3.5-4.6 | 4 | | | |
| 10 | Gasifiers, biomass, staged gasification | 2.9-3 | | | 70000 | 15 |
| 11 | Gasifiers, biomass, updraft | 3 | | | | |
| 12 | Micro combined heat and power systems | | | | | |
| | Gas turbine, 3-10 kW | 0.8-1.4 | | 1-3 | | |
| | Gas engine, 1-20 kW | | | | | |
| 13 | Centralised biogas plants | | | | | |
| | 300 tonnes/day waste input | 5.0 | | 30 | | |
| | 550 tonnes/day waste input | 3.5 | | 25 | | |
| | 800 tonnes/day waste input | 2.9 | | 26 | | |
| **Electricity generation, renewable energy except biomass** | | | | | | |
| 20 | Wind turbines on land | 0.62-0.75 | | 8 | | |
| 21 | Wind turbines, offshore | 1.0-1.3 | | 4-6 | | |
| 22 | Photovoltaic cells, grid-connected systems | 2.5-3.0 | ~1 | | | |
| 23 | Wave power | 1.9-2.2 | | 12 | | |
| **Electricity generation, fuel cells** | | | | | | |
| 30 | Solid oxide fuel cells | 1 | | | 50000-70000 | 0 |
| 31 | Proton exchange membrane fuel cells | 0.9-2.3 | | 5 | | |
| **Electricity storage** | | | | | | |
| 40 | Pumped hydro storage | 0.5 | | | 10000 | - |
| 41 | Compressed air energy storage | | | | | |
| | 10 MW | < 0.67 | | | < 20000 | - |
| | 300 MW | < 0.36 | | | < 11000 | - |
| 42 | Electrolysis and hydrogen storage | | | | | |
| 43 | Batteries | | | | | |
| | Vanadium Redox (VRB) | 2.1 | | | 44000 | 2.3 |
| | Sodium Sulphur (NAS) | 1.8 | | | 41000 | 4.3 |
| **Heat generation** | | | | | | |
| 50 | Heat pumps | | | | | |
| | Very large, 50-100 MJ/s | 0.6-1.3 | | | 1000-3000 | 0 |
| | Very large, 50-100 MJ/s (hot) | | | | | |
| | Large, 0.025-1.5 MJ/s (hot) | 0.6-1.1 | | | 1000-4500 | 0 |
| | Medium, 0.2-1.5 MJ/s | 0.6-1.1 | | | 3000-6000 | 0 |
| | Small, 0.001-0.025 MJ/s | 1.0-2.5 | | | 5000-10000 | 0 |
| 51 | District heating boilers, wood-chips fired | 0.25-0.6 | | | 15000-25000 | 0 |
| 52 | District heating boilers, gas fired | 0.05-0.1 | 2-5 | | | |
| 53 | Geothermal energy | 0.8 | | 3.0 | 13000 | - |
| 54 | Waste-to-energy District Heating | 0.9 | | | 44000 | 4.5 |

| 2020 - 2030 | | Specific investment (M€/MW) | Total O&M % of inv. | Total O&M €/MWh | Fixed O&M €/MW/yr | Variable O&M €/MWh |
|---|---|---|---|---|---|---|
| **Electricity generation, thermal processes** | | | | | | |
| 01 | Advanced pulverized coal power plant | 1.2 | | | 16000 | 1.8 |
| 02 | CO2 sequestration and storage | | | | | |
| 03 | Large-scale biomass power plant | | | | | |
| | 100% biomass | 1.3 | | | 25000 | 2.7 |
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| 04 | Re-powering of steam turbines | | | | | |
| 05 | Waste-to-energy Combined Heat and Power | 5.1 | | | 204000 | 19 |
| 06 | Gas turbines single cycle | | | | | |
| | Large, 40-125 MW | 0.44-0.53 | | | 6700-8000 | 2-3 |
| | Medium, 5-40 MW | 0.57-0.86 | | | 8000 | 2.5-4 |
| | Mini, 0.1 - 5 MW | | | | | |
| | Micro, 0.003 - 0.010 MW | 0.6-1.2 | | | | |
| 07 | Gas turbines combine cycle | | | | | |
| | Large, 100-400 MW | 0.4-0.7 | | | 11000-14000 | 1.5 |
| | Small, 10-100 MW | 0.57-0.83 | | | 10000 | 2.0-3.5 |
| 08 | Gas engines | | | | | |
| | Spark ignition, large, 1-5 MW | 0.8-1.2 | | 6-9 | | |
| | Spark ignition, micro, 0.001-0.020 MW | | | | | |
| | Dual fuel, 0.5-16 MW | | | 7-10 | | |
| 09 | Small-scale biomass cogeneration | | | | | |
| | Wood chips, 0.6-4.3 MW | 2.8-3.8 | 3-4 | | | |
| | Straw, 8-10 MW | 2.9-3.7 | 4 | | | |
| 10 | Gasifiers, biomass, staged gasification | 2-2.5 | | | 50000 | 14 |
| 11 | Gasifiers, biomass, updraft | | | | | |
| 12 | Micro combined heat and power systems | | | | | |
| | Gas turbine, 3-10 kW | 0.6-1.2 | | | | |
| | Gas engine, 1-20 kW | | | | | |
| 13 | Centralised biogas plants | | | | | |
| | 300 tonnes/day waste input | 4.4 | | 30 | | |
| | 550 tonnes/day waste input | 3.1 | | 25 | | |
| | 800 tonnes/day waste input | 2.6 | | 26 | | |
| **Electricity generation, renewable energy except biomass** | | | | | | |
| 20 | Wind turbines on land | 0.5-0.6 | | 7 | | |
| 21 | Wind turbines, offshore | 0.8-1.2 | | 3-5 | | |
| 22 | Photovoltaic cells, grid-connected systems | 1.3-2.1 | ~1 | | | |
| 23 | Wave power | 1.7-2.0 | | 6 | | |
| **Electricity generation, fuel cells** | | | | | | |
| 30 | Solid oxide fuel cells | 0.4 | | | 20000-28000 | |
| 31 | Proton exchange membrane fuel cells | 0.4 | | 0.5 | | |
| **Electricity storage** | | | | | | |
| 40 | Pumped hydro storage | 0.5 | | | 10000 | - |
| 41 | Compressed air energy storage | | | | | |
| | 10 MW | < 0.67 | | | < 20000 | - |
| | 300 MW | < 0.36 | | | < 11000 | - |
| 42 | Electrolysis and hydrogen storage | | | | | |
| 43 | Batteries | | | | | |
| | Vanadium Redox (VRB) | 1.55 | | | 44000 | 2.3 |
| | Sodium Sulphur (NAS) | 1.3 | | | 41000 | 4.3 |
| **Heat generation** | | | | | | |
| 50 | Heat pumps | | | | | |
| | Very large, 50-100 MJ/s | 0.6-1.3 | | | 1000-3000 | 0 |
| | Very large, 50-100 MJ/s (hot) | | | | | |
| | Large, 0.025-1.5 MJ/s (hot) | 0.6 | | | 1000 | 0 |
| | Medium, 0.2-1.5 MJ/s | 0.6 | | | 2000-4000 | 0 |
| | Small, 0.001-0.025 MJ/s | 1.0-2.5 | | | 5000-10000 | 0 |
| 51 | District heating boilers, wood-chips fired | 0.25-0.6 | | | 15000-25000 | 0 |
| 52 | District heating boilers, gas fired | | | | | |
| 53 | Geothermal energy | 0.8 | | 2.9 | 13000 | - |
| 54 | Waste-to-energy District Heating | 0.9 | | | 43000 | 4.4 |

# 3. TECHNOLOGY SHEETS

The following technologies are included in this catalogue:

| Electricity generation, thermal processes | |
|---|---|
| 01 | Advanced pulverized fuel power plant |
| 02 | CO2 capture and storage |
| 03 | Biomasseanvendelse på store kraftværker |
| 04 | Re-powering of steam turbines |
| 05 | Waste-to-energy combined heat and power |
| 06 | Gas turbines single cycle |
| 07 | Gas turbines combine cycle |
| 08 | Gas engines |
| 09 | Small-scale biomass cogeneration |
| 10 | Gasifiers, biomass, staged gasification |
| 11 | Gasifiers, biomass, updraft |
| 12 | Micro combined heat and power systems |
| 13 | Centralised biogas plants |
| **Electricity generation, renewable energy except biomass** | |
| 20 | Wind turbines on land |
| 21 | Wind turbines, offshore |
| 22 | Photovoltaic cells, grid-connected systems |
| 23 | Wave power |
| **Electricity generation, fuel cells** | |
| 30 | Solid oxide fuel cells |
| 31 | Proton exchange membrane fuel cells |
| **Electricity storage** | |
| 40 | Pumped hydro storage |
| 41 | Compressed air energy storage |
| 42 | Electrolysis and hydrogen storage |
| 43 | Batteries |
| **Heat generation** | |
| 50 | Heat pumps |
| 51 | District heating boilers, wood-chips fired |
| 52 | District heating boilers, gas fired |
| 53 | Geothermal energy |
| 54 | Waste-to-energy district heating |

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.

# 01 ADVANCED PULVERIZED FUEL POWER PLANT
2004.10.27

**Brief technology description**
Large base-load units with pulverised fuel (PF) combustion and advanced (super critical) steam data.

Super critical steam data are above 250 bar and 560 $^o$C. Advanced data (AD) goes up to 350 bar and 700 $^o$C. The advanced steam cycle includes up to ten pre-heaters and double re-heating.

The AD plants obtain higher efficiencies, both the electricity efficiency and the total energy efficiency in backpressure mode. The higher efficiencies are obtained in full load mode as well as part load and the high efficiencies remain even after many years of operation.

**Input**
The process is primarily based on coal, but will be applicable to other fuels such as natural gas. It is also possible to partly substitute fossil fuel by some types of biomass (cf. technology 03).

**Output**
Power and possibly heat.

**Typical capacities**
AD plants are built in capacities from 400 MW to 1000 MW.

**Regulation ability**
Comparable to units with sub-critical data.

Load following: 4 % per minute.

**Advantages/disadvantages**
The efficiencies are not reduced as significantly at part load compared to full load as with CC-plants.

Coal fired power plants using the advanced steam cycle possess the same fuel flexibility as the conventional boiler technology. However, AD plants have higher requirements concerning fuel quality. Inexpensive heavy fuel oil cannot be burned due to heavy materials like vanadium, unless the steam temperature (and hence efficiency) is reduced.

**Life cycle assessment**

| kg $CO_2$-equivalent per MWh electricity | Coal | | Natural gas | |
|---|---|---|---|---|
| | Energy quality | Energy content | Energy quality | Energy content |
| Operation | 766 | 524 | 553 | 286 |
| Constr. & decom. | 4.88 | 3.11 | 2.66 | 1.17 |
| Fuel procurement | 62.9 | 40.2 | 48.9 | 31.6 |
| Residues | 0.0084 | 0.0054 | - | - |

The main ecological footprints from coal-fired AD plants are bulk waste (disposal of earth, cinder, and rejects from mining), climate change and acidification (ref. 3). The fly ash can utilized 100% in cement and concrete.

**Research and development**
There is still a considerable potential for increasing the efficiencies, thus decreasing the CO2 emissions and the electricity generation costs. European cooperation is needed in order to develop and demonstrate the reliability of the high temperature, high-pressure components.

There is a need for further R&D in the field of the alloy steels used in the AD plants in order to obtain increased strength, lower costs and thereby cheaper and more flexible plants.

An electricity efficiency of 55 % requires steam at 700 $^{\circ}$C and the use of nickel-based alloys (ref. 2). The best plants currently commercially available operate at up to 600 $^{\circ}$C.

**Examples of best available technology**
- Avedøre Power Plant (Copenhagen), Unit 2, 570 MW, gas fired (www.e2.dk).
- Nordjylland Power Plant, 400 MW, commissioned 1998, coal fired.
- Skærbæk Power Plant, 400 MW, gas fired.

**Special remarks**
For simple calculations, the fuel consumption H (in MJ/s) of a plant based on an extraction steam turbine, can be determined by:

$$H = (P + c_v * Q) / e_c ,$$

where P is the power generation (MW), the $c_v$ coefficient can be read from below table, Q is the heat generation (MJ/s), and $e_c$ is the electricity efficiency in condensation mode, which also can be read from the below table.

**References**
1. Elsam's and Elkraft's update of the Danish Energy Authority's technology catalogue (in Danish), 'Teknologidata for el- og varmeproduktionsanlæg', December 1997.
2. Elforsk: "El från nya anläggningar", Stockholm, January 2000.
3. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.
4. www.ad700.dk

# Data sheet

| Technology | Steam turbine, coal fired, advanced steam process | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | | 400 | | |
| Total efficiency, back-pressure mode, net (%)　　(B) | 93 | 93 | 93 | 1 |
| Electricity efficiency, condensation mode, net (%) | | | | |
| 　　　　　　　　　　100% load | 48.5 | 52.5 | 55 | 1 |
| 　　　　　　　　　　75% load | 48 | 52 | 54.5 | 1 |
| 　　　　　　　　　　50% load | 47 | 51 | 53.5 | 1 |
| Cb coefficient (40$^{o}$C/80$^{o}$C) | | | | |
| 　　　　　　　　　(50$^{o}$C/100$^{o}$C) | 0.78 | 0.95 | 1.08 | 1 |
| Cv coefficient (40$^{o}$C/80$^{o}$C) | | | | |
| 　　　　　　　　　(50$^{o}$C/100$^{o}$C) | 0.15 | 0.15 | 0.15 | 1 |
| Availability (%) | 91 | 91 | 91 | 2;2;3 |
| Technical lifetime (years) | 30 | 30 | 30 | 2;2;3 |
| Construction time (years) | 4.5 | 4.5 | 4.5 | 2;2;3 |
| **Environment** (Fuel: hard coal, 1% sulphor content) | | | | |
| SO$_2$ (kg per GJ fuel)　　　　　　　　　(A) | 0.03 | 0.03 | 0.03 | 2;2;3 |
| SO$_2$ (degree of desulphoring, %)　　　　(A) | 95-97 | 95-97 | 95-97 | 1 |
| NO$_X$ (kg per GJ fuel)　　　　　　　　　(A) | 0.04 | 0.04 | 0.04 | 2;2;3 |
| Particles (mg per GJ fuel),　　　　　　　(C ) | 3.600-18.000 | 3.600-18.000 | 3.600-18.000 | 2;2;3 |
| Ashes (kg per GJ fuel) | 4.0 | 4.0 | 4.0 | 2;2;3 |
| Other residuals, gypsum (kg per GJ fuel) | 2.30 | 2.30 | 2.30 | 2;2;3 |
| **Financial data** | | | | |
| Specific investment (M€/MW)　　　　　　(B) | 1.1 | 1.2 | 1.2 | 1 |
| Fixed O&M (€/MW/year) | 16000 | 16000 | 16000 | 4 |
| Variable O&M (€/MWh) | 1.8 | 1.8 | 1.8 | 4 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (% per sec.) | 4 | 4 | 4 | 1 |
| Minimum load (% of full load) | 20 | 20 | 20 | 1 |

**References:**

1 Elsam, November 2003

2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997

3 Eltra, September 2003

4 Energi E2, October 2004

**Remarks:**

A The data for SO2 and NOx emissions assume flue gas desulphurisation (wet gypsum) and DeNOx equipment of the "high dust" SCR type.

B The cost excludes infrastructure, such as habour, district heating transmission, and electricity transmission. The unit cost refers to the capacity in full condensation mode.

C Calculated from from 10-50 mg/Nm³ assuming this interval refers to dry flue gas at 6% oxygen

# 02 CO$_2$ CAPTURE AND STORAGE

Draft 2004.10.05

**Brief technology description**

CO$_2$ Capture and storage is one option in bringing down greenhouse gas emissions. This method is best suited for large point sources of CO$_2$ such as power plants. The main principal is that fossil fuel that is e.g. burnt in a power plant to generate electricity, goes through a process, where the CO$_2$ is firstly separated from the flue gas stream, secondly transported and thirdly stored or utilised – these three steps are described below.

Several CO$_2$ capture systems are already available, but generally they can be divided into three groups:
- Post-combustion capture
- Pre-combustion capture
- Oxy-fuel combustion

In post-combustion capture the CO2 is separated from the flue gas. Several technologies have been proposed. Commercially technologies comprise CO2 capture by absorption in a aqueous amine solution. After the absorption the solvent is stripped by raising the temperature, dried, compressed and transported to the storage. The absorption technology can be applied on existing power plants.

Pre-combustion capture means that the CO2 is removed prior to combustion either as CO2 or solid. Examples of pre-combustion capture technologies are coal casification or decarbonisation of natural gas.

In the Oxy-fuel approach the Nitrogen in the air the removed prior to combustion and the fuel is combusted in a atmosphere of Oxygen and recycled CO2. The flue gas will only consist of water vapour and CO2. The water vapour can easily be condensed giving a highly concentrated CO2 stream, which can be compressed and transported to the storage.

The major barrier for a broad use of CO$_2$ removal technology is the current high costs of separating the CO$_2$. The extra amount of energy required for this process typically reduces the overall efficiency by 10 percentage points.

There is a need to transport captured CO$_2$. This is possible both through pipelines and also by ships, similar to LPG tankers. As it typically is less costly to pipe CO$_2$ than to transport electricity is it more economically to locate power stations close to demand, rather than close to a storage site (ref. 1).

CO$_2$ storage or utilisation is considerable less expensive than the capture of CO$_2$. The concepts for storage are in: deep saline aquifers, depleted oil and gas reservoirs, oceans, and as a solid on land. The concepts for utilisation are: as a feedstock for manufacture of chemical products, in mineral products, in the food and drink industry, for enhancement of the production of crude oil, gas or coal bed methane, and in growth of plants or algae (ref. 4).

In Denmark, storage in aquifers close to power plants and utilisation by CO$_2$ Enhanced Oil Recovery (EOR) in offshore oil and gas fields has been analysed (costs date fore these two options are in the data sheet) (ref. 8).

**Input**

$CO_2$

**Output**

Of all the utilisation options $CO_2$ for EOR is the most important, as it has the potential to store significant quantities of $CO_2$, while at the same time using it in a cost-effective manner as the storage costs will partly be offset by the increased production of oil and natural gas.

$CO_2$ EOR is a commercially proven technology as it has been used extensively in the USA, where 74 projects are now operating. Naturally occurring $CO_2$ has been used, and there has been little economic incentive to use $CO_2$ recovered form power stations.

In USA the oil companies are willing to pay 12-18 USD (10-15 EUR) per ton $CO_2$ for EOR, this is assumed also to be the case in Denmark (ref. 8). Injection of $CO_2$ offshore does therefore benefit from this income but does also have larger transportation costs compared to $CO_2$ storage in acquire closer to the source of $CO_2$.

**Typical capacities**

The high volumes of $CO_2$, e.g. 1 million tones per year in the case of the Weyburn oilfield in Canada, makes sequestration very attractive for meeting greenhouse-gas emissions targets.

The storage capacities vary significantly, but have the potential to store all energy-related $CO_2$ emission for many years (ref. 2).

**Life cycle assessment**

The benefits from the Weyburn $CO_2$ EOR, on a life-cycle basis, are that it releases only two-thirds as much carbon dioxide (net) compared to oil produced conventionally (ref. 7).

Environmentalists emphasize the risk in storing $CO_2$, while technicians believe that this risk is limited. The $CO_2$ EOR project at the Weyburn oilfield in Southern Saskatchewan in Canada is used to monitor the storage of injected $CO_2$, in a depleted oil reservoir. The reason for this monitoring is to develop confidence in the geological storage of $CO_2$ as a safe and environmentally acceptable mitigation option, and hereby to provide sound scientific information that the $CO_2$ injected into the reservoirs will be stored for geological timescales.

**Research and development**

Considerable research and development work is required in order to further develop and optimise techniques that reduce barriers for a wider use, i.e. to achieve greater efficiency, reliability of storage, integration of technologies that require scale and lower cost.

The Sleipner field, in the North Sea, has a special feature as the gas has a $CO_2$ content of around 9%, which must be reduced to 2.5% before it is sold. The $CO_2$ that is stripped from the gas is injected into a structure 800 metres below the seabed, it is around one million tones of $CO_2$ per year. This was the first practical research and development project in this field.

The CENS ($CO_2$ for EOR in the North Sea) project in Denmark has analysed the option of injecting $CO_2$ form Danish power plants in offshore oilfields as EOR. These analyses are performed by Elsam and Kinder Morgan (USA) (ref. 8).

GEUS (Danish Geological Survey) has in its analyses demonstrated the potential of storing $CO_2$ in aquifers close (30-50 km) to the central Danish power plants. In the analyses, $CO_2$ emissions from other large sources are also included. Almost half of the Danish $CO_2$ emissions are located close to 8 geographical locations. In contrast to the offshore solution, the onshore aquifer solution is not dependent on large scale to improve its economic side and could be implemented for one location. Kalundborg is believed to be the location with the lowest costs, but the socioeconomic $CO_2$ reduction costs are currently estimated to be too high for this solution to be implemented (ref. 8).

EU also supports the R&D on $CO_2$ capture and storage. In the 6th Frame Work Programme, these programs include:

The EU project ENCAP has the stated target to provide pre-combustion decarbonisation technologies in power cycles and achieve at least 90% capture rate for $CO_2$, and 50% capture cost reduction – from a current level of €50-60 per tonne of $CO_2$ captured.

Another EU program is CASTOR. The objective of this project includes a) to enable the capture and geological storage of 10% of European $CO_2$ emissions by developing new technologies, tools and methods, b) reducing the costs of capture and separation of $CO_2$ (from €50-60/tonne $CO_2$ to €20-30/tonne).

The $CO_2$SINK project, also sponsored by the EU, aims at testing geological storage of $CO_2$ and shall advance the understanding of the science and of the practical processes involved in underground storage of $CO_2$ in a saline aquifer. The location is Ketzin, close to Berlin in Germany.

**Examples of best available technology**
In two major projects, where $CO_2$ is being stored underground, refinement of techniques to monitor $CO_2$ in underground strata is currently taking place:
- Saline Aquifer $CO_2$ Storage 2 (SACS2) project offshore Norway is investigating the injection of $CO_2$ form the Sleipner oil field in the Utsira aquifer.
- $CO_2$ EOR at the Weyburn oilfield in Southern Saskatchewan in Canada (PanCanadian Resources). The $CO_2$ is transported through a 325 km long pipeline from the Great Plains Synfuels plany in Beulah, North Dakota, USA.

**Special remarks**
How can the future of $CO_2$ capture and storage be expected to develop? An IEA working paper tries to analyse this question using the Energy Technology Perspective (ETP) model. The analyses, which are connected with large uncertainties, show cost estimates from less than zero USD for coal fired to more than 150 USD per ton $CO_2$ for gas fired. The ETP model also suggested up to 18% of total global power production will be equipped with $CO_2$ capture by 2040, when using a penalty of 50 USD per ton of $CO_2$. The bulk of this is coal-based IGCC-SOFC, a speculative technology (ref. 5).

The current technology cost and efficiency penalties make $CO_2$ capture and storage an unlikely candidate for emission mitigation in the period 2008-2012. $CO_2$ capture can play a key role in a future low-$CO_2$ strategy on the medium term after 2012.

A working paper by Miljøstyrelsen (ref. 8) presents the socioeconomic CO2 reduction costs (shadow price). Here the socioeconomic CO2 reduction costs in Denmark are 42 EUR/ton for aquifer storage project and the reduction costs are 21 EUR/ton for North Sea enhanced oil recovery projects, when looking at Denmark (The socioeconomic reduction price falls to around 6 EUR/ton when considering the North Sea as one).

**References**
1. Putting Carbon Back in the Ground, IEA Greenhouse Gas R&D Program, February 2001
2. $CO_2$ Capture and Storage in Geological Formations, by Jacek Podkanski, IEA 2003
3. $CO_2$ Capture at Power Stations and Other Major Point Sources, Jacek Podkanski, IEA 2003
4. The Utilisation of $CO_2$, Jacek Podkanski, IEA 2003
5. Uncertainties in Relation to $CO_2$ Capture and Sequestration. Preliminary Results, Dolf Gielen, IEA/EET Working Paper 2003
6. The Future Role of $CO_2$ - Capture and Storage Results of the IEA-ETP Model, Dolf Gielen, 2003
7. www.ieagreen.org.uk
8. Hvad koster det at reducere $CO_2$ mankoen? – Reduktionspotentiale og omkostninger i udvalgte sektorer. Danish Environmental Protection Agency, Report No. 7, 2003

## Data sheets

The data sheet presents the investments costs in two ways. The first method is IEA estimation of current and future increase in the investment costs of power production technologies. The second method is the current estimates of Danish projects.

| Technology | CO2 Capture | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Power Plant - Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 500 | | | 1 |
| Generation efficiency decrease (%) | 8 -13% | | 3% | 1; 2 |
| CO2 emission reductions | 80% | | | 1; 2 |
| **Power Plant - Financial data** | | | | |
| Pulverised coal plant | | | | |
|    Additional investment need for CO2 Capture (%) | 80% | 60% | 40% | 1; 2; A |
| CCGT (Combined Cycle Gas Turbine) | | | | |
|    Additional investment need for CO2 Capture (%) | 100% | 75% | 50% | 1; 2; A |
| IGCC (Integrated Gasification Combined Cycle) | | | | |
|    Additional investment need for CO2 Capture (%) | 50% | 38% | 25% | 1; 2; A |

| Technology | CO2 Sequestration | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **CO2 Capture, Transport and Storage - Financial data** | | | | |
|   **Aquifer** | | | | |
| Separation (€/t CO2) | 20,5 | 15 | 10 | 3; B |
| Transport, 100km in pipeline (€/t CO2) | 2,0 | 2 | 2 | 1; 2; 3 |
| Geological storage (€/t CO2) | 7,6 | 7,6 | 7,6 | 3 |
|    Total costs for 100 km - the three issues above (€/t CO2) | 30,2 | 25 | 20 | |
|   **North Sea** | | | | |
| CO2 capture and transport costs to North Sea platform (€/ton) | 29 | 24 | 18 | 3; B |

**References:**
1 Putting Carbon Back in the Ground, IEA Greenhouse Gas R&D Program, February 2001
2 Costs of renewable energy and CO2 capture and storage, by John Davison, IEA Greenhouse Gas R&D Program
3 Hvad koster det at reducere CO2 mankoen? – Reduktionspotentiale og omkostninger i udvalgte sektorer, Arbejdsrapport fra Miljøstyrelsen, Nr. 7, 2003

**Remarks:**
A As with most new technologies, costs of CO2 capture is expected to decrease when applied on a large scale and technical improvements are made. The analogous situation occurred with Flue Gas Desulphurisation (FGD). Capital costs of FGD plants have decreased by about 75% since they were first introduced on a large scale around 1970 (ref. 2). It is here assumed that CO2 capture costs fall by 50%.
B The capture part is here reduced by 50% over time, see remark A
C Based on the September 2004 exchange rate of 1USD = 0,82€
D Based on the September 2004 exchange rate of 1DKK = 0,13€

# 03  LARGE-SCALE BIOMASS POWER PLANT
2004.10.27


**Brief technology description**

Large base-load units with 100% biomass or in combination with pulverised coal combustion.

The technology is similar to large pulverized coal power plants, cf. technology sheet no. 01. The major components are: Fuel treatment and feed-in system, high-pressure steam boiler, steam turbine, generator and flue-gas heat recovery boiler (hot water or steam).

All fuel is grinded or chipped, blown into the furnace and burned while flying (suspension firing). Grate firing is not covered by this technology sheet.

Wood is usually the most favourable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass like straw and miscanthus have higher contents of N, S, K, Cl etc. that leads to higher emissions of NOx and particulates, increased ash, corrosion and slag deposits.

**Input**

Biomass; e.g. residues from wood industries or forests and residues from agriculture (straw), often delivered as pellets.

**Output**

Electricity and heat. The heat may come as steam or hot water.

**Typical capacities**

400 MW.

**Regulation ability**

The plants can be down regulated, but due to high initial investments they should be operated in base load.

**Advantages/disadvantages**

A major advantage with this particular technology (suspension firing) is that it can be applied in existing coal-fired power plants at a much lower cost than building new power plants.

Some biomass resources, in particular straw, contain aggressive components such as chlorine. To avoid or reduce the risk of slagging and corrosion, boiler manufacturers have traditionally deterred from applying steam data to biomass-fired plants at the same level as coal-fired plants. However, recent advances in materials and boiler design constitute a breakthrough, and the newest plants have fairly high steam data and efficiencies.


**Research and development**

Focus of the Danish R&D strategy:
- Reduce the cost of fuel, by improved pre-treatment, better characterisation and measurement methods.
- Reduce corrosion, in particular high-temperature corrosion

- Reduce slagging
- Reduced emissions
- Recycling of ashes
- Improved trouble-shooting

**Examples of best available technology**
- Avedøre Power Plant (Copenhagen), Unit 2; 570 MW; one boiler burning 100% biomass, another co-firing wood pellets with natural gas and oil (www.e2.dk).
- Amagerværket, Unit 2, Copenhagen; coal-fired plant from 1972; in 2004 converted to130,000 tonnes of straw pellets per year; 73 MW in condensation mode and 50 MW + 165 MJ/s in back-pressure mode (www.e2.dk)
- Studstrupværket, Århus; chipped straw, up to 10 cm (www.elsam.com)

# Data sheets

| Technology | Steam turbine, 100% biomass | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 400 | | | |
| Total efficiency (%) net | 90 | 90 | 90 | 1 |
| Electricity efficiency (%) net - 100% load | 45 | 46.5 | 48.5 | 1 |
|                         75% load | 43.5 | 45 | 47 | 1 |
|                         50% load | 42.5 | 44 | 46 | 1 |
| Start-up fuel consumption (GJ) Time for varm start-up (hours) | | | | |
| Cb coefficient ($40^{\circ}C/80^{\circ}C$)                 ($50^{\circ}C/100^{\circ}C$) | 0.7 | 0.76 | 0.84 | 1 |
| Cv coefficient ($40^{\circ}C/80^{\circ}C$)                 ($50^{\circ}C/100^{\circ}C$) | 0.15 | 0.15 | 0.15 | 1 |
| Forced outage (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Availability (%) | 89 | 90 | 90 | 1 |
| Technical lifetime (years) | 30 | 30 | 30 | 1 |
| Construction time (years) | 4.5 | 4.5 | 4.5 | 1 |
| **Environment** (Fuel: Wood, 0,03% S / Straw, 0,15% S) | | | | |
| $SO_2$ (kg per GJ fuel) | 0,015/0,08 | 0,015/0,08 | 0,015/0,08 | **1** |
| $SO_2$ (degree of desulphoring, %) | 0 | 0 | 0 | 1 |
| $NO_X$ (kg per GJ fuel) | 0.04 | 0.04 | 0.04 | 1 |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | 10-50 | 10-50 | 10-50 | 1 |
| Ashes (kg per GJ fuel) | 0,3/2,2 | 0,3/2,2 | 0,3/2,2 | 1 |
| Other residuals, gypsum (kg per GJ fuel) | 0 | 0 | 0 | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 1.3 | 1.3 | 1.3 | 1 |
| Fixed O&M (€/MW/year) | 25000 | 25000 | 25000 | 1 |
| Variable O&M (€/MWh) | 2.7 | 2.7 | 2.7 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | 4 | 4 | 4 | 1 |
| Minimum load (% of full load) | 20 | 20 | 20 | 1 |

**References:**

1 Energi E2, October 2004

| Technology | Steam turbine, coal fired advanced steam process, 20% co-firing of biomass | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 400 | | | 1 |
| Total efficiency (%) net | 93 | 93 | 93 | 1 |
| Electricity efficiency (%) net - 100% load | 48.5 | 52.5 | 55 | 1 |
| 75% load | 48 | 52 | 54.5 | 1 |
| 50% load | 47 | 51 | 53.5 | 1 |
| Start-up fuel consumption (GJ) | | | | |
| Time for varm start-up (hours) | | | | |
| Cb coefficient ($40^{o}C/80^{o}C$) | | | | |
| ($50^{o}C/100^{o}C$) | 0.78 | 0.95 | 1.08 | 1 |
| Cv coefficient ($40^{o}C/80^{o}C$) | | | | |
| ($50^{o}C/100^{o}C$) | 0.15 | 0.15 | 0.15 | 1 |
| Forced outage (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Availability (%) (A) | 91 | 91 | 91 | 1 |
| Technical lifetime (years) | 30 | 30 | 30 | 1 |
| Construction time (years) | 4.5 | 4.5 | 4.5 | 1 |
| **Environment** | **(Coal & Wood / Coal & Straw)** | | | |
| $SO_2$ (kg per GJ fuelmix) (B) | 0,027/0,025 | 0,027/0,025 | 0,027/0,025 | 1 |
| $SO_2$ (degree of desulphoring, %) | 95 - 97 | 95 - 97 | 95 - 97 | 1 |
| $NO_X$ (kg per GJ fuel) | 0.04 | 0.04 | 0.04 | 1 |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuelmix) | 10-50 | 10-50 | 10-50 | 1 |
| Ashes (kg per GJ fuelmix) (C) | 3,3 / 3,6 | 3,3 / 3,6 | 3,3 / 3,6 | 1 |
| Other residuals, gypsum (kg per GJ fuel) (D) | 1,9 / 1,9 | 1,9 / 1,9 | 1,9 / 1,9 | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW) (E) | 1.2 | 1.2 | 1.2 | 1 |
| Fixed O&M (€/MW/year) (F) | 22000 | 22000 | 22000 | 1 |
| Variable O&M (€/MWh) (G) | 3 | 3 | 3 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | 4 | 4 | 4 | 1 |
| Minimum load (% of full load) | 20 | 20 | 20 | 1 |

**References:**
  1 Elsam, October 2004

**Remarks:**
  A 80/20 Fuelmix. Coal = 91; Biomass = 90
  B 80/20 Fuelmix. Coal=1; Wood=0.03; Straw=0.15
  C 80/20 Fuelmix. Coal=4.0; Wood=0.3; Straw=2.2
  D 80/20 Fuelmix. Coal=2.3; Wood=0.086; Straw=0.45
  E Coal + Straw = 1.1 + 0.1 = 1.2
  F Coal + Straw = 20000 + 2000 = 22000
  G Coal + Straw = 2 + 1 = 3

# 04  RE-POWERING OF STEAM TURBINES

2003.12.08

**Brief technology description**

Traditionally, a steam turbine plant uses fuel as heat source to boil water. However, water can be converted to steam by other heat sources. For a gas turbine, a minor part of the energy content in the fuel is converted to electricity. The remaining part is converted to high-temperature exhaust gas, which can be used as heat source for a steam process.

Adding a gas turbine to an existing steam power plant is called re-powering or boosting. The result is higher capacity and higher efficiency.

There are several options to re-power a steam power plant. The most used principles are:
1. The exhaust gas from the gas turbine heats the condensate water that is fed into the boiler of the steam cycle (called 'feed water pre-heating'). Thereby less steam needs be extracted from the steam turbine, increasing the output of the steam turbine with up to 30% - provided it is designed to increase its capacity this much. The improvement in electricity efficiency is typically +1%.
2. The exhaust gas from the gas turbine is led directly into the steam plant boiler as pre-heated air. This is called 'fresh air pre-heating' or 'topping'. Additional firing, e.g. with coal or gas, of the boiler is required. The improvement in electricity efficiency is typically +1-1.5%.

**Input**

Extra fuel: Gas.

**Output**

From gas turbine: Electricity and heat as hot exhaust gas.
From the total plant: Higher capacity and higher efficiency.

**Typical capacities**

The capacity of the gas turbine is typically 1/7 to 1/3 of the original unit.

**Regulation ability**

Load regulation is less straightforward with combined cycle than single cycle technologies.

**Advantages/disadvantages**

New capacity can be established at a competitive cost.

**Examples of best available technology**

See below.

**Special remarks**

When adding an extra fuel to a power plant, in casu natural gas, investments in new infrastructure (e.g. gas pipelines) are needed. Such investments are very site specific and are therefore not included in the financial data quoted below.

# 05 WASTE-TO-ENERGY CHP PLANT
Draft 2004.10.10


**Brief technology description**
The major components are: A waste reception area, a feeding system, a grate fired furnace interconnected with a steam boiler, a back pressure steam turbine, a generator, an extensive flue gas cleaning system and systems for handling of combustion and flue gas treatment residues.

The plant is primarily designed for incineration of municipal solid waste (MSW) and similar non-hazardous wastes from trade and industry. Some types of hazardous wastes may, however, also be incinerated.

The waste is delivered by trucks and is normally incinerated in the state in which it arrives. Only bulky items are shredded before being fed into the waste bunker.

**Input**
MSW and other combustible wastes, water and chemicals for flue gas treatment, gasoil or natural gas for auxiliary burners (if installed).

**Output**
Electricity and heat as hot (> 120 $^o$C) or warm (<120 $^o$C) water, bottom ash (slag), residues from flue gas treatment, including fly ash. If the flue gas is treated by wet methods, there may also be an output of treated process wastewater.

**Typical capacities**
10-30 tonnes of waste per hour, corresponding to a thermal input in the range 30-100 MW. Power production is rarely feasible in Denmark on plants smaller than 10 tonnes/h.

**Regulation ability**
The plants can be down regulated to 70-75% of the nominal capacity, under which limit the boiler may not be capable of providing adequate steam quality. For emissions control reasons and due to high initial investments they should be operated as base load.

**Advantages/disadvantages**
By incinerating the non-recyclable, combustible waste its energy content is utilised thereby replacing equivalent quantities of energy generated on fossil fuels. Moreover, the waste is sterilised, and its volume greatly reduced. The remaining waste (bottom ash/slag) may be utilised in construction works, and it will no longer generate methane. Consequently, by incinerating the waste, the methane emission generated, when landfilling the same quantity of waste, is avoided.

The disadvantages are that a polluted, corrosive flue gas is formed, requiring extensive treatment, and that the flue gas treatment generates residues, which are classified as hazardous waste. The corrosive nature of the flue gas limits the permissible steam data to 40 bar/400 $^o$C and hence the electrical efficiency to around 20%.

In the low capacity range (less than 15 MW thermal input) the scale of economics is out of proportion.

**Environmental aspects**

Waste is a mixture of $CO_2$ neutral biomass and products e.g. plastics of fossil origin. A typical $CO_2$ emission factor may be approximately 18 g/MJ for the waste mixture currently incinerated in Denmark. This is based on an emission factor for mixed plastics of 78.7 g/MJ (2) and assessed 6.6% of mixed plastic in the incinerated waste (3).

Ecological footprints are: air and water emissions including dioxins as well as solid residues to be disposed of.

**Research and development**

There is a potential of increasing the energy efficiency of waste fired CHP-plants by application of condensation of flue gas moisture.

There is a potential for increasing the electrical efficiency of waste fired CHP-plants by increasing the steam temperature and pressure, with due consideration to corrosion and the operational availability.

Further challenges are the amount and quality of the residues (bottom ash, fly ash and flue gas cleaning residue). The continued use of bottom ash for road construction etc. is expected to take place under tightening demands on the contents and leachability of a range of pollutants, including salts, heavy metals and dioxin.

Similarly, the amount of hazardous waste (fly ash and flue gas cleaning residue) may be reduced by optimisation of the overall process. Also, treatment of residues may be further developed for recycling and/or disposal in landfills not dedicated for hazardous waste.

**Examples of best available technology**

Denmark has one of the major international suppliers of Waste-to-Energy CHP plants: Babcock & Wilcox Vølund ApS, Esbjerg, Denmark.

Moreover, the Danish energy policy in the 90s has favoured CHP including Waste-to-Energy CHP.

Some recent example plants are:

| Plant | Unit | Commissioned | Capacity | Thermal input | Total efficiency | Electrical efficiency |
|---|---|---|---|---|---|---|
| Vestforbrænding | 5 | 1998 | 26 t/h | 87 MW | 86.7% | 19.6% |
| REFA | 3 | 1999 | 9 t/h | 30 MW | 86.9% | 22.3% |
| Svendborg | 1 | 1999 | 6 t/h | 20 MW | 87.9% | 22.5% |
| Odense | 3 | 2000 | 18 t/h | 60 MW | 92% | 26.7% |
| Reno-Nord | 4 | 2005 | 20 t/h | 65 MW | 98.0%[1]) | 26.9% |

[1]) Because of flue gas condensation, see below

In Demark, the most energy efficient plant will be Unit 4 at Reno-Nord, Aalborg, which will be commissioned in 2005.

**Special remarks**

Contrary to other fuels used for energy generation, waste has a negative price and is received at a gate fee. The primary objective of a waste-to-energy plant is the treatment of waste, energy production may be considered a useful by-product.

To comply with European Union requirements (cf. Directive 2000/76) the flue gas must be heated to min. 850 $^o$C for min. 2 seconds and the gas must be treated for $NO_x$, dust (fly ash), HCl, HF, $SO_2$, dioxins and heavy metals. If HCl, HF and $SO_2$ are removed by wet processes, the wastewater must be treated to fulfil some specific water emission limit values.

By condensing most of the water vapour content of the flue gas in the flue gas treatment, a thermal efficiency (based on the net calorific value) of around 100% is achievable. At the same time the plant becomes self-sufficient in water.

The solid residues from flue gas and water treatment are hazardous wastes and are often placed in an underground storage for hazardous waste (cf. Council Decision 2003/33).

Recently, the Danish governmental subsidies on electricity produced in e.g. Waste-to-Energy CHP plants have been reduced. Consequently, the plants will now have to sell their electricity at market prices. This decision reduces the incentive to establish new incineration capacity based on CHP in Denmark.

**References[1]**

1. Kleis, H. and Dalager, S.: 100 Years of Waste Incineration in Denmark. Babcock & Wilcox Vølund and RAMBØLL, 2004, p. 43.
2. Lov om $CO_2$-kvoter, LOV nr.493 af 09/06/2004. (Law of the Danish parliament on $CO_2$-allowance trading, cf. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC)
3. Affald 21, Miljø- og Energiministeriet, 1999, "Waste 21".

## Data sheet

| Technology | Waste to energy CHP plant | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Waste treatment capacity (tonnes/h) | 15 | 15 | 15 | 1 |
| Thermal input (MW) | 50.0 | 50.0 | 50.0 | 1 |
| Own consumption (MW-e) | 1.5 | 1.5 | 1.5 | 1 |
| Generating capacity for one unit (MW-e), gross | 11.3 | 13.5 | 14.5 | 1 |
| Generating capacity for one unit (MW-e), net | 9.8 | 12.0 | 13.0 | 1 |
| Total efficiency (%) gross | 87.9 | 98    A | 100    A | 1 |
| Total efficiency (%) net | 84.9 | 95    A | 97    A | 1 |
| Electricity efficiency (%) gross - 100% load | 22.5 | 26.9 | 29 | 1 |
| Electricity efficiency (%) net - 100% load | 19.5 | 23.9 | 26 | 1 |
| 75% load | 19.5 | 23.9 | 26 | 1 |
| 50% load | n.a. | n.a. | n.a. | 1 |
| Start-up fuel consumption (GJ) | 1080 | 1080 | 1080 | 1 |
| Time for varm start-up (hours) | 12 | 12 | 12 | 1 |
| Cb coefficient | 0.30 | 0.34 | 0.37 | 1 |
| Cv coefficient ($40^{o}$C/$80^{o}$C) | n.a. | n.a. | n.a. | 1 |
| ($50^{o}$C/$100^{o}$C) | n.a. | n.a. | n.a. | 1 |
| Forced outage (%) | 2 | 1 | 1 | 1 |
| Planned outage (weeks per year) | 3 | 3 | 3 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 1 |
| Construction time (years) | 3 | 3 | 3 | 1 |
| **Environment** (Fuel: Waste, 12 MJ/kg, 0.4%S) | | | | |
| $SO_2$ (kg per GJ fuel) | 0.027 | 0.014 | 0.011 | 1 |
| $SO_2$ (degree of desulphurisation, %) | 95.9 | 98.0 | 98.4 | 1 |
| $NO_X$ (kg per GJ fuel), note C | 0.109 | 0.082 | 0.011 | 1 |
| $CH_4$ (kg per GJ fuel) | ~ 0 | ~ 0 | ~ 0 | 1 |
| $N_2O$ (kg per GJ fuel) | ~ 0 | ~ 0 | ~ 0 | 1 |
| Particles (mg per GJ fuel) | 5500 | 2700 | 1100 | 1 |
| Ashes (kg per GJ fuel), bottom ash | 14 | 12 | 11 | 1 |
| Other residuals (kg per GJ fuel) | 1 | 1 | 1 | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW-e), note B | 6.8 | 5.5 | 5.1 | 1 |
| Fixed O&M (€/MW/year), note B | 272,000 | 222,000 | 204,000 | 1 |
| Variable O&M (€/MWh), note B | 25 | 21 | 19 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | n.a. | n.a. | n.a. | 1 |
| Regulation speed (MW per sec.) | n.a. | n.a. | n.a. | 1 |
| Minimum load (% of full load) | 75 | 75 | 75 | 1 |

**References:**

1 Rambøll Danmark, 2004

**Remarks:**

A With flue gas condensation
B Energy reference is net electricity production.
  Total costs are included, including the ones relating to waste treatment and heat production
C NOx emissions are foreseen to be controlled by the SNCR process until 2015,
  and in 2020-30 application of the SCR-process is foreseen.

# 06 GAS TURBINE SINGLE CYCLE
2005.02.24


**Brief technology description**
The major components are: Industrial (also called heavy duty) or aero-derivative single-cycle gas turbine, gear (when needed), and generator. For combined heat and power production a heat recovery boiler (hot water or steam) is also needed.

Aero-derivative turbines have generally higher efficiency than industrial ones. Industrial gas turbines have higher flue gas temperatures and longer intervals between services compared to the aero-derivatives. However the most service-demanding module of the aero-derivative gas turbine normally can be exchanged in a couple of days thus keeping a high availability of the machine.

A few gas turbines are equipped with an integrated recuperator (preheating of combustion air) to increase efficiency - at the expense of the exhaust gas temperature in the heat recovery boiler.

**Input**
Typical fuels are natural gas and light oil. Some gas turbines can be fuelled with other fuels such as LPG, biogas etc., and some gas turbines are available in dual-fuel versions (gas/oil).

Gas fired gas turbines need fuel gas pressure of 20-45 bar, dependent on the gas turbine compression ratio.

**Output**
Electricity and heat (optional). All heat is found in the exhaust gas and is extracted by an exhaust gas boiler. Usually, emergency units do not utilize the heat.

**Typical capacities**
Single-cycle gas turbines are presently available in the 20 kWe - 330 MWe range (ref. 4).

The enclosed data tables cover large scale (40 – 125 MW), medium-scale (5 - 40 MW), small-scale (0.1 – 5.0 MW), and micro gas turbines (0.003 – 0.010 MW).

**Regulation ability**
Gas turbines are able to operate part load. This will reduce the electrical efficiency. Normally, gas turbines with dry low NOx burners can keep emissions below 15-25 ppm in a load range of 60-100%, but at lower loads the emission will increase and can thereby limit the regulation ability.

Gas turbines equipped with exhaust gas boilers can generate power only, if the exhaust system is designed with a bypass.

The heat produced based on the heat content of the exhaust gas can be either hot water (for heating or low-temperature process needs) or steam for process needs. Steam production is closely linked to the actual load of the turbine. Variations in steam production may be achieved by supplementary firing in the exhaust boiler.

For a 54 MW plant, 20 GJ fuel is required to start from cold, 8 GJ fuel from warm turbine. The start costs are approx. € 400 EUR per start (ref. 6).

**Advantages/disadvantages**
For larger units, plants above 15 MW, the combined cycle technology has so far been more attractive, when used as cogeneration plants for district heating (ref. 5).

Single-cycle gas turbine plants have short start up/close down time if needed.

Construction times for gas turbine based single cycle plants are shorter than steam turbine plants.

The high air/fuel ratio for gas turbines leads to lower overall efficiency for a given flue gas cooling temperature compared to steam cycles and cogeneration based on internal combustion engines.

A major disadvantage is the low fuel flexibility, as only natural gas or low-sulphur light oil can be used. This may pose a problem, both with regard to security of supply and price stability of the fuel.

Small (radial) gas turbines below 100 kWe are now on the market, the so-called micro-turbines. These are often equipped with preheating of combustion air based on heat from the exhaust (recuperator) to achieve reasonable single-cycle electrical efficiency (25-30 %)

**Life cycle assessment**

| kg $CO_2$-equivalent per MWh electricity | Energy quality | Energy content |
|---|---|---|
| Operation | 521 | 224 |
| Construction and decommissioning | 3.57 | 1.53 |
| Fuel procurement and transport | 41.4 | 17.8 |
| Residues | - | - |

(ref. 8).

**Research and development**
Continuous research is being done concerning higher inlet temperature at first turbine blades to achieve higher electrical efficiency and output. This research is focussed on materials and/or cooling of blades, nozzles and combustors.

For several years large efforts have been spent on improving the efficiency of gas turbines. The most important issue has been to increase the turbine inlet temperature (TIT). Today, the best large industrial gas turbines have TIT of approx. 1275 °C. In the near future TIT is expected to increase to almost 1400 °C for the current generation of turbines. For new generations the TIT is likely to become even higher. A higher TIT will invariably lead to a higher NOx emission. It is therefore necessary to develop new burner technologies, e.g. catalytic burners or use catalytic cleaning of the exhaust gas (ref. 5).

For 50-100 MW gas turbines, high efficiencies (above 46 %) have been reached through inter-cooling and recuperators, but these turbines are not yet commercially available.

Continuous development for less polluting combustion is taking place.

Development to achieve shorter time for service is also being done.

In the long perspective there are great expectations to temperature resistant ceramic materials and a new combustion technique (sequential combustion), which will allow even the small turbines to become more efficient (ref. 5).

Micro-turbines:
- Remote operation
- Low-cost recuperators
- Multi fuel availability and improved lifetime of critical components.

**Examples of best available technology**

**Special remarks**
The economic data do not include additional environmental equipment.

Low-NOx technology is assumed. Water or steam injection may reduce the NOx emission, but also the total efficiency and thereby possibly the financial viability. The trend is more towards dry low-NOx combustion, which increases the specific cost of the gas turbine (ref. 5).

Small (radial) gas turbines below 100 kWe are now on the market, the so-called micro-turbines. These are often equipped with preheating of combustion air based on heat from the exhaust (recuperator) to achieve reasonable electricity production efficiency. If micro-turbines are installed in combination with fuel cells (hybrid cycle), an electricity efficiency of some 50-60 % may be expected. With further developments, this will increase up to 70 % according to /3/

**References**
1. Diesel & Gas Turbine World Wide Catalogue, Brookfield US
2. Cogeneration and On-site Power Production, James and James UK
3. Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications, Arthur D. Little, 2000, US
4. Gas Turbine World Handbook, 2003.
5. Danish Energy Authority: "Teknologidata for el- og varmeproduktionsanlæg", 1995.
6. Sjællandske Kraftværker: 'Grovdata IRP99', November 1999.
7. The European Commission's 'Scientific and technological References - Energy Technology Indicators'.
8. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.

## Data sheets

Large scale plants:

| Technology | Gas turbine single cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **40 - 125** | | | |
| Total efficiency (%) net | 91 | 92 | 92 | 5 |
| Electricity efficiency (%) net - 100% load      (A) | 41 - 42 | 42 - 47 | 42 - 50 | 4, 5 |
| 75% load | 39 - 40 | | | 5 |
| 50% load | 36 - 38 | | | 5 |
| Cb ($50^oC/100^oC$) | 0.82 - 0.86 | 0.84 - 1.04 | 0.84 - 1.3 | 5 |
| Forced outage (%) | 5 | 5 | 5 | 5 |
| Planned outage (weeks per year) | 3 | 3 | 3 | 5 |
| Technical lifetime (years) | 25 | 25 | 25 | 5 |
| Construction time (years) | 2 | 2 | 2 | 5 |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel) (B) | 0.015 | < 0,006 | < 0,002 | 5 |
| $CH_4$ (kg per GJ fuel) | 0.0015 | 0.0015 | 0.0015 | 1 |
| $N_2O$ (kg per GJ fuel) | 0.0022 | | | 1 |
| **Financial data**                       (A) | | | | |
| Specific investment (M€/MW) | 0.44 - 0.53 | 0.44 - 0.53 | 0.44 - 0.53 | 4;5;5 |
| Fixed O&M (€/MW/year) | 6700-8000 | 6700-8000 | 6700-8000 | 2+3;5;5 |
| Variable O&M (€/MWh) | 2 - 3 | 2 - 3 | 2 - 3 | 5 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes)        (D) | 40-125 | | | 5 |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load)           (C) | 40 - 60% | 40 - 60% | 40 - 60% | 5 |

**References:**

1 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

2 Sjællandske Kraftværker: Grovdata IRP99, November 1999. Generic data.

3 Niels Laursen, internal memo, October 2002. Plant specific data.

4 Gas Turbine World Handbook, 2003

5 Elsam, 2003

**Remarks:**

A The data are valid for high-efficiency (aero-derivative) gas turbines. Current investment costs of low-efficiency turbines (industrial; 32-35% electrical efficiency) are typically 0.29-0.44 M€/MW (ref. 4). Variable O&M for industrial turbines is typically 0.8-1.4 €/MWh (ref. 2+3)

B NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

C Technically 0%, but due to emissions 40 - 60%

D Load gradient for GT's are 10-20 MW/min.

Data for medium-scale plants:

| Technology | Gas turbine single cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **5 - 40** | | | |
| Total efficiency (%) net | 91 | 92 | 92 | 2;2;3 |
| Electricity efficiency (%) net - 100% load | 29-38 | 36-46 | 36-47 | 2+4;3;3 |
|         75% load | | | | |
|         50% load | | | | |
| Cb ($50^oC/100^oC$) | 0.60-0.72 | 0.64-1.00 | 0.64 - 1.04 | 2;3;3 |
| Availability (%) | 90 | 90 | 90 | 2;2;3 |
| Technical lifetime (years) | 25 | 25 | 25 | 2;2;3 |
| Construction time (years) | 1-2 | 1-2 | 1-2 | 2;2;3 |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel)       (A) | 0.12 | < 0,006 | < 0,002 | 4;3;3 |
| $CH_4$ (kg per GJ fuel) | 0.0015 | 0.0015 | 0.0015 | 1;3;3 |
| $N_2O$ (kg per GJ fuel) | 0.0022 | | | 1 |
| Particles (mg per GJ fuel) | 0 | 0 | | 2 |
| Ashes (kg per GJ fuel) | 0 | 0 | | 2 |
| Other residuals (kg per GJ fuel) | 0 | 0 | | 2 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.57-0.86 | 0.57-0.86 | 0.57-0.86 | 3 |
| Fixed O&M (€/MW/year) | 8000 | 8000 | 8000 | 3 |
| Variable O&M (€/MWh) | 2.5 - 8 | 2.5 - 4 | 2.5 - 4 | 3+4;3;3 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003
2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
3 Elsam, 2003
4 Danish Gas Technology Centre, February 2005

**Remarks:**
A NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

Data for mini gasturbines:

| Technology | Gas turbine single cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **0.1 - 5** | | | |
| Total efficiency (%) net | 70-75 | 80-90 | | 4;1 |
| Electricity efficiency (%) net - 100% load | 30 | 32-42 | | 4;1 |
| 75% load | 28 | | | 4 |
| 50% load | 25 | | | 4 |
| Cb (50$^o$C/100$^o$C) | 0.25-0.4 | 0.55-1.1 | | 1 |
| Availability (%) | > 90% | | | |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 10 | | | |
| Construction time (years) | < 0.5 | | | |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel) | 0.08 | | | 1 |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| Ashes (kg per GJ fuel) | | | | |
| Other residuals (kg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 1.1 - 1.7 | 0.8-1.7 | | 4/3;1 |
| Total O&M (€/MWh) | >7 | 1.4 | | 4;1 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1 Elforsk rapport nr 00:01: "El från nya anläggningar", January 2000
2 Gas Turbine World Handbook, 2003
3 Energi E2, November 2003 (100 kW gas turbines)
4 Danish Gas Technology Center, February 2005

**Remarks:**
Investment costs include all costs except land

Data for micro gas turbines:

| Technology | Gas turbine single cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **0.01** | | | |
| Total efficiency (%) net | 65-80 | | | 1 |
| Electricity efficiency (%) net - 100% load | 15 | 20 | 22 | 1 |
| 75% load | | | | |
| 50% load | | | | |
| Cb (50$^o$C/100$^o$C) | | | | |
| Availability (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 8-10 | | | 1 |
| Construction time (years) | | | | |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel) (B) | < 0.015 | < 0,006 | < 0,002 | 1 |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) (A) | 1.0 | 0.6 | 0.4 | 1 |
| Total O&M (€/MW/year) | 10-15 | 8-12 | | 2 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 EU's 'Scientific and technological References - Energy Technology Indicators', sector: CHP Microturbines, December 2002.

2 Danish Gas Technology Center, February 2005

**Remarks:**

A The future investment estimates are targets set by an EU science and technology programme (10 kW gas turbines). The estimates may thus be too optimistic for energy planning purposes. It is assumed that the source has quoted unit costs only (1.0, 0.6 and 0.4 M€/MW respectively). Installation costs of 0.2-0.8 M€/MW have been added in the table.

B Calculated from from <25, <9 and < 3 ppmv, respectively, assuming these data refer to dry flue gas at 5% oxygen

# 07 GAS TURBINE COMBINED CYCLE
2003.12.16

More specific details on gas turbine technology are presented in technology sheet '03 Gas Turbine Single Cycle'.

**Brief technology description**
Industrial or aero-derivative gas turbine, gear (if needed) and generator. Exhaust gas is led to steam producing heat recovery boiler. The steam is used in a power producing steam turbine – either in back-pressure or condensation mode.

**Input**
Typical fuels are natural gas and light oil. Some gas turbines can be fuelled with other fuels such as LPG, biogas etc., and some gas turbines are available in dual-fuel versions (gas/oil).
Gas fired gas turbines need fuel gas pressure of 20-40 bar.

**Output**
Electricity and heat. All heat is generated by the exhaust gas boiler.

**Typical capacities**
The largest plant in the World with one gas turbine only is 490 MW (ref. 3).
The enclosed datasheets cover large scale (100 – 400 MW) and medium scale (10– 100 MW).

**Regulation ability**
To some extent combined-cycle gas turbines (CCGT) are able to operate part load. This will reduce the electrical efficiency.

CCGT's are normally equipped with variable inlet guide vanes, which will improve the part-load efficiencies in the 85-100 % load range, thus making the part load efficiencies comparable with conventional steam power plants in this load range. Another means to improve part-load efficiencies is to split the total generation capacity into more CCGT's.

A combined cycle gas turbine plant can generate power only, if the steam cycle is bypassed.

For a 35 MW plant, 75 GJ is required to start from cold condition, 25 GJ from warm condition. The start costs are approx. € 400 EUR per start (ref. 5).

**Advantages/disadvantages**
Smaller CCGT units have lower electrical efficiencies compared to larger units. Units below 20 MWe are seldom seen and will face close competition with single cycle gas turbines and reciprocating engines.

Natural gas fired CCGT's are characterised by low capital costs, high electricity efficiencies, short construction times and short start-up times.

A drawback is that relatively expensive fuels are needed, e.g. natural gas or light oil.

The scale of economics is substantial, i.e. the specific cost of plants below 200 MWe is increasing considerably as capacity decreases. The general trend towards higher efficiencies may result in slightly higher specific costs (ref. 4).

The steam turbine can be fed with both steam produced based on the exhaust from the gas turbine and steam produced from boilers fed with other fuels (municipal waste etc).

The high air/fuel ratio for gas turbines leads to lower overall efficiency for a given flue gas cooling temperature compared to steam cycles and cogeneration based on internal combustion engines. However, combined cycle units are among the best technologies with regard to the electricity/heat ratio. The somewhat lower total efficiency can therefore be excused by the extremely high electricity efficiency.

**Life cycle assessment**

| kg $CO_2$-equivalent per MWh electricity | Energy quality | Energy content |
|---|---|---|
| Operation | 449 | 255 |
| Construction and decommissioning | 1.87 | 1.07 |
| Fuel procurement and transport | 40.9 | 26.7 |
| Residues | - | - |

(ref. 6).

**Research and development**
Continuous research is done concerning higher inlet temperature at first turbine blades to achieve higher electricity efficiency. This research is focused on materials and/or cooling of blades.

Continuous development for less polluting combustion is taking place. Increasing the turbine inlet temperature will by itself increase the NOx production. To keep a low NOx emission different options are at hand or are being developed, i.e. catalytic burners and dry low-NOx burners.

Development to achieve shorter time for service is also being done.

**Examples of best available technology**
GE's H technology and Mitsubishi's G technology giving CCGT units of 500 MW and 60% electrical efficiency are among the best – but not yet fully commercially available.

**References**

1. Diesel & Gas Turbine World Wide Catalogue, Brookfield US
2. Cogeneration and On-site Power Production, James and James UK
3. Gas Turbine World Handbook, 2003.
4. Danish Energy Authority: "Teknologidata for el- og varmeproduktion", 1995
5. Sjællandske Kraftværker: 'Grovdata IRP99', November 1999.
6. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.

# Data sheets

| Technology | Gas turbine combined cycle | | | |
| --- | --- | --- | --- | --- |
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **100 - 400** | | | |
| Total efficiency (%) net | 89 | 90 | 91 | 2 |
| Electricity efficiency (%) net - 100% load, cond. | 56-60 | 58-62 | 59-64 | 5 |
| 75% load | 54 - 58 | 56 - 60 | 57 - 62 | 5 |
| 50% load | 50 - 54 | 52 - 56 | 53 - 57 | 5 |
| Cb ($50^oC/100^oC$) | 1.32 - 1.67 | 1.45 - 1.8 | 1.47 - 1.93 | 5 |
| Cv coefficient ($50^oC/100^oC$) | 0.13 | 0.13 | 0.13 | 5 |
| Availability (%) | 94 | 94 | 94 | 2;2;5 |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 30 | 30 | 30 | 2;2;5 |
| Construction time (years) | 2.5 - 3 | 2.5 - 3 | 2.5 - 3 | 5 |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $SO_2$ (kg per GJ fuel) | 0 | 0 | 0 | 2 |
| $NO_X$ (kg per GJ fuel) (A) | <0.05 | < 0.02 | < 0.01 | 5 |
| $CH_4$ (kg per GJ fuel) | 0.005 | 0.005 | 0.005 | 2 |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | 0 | 0 | 0 | 2 |
| Ashes (kg per GJ fuel) | 0 | 0 | 0 | 2 |
| Other residuals (kg per GJ fuel) | ~0 | ~0 | ~0 | 2 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.35-0.70 | 0.4-0.70 | 0.4-0.70 | 4;5 |
| Fixed O&M (€/MW/year) | 14000 | 11000-14000 | 11000-14000 | 3 |
| Variable O&M (€/MWh) | 1.5 | 1.5 | 1.5 | 5 |
| **Regulation ability** | | | | |
| Fast reserve (% per minute) | 10 | 10 | 10 | 5 |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Danish Energy Authority, personal communication, September 2003

2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997

3 Elforsk rapport nr 00:01: "El från nya anläggningar", January 2000

4 Gas Turbine World Handbook, 2003.

5 Elsam, 2003

**Remarks:**

A NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

| Technology | Gas turbine combined cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **10 - 100** | | | |
| Total efficiency (%) net | 89 | 90 | 91 | 4 |
| Electricity efficiency (%) net - 100% load, back-pres. | 46-54 | 47 -55 | 48 - 56 | 3;4;4 |
| 75% load | | | | |
| 50% load | | | | |
| Cb (50$^o$C/100$^o$C) | 1.07 - 1.5 | 1.09 - 1.57 | 1.12 - 1.6 | 4 |
| Availability (%) | 94 | 94 | 94 | 4 |
| Planned outage (weeks per year) | 2 - 3 | 2 - 3 | 2 - 3 | 4 |
| Technical lifetime (years) | 25 | 25 | 25 | 4 |
| Construction time (years) | 2.5 | 2.5 | 2.5 | 4 |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $SO_2$ (kg per GJ fuel) | | | | |
| $NO_X$ (kg per GJ fuel) | <0.05 | < 0.02 | < 0.01 | 4 |
| $CH_4$ (kg per GJ fuel) | 0.005 | 0.005 | 0.005 | 4 |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| Ashes (kg per GJ fuel) | | | | |
| Other residuals (kg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) - CHP | 0.57-0.83 | 0.57-0.83 | 0.57-0.83 | 4;2;4 |
| Fixed O&M (€/MW/year) | 10000 | 10000 | 10000 | 4 |
| Variable O&M (€/MWh) | 2.0 - 3.5 | 2.0 - 3.5 | 2.0 - 3.5 | 4 |
| **Regulation ability** | | | | |
| Fast reserve (% per minute) | 10 | 10 | 10 | 4 |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Danish Energy Authority, personal communication, September 2003

2 Elforsk rapport nr 00:01: "El från nya anläggningar", January 2000

3 Elsam, November 2003

4 Elsam, 2003

**Remarks:**

A NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

# 08  GAS ENGINES

2005.02.15

**Brief technology description**

A gas engine drives an electricity generator, whereas engine cooling and exhaust gas can be used for heat generation, e.g. for district heating or low-pressure steam.

The technology sheet covers two types of engines: Spark ignition engines and dual-fuel engines.

Spark ignition engines are commonly categorized according to the air/fuel-ratio:
- In stoichiometric combustion the amount of air is just sufficient for (theoretically) complete combustion. This is employed in engines with 3-way catalysts.
- Lean-burn engines have a high air/fuel-ratio. The combustion temperature and hence the NOx emission is thereby reduced. The engines are at times equipped with oxidation catalysts for CO-reduction. Engines with air/fuel ratios above 1.8 are ignited by a flame in a precombustion chamber (prechamber engines). These usually require a gas inlet pressure of 3.5 – 4 bar.

A dual-fuel engine is a gas engine that - instead of spark plugs - uses a small amount of oil (3 – 12 %) to ignite the air-gas mix by compression (similar to the diesel engine).

Low-pressure dual-fuel engines are more robust with regards to gasses with low octane values or low heating values than spark ignition engines.

High-pressure dual-fuel engines can principally operate on any gas, regardless of methane content.

**Input**

Spark ignition: Gas, e.g. natural gas, biogas, landfill gas, and bio gen-gas (producer gas).
In recent years multi-fuel engines have appeared on the market.

Dual fuel: Gas and ignition oil (light oil)

In recent years, engines have been developed to use gasses with increasingly lower heating values and higher contents of impurities.

**Output**

Electricity and heat (district heat; low-pressure steam; industrial drying processes; absorption cooling)

**Typical capacities**

Spark ignition engines: 5 $kW_e$ - 8 $MW_e$ per engine.

Dual-fuel engines: 0.5 - 16 MW per engine; up to 40 MW per engine for high-pressure engines.

**Regulation ability**

Fast start-up.
Part load possible; with slightly decreased electric efficiencies. The dual-fuel engines have the least decrease of efficiency at part load.

**Advantages/disadvantages**
The technology has been commercial and been widely used for many years. During the years shaft efficiency has been steadily improved and emissions reduced.

Compared with gas turbines, engines cannot be used to produce considerable amounts of high-pressure steam, as most of the waste heat is released at low temperature.

It is difficult for dual-fuel engines to compete with spark ignition engines in the smaller range, due to the need for auxiliary equipment (e.g. exhaust gas cleaning). Dual-fuel engines are more attractive, when large units (5 – 40 MW) are required, or where fuel flexibility is important (they can operate on light oil alone), or where the gas has a low content of methane and/or low heating value.

**Environment**
Spark ignition engines comply with national regulations within EU by using catalysts and/or lean-burn technology.

High-pressure dual-fuel engines usually need deNOx equipment. Some soot is emitted due to ignition oil.

**Life cycle assessment**

| kg $CO_2$-equivalent per MWh electricity | Energy quality | Energy content |
|---|---|---|
| Operation | 538 | 309 |
| Construction and decommissioning | 0.417 | 0.240 |
| Fuel procurement and transport | 40.7 | 23.4 |
| Residues | - | - |

The main ecological footprint from gas engines is climate change. Gas engines usually emit 20% more $CO_2$-equivalents than other gas technologies, due to unburned methane in exhaust (ref. 2).

**Research and development**
Spark ignition engines:
- There is a need to further reduce emissions.
- Use of various gasses, or gasses with varying composition, need be investigated.
- Efficiencies can be improved by new engine designs and optimised operation.

Dual fuel engines:
- The trend is towards less ignition oil, less soot and less NOx.
- There is a need to further develop catalytic exhaust gas cleaning.
- Improved efficiencies are expected.

New engine concepts:
The homogenous compression ignition engine combines the homogenous air-fuel mix of the spark ignition engine with the compression ignition of the diesel engine.

**Examples of best available technology**

| Plant | Engine | Production (MWh) | | Efficiency (%) | | |
|---|---|---|---|---|---|---|
| | | Electricity | Heat | Electrical | Heat | Total |
| Ringkøbing | Wärtsilä | 3.170 | 3.856 | 41,9 | 50,9 | 92,8 |
| Sæby | Caterpillar CM | 2.854 | 3.321 | 43,3 | 50,4 | 93,7 |

(Ref. 4)

**Special remarks**

**References**
1. Danish Energy Authority, 2003.
2. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.
3. Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003.
4. http://www.fjernvarmen.dk/upload/files/driftsdata/Juni%2004.pdf

# Data sheets

Large engines:

| Technology | Spark ignition engine, natural gas | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **1 - 5** | | | |
| Total efficiency (%) net                          (D) | 88 - 96 | 88 - 96 | 88 - 96 | 4 |
| Electricity efficiency (%) net - 100% load | 40 - 44 | 41-44 | 43-46 | 5 |
| 75% load | 40 - 43 | | | 1 |
| 50% load | 38 - 40 | | | 1 |
| Cb ($50^{o}$C/$100^{o}$C) | 0.9 | | | |
| Availability (%)                                  (A) | 95 | 95 | 95 | 1+3 |
| Technical lifetime (years)                        (B) | 20 - 25 | 20 - 25 | 20 - 25 | 1+3 |
| Construction time (years) | < 1 | < 1 | < 1 | 1 |
| **Environment** (Fuel: Natural gas) | | | | |
| $NO_X$ (kg per GJ fuel) | 0.17 | 0.08-0.2 | | 2/3 |
| $CH_4$ (kg per GJ fuel)                           (F) | 0,26-0,58 | 0-0,26 | | 2; 5 |
| $N_2O$ (kg per GJ fuel) | 0.0013 | | | 2 |
| Particles (mg per GJ fuel),                       (E) | 0-3000 | 0-3000 | 0-3000 | 3 |
| Ashes (kg per GJ fuel) | | | | |
| Lubricating oil (kg per GJ fuel) | 0.012 | | | 2 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.8 - 1.2 | 0.8 - 1.2 | 0.8 - 1.2 | 1 |
| Total O&M (€/MWh) | 6-9 | 6-9 | 6-9 | 5 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | From cold to full load within 15 minutes | | | 1 |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load)                     (C) | 50 | | | 1 |

**References:**
1. Danish Energy Authority, September 2003
2. Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003
3. Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
4. Danish Association of District Heating Companies (DFF), December 2003
5. Danish Gas Technology Centre (DGC), September 2004

**Remarks:**
A. Regular service typically every 1,000 hours. Extra service usually every 2,000, 5,000 and 10,000 hours. Major overhauls usually at 20,000 and 40,000 hours.
B. Continual more rigorous environmental regulations offen shorten the practical lifetime.
C. The minimum load can be lower, but this is usually not advisable due to lower efficiency
D. May be higher than 100% (flue gas condensation), if hydrogen rich fuels are used.
E. Calculated from from 0-10 mg/Nm³ assuming this interval refers to dry flue gas at 5% oxygen
F. Mean values for open chamber and precombustion chamber technologies respectively.

Micro engines:

| Technology | Spark ignition engine, natural gas | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **0.001 - 0.02** | | | |
| Total efficiency (%) net | | | | |
| Electricity efficiency (%) net - 100% load | < 25 | | | 2 |
| 75% load | | | | |
| 50% load | | | | |
| Cb (50$^o$C/100$^o$C) | | | | |
| Availability (%) | | | | |
| Technical lifetime (years) | | | | |
| Construction time (years) | | | | |
| **Environment** (Fuel: Natural gas) | | | | |
| NO$_X$ (kg per GJ fuel) | | | | |
| CH$_4$ (kg per GJ fuel) | | | | |
| N$_2$O (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| Ashes (kg per GJ fuel) | | | | |
| Lubricating oil (kg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW)          (A) | 2.9 | | | 1 |
| Total O&M (€/MWh) | 13-27 | | | 3 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1 "Afprøvning af mikrokraftvarmeanlæg", Elfor, Elsam, and Techwise, January 2002.
2 Danish Gas Technology Centre (DGC), October 2003
3 Danish Gas Technology Centre (DGC), September 2004
**Remarks:**
A All costs; also connection costs, included

| Technology | Dual fuel engine | | | |
|---|---|---|---|---|
| | **1994** | **2005** | **2015** | **Ref** |
| **Energy/technical data** | | | | |
| Installed generating capacity (MW) | | 0.5-16 | | 1 |
| Total efficiency (%) net | 90 | 93-95 | 95 | 1 |
| Electricity efficiency (%) net - 100% load | 40-45 | 45-47 | 47 | 1 |
| 75% load | 40-45 | 45-47 | 47 | 2 |
| Cb coefficient | 0.9 | 1.0 | 1.0 | 1 |
| Availability (%) | 90-95 | 95 | 95 | 1 |
| Technical lifetime (years) | 20-25 | 20-25 | 20-25 | 1 |
| Construction time (years) | 1-2 | 1-2 | 1-2 | 1 |
| **Environment** (Fuel: natural gas and light oil) | | | | |
| $SO_2$ (kg per GJ fuel) | 0 | 0 | 0 | 1 |
| $NO_X$ (kg per GJ fuel) | 0.15-0.20 | 0.15-0.20 | 0.15-0.20 | 1 |
| Particles (mg per GJ fuel), (A) | 0-6.000 | 0-6.000 | 0-6.000 | 1 |
| Other residuals (kg per GJ fuel) | 0 | 0 | 0 | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.9 | 0.9 | | 1 |
| Total O&M (€/MWh) | 10 | 7-10 | 7-10 | 2 |

**References:**

1 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997

2 Danish Gas Technology Centre (DGC), September 2004

**Remarks:**

A Calculated from from 0-20 mg/Nm³ assuming this interval refers to dry flue gas at 5% oxygen

# 09  SMALL-SCALE BIOMASS COGENERATION, STEAM TURBINE

2004.10.12

**Brief technology description**

The major components are: Fuel treatment and feed-in system, high-pressure steam boiler, steam turbine, generator and flue-gas heat recovery boiler (hot water or steam).

Combustion can be applied for biomass feedstocks with moisture contents up to 60%. Wood is usually the most favourable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass like straw and miscanthus have higher contents of N, S, K, Cl etc. that leads to higher emissions of NOx and particulates, increased ash, corrosion and slag deposits.

Straw is usually delivered in 500 kg Hesston bales (15 GJ/tonnes) to the CHP plant. Compared to coal the energy density is about 9 times lower. The bales are most commonly shredded and fed by stoker screws.

Forest residues are typically delivered as wood chips. Both straw and wood residues may also be delivered as pellets.

The furnace technology can be of different nature: Grate firing, suspension firing (where the biomass is pulverized or chopped and blown into the furnace, possibly in combination with a fossil fuel), and fluidised bed. Grate combustion is very robust with regard to using varying types of biomass.

The data sheet describes plants used for combined production of electricity and district heat. These data do not apply for industrial plants, which typically deliver heat at higher temperatures than district heating plants, and therefore they have lower electricity efficiencies. Also, industrial plants are often cheaper in initial investment and O&M, among others because they are designed for shorter technical lifetimes, with less redundancy, low-cost buildings etc.

Co-combustion of biomass with fossil fuels in large power plants is covered by technology sheet no. 03.

**Input**

Biomass; e.g. residues from wood industries, wood chips (collected in forests), peat, straw and energy crops.

**Output**

Electricity and heat. The heat may come as steam or hot water.

**Typical capacities**

The capacities of cogeneration plants supplying heat to district heating systems are primarily determined by the heat demands. This datasheet covers small-scale grate fired systems, 5 – 15 MW.

**Regulation ability**

The plants can be down regulated, but due to high initial investments they should be operated in base load.

**Advantages/disadvantages**

Some biomass resources, in particular straw, contain aggressive components such as chlorine. To avoid or reduce the risk of slagging and corrosion, boiler manufacturers have traditionally deterred from applying steam data to biomass-fired plants at the same level as coal-fired plants. However, recent advances in materials and boiler design constitute a breakthrough, and the newest plants have fairly high steam data and efficiencies.

In the low capacity range (less than 10 MW) the scale of economics is quite considerable.

**Life cycle assessment**

| kg $CO_2$-equivalent per MWh electricity | Energy quality | Energy content |
|---|---|---|
| Operation | 4.29 | 3.11 |
| Construction and decommissioning | 2.04 | 1.48 |
| Fuel procurement | 16,8 | 12.2 |
| Fuel transport | - | - |
| Residues | 0.00276 | 0.00200 |

The main ecological footprints from biomass combustion are hazardous waste, acidification and persistent toxicity. However, the footprints are small (ref. 2).

**Research and development**

Focus of the Danish R&D strategy:
- Reduce the cost of fuel, by improved pre-treatment, better characterisation and measurement methods.
- Reduce corrosion, in particular high-temperature corrosion
- Reduce slagging
- Reduced emissions
- Recycling of ashes
- Improved trouble-shooting

A key objective of EU's 6'th Framework Programme on R&D is to reduce the cost of generating electricity from biomass to 0.05 €/kWh by 2015-2020.

**Examples of best available technology**

In Denmark, the most recent small-scale plants are Maribo/Sakskøbing (straw; 11 MW; commissioned in 2000) and Assens (wood chips; 5 MW; commissioned in 1999).

**Special remarks**

The data sheets indicate that wood-fired plants have lower electricity efficiencies than straw-fired plants. This has no reason in technology constraints, but reflects the fact that the development of straw-fired plants has been driven by power utilities focusing on high efficiencies.

## References

1.	Nussbaumer, T.: "Combustion and Co-combustion of Biomass", 12th European Conference on Biomass for Energy, Industry and Climate Protection. 17-21 June 2002, Amsterdam.
2.	"Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.

## Data sheets

| Technology | Steam turbine, grate firing, wood chips | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **0.6 - 4.3** | | | |
| Total efficiency (%) net            (A) | 105 | 105 | 105 | 1 |
| Electricity efficiency (%) net - 100% load | 25 | 25 | 25 | 1 |
| 75% load | 25 | 25 | 25 | 1 |
| 50% load | - | - | - | 1 |
| Time for varm start-up (hours) | 3 | | | 4 |
| Cb ($50^oC/100^oC$) | 0.3 | 0.3 | 0.3 | |
| Availability (%) | 90 -92 | 90 -92 | 90 -92 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 5 |
| Construction time (years) | 2-3 | 2-3 | 2-3 | 5 |
| **Environment** (Fuel: wood chips from forestry) | | | | |
| $SO_2$ (kg per GJ fuel) | < 0.0018 | | | 3 |
| $NO_X$ (kg per GJ fuel) | 0.069 | | | 3 |
| $CH_4$ (kg per GJ fuel) | < 0.0021 | | | 3 |
| $N_2O$ (kg per GJ fuel) | < 0.0008 | | | 3 |
| Particles (mg per GJ fuel) | 0.02 | | | 2 |
| Ashes (kg per GJ fuel) | 1 | 1 | 1 | 5 |
| **Financial data** | | | | |
| Specific investment (M€/MW)            (B) | 4.2-5.7 | 3.4-4.7 | 2.8-3.8 | 1 |
| Total O&M (% of investment per year) | 3 - 4 | 3 - 4 | 3 - 4 | 1 |
| Fixed O&M (% of investment per year) | 2 | | | 2 |
| Variable O&M (€/MWh) | 7.1 | | | 2 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
  1 Danish Energy Authority, September 2004
  2 Elforsk: "El från nya anläggningar", Stockholm, January 2000.
  3 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003
  4 Danish Technology Institute: "Udvikling af computerbaseret værktøj, energyPRO, til simulering og optimering af driftsstrategi for biobrændselsfyrede kraftvarmeværker", September 2001
  5 Elkraft System, October 2003 and September 2004
**Remarks:**
  A Condensation mode
  B A cost reduction of 2 % per year cost is assumed

| Technology | Steam turbine, grate firing, straw combustion | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **8 - 10** | | | |
| Total efficiency (%) net | 88 - 90 | 90 | 90 | 1 |
| Electricity efficiency (%) net - 100% load | 29 - 30 | 29 - 30 | 29 - 30 | 1 |
|         75% load | 29 - 30 | 29 - 30 | 29 - 30 | 1 |
|         50% load | | | | |
| Time for varm start-up (hours) | 2 | | | 4 |
| Cb ($50^oC/100^oC$) | 0.5 | 0.5 | 0.5 | |
| Availability (%) | 91 | 91 | 91 | 2 |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 20 | 20 | 20 | 5 |
| Construction time (years) | 2 - 3 | 2 - 3 | 2 - 3 | 2 |
| **Environment** (Fuel: straw; LHV 14.2 GJ/t; ashes 4%; sulphur 0.2%) | | | | |
| $SO_2$ (kg per GJ fuel) | 0.047 | | | 3 |
| $NO_X$ (kg per GJ fuel) | 0.131 | 0.09 | | 3;2 |
| $CH_4$ (kg per GJ fuel) | < 0.0005 | | | 3 |
| $N_2O$ (kg per GJ fuel) | < 0.0014 | | | 3 |
| Particles (mg per GJ fuel) | 40 | 40 | 40 | 2 |
| Ashes (kg per GJ fuel) | 2-4 | 2-4 | 2-4 | 2 |
| **Financial data** | | | | |
| Specific investment (M€/MW)    (A) | 4.3-5.5 | 3.5-4.6 | 2.9-3.7 | 1 |
| Total O&M (% of investment per year) | 4 | 4 | 4 | 1 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Danish Energy Authority, September 2004

2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997

3 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

4 Danish Technology Institute: "Udvikling af computerbaseret værktøj, energyPRO, til simulering og optimering af driftsstrategi for biobrændselsfyrede kraftvarmeværker", September 2001

5 Elkraft System, October 2003

**Remarks:**

A A cost reduction of 2 % per year cost is assumed

# 10 GASIFIERS, BIOMASS, STAGED GASIFICATION
2004.11.09

**Brief technology description**

A solid biomass fuel is converted into gas (producer gas), which can be used in gas engines, boilers, gas turbines or fuel cells for power and heat production. The data in this technology sheet are for a system including a gas engine.

The biomass is converted through several stages. Up to 100°C the water is vaporized. By pyrolysis the dry fuel is converted to a tarry gas and a char residue. Subsequently, the char residue is gasified at 800-1200°C, while water vapour and/or oxygen (air) is added.

In staged gasification, pyrolysis and gasification are separated into two reactors, enabling a partial oxidisation of tar products between the stages. Thus, staged gasifiers are producing a gas with low tar content, which is essential for engine operation. The tar content is often below 100 mg/Nm$^3$ and can be below 10 mg/Nm$^3$.

The pyrolysis process can be with either internal or external heating. Internal heating is performed by addition of air/oxygen, while external heating utilises waste heat from the produced gas and from the engine to dry and pyrolyse the fuel. The data in the table are valid for external heating, as this results in higher efficiencies.

**Input**

Wood chips (collected in forests), industrial wood residues, straw and energy crops can be used in the form of chips, briquettes or pellets. Requirements to moisture content and size of the fuel are depending on the design of the reactor and the process.

**Output**

Producer gas primarily consists of the components $N_2$, $H_2$, CO, $CO_2$, $CH_4$, and water. The lower heating value of the gas is 4.5-6.5 MJ/Nm$^3$. The gas is converted to electricity and heat by a gas engine.

**Typical capacities**

The attractive market segment is for plants with fuel inputs around 1-20 MJ/s.
The economy-of-scale is important.

**Regulation ability**

It can be fully regulated within a few seconds.

**Advantages/disadvantages compared to other technologies**

Gasification of biomass for use in decentralized combined heat and power production can decrease the emission level compared to power production with direct combustion and a steam cycle.

Existing natural gas fuelled engines can be converted to use 100% producer gas or a combination of producer gas and natural gas.

One disadvantage is long start-up time (from cold). Also, excessive soot-formation may occur at start/stop.

**Environment:**
The electricity efficiency is higher than combustion technologies, in the low capacity range. For gasification technology with external pyrolysis the electricity efficiency is higher than large-scale combustion technologies, and emissions are less - relative to electricity generation.

The Danish Environmental Protection Agency intends to regulate emissions and other environmental impacts by so-called 'business papers', which are under preparation.

Ashes from gasification of wood contain most of the amount of cadmium that was in the wood. Today's regulation doesn't allow spreading the ashes in the forest or on fields, and ashes are today brought to deposits.

**Research and development¨**
- Scale up
- Load regulation; incl. automatic start/stop
- Further automation and safety documentation
- Optimised engine operation
- Low temperature corrosion; materials
- Soot formation

**Examples of best available technology**
1) Technical University of Denmark, Biomass Gasification Group: 4-5 test plants have been built. The most recent pilot plant, called "Viking" (75 kJ/s fuel), has been operated un-manned 1,800 hours (September 2003).
2) TK Energi: Test plant of 300 kJ/s fuel.
3) Bio Synergi: The Græsted pilot project (450 kJ/s fuel).

**Data sheet:**

| Technology | | Biomass gasifiers, down-draft, staged | | | |
|---|---|---|---|---|---|
| | | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | | |
| Generating capacity for one unit (MW) | | 0.1-0.6 | 1-10 | 1-20 | 1 |
| Total efficiency (%) net | (A) | 100 | 103 | 105 | 1 |
| Electricity efficiency (%) net - 100% load | (A) | 35 | 35 - 40 | 37 - 45 | 1 |
| 75% load | | 32 | 33 - 38 | 35 - 45 | 1 |
| 50% load | | 30 | 30 - 35 | 32 - 45 | 1 |
| Start-up fuel consumption (GJ) | | | | | |
| Cb coefficient (40$^o$C/80$^o$C) | | 0.5 | 0.6 | 0.7 | 1 |
| Availability (%) | | 85 | 95 | 97 | 1 |
| Technical lifetime (years) | | 10 | 15 - 20 | 20 | 1 |
| Construction time (years) | | 1 | 1 | 1 | 1 |
| **Environment** (Fuel: Wood chips; 45% moisture; LHV of gas 4.8 - 6.2 MJ/kg) | | | | | |
| NO$_X$ (kg per GJ fuel) | | 0.1 | 0.1 | 0.1 | 1 |
| SOx (kg per GJ fuel) | | 0 | 0 | 0 | 1 |
| Particles (mg per GJ), | (B) | < 360 | < 360 | < 360 | 1 |
| Ashes, straw / wood chips (kg per GJ fuel) | | 2.1-4.1 / 0.2-1.3 | | | 1 |
| Condensate, ammonium (liters per GJ fuel) | | 0.1-0.3 | 0.1-0.3 | 0.1-0.3 | 1 |
| **Financial data** | | | | | |
| Specific investment (M€/MW) | | 3.5 | 2.8-3 | 2-2.5 | 1+2 |
| Fixed O&M (€/MW/year) | | 150000 | 70000 | 50000 | 1 |
| Variable O&M (€/MWh) | | 15 | 15 | 14 | 1 |
| **Regulation ability** | | | | | |
| Fast reserve (MW per 15 minutes) | | | | | |
| Regulation speed (MW per sec.) | | | | | |
| Minimum load (% of full load) | | 10 | 10 | 10 | 1 |

**References:**

1 Biomass Gasification Group, Technical University of Denmark, and COWI A/S, November 2004
2 TK Energi, November 2004

**Remarks:**

A With external heating of the pyrolysis process through waste heat recovery
B Calculated from < 1 mg/m³ assuming this value refers to dry flue gas at 6% oxygen

# 11 BIOMASS GASIFIER, UPDRAFT

2004.10.04

**Brief technology description**

A solid biomass fuel is converted into gas (bio gen-gas; in the past producer gas), which in turn is used in gas engines, boilers or gas turbines for power and heat production.

The biomass is converted through several stages. Up to 100°C the water is vaporized. By pyrolysis (extra heating and limited addition of oxygen) the dry fuel is converted to a tarry gas and a coke residue. Subsequently, the coke residue is gasified at 800-1200°C, while water vapour and/or oxygen (air) is added. Depending on the process, the tar shall either be incinerated or cracked before it is cleaned of particles etc.

The updraft gasifier is characterised by the fuel and the gas having opposite flow directions. The gas has low temperature (~75°C) but a large content of tar, typically 30-100g/Nm$^3$. The updraft gasifier has been used for the last 75-100 years for electricity, heat, steam and industrial processes such as burning of ceramics, glass making, drying and town gas (ref 5).

Electricity efficiencies are expected to pass 30%[1].

**Input**

Wood chips, pellets, chunks and briquettes, industrial wood residues and energy crops can be used. Requirements to moisture content and size of the fuel are depending on the design of the reactor and the process.

At Babcock & Wilcox Volund research primarily concentrates on use other fuels than biomass especially use of hazardous waste materials.

**Output**

Bio gen-gas primarily consists of the components CH4, H2, CO, CO2, N2, H2O and tar with a lower heating value of 6.6 – 6.8 MJ/Nm3 (ref. 10).

**Typical capacities**

The capacity of the only Danish demonstration plant at Harboøre is 4 MJ/s fuel for CHP operation but can be up-rated to 8 MJ/s fuel for district heating operation only. In 2003 Harboøre has an electricity efficiency of 29% (ref. 10).

Since the economy-of-scale is moderate, this gasifier is well suited for modular plants. Each module can then be tailored to a specific fuel.

**Regulation ability**

At Harboøre tests has shown that the load can quickly be changed from 10 to 100 % and vice versa, which is not possible in a conventional wood chip boiler (ref. 1).

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[1] Elforsk in Sweden claims that electrical efficiencies of 30-45% are currently being achieved (Ref 9).

**Advantages/disadvantages**
The updraft gasifier has limited requirements to fuel quality, both concerning the contents of moisture and ash. The load interval has proven to be noticeably higher than expected, which fits with a typical load in district heating.

**Environment**
The electricity efficiency is higher than combustion technologies, in the low capacity range. Thus, emissions are less - relative to electricity generation.

**Research and development**
 "The Danish development activities for smaller gasification plants are wished to concentrate on few development tracks over some years and there is a special aim of concrete uses. It is prioritised to conduct long-term tests in pilot size and demonstration of few technologies. In connection with this R&D is carried out, which is expected to solve operational problems such as corrosion, process regulation etc." (ref. 11)

The main issues to be solved with biomass gasification include:
- Long-term stability and reliability; plants should be operated unmanned and with at least 1-2 years between major overhauls.
- Ability to handle a wider range of fuel properties
- Gas purification for tar and particles
- Purification of wastewater with tar in; in particular capital cost reduction
- Re-introduction into gasifier of tar from waste water clean-up
- Meeting emissions regulations
- Reactor calculations; kinetic models of significance for design and control
- Conversion of coke
- Studies of basic chemical processes in the various phases of conversion
- Methods for continuous measuring and analysis of the gas quality
- Producing plants at a sufficiently low price

**Examples of best available technology**
Examples of Danish produced updraft gasifiers (ref. 8):
- At Harboøre a 4800 $kW_{in}$ updraft counter-current fixed bed gasifier was installed in 1994. The gasifier is used for CHP production and has a gross electrical output of 1400 $kW_e$. The gasifier utilises woodchips. The gasifier is owned by Babcock & Wilcox Volund R&D Centre.
- At Ansager a 200 $kW_{in}$ updraft counter-current fixed bed gasifier was installed in 2001. The gasifier is produced by Babcock & Wilcox Vølund. It utilises woodchips and is coupled to a stirling engine.
- In 1998 a 600 kW test plant was installed at Kommunekemi. The plant utilises waste such as impregnated wood and tannery waste (ref.7).
- In 1999 a 500$kW_{in}$ updraft counter-current fixed bed gasifier produced by KN Consult was installed in Pulawy, Poland.

The technology has been tested several places abroad, but not aimed directly at CHP production with direct use of the gas for a gas engine.

Notably USA, Denmark, Germany and Finland are involved in developing biomass gasification processes. Companies in Denmark due to a reduced demand for decentralised CHP plants have scaled activities down. The European Commission framework programmes for R&D support gasification as well as national programmes in a number of countries including the USA.

**Special remarks**

There is still a way to go before the technology becomes commercial. Elforsk in Sweden assesses that it is unlikely within the next 10 years (ref 9).

**References**

1: Danish Bioenergy Solutions - reliable and efficiency. Centre for Biomass Technology, Danish Energy Authority, 2000

2: http://www.volund.dk/rd2.html

3: Økonomisk vurdering af vedvarende energikilder i et grønt el-marked - Decentral biomasse kraftvarme, ekskl. Industrianlæg - Solceller - Vandkraft. Rambøll. Danish Energy Authority, January 2000

4: The Danish Follow-up Programme for Small-scale Solid Biomass CHP Plants - Status Report 1999. Danish Energy Authority.

5: Teknologidata for vedvarende energianlæg, Del 2 - Energi 21. Lars Rasmussen og Henrik Flyver Christiansen. Danish Energy Authority, 1996

6: Grovdata - IRP99. Sjællandske Kraftværker. Nov. 1999

7: Biomasse kraftvarme udviklingskortlægning – Resume-rapport. Eltra. Elkraft System. Danish Energy Authority, August 2003

8: http://www.gasifiers.org

9: El från nya anläggningar – Jämförelse mellen olika tekniker för elgenerering med avseende på kostnader och utvecklingstendenser. Bärring et al. Elforsk Rapport nr. 00:01. Jan 2000

10: Bjørn Teislev, R&D Manager, Babcock and Wilcox Volund (BWV), August 2003.

11: Strategi for forskning, udvikling og demonstration af biomasseteknologi til el- og kraftvarmeproduktion i Danmark, Danish Energy Authority, Elkraft System og Eltra, August 2003-09-03

# Data sheets

| Technology | Updraft counter-current fixed bed gasifier | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 1.4 | 1.4 | | 1 |
| Total efficiency (%) net                                 (A) | 105 | | | 1 |
| Electricity efficiency (%) net - 100% load | 29 | 33 - 35 | | 2;1 |
| Start-up fuel consumption (GJ) Time for varm start-up (hours) | 0.25 | | | 3 |
| Cb coefficient ($40^oC/80^oC$) | | | | |
| Forced outage (%) | 5 | | | 2 |
| Planned outage (weeks per year) | 3 | | | 2 |
| Technical lifetime (years) | 20 | | | 2 |
| Construction time (years) | 1.5 | | | 2 |
| **Environment** (fuel: Woodchips; size 1-8 cm; LHV 10 MJ/kg (42% moisture); ashes 1%; bulk density 250 kg/m3) | | | | |
| $NO_X$ (kg per GJ fuel) | 0.1 | | | 2 |
| $CH_4$ (kg per GJ fuel) | 0.02 | | | 2 |
| Particles (mg per GJ fuel) | 0.1 | | | 2 |
| Ashes (kg per GJ fuel) | 0.6 | | | 2 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 4.00 | 3 | | 2 |
| Fixed O&M (€/MW/year) | 150000 | | | 2 |
| Variable O&M (€/MWh) | 15 | | | 2 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | 1.4 | | | 2 |
| Regulation speed (MW per sec.) | about 0.1 MW/s | | | 2 |
| Minimum load (% of full load) | 10% | | | 2 |

**References:**

1 Danish Energy Authority, personal communication, September 2003

2 Bjørn Teislev, R&D Manager, Babcock and Wilcox Volund (BWV), personal communication, 2003

3 Danish Technology Institute: "Udvikling af computerbaseret værktøj, energyPRO, til simulering og optimering af driftsstrategi for biobrændselsfyrede kraftvarmeværker", September 2001

**Remarks:**

A 105% efficiency is with flue-gas condensation; without the efficiency is around 85%

# 12  MICRO COMBINED HEAT AND POWER SYSTEMS
2004.10.04


**Brief technology description**
In this context, a micro combined heat and power (CHP) system is defined as a system, which can provide a household's electricity needs as a bonus to the space and water heating.

Potential technologies:
- Fuel cells; natural gas or hydrogen. **See dedicated technology sheet.**
- Gas turbines; natural gas. **See dedicated technology sheet.**
- Gas engine; natural gas, LPG, landfill gas, biogas. **See dedicated technology sheet.**
- Diesel engine; light fossil oil, vegetable oil
- Stirling engine; fired by natural gas or biomass

Micro CHP systems are beginning to be commercialised. It is anticipated that micro CHP units will sell at € 800-2500 more than a conventional gas boiler (ref. 1).

In Germany, various engine-based systems have been marketed for some years; in 1997 by 18 companies (ref. 2).

**Input**
Gas or oil.
Hydrogen is being much investigated for future applications.

**Output**
Electricity and heat.

**Typical capacities**
A small micro system (1 kWth) may suit modern, low-energy homes, a somewhat larger system (4-6 kWth) a typical family home, and an even larger system (8-10 kWth) would ideally be suited to larger family homes and the majority of older, less well insulated homes.

Systems based on piston engines should for Danish climatic conditions be around 1 – 5 kWe. However, at present there are no commercial engines below 5 kWe (ref. 3).

**Regulation ability**
With a hot water store, the system may generate electricity at times, which are favourable for the overall electricity system.

**Advantages/disadvantages**
CHP is one of the most cost-effective $CO_2$ abatement measures. In case of CHP home systems, emissions from electricity production are effectively zero since the power is a by-product of the heating system.

Micro CHP systems can be readily implemented in homes that are connected to a gas supply. The lead-time is short; systems can be installed in hours rather than years.

Often more than half the typical domestic electricity price is accounted for by transport costs and utility margins (ref. 1). The availability of electricity at the point of demand (distributed generation) thus avoids these costs.

Distributed generation allows a smooth expansion of generation capacity, rather than the step-by-step expansion that characterises traditional power plants.

No resource problems (cooling water, network access).

No requirement of other infrastructure.

**Life cycle assessment**
Micro gas engines:

| kg $CO_2$-equivalent per MWh electricity | Energy quality | Energy content |
|---|---|---|
| Operation | 218 | 504 |
| Construction and decommissioning | 0.584 | 1.35 |
| Fuel procurement | 17.8 | 41.0 |
| Fuel transport | - | - |
| Residues | - | - |

The main ecological footprints from micro gas engines are climate change and hazardous waste (ref. 4).

Ref. 3 has done an LFA for piston engine based systems.

**Research and development**
Development of piston engines in the 1 – 5 kW range.

**Examples of best available technology**


**Special remarks**


**References**
1.      "Gas boilers of the future turn homes into power plants", Newsletter of the International Network for Domestic Energy-Efficient Appliances (IDEA), issue 3, volume 4, 2000.
2.   "Mikrokraftvarme: Millionvis af nye anlæg er på vej", Nordvestjysk Folkecenter for Vedvarende Energi, December 1997.
3.   "Afprøvning af mikrokraftvarmeanlæg", Elfor, Elsam, and Techwise, January 2002. Eltra PSO-F&U project
4.   "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.

# Data sheets

| Technology | Gas turbine single cycle | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | **0.003 - 0.010** | | | |
| Total efficiency (%) net | 65-80 | | | 1 |
| Electricity efficiency (%) net - 100% load | 15 | 20 | 22 | 1 |
| 75% load | | | | |
| 50% load | | | | |
| Cb (50$^o$C/100$^o$C) | | | | |
| Availability (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 8-10 | | | 1 |
| Construction time (years) | | | | |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel)                (B) | < 0.015 | < 0,006 | < 0,002 | 1 |
| $CH_4$ (kg per GJ fuel) | | | | |
| $N_2O$ (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW)          (A) | 1.2 - 1.8 | 0.8 - 1.4 | 0.6 - 1.2 | 1 |
| Total O&M (€/MWh) | 5-10 | 1-3 | | 1 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 EU's 'Scientific and technological References - Energy Technology Indicators', sector: CHP Microturbines, December 2002.

**Remarks:**

A The future investment estimates are targets set by an EU science and technology programme (10 kW gas turbines). The estimates may thus be too optimistic for energy planning purposes. It is assumed that the source has quoted unit costs only (1.0, 0.6 and 0.4 M€/MW respectively). Installation costs of 0.2-0.8 M€/MW have been added in the table.

B Calculated from from <25, <9 and < 3 ppmv, respectively, assuming these data refer to dry flue gas at 5% oxygen

| Technology | Spark ignition engine, natural gas | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 0.001 - 0.02 | | | |
| Total efficiency (%) net | | | | |
| Electricity efficiency (%) net - 100% load | < 25 | | | 2 |
| 75% load | | | | |
| 50% load | | | | |
| Cb (50$^o$C/100$^o$C) | | | | |
| Availability (%) | | | | |
| Technical lifetime (years) | | | | |
| Construction time (years) | | | | |
| **Environment** (Fuel: Natural gas) | | | | |
| NO$_X$ (kg per GJ fuel) | | | | |
| CH$_4$ (kg per GJ fuel) | | | | |
| N$_2$O (kg per GJ fuel) | | | | |
| Particles (mg per GJ fuel) | | | | |
| Ashes (kg per GJ fuel) | | | | |
| Lubricating oil (kg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) (A) | 2.9 | | | 1 |
| Total O&M (€/MWh) | 13-27 | | | 3 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
  1 "Afprøvning af mikrokraftvarmeanlæg", Elfor, Elsam, and Techwise, January 2002.
  2 Danish Gas Technology Centre (DGC), October 2003
  3 Danish Gas Technology Centre (DGC), September 2004
**Remarks:**
  A All costs; also connection costs, included

# 13  CENTRALISED BIOGAS PLANTS

2004.10.04

**Brief technology description**

Animal manure from a number of farms and organic waste from food processing and other industries are transported to a plant. The biomass is either transported by road or pumped in pipes. At the plant, the biomass is treated in an anaerobic process, which generates biogas. The biogas is converted into heat and power in a CHP plant. The CHP plant can either be located at the biogas plant, or it can be an external plant to where the gas is piped.

The biomass is received and stored in pre-storage tanks. Danish plants use continuous digestion in fully agitated digesters. This implies removing a quantity of digested biomass from the digesters and replacing it with a corresponding quantity of fresh biomass, typically several times a day. The digesters are heated to either 35 - 40 $^\circ$C (mesophilic digestion) or 50 - 55 $^\circ$C (thermophilic digestion).

This technology sheet does not include single-farm biogas digesters, biogas from wastewater treatment plants and landfill sites.

**Input**

Bio-degradable organic waste without environmentally harmful components. Typically, animal manure (80 - 90 %) and organic waste from industry (10 - 20 %). Sludge from sewage treatment plants and the organic fraction of household waste may also be used.

Rules for using animal products have been tightened by EU Directive 1774/2002 of 3 October 2002, amended by Directive 808/2003 of 12 May 2003.

**Output**

Biogas containing 60-70% methane ($CH_4$), 30-40% carbon dioxide ($CO_2$) and < 500 ppm $H_2S$ (after gas cleaning). With 65% methane, the lower heating value of the gas is 23 MJ/m$^3$.

The data presented in this technology sheet assume that the biogas is used as fuel in an engine, which produces electricity and heat. However, the gas may also be used as fuel for vehicles. The digested biomass is used as fertiliser in crop production.

In 2002 the average Danish biogas output was 41 m$^3$ per tonne biomass. The output of biogas primarily depends on the amount and quality of supplied industrial waste. For manure the gas output typically is 20 – 22 m$^3$/tonne, and for industrial waste the gas output typically is 50 – 200 m$^3$/tonne.

**Typical capacities**

Currently (2003), there are 20 centralised biogas plants in operation in Denmark. The average daily input is 50 – 600 tonnes raw material, typically delivered by 10 – 100 farms. The average daily yield is 1,000 – 25,000 Nm$^3$ biogas, which can be converted to 0.1 – 3 MW electricity. Due to economy-of-scale, the trend is towards larger plants.

**Regulation ability**

A typical plant has a gas store of approximately a half day's production. This implies, that gas can be delivered, when demand is highest within the day. A potential for further regulation can be materialised through appropriate economic incentives.

**Environment**

The biogas is a $CO_2$-neutral fuel. Also, without biogas fermentation significant amounts of the greenhouse gas methane will be emitted to the atmosphere. For biogas plants in Denmark the $CO_2$ mitigation cost has been determined to approx. 5 € per tonne $CO_2$-equivalent (ref. 5).

The anaerobic treated organic waste product is almost odour free compared to raw organic waste.

**Advantages/disadvantages**

- The $CO_2$ abatement cost is quite low, since methane emission is mitigated.
- Saved expenses in manure handling and storage; provided separation is included and externalities are monetised.
- Environmentally critical nutrients, primarily nitrogen and phosphorus, can be redistributed from overloaded farmlands to other areas.
- The fertilizer value of the digested biomass is better than the raw materials. The fertilizer value is also better known, and it is therefore easier to distribute the right amounts on the farmlands.
- Compared with other forms of waste handling, biogas digestion of solid biomass has the advantage of recycling nutrients to the farmland – in an economically and environmentally sound way.
- Biogas, a renewable energy source, can replace fossil fuels and thereby increase security of supply

**Research and development**

Lack of sufficient organic industrial wastes can become a barrier as more centralised biogas plants are established. Therefore, the main objective of the Danish biogas programme has been to improve the plants to become economically attractive either digesting only manure or by adding less attractive organic wastes with more secure supplies in the long term. The current focus of R&D activities is:
- Improved process design
- Improved process control
- Reduced operation and maintenance costs
- Utilisation of other organic products such as energy crops

Other developments include piped transport of manure, pre-treatment of biomass, post-treatment of digested biomass (separation, N-stripping, improved utilization as fertilizer etc.)

**Special remarks**

Biogas plants are primarily established for agricultural and environmental reasons, not for energy. Therefore, biogas plants are not established by energy companies, and in determining the feasibility, alternative energy solutions are rarely considered.

**References**

1. ”Økonomien i biogasfællesanlæg, Udvikling og status medio 2002”, Report no. 150, Fødevareøkonomisk Institut, Copenhagen, 2003.
2. ”Samfundsøkonomiske analyser af biogasfællesanlæg”, Report no. 136, Fødevareøkonomisk Institut, Copenhagen, 2002.
3. ”Biogas månedsstatus”, Monthly status, Danish Energy Authority, periodical.
4. “Danish Centralised Biogas Plants”, Danish Institute of Agriculture and Fisheries Economics, 1999.
5. Danish Climate Strategy, Ministry of Environment, February 2003.

## Data sheets

Data are given for three plant sizes: 300, 550, and 800 tonnes input per day.

| Technology | Centralised Biogas Plant | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Daily input of manure & organic waste in tonnes | 300 | | | 1 |
| Biogas output Nm3/m3 raw material (C) | 30 - 40 | | 28 - 35 | 7 |
| Generating capacity for one plant (MW) | 1 | | | 3 |
| Electricity efficiency (%) net - 100% load | 39.3 | | | 4 |
| Availability (%) | 98 | | | 4 |
| Technical lifetime (years) | 20 | | | 2 |
| Construction time (years) | 1 | | | 2 |
| Own electricity consumption, kWh per ton biomass | 6 | | | 1 |
| Own heat consumption, kWh per m3 of raw material | 34 | | | 5 |
| **Environment, emissions from co-generation plant** | | | | |
| $SO_2$ (g per GJ fuel) | 0.019 | | | 8 |
| $NO_X$ (kg per GJ fuel) | 0.54 | | | 8 |
| $CH_4$ (kg per GJ fuel) | 0.323 | | | 8 |
| $N_2O$ (kg per GJ fuel) | > 273 | | | 8 |
| **Financial data** | | | | |
| Total plant investment, excl. transport equipment and co-generation plant (M€) (A+B) | 5.3 | 4.8 | 4.2 | 1;7;7 |
| Total investment, co-generation plant (M€) | 0.20 | 0.20 | 0.20 | 1 |
| Specific investment, incl. co-generation plant (M€/MW) | 5.5 | 5.0 | 4.4 | |
| Total O&M (€/tonnes supplied raw material), excl. transport | 2.5 | 2.5 | 2.5 | 1;7;7 |
| Total O&M (€/MWh) | 30 | 30 | 30 | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1 Samfundsøkonomiske analyser af biogasfællesanlæg 2002. Fødevareøkonomisk Institut. Rapport 136
2 "Teknologidata for vedvarende energianlæg, Del 2, Biomasseteknologier. Danish Energy Authority, 1996.

3 Ramboll estimate based on data from Lemvig Centralised Biogas Plant (Daily input app. 500 tonnes)
4 Lemvig Biogas Plant
5 Ramboll estimates based on monthly biogas data from Danish Energy Authority
6 Varme Ståbi
7 Danish Energy Authority, September 2003.
8 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

**Remarks:**
A Transport is typically 1.6-2.4 €/tonne; average distance between farms and plant 4-8 km.
B The deceasing investment costs presume an escalated market
C The output figures are estimated avarages for Danish conditions, recognizing the limited availability of industrial wastes

| Technology | Centralised Biogas Plant | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Daily input of manure & organic waste in tonnes | **550** | | | 1 |
| Biogas output Nm3/m3 raw material (C) | 28 - 35 | | 25 - 30 | 7 |
| Generating capacity for one plant (MW) | 2 | | | 3 |
| Electricity efficiency (%) net - 100% load | 39.3 | | | 4 |
| Availability (%) | 98 | | | 4 |
| Technical lifetime (years) | 20 | | | 2 |
| Construction time (years) | 1 | | | 2 |
| Own electricity consumption, kWh per ton biomass | 5 | | | 1 |
| Own heat consumption, kWh per m3 of raw material | 34 | | | 5 |
| **Environment, emissions from co-generation plant** | | | | |
| $SO_2$ (g per GJ fuel) | 0.019 | | | 8 |
| $NO_X$ (kg per GJ fuel) | 0.54 | | | 8 |
| $CH_4$ (kg per GJ fuel) | 0.323 | | | 8 |
| $N_2O$ (kg per GJ fuel) | > 273 | | | 8 |
| **Financial data** | | | | |
| Total plant investment, excl. transport equipment and co-generation plant (M€) (A+B) | 7.5 | 6.7 | 6.0 | 1;7;7 |
| Total investment, co-generation plant (M€) | 0.33 | 0.33 | 0.33 | 1 |
| Specific investment, incl. co-generation plant (M€/MW) | 3.9 | 3.5 | 3.1 | |
| Total O&M (€/tonnes supplied raw material), excl. transport | 2.0 | 2.0 | 2.0 | 1;7;7 |
| Total O&M (€/MWh) | 25 | 25 | 25 | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Samfundsøkonomiske analyser af biogasfællesanlæg 2002. Fødevareøkonomisk Institut. Rapport 136

2 "Teknologidata for vedvarende energianlæg, Del 2, Biomasseteknologier. Danish Energy Authority, 1996.

3 Ramboll estimate based on data from Lemvig Centralised Biogas Plant (Daily input app. 500 tonnes)

4 Lemvig Biogas Plant

5 Ramboll estimates based on monthly biogas data from Danish Energy Authority

6 Varme Ståbi

7 Danish Energy Authority, September 2003.

8 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

**Remarks:**

A Transport is typically 1.6-2.4 €/tonne; average distance between farms and plant 4-8 km.

B The deceasing investment costs presume an escalated market

C The output figures are estimated avarages for Danish conditions, recognizing the limited availability of industrial wastes

| Technology | Centralised Biogas Plant | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | | | |
| Daily input of manure & organic waste in tonnes | 800 | | | 1 |
| Biogas output Nm3/m3 raw material (C) | 25 - 30 | | 24 - 28 | 2 |
| Generating capacity for one plant (MW) | 3 | | | 3 |
| Electricity efficiency (%) net - 100% load | 39.3 | | | 4 |
| Availability (%) | 98 | | | 4 |
| Technical lifetime (years) | 20 | | | 2 |
| Construction time (years) | 1 | | | 2 |
| Own electricity consumption, kWh per ton biomass | 4 | | | 1 |
| Own heat consumption, kWh per m3 of raw material | 34 | | | 5 |
| **Environment, emissions from co-generation plant** | | | | |
| $SO_2$ (g per GJ fuel) | 0.019 | | | 8 |
| $NO_X$ (kg per GJ fuel) | 0.54 | | | 8 |
| $CH_4$ (kg per GJ fuel) | 0.323 | | | 8 |
| $N_2O$ (kg per GJ fuel) | > 273 | | | 8 |
| **Financial data** | | | | |
| Total plant investment, excl. transport equipment and co-generation plant (M€) (A+B) | 9.1 | 8.2 | 7.3 | 1;7;7 |
| Total investment, co-generation plant (M€) | 0.40 | 0.40 | 0.40 | 1 |
| Specific investment, incl. co-generation plant (M€/MW) | 3.2 | 2.9 | 2.6 | |
| Total O&M (€/tonnes supplied raw material), excl. transport | 1.75 | 1.75 | 1.75 | 1;7;7 |
| Total O&M (€/MWh) | 26 | 26 | 26 | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Samfundsøkonomiske analyser af biogasfællesanlæg 2002. Fødevareøkonomisk Institut. Rapport 136
2 "Teknologidata for vedvarende energianlæg, Del 2, Biomasseteknologier. Danish Energy Authority, 1996.

3 Ramboll estimate based on data from Lemvig Centralised Biogas Plant (Daily input app. 500 tonnes)
4 Lemvig Biogas Plant
5 Ramboll estimates based on monthly biogas data from Danish Energy Authority
6 Varme Ståbi
7 Danish Energy Authority, September 2003.
8 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

**Remarks:**

A Transport is typically 1.6-2.4 €/tonne; average distance between farms and plant 4-8 km.
B The deceasing investment costs presume an escalated market
C The output figures are estimated avarages for Danish conditions, recognizing the limited availability of industrial wastes

# 20  WIND TURBINES ON LAND
2004.10.01

**Brief technology description**

The typical Danish concept is a horizontal axis wind turbine. The basic design is a three-bladed propeller-type rotor placed on the upwind side of a tubular steel tower. A yaw mechanism maintains the rotor upwind. The rotor drives a gearbox and an asynchronous generator. The rotational speed (torque) is controlled either by pitching or stalling the blades. The wind turbine can be remotely monitored and controlled.

Wind turbines on land are installed either as single turbines, in small clusters of in wind farms with a large number of turbines.

**Input**

Cut-in wind speed: 3-4 m/s.
Maximum rated output reached at 8-25 m/s depending on type and site.
Maximum operational wind speed: 25-30 m/s.

**Output**

Electrical energy

**Typical capacities**

Electricity generating wind turbines on land can be categorised according to nominal electrical power and application:

| | |
|---|---|
| Large wind turbines: | 0.6 – 4 MW |
| Household wind turbines: | 5 – 25 kW |
| Stand alone wind turbines: | 5 - 500 kW |
| Battery chargers: | 0.5 - 5 kW |

This technology sheet deals with large wind turbines only.

**Regulation ability**

Wind energy is a fluctuating energy source depending on the energy in the wind. Wind energy can participate in the regulation and balancing of the grid. Wind turbines can regulate down very fast (within seconds).

Technically, wind turbines can also give a spinning reserve with the option to increase output (depending on actual wind speed), although this may not be economically feasible. In particular if placed in farms, wind turbines may provide a variety of grid balancing services.

**Advantages/disadvantages**

Advantages:
- No emissions
- Stable and predictable costs; in particular due to no fuel costs and low operating costs
- Modular technology - capacity can be expanded according to demand. This saves systems overbuilds and avoids stranded debts.

Disadvantages:
- High initial investment costs
- Generation dependent of the wind (however, there is some correlation between electricity demand and wind energy production – day/night and winter/summer).
- Aspects of visual impact
- Noise

**Life cycle assessment**
Energy pay back time less than 3 months (ref. 1).

| kg $CO_2$-equivalent per MWh electricity | Energy quality (= content) |
|---|---|
| Operation | 4.42 |
| Construction and decommissioning | 4.84 |
| Equipment transport | 6.35 |

The main ecological footprint from wind turbines on land is hazardous waste; i.e. from steel production and powder lacquering the tower (ref. 4).

**Research and development**
R&D potential:
- Reduced investment costs by improving the design methods for up-scaling and the physical models of structural design, aero-elastic and other material properties, load and safety and interactions with the energy systems
- Increased length of blades (includes aerodynamics, strength, safety and materials)
- Reduced costs of power electronics
- Reduced operational and maintenance costs
- Tools for wind power forecasting; incl. boundary surface meteorology
- New concepts; e.g. gearless generators and hybrid systems
- Grid integration (regulation ability)

**Examples of best available technology in 2003**
The market is dominated by 0.5 - 3 MW turbines. See detailed information in. ref. 1 and 2.

**Special remarks**

**References**
1. www.windpower.org
2. www.vindmoellegodkendelse.dk
3  www.ens.dk
4. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.
5. "Strategi for dansk vindenergiforskning" (Strategy for Danish Windpower Research; in Danish), Danish Energy Authority, July 2004.

## Data for wind farms on land

| Technology | Windturbines on land | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one turbine (MW) | 1.5 | 3 | 5 | 5 |
| Rotor diameter (m) | 65 | 90 | 120 | 2 |
| Hub height (m) | 60 | 80 | 100 | 2 |
| Annual generated electricity (kWh per kW)        (A) | 2400 | 2500 | 2600 | 5 |
| Availability (%) | 98 | 98 | 98 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 2 |
| Construction time (years) | <0,5 | <0,5 | <0,5 | |
| **Environment** | | | | |
| Noise at nearest neighbour, open land (Danish legislation) | < 45 dbA | | | 7 |
| **Financial data** | | | | |
| Specific investment, total costs (M€/MW)        (B) | 0.80-0.85 | 0.62-0.75 | 0.5-0.6 | 7;4;4 |
| O&M (€/MWh)        (C) | 9 | 8 | 7 | 5+6+7 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 IEA Wind Energy Annual Report 2002
2 www.vindmoellegodkendelse.dk
3 E&M-Data, November 2001
4 International Association of Energy Economics, Newsletter, 3rd Quarter 2003
5 Danish Energy Authority, 2003.
6 Risoe National Laboratory, Denmark, 2003
7 Elsam, 2003

**Remarks:**

A For turbines situated in roughness class 1.5
B Specific investment for turbines ex works, including transport, erection and commissioning is typically 80% of total costs (ref. 7)
C Average costs for the entire lifetime. O&M costs tend to increase the first 10-15 years, whereafter the costs may decrease

# 21 WIND TURBINES, OFFSHORE

2004.09.27

More specific details on wind turbine technology are presented in technology sheet '09 Wind Turbines, On Land'.

**Brief technology description**
The typical concept is a tower with a three-bladed rotor mounted on a horizontal axis. The rotor drives a gear and generator.

To minimize specific costs, offshore wind farms are typically based on large turbines in considerable numbers.

For offshore applications the electricity is usually transformed to approx. 34 kV within each turbine. The electricity from all the turbines (or a group hereof) is then collected and cabled to a transformer station, which is either offshore or on land.

**Input**
Cut-in wind speed: 3-4 m/s.
Maximum rated output reached at 8-25 m/s depending on type and site.
Maximum operational wind speed: 25-30 m/s.

**Output**
Electricity.

**Typical capacities**
The physical limit is probably well above 20 MW, maybe above 40 MW (with current technologies). Whether the economic optimum is reached before then is yet to be seen.

**Regulation ability**
See technology sheet '09 Wind Turbines, On Land'.

**Advantages/disadvantages**
The case for offshore wind power is that the wind conditions generally are much better offshore than on land, and therefore the higher cost for offshore wind farms can be justified by a larger electricity production per installed megawatt.

The wind speeds do not increase as much with the height above sea level as they do on land. This implies that it may be economic to use lower (and thus cheaper) towers.

The wind is less turbulent at sea than over land, resulting in less mechanical fatigue.

See also 'Wind turbines, onshore' for general advantages and disadvantages of wind turbines.

**Environment**
For offshore wind turbines some disturbance to sea-life must be anticipated during the construction phase. So far only a few studies have been carried out addressing the impact during operation. The studies show, that offshore wind farms show negligible impact to sea-life, including birdlife. In fact,

some evidence suggests an increase in populations of certain species, e.g. shellfish and seals. After decommissioning the site may be fully restored to its previous state (ref. 1).

**Research and development**
Besides the R&D potential described in the technology sheet for on land wind turbines, the following challenges need be addressed:
- Monitoring and maintenance strategies
- New foundation concepts
- Foundations for water depths beyond 15 meters
- Impacts on ocean environment

**Examples of best available technology**
Recent offshore wind farms in Denmark:
- Middelgrunden; 40 MW, 2001.
- Horns Rev; 160 MW, 2002.
- Nysted (Rødsand); approx. 158 MW, 2003.
- Samsø, 23 MW (10 turbines), 2003

**Special remarks**
The investment in foundations and cables and the O&M costs per installed MW will decrease with the use of larger wind turbines. For the offshore wind farms it is however also very important that the concept of the new large wind turbines has been thoroughly tested before it is installed offshore.

The increase of cost related to grid connection and landfall are proportional with the distance to the shore up to a distance of about 50 kilometres. Hereafter the cost increases considerably.

The increase of foundation costs can be considered as fairly proportional with the water depth within water depths until 15 to 20 meters. For water depths above 20 meters an exponential increase in foundations costs can be expected (ref. 2).

**References**
1. National Environmental Research Institute, Denmark.
2. Elsam, 2003.
3. "Strategi for dansk vindenergiforskning" (Strategy for Danish Windpower Research; in Danish), Danish Energy Authority, July 2004.

## Data for offshore wind farms

| Technology | Offshore windturbines | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one turbine (MW) | 2-3 | 10 | 20 | |
| Rotor diameter (m) | 70 - 90 | 160 | 225 | 2;5;5 |
| Hub height (m) | 60 - 80 | 130 - 150 | 180 - 200 | 2;5;5 |
| Annual generated electricity (kWh per kW) | 3600 - 4200 | 4200 | | 5;1 |
| Availability (%) | 95 | 95 | 95 | 4 |
| Technical lifetime (years) | 20 | 20 | 20 | 4 |
| Construction time (years) | < 1 | < 1 | < 1 | 4 |
| **Financial data** | | | | |
| Specific investment, total costs (M€/MW) (A) | 1.5 - 1.7 | 1.0 - 1.3 | 0.8 - 1.2 | 4 |
| Fixed O&M (€/MWh) | 5 - 8 | 4 - 6 | 3 - 5 | 4+5 |
| Variable O&M (€/MWh) | 5 - 8 | 4 - 6 | 3 - 5 | 4+5 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per second) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Danish Energy Authority: "Udbudsprocedure og vilkår for havvindmøller", October 2002
2 www.vindmoellegodkendelse.dk
3 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
4 Danish Energy Authority, 2004.
5 Risoe National Laboratory, 2003.

**Remarks:**

A The costs include sub-station and cable to the shore.
Total costs for wind farms at 5-10 metres depth are typically allocated as follows (approximately): 1) Wind turbines 53 %; 2) foundations 26 %; 3) electrical infrastructure 11%; 4) Sub-station (transformer) 7%; and 5) financing costs 3 % (Ramboll, 2003).

# 22 PHOTOVOLTAIC CELLS, GRID-CONNECTED SYSTEMS
2004.10.015

**Brief technology description**

A photovoltaic cell (PV) generates electricity, when exposed to light such as solar radiation.

PV modules can be produced from many different materials (ref. 1):
1.  First generation cells are based on mono- or poly-crystalline silicon. More than 80 % of PV systems in the world are made from these types of silicon.
2.  Second generation cells are thin film made of e.g. amorphous silicon, cadmium-telluride or copper-indium-selenide (CdTe, CIS or CIGS).
3.  Third generation cells can for example be several cells stacked on top of each other, photo-electro-chemical (PEC) cells, organic cells or plastic cells.

Other types of PV cells are found, such as special cells for concentrated sunlight or for conversion of infrared radiation from a combustion process (thermo photovoltaic)

The stand-alone PV system was most common up to the mid 1990,since then the grid-connected PV system has taken over. This technology sheet deals with grid-connected systems only. The major components of such a system are PV modules, inverter, mechanic and electrical assembly equipment.

**Input:**
Solar radiation

**Output:**
Direct current (DC) electricity.
The DC electricity can be converted to alternating current electricity by using an inverter.
The electrical output depends on:
- Solar radiation
- Installed capacity; typically stated in $W_P$ (peak watt; i.e. generation capacity at peak sun; 1000 $W/m^2$ and 25 $^o$C cell temperature).
- Orientation of the PV panel; i.e. azimuth (angle relative to direction towards Equator) and pitch (angle relative to horizontal). In Denmark the optimum orientation is azimuth 180 degrees and pitch 42 degrees.
- Panel temperature (minor impact)
- Efficiency of PV-system (15-17%)

**Typical capacities**

PV systems are available from a few milliwatt and up to megawatt sizes.

PV cells are often assembled in modules of 30-80 PV cells. The module voltage is typically 15-30 volt DC; higher voltage can be obtained by connecting more modules in series or in parallel. Most common in the market are PV modules with a capacity of 5-150 $W_P$., but up to 300 $W_p$ is available The typical capacity for a solar home system in Denmark is 1 – 4 kW; equivalent to an area of 8 – 32 $m^2$ for crystalline silicon.

In Germany more than four centralised ground-based PV-systems are under construction in sizes up to 15 MW due to favourable electricity tariffs.

The world PV-module production was 512 MW in 2002, hereof 251 MW in Japan.

**Regulation ability**

PV system reflects the daylight variations. To the extend the grid peak load follows the daylight, PV systems can be – and often are, such as in California and southern Europe – used as peak shavers or as grid support at the end of feeder lines.

State of art, PV inverters only have a positive impact on power quality, as their control function is of high speed allowing them to improve local power quality.

**Advantages/disadvantages**

Advantages:

- PV uses no fuel for producing the electricity.
- There are no air or other emissions from electricity generation itself
- Electricity is produced in the daytime, when demand is highest
- PV modules have a long lifetime, 30 years or more.
- PV systems are easy to install and operate, no moving parts

Disadvantages:

- Grid-connected PV systems have high initial costs.
- The output of a PV-system is directly proportional to the solar radiation. (The contribution decrease slightly by increasing temperature)
- Relatively high area demand per kWh produced

**Life cycle assessment**

Under Danish climatic conditions, the energy payback time is 3 – 5 years (ref. 1).

| Kg $CO_2$-equivalent per MWh electricity | Mono-crystalline silicon | Poly-crystalline silicon |
|---|---|---|
| Operation | 40.9 | 40.9 |
| Construction and decommissioning | 105 | 173 |

The main ecological footprints from silicon cells stem from the energy consumed to produce the cells (ref. 2).

The environmental impacts from silicon based PV modules are very limited, as they only contain small amounts of harmful chemicals. Other PV modules containing very small amounts of cadmium and arsenic may have environmental impact at demolition, if not carefully treated. Recycling of PV-modules is well known, although the processes are still being developed and refined, and the typical main components such as PV cells, glass and aluminium can safely be recycled.

**Research and development**

R&D is primarily conducted in countries, which have already implemented PV technologies in large volumes, such as Japan, USA and Germany.

The research priorities in Denmark are (Ref. 4):

- silicon feedstock for high-efficiency cells

- new PV cells like photo-electro-chemical and polymer cells
- inverters; increased technical lifetime and lower costs
- system technology, incl. accommodation within the overall electricity system
- building integration of PV modules
- design and aesthetics

**Special remarks**

The global market has expanded approximately 30 % per annum the latest years, while prices have decreased approximately 4% per year (ref. 1).

The total installed capacity of PV systems in Denmark was 1.9 MW by the end of year 2003, equal 0.35 W/inhabitant.

The development of PV technologies in Denmark comes partly from development and demonstration projects like Sol 300 and Sol 1000, and partly from dedicated R&D programmes.

New countries as China and India have a very fast growing PV industry and will be among the Top 5 PV-producers in 2005.

IEA (ref 3) expects that the cost of PV-generated electricity will decrease from 14.5 – 16 Eurocents/kWh in 2004 to 8-12 Eurocents/kWh in 2010, and that it will be comparable with common grid electricity in 2015.

The EU vision for year 2030 is (ref. 3):
- 200 GW PV-systems are implemented in EU
- The PV-generation cost will be around 5 Eurocent per kWh.
- Export of PV-systems to more than 100 millions families in poor countries

**References**

1. "Statusnotat om solcelleteknologi", Danish Energy Authority, Elkraft System and Eltra, 2003.
2. "Life cycle assessment of Danish electricity and cogeneration", Main report October 2000 and update November 2003 (both in Danish), prepared by Danish electricity utilities. The update is based on 2001 data.
3. Renewables for power generation, Status & Prospects, IEA 2003
4. "Solceller - Oplæg til en national strategi for forskning, udvikling og demonstration. 2. udkast" Danish Energy Authority, Elkraft System and Eltra, 2004

**Data sheet:**

| Technology | Photovoltaic cells, grid connected | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generation capacity for one plant, peak (kW) | 2.1 | | | 1 |
| Module efficiency (%) | | | | |
|   Mono-crystalline | 15-17 | 20-22 | 22-25 | 5 |
|   Poly-crystalline | 12-13 | 13-15 | 15-17 | 5 |
|   Thin film | 7-11 | 11-13 | 13-15 | 5 |
|   Third generation (PEC, polymer cells) | 3-5 | 5-7 | 7-9 | 5 |
| Inverter efficiency (%) | 96 | 97 | 98 | 2;5;5 |
| System efficiency (%) | 90% of module efficiency | | | 5 |
| Net electricity generation (in Denmark) | | | | |
|   per installed m2 (kWh/m2/year) | 80-90 | | | 1 |
|   per installed kW (kWh/kW)     (B) | 800-900 | | | 1 |
| Availability (%) | | | | |
| Technical lifetime (years)     (C) | > 25 | > 30 | > 30 | 2;5;5 |
| Inverter lifetime | 10 | | | 2 |
| Construction time (years) | 0.01 | | | |
| **Financial data** | | | | |
| Specific investment, PV modules (M€/MW) | 3.87 | | | 4 |
| Specific investment, total system (M€/MW)   (D) | 4.9 | 2.5 - 3.0 | 1.3 - 2.1 | 3;6;6 |
| Total O&M (% of investment per year) | ~1% | ~1% | ~1% | 7 |
| Total O&M (€/MW/year) | 50000 | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | - | | | |
| Regulation speed (MW per sec.) | - | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Sol 300 http://www.sol300.dk/
2 European Commission's Energy Technology Indicators
3 Sol 1000 http://www.sol1000.dk
4 IEA Renewables for Power Generation, 2003
5 Danish Energy Authority, personal communication, September 2003
6 International Association of Energy Economics, Newsletter, 3rd Quarter 2003
7 EnergiMidt (Flemming Kristensen), personal communication, September 2003

**Remarks:**

A Annual insolation in Denmark: 1000 kWh/m2
B In Southern Europe this would be 1800 kWh/kW (ref. 6)
C For crystalline modules
D The 2004 cost is with crystalline cells; the soruce for future costs does not specify cell technology

# 23 WAVE POWER CONVERTERS
Draft 2004.10.07

**Brief technology description**
There is no commercially leading technology on wave power conversion at the present time. However a few different systems are presently at a stage of being developed at sea for prototype testing or developed at a more fundamental level including tank testing, design studies and optimisation.

A wave power converter comprises a structure interacting with the incoming waves. The wave power is converted by a Power Take-off (PTO) system based on hydraulic, mechanical or pneumatic principles driving a rotating electrical generator producing electricity or by a linear generator directly driven by the structure.

The structure is kept on a fixed mean position by a mooring system or placed directly at the seabed/ seashore. The power is transmitted to the seabed by a flexible submerged electrical cable and to shore by a sub-sea cable. (Some systems are bottom-mounted, e.g. near-shore Oscillating Water Column systems)

**Input**
Ocean Waves: The Wave conditions are described in a "scatter diagram" related to the site where the wave power plant is going to operate. The scatter diagram contains statistical information on how many hours per year a given sea state (in terms of significant wave height Hs and wave period Tz) will fall between certain intervals or "bins". (Ref. 1 and 2)

There is not enough operational data to conclude when a wave energy converter will cut in or at what condition it will cut out. A likely order of magnitude is indicated below.

The wave power converter cut in condition is when Hs is about 0.5 meter.
The maximum rated output will be reached at significant wave heights about 5 meters.
The survival conditions at Hs = 10 - 12 meters (depending on the selected site).

**Output**
Electricity (Some systems are designed to pump water and produce potable water)

**Typical capacities**
The potential capacities depend on the wave heights.

The electrical output from wave power converters in some cases are generated by electrical connected groups of smaller generator units of 100 – 500 kW, in other cases several mechanical or hydraulically interconnected modules supply a single larger turbine-generator unit of 2 – 20 MW.

**Regulation ability**
The ability to regulate the system operation depends on the design of the PTO system. In general the systems are developed with the aim of regulating the system to absorb most of the incoming waves at a given time, but also to enable disconnection of the system from the grid if required for safety or other reasons. But, like wind energy, the wave energy technology cannot help stabilizing the electrical grid. However, wave power is more predictable compared to wind power and the

waves will continue to exist some time after the wind stops blowing – this could help increase the value of both wind and wave power.

**Advantages/disadvantages**
Advantage: Wave Power Converters produces power without the use of fossil fuels. The power plants are located in the Ocean without much visual intrusion. Wave power is a predictable resource compared to wind.

Disadvantages: The initial prototype development at sea is costly and the successful development to reach costs comparable with i.e. off shore wind will require dedicated development programmes and substituted electricity prices until the technology has matured. The big waves are mostly found at great distances from the shore why costly sub-sea cables are needed to transmit the power to shore. Wave Power Converters, albeit at sea, take up large amounts of space.

**Environmental aspects**
As for wind-energy a positive life cycle impact is expected. Planned in cooperation with navigation, oil exploitation, wind farms and fishing industry wave power plants are expected to have a positive impact on the living conditions for fish in the sea, by providing sheltered areas. Furthermore, in some cases benefits from reduced coastal erosion could be expected, as the wave heights will be smaller after passing the wave power plants.

**Research and development**
In Denmark the "Wave Energy Programme 1997 – 2001" generated a coordinated Danish research and development effort on Wave Energy Systems [1]. Since this programme stopped the development in Denmark has slowed down. However in the same period the UK is coming up to speed with focused R&D programmes on the development of Marine Energy.

A number of wave energy projects are being developed and evaluated in the UK under the Carbon trust MEC Marine Energy Challenge programme. Some of the wave power technologies included are:

- The Pelamis system developed by Ocean Power Delivery, OPD, UK
- The Wave Dragon developed by Wave Dragon Aps Denmark
- The AquaBuOY, Aqua Energy, UK,
- The Wave Rotor, Eric Rossen, Denmark
- SeaVolt, SeaVolt technologies USA
- PS Frog, Lancaster University, UK
- Wave Bob, Clear Power Technology, Ireland

International cooperation on Ocean energy has started with the International Enegy Agency implementing agreement on Wave and Tidal energy projects. Two annexes to the agreement have been produced, one on the state of the art and one on guidelines for testing and presentation of results. www.iea-oceans.org

European cooperation "Wavenet" has been supported by the European Commission and this cooperation will expand under the Co-ordinated Action on Ocean Energy. www.wave-energy.net

Results emerging from the new prototypes deployed at sea and ongoing research in terms of cost and performance will be gathered and analysed as part of the Co-ordinated Action on Ocean Energy (October 2004 - 2007) and reviewed as part of the IEA cooperation on Ocean Energy.

**Examples of best available technology**
It is too early to define best available technology, but a few different systems are at the moment being tested in large prototype scale at sea.

- The Pelamis, 750 kW , Ocean Power Delivery, www.oceanpd.com
- AWS, 2MW, Teamwork Technology, www.waveswing.com
- OWC, 500 kW , Wavegen www.wavegen.com

Other newly started wave power companies like Ocean Power Tecknology (OPT) has received large private investments and are currently planning wave power plants at different locations in the world, however very little information is available on the principal of this technologies.

**References**
1 Bølgekraft program, Afsluttende rapport fra Energistyrelsens Rådgivende Bølgekraftudvalg, August 2002.
2. IEA-OES reports:
Annex I Wave and Marine Current Energy, Status and Research and development priorities
Annex II Development of recommended practices for testing and evaluating ocean energy systems.

# Data sheet

| | Wave Power | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one power plant (MW) | 0,75 -2 | 1,0 - 10 | 2,0 - 50 | 1,2,2 |
| Length of installation of one power plant km | 0.15 | 0,2 - 1 | 0,2 - 5,0 | 1,2,2 |
| Annual generated electricity production [MWh per MW] | 3500 | 4000 | 4800 | 1,2,2 |
| Availlability | - | 96 | 90 | 2 |
| Technical lifetime (years) | > 10 | >15 | >20 | estimate |
| Construction time | <1 YEAR | <1 YEAR | <1 YEAR | |
| | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 2.5-4 | 1.9-2.2 | 1.7-2.0 | 1,2,2 |
| | | | | |
| O&M (€/MWh) | - | 12 | 6 | 2 |

**References:**

1 E21 EPRI Assessment, Offshore Wave Energy Conversion Devices, June 16, 2004
2 Wave Net final report, Project no. ERK5 – CT –1999-20001 (2000 - 2003)

**Remarks:**

A The estimated cost of wave power for the future is based on information in reference [1]. The cost presented provides an estimate for what capital cost and operating costs of wave power converters might be in the future assuming all R&D challenges have been overcome, that economics of scale have been realized and that efficiencies in production and operation due to the learning curve effect have been achieved.
The present cost of the first large scale Wave Power systems is high and reflect that these first prototype devices are the first step on the road towards establishing a new and unproven technology.

B The specific investmen for the tecnology year 2004 is excluding the cost of installation, mooring and power transmission

C The difference in availability in the medium to long term is due to their difference in location being near-shore and off-shore respectably

# 30 SOLID OXIDE FUEL CELLS

2004.10.15.

**Brief technology description**

In a Solid Oxide Fuel Cell (SOFC) an electrochemical conversion of hydrogen or other combustible compounds into electricity and heat takes place. The development of SOFC has so far gone in the direction of a tubular design (SiemensWestinghouse; Mitsubishi) and a planar. In Denmark focus has been on the planar design, as the production cost is lower. In the long run it is expected that the tubular design will be abandoned.

The SOFC is a high-temperature fuel cell (600-1000°C) and the exhaust gas can be used to drive gas or steam turbines in combined cycle mode. Electricity efficiency of a SOFC-plant in the range 1-200 kW can be approximately 60%[2], when fuelled with natural gas at atmospheric pressure. The systems may achieve overall efficiencies up to 88 % (Ref. 7). Some vendors expect electrical efficiencies of 70-75 % when combining with gas turbines.

SOFCs are expected to become commercially viable within 10-15 years[3].

**Input**

Hydrogen.

Natural gas, methane, or methanol can be used as fuel. Carbon containing fuels tend to provide a slightly superior performance because the overall reaction is less exothermic, and the parasitic losses in connection with stack cooling are reduced. In case natural gas with significant amounts of hydrocarbons heavier than methane is used as feed, a light pre-reforming is needed. This ability to handle unreformed methane is only found in high temperature fuel cells like SOFC.

Gas from gasification of for instance biomass can also be used as fuel.

**Output**

Electricity (DC) and heat.
If AC is needed, a DC/AC inverter is required.

**Typical capacities**

The capacities can range from kW to MW. For domestic heat and power typical capacities could be 1 to 5 kW and for power stations it would be MW sizes.

**Regulation ability**

SOFC's have a potentially very high load change speed for minutes reserve and regulation reserve in the seconds range is also potentially possible through fast load adaptation. It is expected, that SOFC fuel cells will have good part load capabilities between 100 - 20 % load.

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[2] ESTO report expects 45-47% electrical efficiency and 80-85% overall efficiency of a similar system (ref. 2). Also other sources of information predicts electricity efficiencies around 50 % or higher for natural gas fuelled SOFC-systems (Ref. 4,7,8)

[3] Risø and Haldor Topsøe however expect SOFCs to be commercial around 2010 (Ref. 1 and 7). Siemens Westinghouse is aiming to offer commercial plants of 250-1000 kW already in 2004. They will be comprised of cell stacks of the tubular type combined with a gas turbine and with an electrical efficiency of 60-70% (Ref. 5 and 6).

To guarantee optimal running high temperature fuel cells need to be constantly maintained at working temperature, requiring sufficient insulation or additional energy during the idle running phases.

**Advantages/disadvantages**
One advantage is high electrical efficiency also at reduced load. Together with the ability for fast load changes, this can be beneficial for a liberalised and volatile energy market, since the need for regulation of decentralised power plants may increase. Furthermore, the total waste heat is made available in a flexible way at high temperatures. This means that the waste heat can be utilised in combined cycle plants, not just for district heating. In other words, the exergy efficiency is high compared to low temperature fuel cells.

A disadvantage is the long start up time needed to heat up the fuel cell from cold-state (10-20 hours).

**Environment**
Due to fuel pre-treatment, higher efficiencies, lower flame temperatures as well as other features, fuel cells are expected to be less polluting per kWh electricity than conventional technologies. The systems will be equipped with an afterburner with an oxidation catalyst, removing all hydrocarbons and reducing CO to a very low value. There will be no emission of sulphur containing compounds and soot. $NO_x$ levels will be very modest as well

If a fossil fuel is used as fuel for a SOFC system, $CO_2$ will be emitted.

**Research and development**
In Denmark a document describing the Overall Strategy for Development of Fuel Cell Technology was recently issued by Eltra, Elkraft System and the Danish Energy Authority (Ref. 4). Among other conclusions it states that fuel cell systems have potential interest for society based on environmental-, economical-, energy-, and system considerations. However, a considerable R&D effort is needed primarily to reduce costs of fuel cells, stacks, and systems, and to ensure high efficiency and long durability.

There is focus on development of cells and cell-stacks for different purposes. Currently work is progressing on two types of SOFCs:
- Anode supported cells optimized for operation at 700-800°C (2nd generation)
- Metal-supported cells optimized for operation at approximately 600°C (3rd generation)

In the Sixth Framework Programme of EU (Ref. 9) fuel cells are included in the Research activities having an impact in the medium and the longer term. For high temperature stationary fuel cell systems the program describes that the main targets are to provide future commercial systems with a cost less than 1000 EURO/kW and a stack durability of more than 40000 hours.

**Examples of best available technology**
- During 2004 Risø and Topsøe in collaboration have demonstrated stack durability in excess of 10,000 hours with very low performance degradation. A 5 kW$_e$ stack will be demonstrated around the end of year 2004 (Ref. 12)
- In 1997 Dutch energy providers and Elsam participated in establishment of a pilot power plant of 100 kW (el) in Westervoort (NL). Siemens Westinghouse delivered the original cell

stack and a replacement in 1999, both based on tubular cells. The measured electric efficiency of the latest cell stack amounts to 46% (Ref. 5). In 2001 a test of over 10.000 hours was completed. The plant has since been moved from Holland where the test was performed to Germany, where the operation continues.

- By the end of 2003, 20-40 1 kWel units have been installed in Germany. They have the possibility of a higher heat production due to an extra burner installed. The plants will demonstrate the SOFC technology (micro CHP) (Ref. 11)

Haldor Topsøe has also entered into cooperation with the Finnish company Wärtsilä with the goal of developing SOFC power generators for marine purposes and CHP with capacities of over 200 kW. The plants will primarily run on natural gas. (Ref. 3)

**Special remarks**
As fuel cells is a new technology which is not yet fully developed it is difficult to get reliable estimates for the future. The technology is not sold on the open market and prices are not readily available. The table below however attempts to present rough estimates, which there is some consensus about in the fuel cell community. It is assessed that the financial data can be used as conservative estimates for SOFC run on hydrogen, excluding costs for reforming etc. Furthermore, several references to the financial data are not specific with the fuel used for the SOFC.

Up to now there is no international norm on how to define the efficiency of a fuel cell. This should be taken into account when comparing efficiencies from different references.

**References**
1: Risø Energy Report 1. New and emerging technologies – options for the future. Edited by Hans Larsen and Leif Sønderberg Petersen. Risø National Laboratory. October 2002
2: Fuel Cells – Impact and consequences of fuel cells technology on sustainable development. t. Fleischer and D. Oertel. An ESTO Project Report prepared for Prospective Technology Studies Joint Research Centre by Institut für Technikfolgenabschätzung und Systemanalyse (ITAS). March 2003
3: Teknologisk Fremsyn. Fremtidens Energi. Hovedrapport. Ingeniørforeningen i Danmark. February 2003.
4: Overordnet strategi for udvikling af brændselscelle teknologi i Danmark. Eltra, Danish Energy Authority og ElkraftSystem, July 2003.
5: https://www.elsam.com/fogu/produktionsteknologier-udv.htm
6: http://www.siemenswestinghouse.com/en/fuelcells/fieldunit/index.cfm
7: Solid Oxide Fuel Cells - Assessment of Technology from an Industrial Perspective. Pålsson et. al. Haldor Topsøe A/S Lyngby, Denmark. May 2003
8. Fuel Cell Report to Congress, Department of Energy, United States, February 2003
9. Sixth Framework Programme, EU Commission, 6.1 Sustainable energy systems, work programme
10. Eltra, 2003
11. Yearly report EnBW. Sulzer Hexis plant
12. Haldor Topsøe A/S, September 2004

# Data sheet

| Technology | Solid Oxide Fuel Cell (SOFC) Example: CHP, single cycle, fuelled by natural gas at atmospheric pressure | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 0.1-0.2 | 1-5 | > 5 | 1; 4 |
| Total efficiency (%) net | 80-85 | 88 | | 1; 4 |
| Electricity efficiency (%) net - 100% load | 50 (A) | 60 (B) | 60 | 5 |
| Working temperature (oC) | 700-1000 | 700 | 600 | 3; 4; 5 |
| Maximum time for cold start-up (hours) | 10 to 20 | | | 1 |
| Technical lifetime (hrs)                (C+D) | 1000-2000 | 40000 | > 40000 | 7; 1; 5 |
| Construction time (years)               (H) | 1 | 1 | 1 | 9; 9; 6 |
| **Environment** (fuel: natural gas) | | | | |
| SO$_2$ (mg per kWh) | nil | | | 8 |
| NO$_X$ (kg per GJ fuel)                  (I) | 0.0001 | | | 8 |
| CH$_4$ (mg per kWh) | nil | | | 8 |
| N$_2$O (kg per GJ fuel) | | | | |
| CO (mg per kWh) | negligible | | | 8 |
| NMVOC (mg per kWh) | nil | | | 8 |
| Particles (mg per GJ fuel) | nil | | | 8 |
| **Financial data (E)** | | | | |
| Specific investment targets (M€/MWel) | | 1 (F) | 0.4 (G) | 4; 2 |
| Total O&M (€/MW/year) | | 50-70000 | 20-28000 | 9 |

**References:**

1  Fuel Cells – Impact and consequences of fuel cells technology on sustainable development. t. Fleischer and D. Oertel. An ESTO Project Report prepared for Prospective Technology Studies Joint Research Centre by Institut für Technikfolgenabschätzung und Systemanalyse (ITAS). March 2003

2  Risø Energy Report 1. New and emerging technologies – options for the future. Edited by Hans Larsen and Leif Sønderberg Petersen. Risø National Laboratory. October 2002

3  Status for energiteknologier og forskningsbehov – Notat til REFU møde 31. maj 2001. Energistyrelsen.

4  Solid Oxide Fuel Cells - Assessment of Technology from an Industrial Perspective. Pålsson et. Al. Haldor Topsøe A/S Lyngby, Denmark. May 2003

5  Overordnet strategi for udvikling af brændselscelle teknologi i Danmark. Eltra, Danish Energy Authority and Elkraft System, July 2003

6  Fritz Luxhøi, Eltra 30/9 2003

7  Niels Træholt Franck, Elkraft System 25/9 2003

8  Haldor Topsøe and Risø, October 2003.

9  Haldor Topsøe A/S, September 2004. Haldor Topsøe A/S estimates O&M costs to be around 5-7% of initial investments

10  "Recent Advances in Solid Oxide Fuel Cell Technology" Nguyen Minh, American Ceramic Society PCRM Seattle, WA, October 1-4, 2002 (http://www.ceramicbulletin.org/months/July03/minh.pdf)

11  "Fuel Cell Report to Congress" Department of Energy, USA, February 2003

**Remarks:**

A)  Ectos report expects 45-47% electrical efficiency for a single cycle SOFC of 100-200 kW and 60%  for a SOFC - Gas turbine plant with compression above 250 kW (Ref. 1 Table 17)

B)  Haldor Topsøe expects 56% electrical efficiency for 250 kW plant (Ref. 4). Ectos report expects 47% for 100-500 kW, 57% for 3-10 MW and 65% for 20-200 MW. Total efficiencies expected are 80%. (Ref.

C)  RISØ currently has 1000-2000 hrs of operation with their SOFCs (Ref. 7). Ectos report expects >13000 hours of operation (Ref. 1 Table 17)

D)  The stated lifetimes are for the stacks only. System durability will be longer, as stacks will be replaced at regular intervals.

E)  Currency conversion 1USD=1EURO

F)  Haldor Topsøe finds that a goal of 1000 USD/kW is within reach and aims at commercial products at the end of this decade (Ref. 4+9). Ectos report expects investment costs of 1300 €/kWel for SOFC-GT of more than 250 kW el. No data is available for SOFC in the 1-200 kW range (Ref. 1 Table 19). Investment costs of 1035-1550 €/kWel is expected by 2006 in EU R&D Strategy plan (Ref. 3). In the EU strategy paper from 1998 the target for 2005 was set to 1000-1500 €/kWel.

G)  Cost estimated by Siemens-Westinghouse once high-volume production has been reached (Ref. 2). Cost goal for SOFC system in USA (Ref. 11) Haldor Topsøe A/S assesses that the estimates of future specific investments are correct or maybe even too high (Ref. 9) Nguyen Minh from American Ceramic Society estimates an SOFC system cost when fully developed of 388 $/kW. (Ref. 10)

H)  Small units may be delivered on request

I)  Calculated from from 0,2 ppm assuming this value refers to dry flue gas at 3% oxygen

# 31 PROTON EXCHANGE MEMBRANE FUEL CELLS
2004.09.14


**Brief technology description**

In a Proton Exchange – or Polymer Electrolyte - Membrane Fuel Cell (PEMFC) an electrochemical conversion of hydrogen into electricity and heat takes place. It is a relatively low temperature fuel cell, which can change load very fast. It consists of a thin polymer membrane, which allows penetration of hydrogen ions.

In Denmark, two types are being developed:
- Low temperature, water cooled; by IRD Fuel Cells A/S
- High temperature, oil cooled; by Technical University of Denmark

Low temperature PEMFCs operate around 80°C and are sensitive to carbon monoxide in the fuel gas. High temperature PEMFCs operate up till 200°C, and at that temperature the cells can work with several percentages of carbon monoxide in the fuel gas. PEMFCs working at 150-200°C can be run with hydrogen from the reformer/shift unit, which is not purified. Efficiency of the high temperature PEMFCs is not yet on the level of the best low temperature PEMFCs, but the potential is there (ref. 3).

PEMFC is the fuel cell technology, which is most developed so far, and it is currently available on the market up to 250 kW.

**Input**

Hydrogen

If another hydrogen carrying agent such as methane is used, it needs to be reformed into hydrogen in an external reformer.

**Output**

Electricity (DC) and heat.
If AC is needed, a DC/AC inverter is required.

**Typical capacities**

The typical capacities can range from 1 to 200 kW and are expected to reach up to 20 MW by 2030. A total installed generating capacity of around 1-5 MW is expected in Denmark by 2010-15 and 5-100 MW by 2020-30. (Ref. 6)

**Regulation ability**

Very short start up time and fast regulation of load.

**Advantages/disadvantages**

PEMFC has a short start up period due to the low operating temperature. PEMFC can be used for transportation purposes and large car companies all over the world are undertaking research to develop the technology. There is a possible synergy effect, when using the PEMFC for stationary production of power and heat (ref. 1).

Low temperature PEMFC only operates on very clean hydrogen (the content of CO must be below 10-20 ppm) (ref. 2).

**Environment**

Primarily due to the higher efficiencies, fuel cells are expected to be less polluting per kWh than conventional technologies (except for NMVOC – non-methane volatile organic compounds). Also, fuel cell systems might be developed as CHP-plants in small scale (micro - for individual homes) with relatively high efficiencies. That may enlarge the market and application of micro scale CHP and thus increase the overall efficiency of the electricity and heat systems.

However, if a fossil fuel is reformed to hydrogen, the emissions from reforming must be taken into account. Emission of a greenhouse gas as $CO_2$ will per energy unit of fossil fuel used be the same from a fuel cell system as that of a conventional technology, but if storage of $CO_2$ will be an option, extraction of $CO_2$ from a fuel cell system is expected to be advantageous compared to conventional technology. It implies , that a comprehensive infrastructure system is constructed to handle the $CO_2$.

**Research and development**

In Denmark an Overall Strategy for Development of Fuel Cell Technology was recently issued by Eltra, Elkraft System and the Danish Energy Authority (Ref. 3). Among other conclusions it states that fuel cell systems have potential of interest for society on the grounds of environmental-, economical-, energy-, and system considerations. However, a considerable R&D effort is needed primarily to reduce costs of fuel cells, stacks, and systems, and to ensure high efficiency and long durability.

More detailed targets for R&D are presented in Ref. 1 and Ref. 3.

In the Sixth Framework Programme of EU (Ref. 4) fuel cells are included in the Research activities having an impact in the medium and the longer term. For PEM stationary fuel cell systems the programme describes that the main targets are to provide future commercial stationary systems with a cost less than 100 EURO/kW and a durability of more than 30,000 hours. A specific investment of 100 EURO/kW seems optimistic compared to other expectations.

**Examples of best available technology**
- IRD A/S has entered into contract with a German company regarding supply of 2 kW for use in small CHP systems, with the aircraft industry for delivering of auxiliary systems, and with industries delivering UPS (uninterrupted power supply) systems (ref. 7).
- Numerous prototypes of 3 kW (el) and 200 kW (el) exist (ref. 1 and 5).

The Canadian company, Ballard Power Systems, is one of the main players in the international PEMFC market. They are involved in the following projects:
- Tokyo Gas has a pilot project where 100 PEMFC 3-5 kW (el) plants have been installed in households in Japan.
- The industrial-use version of the AirGen™ fuel cell generator is now being marketed and sold. It is a 1kW portable generator, which works as power backup
- Ballard furthermore began field trials of a 250 kW PEM fuel cell stationary power generator in 1999 in Indiana, USA. Since then, seven more units have been sited in Japan, Switzerland and Belgium.

- Ballard currently supplies fuel cell engines and systems to automotive manufacturers who have fleet demonstration vehicles on the road.

**Special remarks**

Denmark is one of the few places in the world, where PEMFC in the kW-size for stationary purposes can be bought as other stakeholders focus on the use of PEMFC for transport purposes. (Ref. 2)

As fuel cells is a new technology which is not yet fully developed it is difficult to get reliable estimates for the future. Furthermore the technology is not being sold on the open market and prices are not readily available. The table below however attempts to present rough estimates, which there is some consensus about in the fuel cell community.

Up to now there is no international norm on how to define the efficiency of a fuel cell. This should be taken into account when comparing efficiencies from different references.

**References**

1. Fuel Cells – Impact and consequences of fuel cells technology on sustainable development. t. Fleischer and D. Oertel. An ESTO Project Report prepared for Prospective Technology Studies Joint Research Centre by Institut für Technikfolgenabschätzung und Systemanalyse (ITAS). March 2003
2. Teknologisk Fremsyn. Fremtidens Energi. Hovedrapport. Ingeniørforeningen i Danmark. February 2003.
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4. Sixth Framework Programme, EU Commission, 6.1 Sustainable energy systems, work programme
5. Annual report for Innovation 2002 EnBW.
6. Fritz Luxhøi, Eltra.
7. IRD A/S, November 2003.

## Data sheet

| Technology | Proton Exhange Membrane Fuel Cell (PEMFC) CHP, fuelled by natural gas | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | up to 0.25 | 1 | 20 | 1;4;4 |
| Total efficiency (%) net | 80 | | | 1 |
| Electricity efficiency (%) net - 100% load   (A) | 31-39 | | | 1 |
| 50% load | | | | |
| Working temperature (oC) | 60-80 | <200 | | 1;5 |
| Technical lifetime (hrs)                    (B) | >5000 | 30000 | 40000 | 6;3;1 |
| Construction time (years) | | | | |
| **Environment** (fuel: natural gas)         (C) | | | | |
| $CO_2$ (g per MJ fuel) | 55.3 | | | 1 |
| $SO_2$ (mg per MJ fuel) | 0.0 | | | 1 |
| $NO_X$ (mg per MJ fuel) | 1.2 | | | 1 |
| $CH_4$ (mg per MJ fuel) | 8.3 | | | 1 |
| $N_2O$ (kg per GJ fuel) | | | | 1 |
| CO (mg per MJ fuel) | 2.7 | | | |
| NMVOC (mg per MJ fuel) | 0.3 | | | 1 |
| Particles (mg per MJ fuel) | 0 | | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 10 | 0.9-2.3 (D) | 0.4 (E) | 7;2;9 |
| Total O&M (€/MWh el) | 50 | 5 | 0.5 | 8;1;8 |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |

**References:**

1 Fuel Cells – Impact and consequences of fuel cells technology on sustainable development. t. Fleischer and D. Oertel. An ESTO Project Report prepared for Prospective Technology Studies Joint Research Centre by Institut für Technikfolgenabschätzung und Systemanalyse (ITAS). March 2003

2 Status for energiteknologier og forskningsbehov – Notat til REFU møde 31. maj 2001.

3 Sixth Framework Programme, EU Commission, 6.1 Sustainable energy systems, work programme

4 Eltra 2003

5 Overordnet strategi for udvikling af brændselscelle teknologi i Danmark. Eltra, Danish Energy Authority and Elkraft System, July 2003

6 Elkraft System, September 2003

7 IRD, 2003

8 IRD, 2004

9 "Towards a European Hydrogen Energy Roadmap" Preface to HyWays – the European Hydrogen Energy Roadmap Integrated Project, Executive Report, HyNet, 12/05/2004

10 "Fuel Cell Report to Congress" Department of Energy, USA, February 2003

**Remarks:**

A 38-42% in Ref. 1 table 22. 40-55% with hydrogen as direct fuel in Ref. 2

B IRD Fuel Cells currently guarantees a minimum of 5000 hours of operation. (ref. 6)

C Generic fuel cell data (ref. 1)

D Expected investments for natural gas powered PEMFC systems with 2.0-3.5 kW el, approx. 2500 USD/kW el (Ref. 1). Investment cost expected by 2006 in EU R&D Strategy plan is 1035 €/kWel (Ref. 3). In the EU strategy paper from 1998 the target for 2005 was set to 1000 €/kWel. Targets are the only price estimates available for the future.

E Key development issues for stationary fuel cells are lifetime (at least > 40.000 hrs), cost (< 500€/kWel) and reliability (> 98%) and these remain significant challenges for the sector. (Ref. 9) From this a price of 400€/kWel is estimated. IRD Fuel Cells has 100€/kWel as their cost target for the future. (IRD, Sept. 2004). This is in line with the EU targets. PEM fuel cell system cost targets for automobiles is down at $45/kW in 2010 and $30/kW in 2015 in USA. (Ref. 10)

# 40 PUMPED HYDRO STORAGE (PHS)
## – IN CONNECTION WITH EXISTING HYDRO PLANT
2004.10.14

**Brief technology description**

Pumped hydro storage (PHS) is used for large-scale energy storage, and is with over 90 GW installed in the World the most common large-scale energy storage system in use. The concept of PHS is to have two water reservoirs in two different vertical locations. At off-peak periods (night) is water pumped from the lower reservoir to the higher reservoir, ready to flow back down, passing through hydraulic turbines to generate power when needed.

A new PHS, including dams, has high capital expenditures and a long construction time. If an existing hydro plant is extended to also be a PHS, the investments per installed MW is significantly lower and the construction time between 2 and 3 years.

**Input**
Electricity

**Output**
Electricity

**Typical capacities**
PHS facilities are dependent on local geography and currently have capacities up to 1,000 MW. In addition to large variations in capacities PHS are also very divers regarding characteristics such as the discharge time, which is ranging from several hours to a few days. Efficiency typically is in the range of 70% to 85%, due to the losses in the process of pumping water up into the reservoirs.

**Regulation ability**
PHS is very suitable for regulation needs.

**Advantages/disadvantages**
A disadvantage with PHS is the need for differences in height between the two reservoirs. When a new PHS is not built in connection with an existing hydro plants there are also environmental concerns in flooding large areas.

The advantage of PHS is the large volumes compared to other storages e.g. various batteries. In addition PHS does not use fossil fuel such as e.g. CAES.

**Life cycle assessment**


**Research and development**
In the 1890's PHS was first used in Italy and Switzerland. After over 100 years of development PHS is considered to be a mature technology. New developments include seawater pumped hydro storage that was built in Japan in 1999 (Yanbaru, 30 MW). It is also technically possible to have a pumped underground storage by using flooded mine shafts or other cavities.

**Examples of best available technology**

Examples of new or planned HPS in the Scandinavian countries include:

- Nygard Pumpekraftverk, Modalen. It is owned by BKK (the fifth largest power producer in Norway) and is expected to be finished December 2004 with a capacity of 56MW.
- Tonstad Pumpekraftverk. It is planned to be developed by Sira-Kvina (which has seven hydro power plants and produces around 5% of Norwegian electricity) and is expected to have a capacity of 1000MW.

**Special remarks**

There are frequently several hydro power plants on the same river, and the operation of these plants is to some degree interlinked. The benefits of a new PHS therefore depend also on the existing hydropower infrastructure.

**References**

1. ESA, Electricity Storage Association, www.electricitystorage.org
2. Energy Storage Council (ESC) White Paper on Energy Storage: The Missing Link in the Electricity Value Chain, May, 2002.
3. U.S. Department of Energy, Energy Efficiency and Renewable Energy: Renewable energy Technology Characterizations, December 1997
4. Tonstad Pumpekraftverk, Sira-Kvina kraftselskap, 2002
5. Nygard Pumpekraftverk, Modalen, www.mika.no
6. BKK (Norway), presentation on Nygard Pumpekraftverk

**Data sheets**

In the Scandinavian countries will new PHS most likely be built in connection with present hydro power plants. The investments costs in the data sheets therefore assume that the PHS is built in connection to an existing hydro infrastructure.

| Technology | New pumped hydro storage | | | |
| --- | --- | --- | --- | --- |
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 10-1000 | 10-1000 | 10-1000 | 1; 2 |
| Total efficiency (%) net | 80% | 80% | 80% | 1 |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 50 | 50 | 50 | 1 |
| Construction time (years) | 2-3 | 2-3 | 2-3 | |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.5 | 0.5 | 0.5 | 1; 2 |
| Fixed O&M (€/MW/year) - 1-2% of investment | 5-10,000 | 5-10,000 | 5-10,000 | 3 |
| Variable O&M (€/MWh) | Depends on power price | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |
| **Storage ability (examples of potential size)** | | | | |
| Storage size (volume in m3) | Varies significantly | | | |
| Generator/compressor operation ratio | 1/1 | 1/1 | 1/1 | 1 |

**References:**
1 BKK, presentation on Nygard Pumpekraftverk
2 Tonstad Pumpekraftverk, Sira-Kvina kraftselskap, 2002
3 BKK and Sira-Kvina

**Remarks:**
A PHS is considered to be a mature tehnology without major improvements
B Based on the September 2004 exchange rate of 1NOK = 0,12€

# 41 COMPRESSED AIR ENERGY STORAGE (CAES)
2004.12.01

**Brief technology description**
CAES is a technology for large-scale electricity storage. Air is compressed, preferably at times with low ele
used together with gas to produce electricity.

In a conventional industrial gas turbine the compressor and turbine are operating on the same axis. The compression typically accounts for up to 2/3 of the total energy input. The generator output is therefore fairly small compared to the power generated by the turbine.

The basic concept of a CAES power plant is to split the gas turbine into a compressor unit for compressing the combustion air and an expansion turbine to generate mechanical power to drive a generator. This enables the utilization of the full capacity of the turbine, while leaving the compressor idle in periods of high demand.

CAES is characterized by being built in modules in form of a) compressors for air injection
cap                                                           ity; and c) underground storage for storage capacity. The storage can therefore be formed to a specific need, by altering one of these variables. This means that the storage is very flexible e.g. the storage capacity (can be doubled by creating another cavern) and the relationship between the loading and consuming time can also be easily altered. The numbers mentioned in the data sheets are only example of how the storage configuration can be.

Since a CAES plant uses fuel to heat air during the discharge generation cycle, it is not truly a 'pure' energy storage plant such as pumped hydro and batteries. In general, a CAES plant provides approximately 25-60% more electricity to the grid during on-peak times than it uses for compression during off-peak times (ref. 5).

Theoretically, all heat generated during compression could be recovered and used later to reheat the stored air during the generation cycle to eliminate the fuel consumption. However, this is rather costly and presently being researched only, and the table below therefore assumes no heat recovery. With this configuration, to generate 1 MWh electricity the electricity needed for compression is 0.6 MWh, while 1.2 MWh of fuel is required for air heating and the turbine. Thus, the storage efficiency is $1 / (0.6 + 1.2) * 100 = 55\%$.

**Input**
Electricity, when the store is filled. Gas for air heating and turbine operation, when the store is emptied.

**Output**
Electricity and heat (optional, as is the case for SCGT or CCGT)

**Typical capacities**
There is no typical capacity. The two currently operating plants have generating capacities of 110 and 290 MW, but new plants can be both smaller and larger. A general output range could be from 5 to 400 MW.

**Regulation ability**

A CAES plant will be able to generate at full capacity within 15 minutes from cold start.

**Advantages/disadvantages**

CAES is in addition to pumped hydro storage the only storage technology that currently is capable of operating over 100 MW for several hours. The potential production period is at any time limited by the actual filling level in storage.

CAES can be built in such a way that it also is possible to produce power by only using gas and no compressed air. In this situation the plant will be similar to a single cycle gas turbine.

The CAES positive environmental profile is the ability to store wind generated power from the time of generation to the time of consumption. On the negative side is that some energy is lost in this process and that fuel is used in the generation process.

**Life cycle assessment**

**Research and development**

World wide there have only been built two CAES plants so far. The CEAS technology has potential for being improved and optimized. A major EU research project is currently being carried out with the aim of significantly improving the efficiency of future CAES power plants by using compression heat.

**Examples of best available technology**

- The CAES plant in Huntorf Germany is operated by E.ON Kraftwerke. It was built in 1978 and has a maximum power output of 290 MW.
- The CAES plant in McIntosh, Alabama, USA operated by AEC (Alabama Electricity Corporation). It was commissioned in 1991 and has a maximum power output of 110 MW.

**Special remarks**

CAES needs to have an underground storage and salt caverns are most suitable, but natural aquifer structures and abandoned mines can also be used. This limits the location of CAES plants, there are however numerous salt deposits in Denmark, along the North Sea cost and some in the Baltic Sea costal area.

Several plats are planned in USA, including one in Northon, Ohio. The planned capacity is 2700 MW (based on 9 units of 300 MW).

**References**

9. Huntorf CAES: More than 20 Years of Successful Operation, by Fritz Crotogino KBB GmbH, Hannover, Germany and Klaus-Uwe Mohmeyer and Dr. Roland Scharf E.ON Kraftwerke Bremen, Germany.
10. U.S. Department of Energy, Energy Efficiency and Renewable Energy: Renewable energy Technology Characterizations, December 1997
11. ESA, Electricity Storage Association, www.electricitystorage.org
12. CAES development company, www.caes.net

13.	EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 20

## Data sheets

| Technology | CAES (10 MW) | | | |
|---|---|---|---|---|
| | **2006** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 10 | 10 | 10 | 1 |
| Electricity efficiency (%) net | 55 | 57 | 59 | 4; E |
| Time for warm start-up (hours) | 0 | 0 | 0 | 2 |
| Starting reliability (%) | 99 | 99 | 99 | 3 |
| Availability (%) | 95 | 95 | 95 | 3 |
| Technical lifetime (years) | 30 | 30 | 30 | 2 |
| Construction time (years) | 3 | 3 | 3 | 2 |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel) | 0.015 | < 0,006 | < 0,002 | 5; G |
| $CH_4$ (kg per GJ fuel) | 0.0015 | 0.0015 | 0.0015 | 5 |
| $N_2O$ (kg per GJ fuel) | 0.0022 | | | 5 |
| Particles (mg per GJ fuel) | 0 | 0 | | 5 |
| Ashes (kg per GJ fuel) | 0 | 0 | | 5 |
| Other residuals (kg per GJ fuel) | 0 | 0 | | 5 |
| **Financial data** | | | | |
| Specific investment, storage capacity (€/MWh) | 67000 | < 67000 | < 67000 | 3 |
| or specific investment, generation capacity (M€/MW) | 0.67 | < 0.67 | < 0.67 | 3; C |
| Fixed O&M (€/MW/year) | 20,000 | < 20,000 | < 20,000 | 3 |
| Variable O&M (€/MW/year) | - | - | - | F |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | 100% | 100% | 100% | |
| **Storage ability (examples of potential sizes)** | | | | |
| Storage size (hours) | 10 | 10 | 10 | A |
| Storage size (volume in m3) | 20 000 | 20 000 | 20 000 | A |
| Generator/compressor operation ratio | 1/1 | 1/1 | 1/1 | B |

**References:**

1 U.S. Department of Energy, Energy Efficiency and Renewable Energy:
Renewable Energy Technology Characterizations, December 1997
2 KBB GmbH (a Schlumberger company),
3 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003
4 CAES plants for balancing power and demand for fluctuating wind-power production, Crotogino et al, October 2004
5 It is estimated that emissions will be similar to gasturbine single cycle so data is copied from technology sheet no. 6

**Remarks:**

A Can be any value, depends on the size of the cavern. If the storage is used for daily fluctuations 10 to 20 hours is a reasonable size.
B Can be any size, depends on the compression capacity. One to one is a reasonable base
C Investments as M€/MW are here constant, as is the case for SCGT. The CAES technology can however most likely be further developed both regarding efficiencies and cost reductions.
D Based on the September 2004 exchange rate of 1USD = 0,82€
E Efficiency improvements are assumed to increase as CCGT
F Variable O&M costs depend mainly on power and gas consumption and the specific fuel costs
G NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

| Technology | CAES (300 MW) | | | |
|---|---|---|---|---|
| | **2006** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 300 | 300 | 300 | 1 |
| Electricity efficiency (%) net | 55 | 57 | 59 | 4; E |
| Time for warm start-up (hours) | 0 | 0 | 0 | 2 |
| Starting reliability (%) | 99 | 99 | 99 | 3 |
| Availability (%) | 95 | 95 | 95 | 3 |
| Technical lifetime (years) | 30 | 30 | 30 | 2 |
| Construction time (years) | 3 | 3 | 3 | 2 |
| **Environment** (Fuel: name, LHV in MJ/kg, and sulphor content) | | | | |
| **Environment** (Fuel: Natural gas, LHV 48.5 MJ/kg) | | | | |
| $NO_X$ (kg per GJ fuel) | 0.015 | < 0,006 | < 0,002 | 5; G |
| $CH_4$ (kg per GJ fuel) | 0.0015 | 0.0015 | 0.0015 | 5 |
| $N_2O$ (kg per GJ fuel) | 0.0022 | | | 5 |
| Particles (mg per GJ fuel) | 0 | 0 | | 5 |
| Ashes (kg per GJ fuel) | 0 | 0 | | 5 |
| Other residuals (kg per GJ fuel) | 0 | 0 | | 5 |
| **Financial data** | | | | |
| Specific investment, storage capacity (€/MWh) | 36000 | < 36000 | < 36000 | 3 |
| or specific investment, generation capacity (M€/MW) | 0.36 | < 0.36 | < 0.36 | 3; C |
| Fixed O&M (€/MW/year) | 11,000 | < 11,000 | < 11,000 | 3 |
| Variable O&M (€/MW/year) | - | - | - | F |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | 100% | 100% | 100% | |
| **Storage ability (examples of potential sizes)** | | | | |
| Storage size (hours) | 10 | 10 | 10 | A |
| Storage size (volume in m3) | 500 000 | 500 000 | 500 000 | A |
| Generator/compressor operation ratio | 1/1 | 1/1 | 1/1 | B |

**References:**

1 U.S. Department of Energy, Energy Efficiency and Renewable Energy:
 Renewable Energy Technology Characterizations, December 1997
2 KBB GmbH (a Schlumberger company),
3 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003
4 CAES plants for balancing power and demand for fluctuating wind-power production, Crotogino et al, October 2004
5 It is estimated that emissions will be similar to Gasturbine single cycle so data is copied from technology sheet no. 6

**Remarks:**

A Can be any value, depends on the size of the cavern. If the storage is used for daily fluctuations 10 to 20 hours is a reasonable size.
B Can be any size, depends on the compression capacity. One to one is a reasonable base
C Investments as M€/MW are here constant, as is the case for SCGT. The CAES technology can however most likely be further developed both regarding efficiencies and cost reductions.
D Based on the September 2004 exchange rate of 1USD = 0,82€
E Efficiency improvements are assumed to increase as CCGT
F Variable O&M costs depend mainly on power and gas consumption and the specific fuel costs
G NOx emission today 25 ppm, 2010-15 < 9 ppm and 2020-30 < 1 ppm.

# 42 ELECTROLYSIS AND HYDROGEN STORAGE

Draft 2004.10.15

**Brief technology description**

**Electrolysis**

Electrolysis is an electrochemical process, where hydrogen is produced from water and electricity. The water decomposition via electrolysis takes place in two partial reactions at both electrodes, which are separated by an ion-conducting electrolyte. At the negative electrode (cathode) hydrogen is produced and on the positive electrode (anode) oxygen is produced. To keep the product gases separated the two reaction compartments are separated by an ion separator (diaphragm).

Three overall types of electrolysis exist (1):

- Conventional Water Electrolysis
  This process works with alkaline, aqueous electrolytes. The anode compartment and cathode compartment are separated by a microporous diaphragm to avoid blending of the product gases.
- High-Pressure Water Electrolysis
  With high-pressure electrolysers hydrogen pressures above 50 bar are possible. This decreases the subsequent costs of compression at storage.
- High-Temperature Electrolysis
  High-temperature electrolysis using a solid oxide electrolyser cell (SOEC) has been discussed and tested as an interesting alternative during the 1970'ies. It would be an advantage to apply part of the energy needed for dissociation as high-temperature heat at around 800-1000°C into the process and then to be able to run the electrolysis with reduced consumption of electric power. Furthermore, SOEC has the possibility of electrolysing mixtures of steam and carbondioxide into a mixture of hydrogen and carbonmonoxide, so-called syngas, from which artificial hydrocarbons may be produced.

The conventional process is the alkaline electrolysis, which has been in commercial use for more than 80 years. Solid polymer electrolysis, which is also low-pressure and low-temperature has the potential of reaching higher efficiencies, but is a less developed technology. In Denmark research is being made in the field of solid oxide electrolysis, which is high-temperature.

Norsk Hydro Electrolysers has a number of reservations in connection with high temperature electrolysis: Requires expensive materials to withstand the high temperature. Safety is a problem. The energy must be waste energy or else it makes no sense. If energy is available at that high temperature it is not normally called waste energy and to put it in an electrolyser for production of hydrogen does not pay.

**Storage**

Hydrogen serves as a storage and transportation medium for energy. In general there are three different ways of storing hydrogen (1):
- storage of pressurised gas
  - in caverns

- in tanks e.g. for mobile applications up to 700 bar
- in pipelines between producers and consumers (like natural gas)
- storage of liquid hydrogen
  - liquefied at -235°C, stored in cryo-tanks
- storage via absorption
  - Metal hydride storage used in submarines commercially today, heavy
  - Carbon Nanotubes, light, under development
- storage in chemical compounds

**Input**
Electricity and water

**Output**
Hydrogen and oxygen
The lower heating value of hydrogen is 10.8 MJ/Nm$^3$ or 3.00 kWh/Nm$^3$.

**Typical capacities**
Electrolysis: Alkaline 1-100 MW, Solid Polymer 10-50 MW (1)

Hydrogen storages can differ greatly in sizes from caverns of 100-100.000 GJ down to pressurised tanks of 300 bar with capacities of 0,4-2,5 GJ (1)[4].

**Regulation ability**
Good dynamic performance is a feature of the latest developments within alkaline electrolysis, which allows for fluctuating operation. Therefore they are perfectly suited for applications with fluctuating power plants. For high temperature electrolysis longer start up times must be expected.

Storage of hydrogen is a tool to enhance regulation ability of the overall energy system. How fast the hydrogen can be converted into energy depends on the type of fuel cell it is used in.

**Advantages/disadvantages**
Electrolysis can be performed in centralised or decentralised plants. Decentralised production of hydrogen makes sense, when the hydrogen needs to be used locally. With decentralised production, distribution of the energy can take place through the electricity grid, which creates lower losses than transport of hydrogen. Furthermore, electrolysis is not necessarily more efficient in large scale than in small scale. With centralised production and utilisation, losses during distribution are avoided.

When storing electricity indirectly through production, compression and storage of hydrogen a substantial amount of the energy is lost. Estimates of the accumulated efficiency range from 84% for production, compression and storage in a cavern at 50-200 bar (2) down to 75% for production, compression and storage in a tank at 200 bar (3).

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[4] General Motors and QUANTUM Fuel System Systems Technology Worldwide has furthermore developed and tested a 700 bar hydrogen storage system which extends the range of a fuel cell vehicle by 60-70 percent compared to an equivalent-sized 350 bar system. (4)

**Environmental aspects**

Hydrogen is, like electricity, an energy carrier, which is only as clean as the energy source from which it is produced. Electrolysis can be used to enhance the value and thereby possibly the capacity of surplus energy produced from fluctuating renewable energy sources such as wind.

Some emissions of hydrogen will take place during storage, distribution and utilisation of the hydrogen. Hydrogen emits to the stratosphere, where it connects with oxygen to form water. An increased amount of water in the stratosphere will lead to further destruction of the ozone layer. It is however calculated that the increase in water in the stratosphere due to hydrogen will be significantly less than the increases, which are expected already to have appeared in the stratosphere during the last 50 years. Therefore, it is uncertain whether future emissions of hydrogen may lead to further damages on the ozone layer. (5) (6)

**Research and development**

In the white paper of Risø about research in the field of hydrogen in Denmark (7) neither electrolysis nor storage in caverns are mentioned as primary priorities of the future field of research in Denmark.

However, within hydrogen production, the white paper does mention some research priorities also in the field of electrolysis. To improve efficiency of electrolysis it is necessary to raise the temperature. Therefore development of new electrode materials with reduced over-potentials is a priority. Research in this field is closely connected to research in the field of SOFC.

Most research in hydrogen storage is directed towards storage in tanks for mobile applications, where the challenge is to store hydrogen in tanks under high pressure or liquefied with low weight while ensuring safety and energy amounts for ranges comparable to cars run on fossil fuels today.

**Examples of best available technology**

Norsk Hydro has produced hydrogen with hydropower since 1934. An example of their technology is an output of hydrogen of 300-377 $Nm^3$/hr an energy consumption of ca. 4.1 kWh/Nm3H$_2$ with an efficiency of 73% at 1 bar pressure (8).

When it is necessary to store large amounts of hydrogen in a future energy economy then hydrogen can be pumped into subterranean cavern storages. In UK (Tees Valley) as well as in France and in the USA this method is already in use. Caverns used for storage of natural gas could be used for the storage of hydrogen in the future.

**References**

1) http://www.hynet.info/hydrogen_e/index00.html
2) "Scenarier for samlet udnyttelse af brint som energibærer i Danmarks fremtidige energisystem". RUC, april 2001.
3) The Future of the Hydrogen Economy: Bright or Bleak? Version of 15 April 2003 updated for distribution at the 2003 Fuel Cell Seminar at Miami Beach, Florida. 3 – 7 November 2003. Bossel, Eliasson og Taylor (www.efcf.com/reports)
4) http://www.gm.com/company/gmability/adv_tech/600_tt/650_future/hydrogen_milestone_021003.html
5) http://www.dmi.dk/dmi/brint_fra_brandselsceller_kan_maske_skade_ozonlaget
6) http://www.sciencemag.org/cgi/content/full/300/5626/1740

7) "Brintforskning i Danmark – udfordringer og perspektiver" Red. Jens Kehlet Nørskov, DTU
Robert Feidenhans'l, Risø, May 2004
8) http://www.hydroelectrolysers.com/

## Data sheets

| Technology | Electrolyser | | | |
|---|---|---|---|---|
| | **2004** A | **2010-15** B | **2020-30** C | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one unit (MW) | 0.9-1.1 | 5-50 | 5-50 | 1; 4; 4 |
| Energy consumption (kWh/Nm3H2) | 4.0-4.2 | n.a. | 3.5 | 1; 6 |
| Output (bar) (H2: LHV 3.00 kWh/Nm3) | 1 | n.a. | n.a. | 1 |
| Operating temperature (degr. C) | 70-90 | 80-100 | 850-1000 | 4; 4; 2 |
| Total efficiency (%) net | 71-75 (F) | 80 | 90-95 | 1; 2; 6 |
| Water consumption (l/Nm3H2) | 1 | n.a. | n.a. | 1 |
| Time for warm start-up (hours) | | | | |
| Forced outage (%) | | | | |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | | 15 | 20 | 4 |
| Construction time (years) | | | | |
| **Environment** | | | | |
| **Financial data** | | | | |
| Specific investment (M€/MW) | 0.2-1.4 (G) | 0.2 | 0.18 | 3; 2; 2 |
| Fixed O&M (€/MW/year) | 6000-42000 | 6000 | 5400 | 5 |
| Variable O&M (€/MWh)               (D) | | | | 5 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes)     (E) | 0.9-1.1 | 5-50 | 5-50 | 5 |
| Regulation speed (MW per sec.) | 0.004 | | | 5 |
| Minimum load (% of full load) | 20 | | | 5 |

**References:**
1 http://www.hydroelectrolysers.com/
2 Risø, 2003
3 "Feasibility study on hydrogen refueling infrastructure for fuel cell vehicles using the off-peak power in Japan" Oi T og Wada K. International Journal of Hydrogen Energy 29 (2004) s. 347-354
4 "Scenarier for samlet udnyttelse af brint som energibærer i Danmarks fremtidige energisystem". RUC, april 2001
5 Norsk Hydro's Electrolysers, September 2004
6 Risø, 2004

**Remarks:**
A Electrolyte 25% KOH Aqueous solution (alkaline). Norsk Hydro considers that after 70 years of improvement the atmospheric alkaline electrolyser will be the most efficient for many years ahead.
B Solid Polymer Electrolysis
C Solid Oxide Electrolysis
D Variable O&M costs are mainly electricity costs, which depend on type of compressor used (Ref. 5)
E Norsk Hydro's electrolysers are up in full production from zero in less than 10 minutes (Ref. 5)
F The efficency of the electrolyser is based on a current density, which is the most economique at the moment. A lower current density will decrease power consumption to 4.0 kWh/Nm3 or below but increase the investment. (Ref. 5)
G The price for a complete electrolyser plant from Norsk Hydro with capacity 485 Nm3/h and with transformer, rectifier, water purifier, lye and lye tank, electrolyser, scrubber and gasholder is approx. NOK 9 000 000.- ( close to € 1 mill. ) This will be a plant of approx. 2 MW. For larger power plants the price will be lower pr. unit since part of the equipment is common. (Ref. 5)

| Technology | Hydrogen storage, cavern | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Capacity for one unit (MWh fuel) | 28-28.000 | 28-28.000 | 28-28.000 | 1 |
| Pressure (bar) | 50-200 | 50-200 | 50-200 | 1 |
| Losses at filling (%) | 3 | 2 | 2 | 1 |
| Stationary losses (% per day) | 0.01 | 0.005 | 0.005 | 1 |
| Total efficiency (% of H2 in) | 67 | 83 | 83 | 1 |
| Supplementary energy (kWh el/Nm3) | 0.17 | 0.16 | 0.14 | 1 |
| Total efficiency including supplementary energy(% of H2 in) | 84 | 88 | 89 | 1 |
| Planned outage (weeks per year) | | | | |
| Technical lifetime (years) | 20 A | 20 | 25 | 2; 1 |
| Construction time (years) | | | | |
| **Environment** | | | | |
| **Financial data** | | | | |
| Specific investment, storage capacity (€/MWh) | 96 | 72 | 58 | 1 |
| Or specific investment, generation capacity (M€/MW) | 0.00096 | 0.00072 | 0.00058 | 2B |
| Fixed O&M (€/MW/year) | | | | |
| Variable O&M (€/MWh) | | | | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 "Scenarier for samlet udnyttelse af brint som energibærer i Danmarks fremtidige energisystem". RUC, april 2001

2 Rambøll, 2004

**Remarks:**

A Guess

B Estimate based on a storage size of 100 MWh and an off-take generation capacity of 10 MWel

# 43 BATTERIES
2004.10.20

**Brief technology description**

There are several technologies available or being developed for storing electricity. Below is a classification of a selection of these technologies regarding their capacities and discharge times.
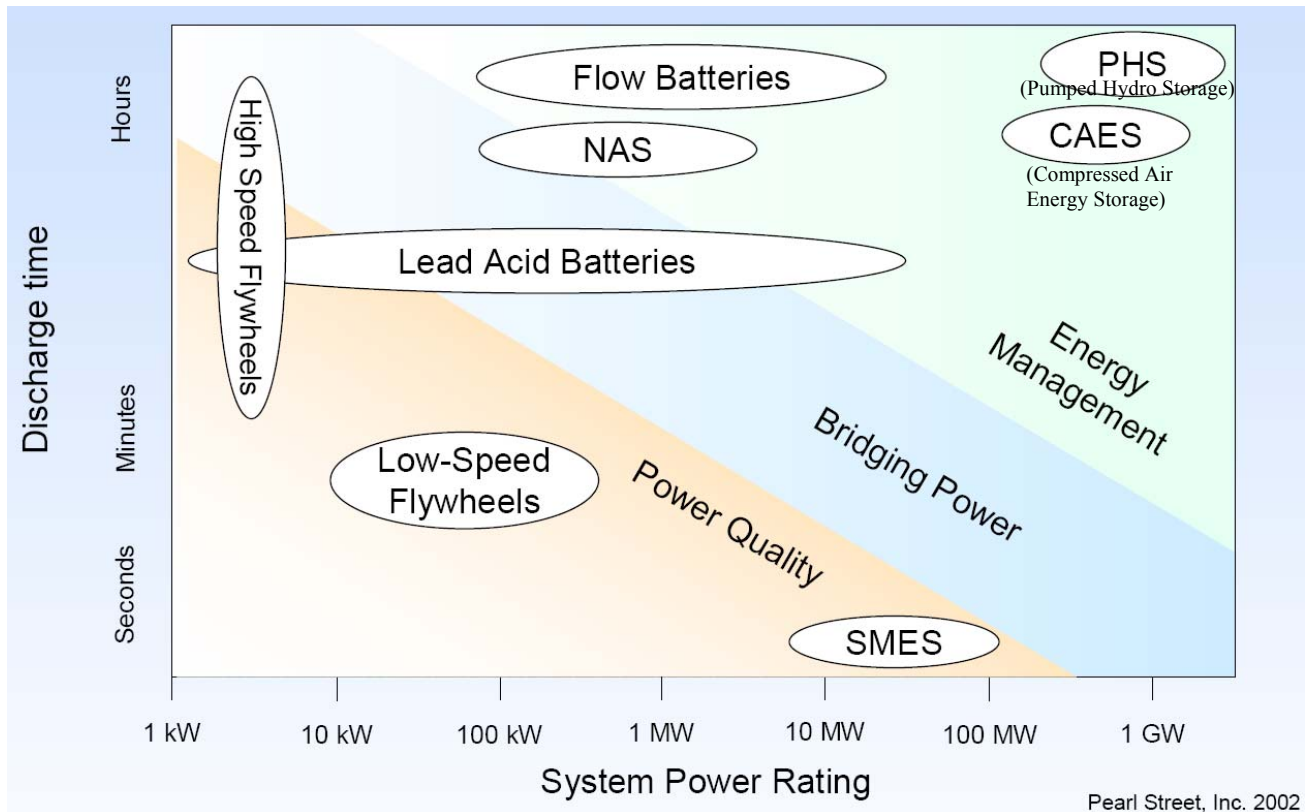


Source: Energy Storage Council and Pearl Street (ref. 2).

NOTE:
Energy management: large capacities over a long period of time e.g. management of daily/seasonal variations
Bridging power: assures continuity for seconds to minutes
Power Quality: protects from unpredictable changes measured in milliseconds (voltage/frequency)

The figure above shows that there are 3 main battery types that can be relevant for large-scale energy storage. In addition the Electricity Storage Association (ref. 3) uses the same grouping of technologies.

- Lead Acid Batteries
- NAS (Sodium Sulphur)
- FLOW Batteries (which can be grouped into 3 different types)
  - Regenerative fuel cell (Polysulfide Bromide battery [PSB] or Regenesys)
  - Vanadium Redox (VRB)
  - Zinc Bromin (ZnBr)

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The lead-acid battery is one of the oldest and most developed battery technologies.
A lead-acid battery is a electrical storage device that uses a combination of lead plates or grids and an electrolyte consisting of a diluted sulphuric acid to convert electrical energy into potential chemical energy and back again.

The NAS (Sodium Sulphur) battery was firstly developed in the 1960s for electricity vehicle application and by the early 1980s it has also been applied as large stationary power. When the NAS (Sodium Sulphur) battery cell is discharged, sodium at the negative electrode separates into a sodium ion and an electron, and the sodium ion migrates through the solid electrolyte to the positive electrode. The electron moves from the negative electrode through the external circuit to the positive electrode. The battery is kept at about 290-360 degrees C to allow this process. The NAS battery cells use a beta-alumina ceramic tube as the electrolyte, ensuring both performance and reliability. When the cell is recharged, these reactions are reversed.

Three types of flow batteries are included:
- Regenerative fuel cell provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulfide). It is an electrochemical system incorporating a regenerative fuel cell. The capacity is mainly determined by the size of the electrolytic tank.
- Vanadium Redox (VRB) is based on vanadium as the only element, and is based on the reduction and oxidation of the different ionic forms of Vanadium. Energy can be stored indefinitely in a liquid – very low self-discharge.
- Zinc Bromin (ZnBr) battery is based on cells with two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane.

**Typical capacities**

| Technology | Cell Batteries | | Flow Batteries | | |
|---|---|---|---|---|---|
| | **Lead Acid Batteries** | **NAS** | **Regenerative fuel cell** | **VRB** | **ZnBr** |
| *Product line, 1 unit*<br>Generation Capacity (kW)<br>Storage Capacity (kWh) | to 4000Ah | 50<br>360-430 | | 250<br>Varies | 250<br>500 |
| *Operating Systems, >1 unit*<br>Generation Capacity (MW)<br>Storage Capacity (MWh) | 10<br>15 | 6<br>48 | 15<br>120 | 1.5<br>1.5 | 0.4 |
| Charge/discharge ratio | 5:1 | 2:1 | ? | 1.2:1 | 2.5:1 |
| Target markets | Vehicular | Utility | Utility | Utility | Utility |
| Commercial status | Commercial globally | Newly in Japan | Pre-commercial | Early commercial | Beta prototype |

Most batteries are built as small modules (kW) that can be connected to create batteries with several MW.

Since most electricity storage systems are pre-commercial or at market entry stage, prices are not yet fully mature.

The batteries best suited for energy management are the NAS and VRB technologies (ref. 1, page 3-34) and therefore are only these two technologies analysed further. The regenerative fuel cell, from Regenesys, is not included since the developer has stopped further development.

**Input**
Electricity

**Output**
Electricity

**Regulation ability**

**Advantages/disadvantages**
Advantages of the Vanadium Redox (VRB) system is a high-energy efficiency of over 75% (AC to AC) and over 85% (DC to DC); a very low self discharge; storage capacity can be increased by increasing electrolyte volume (no change to battery cell-stacks); the lifetime charge-discharge cycle is over 13,000 cycles without need for membrane replacement. The battery has a charge/discharge window of 1 to 1.

The strengths of the NAS battery are also the high average DC energy efficiency (charging/ discharging) of 85%, its relative long-term durability of 15 years and assumed specification of 2,500 cycles, and a high energy density i.e. reduced space requirements.

**Life cycle assessment**

**Research and development**
The basic principals behind the NaS battery were discovered in the 1960s by the Ford Motor Company. NGK of Japan began research in NAS batteries in 1987, began testing of prototypes for commercial use at the Tokyo Electric Power in 1992 and in Japan are currently 19 sites totalling 52 MW, mainly for demonstration purposes. The major stakeholders are NGK (producer) and Tokyo Electricity Power (alliance with NGK).

Early work on VRB was undertaken by NASA in the 1970s. Currently the major stakeholders and developers are VRB Power Systems (Canada), Sumitomo Electric Industries (Japan) and Squirrel Holdings (Thailand).

**Examples of best available technology**
**<u>VRB</u>**
- PacifiCorp installation of 250kW, 8 hours (2MWh) battery completed in February 2004, which also should be used for peak shaving.
- Hydro Tasmania has a 200kW, 4 hours (0.8MWh) battery completed in November 2003, in connection with wind turbines on Kings Island.
- Tottori SANYO Electric Co. has a 1500kW and 1500 kWh battery for Peak shaving.

## NAS

- At end of September 2003 had 16 NAS systems been sold to commercial and industrial customers that demand extremely reliable power supply, including shopping centres (4) and water works (3).
- The largest NAS installation is a 6MW, 8 hour unit, owned by Tokyo Electric Power
- American Electric Power (AEP) in Columbus, Ohio, USA has a 100 kW/375kWh NAS battery in a two-year test operation (2002-2004)

## References

1. EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003
2. Energy Storage Council and Pearl Street http://www.energystoragecouncil.org/1%20-%20Jason%20Makansi-ESC.pdf
3. Electricity Storage Association http://www.electricitystorage.org/tech/technologies_comparisons_ratings.htm

**VRB**
4. VRB Power Systems, An electrochemical Energy Storage Company, Executive Summary
5. VRB Power Systems, Technical Introduction
6. Sumitomo Electronic, www.sei.co.jp
7. Hydro Tasmania, King Island Wind Farm
8. ESA, Electricity Storage Association, www.electricitystorage.org

**NAS**
9. Commercial Deployment of the NAS Battery in Japan, Hyogo Takami , Tokyo Electric Power Company and Toyoo Takayama, NGK Insulators, Ltd.
10. NAS battery energy storage system for power quality support in Malaysia, Amir Basha Ismail, (TNB Research Sdn. Bhd.), Mohd Fadzil Mohd (TNB Research Sdn. Bhd.) and Siam, Hyogo Takami, (Tokyo Electric Power Company)
11. ESA, Electricity Storage Association, www.electricitystorage.org

## Data sheets

| Technology | Vanadium Redox (VRB) | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | E | F | |
| Generating capacity for one unit (MW) | | 10 | 10 | 1 |
| Total efficiency (%) net | | 78% | | 1 |
| Efficiency is expected to fall over its lifetime | 13,000 cycles is no difficulty | | | 1 |
| Lifetime in full charge-discharge cycles | | 13000 | | 1 |
| Construction time (months) | | 6-8 | | 1 |
| **Financial data** | | | | |
| Specific investment, storage capacity (€/MWh) | | 210000 | 150000 | 2; A, B |
| or specific investment, generation capacity (M€/MW) | | 2.11 | 1.55 | 2; A, B |
| Fixed O&M (€/MW/year) | | 44,000 | 44,000 | 2; A, |
| Variable O&M (€/MWh) | | 2.3 | 2.3 | 2; A, G |
| **Storage ability (examples of potential size)** | | | | |
| Storage size (hours) | | 10 | 10 | 2; C |
| Storage size (MWh) | | 100 | 100 | 2 |
| Charge-Discharge ratio | | 1.2:1 | | 1; D |

**References:**
1 VRB Power Systems Incorporated, an electrochemical Energy Storage Company, Executive Summary
2 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003

**Remarks:**
A Based on the September 2004 exchange rate of 1USD = 0,82€
B Mature represents the expected future cost and is here reduced by 27%
C Storage size is simply a function of liters of Electrolyte in the system
D Number of hours it take to charge the battery for having one hour to discharge/production from the battery?
E The EPRI-DOE Handbook has numbers for 2006 which assume that first-of-a-kind and prototyping costs have been resolved in prior projects - these numbers are here are used for 2010-2015
F The EPRI-DOE Handbook also has numbers for the future when the technology is Mature 2010 - these numbers are here used for 2020-2030 and can therefore be considered to be conservative estimates
G Based on 2500 operating hours a year

| Technology | Sodium Sulphur (NAS) | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | D | E | |
| Generating capacity for one unit (MW) | | 10 | 10 | 2 |
| Total efficiency (%) net | | 85% | | 3 |
| Lifetime in full charge-discharge cycles | | 2500 | | 2 |
|   - Technical lifetime (years) | | 15 | 15 | 2 |
| Construction time (months) | | 6-8 | | 1 |
| **Financial data** | | | | |
| Specific investment, storage capacity (€/MWh) | | 180000 | 130000 | 4; A, B |
| or specific investment, generation capacity (M€/MW) | | 1.82 | 1.34 | 4; A, B |
| Fixed O&M (€/MW/year) | | 41000 | 41000 | 4 |
| Variable O&M (€/MWh) | | 4.3 | 4.3 | 4, F |
| **Storage ability (examples of potential size)** | | | | |
| Storage size (hours) | | 10 | 10 | 2 |
| Storage size (MWh) | | 100 | 100 | 2 |
| Charge-Discharge ratio | | 2:1 | | 2; C |

**References:**

1 Commercial Deployment of the NAS Battery in Japan, by Hyogo Takami, Tokyo Electric Power Company and Toyoo Takayama, NGK Insulators, Ltd.

2 Electric energy storage solution group, R&D center, engineering R&D division, Tokyo electric power company (e-m

3 NAS battery energy storage system for power quality support in Malaysia, Siam, Hyogo Takami, (TEPCO)

4 EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications, EPRI, 2003

**Remarks:**

A Based on the September 2004 exchange rate of 1USD = 0,82€

B Mature represents the expected future cost and is here reduced by 27%

C Number of hours it take to charge the battery for having one hour to discharge/production from the battery?

D The EPRI-DOE Handbook has numbers for 2006 which assume that first-of-a-kind and prototyping costs have been resolved in prior rejects - these numbers are here are used for 2010-2015

E The EPRI-DOE Handbook also has numbers for the future when the technology is Mature 2010 - these numbers are here used for 2020-2030 and can therefore be considered to be conservative estimates

F Based on 2500 operating hours a year

# 50  HEAT PUMPS
2005.02.21

**Brief description**

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature location to a warmer location. Heat pumps usually draw heat from the ambient (input heat) and convert the heat to a higher temperature (output heat) through a closed process driven by mechanical energy (drive energy); either compressor heat pumps (using electricity) or absorption heat pumps (using fuel).

Heat pumps serve different purposes, e.g. industrial purposes, individual space heating, heat recovery and district heat production. Today all small heat pump systems used for individual space heating are driven by electricity. Large heat pump systems are primarily dimensioned from an appraisal of the actual demand.

With low temperature levels of the heat source and the delivered heat, the heat output will be 2 to 5 times (the coefficient of performance) the drive energy. It is not possible to make general formulas for calculating the coefficient of performance (COP) since the efficiency of the systems can vary significantly depending on the compressor type etc. A rule of thumb is that the COP increases 2-5% when the heat source raises one degree. This is only true in a relatively narrow span. Likewise, the COP increases 1-3%, when the heat delivered is lowered one degree.

In Denmark the heat source is primarily renewable energy in the form of solar heat, either directly via solar panels or via accumulated solar heat in top soil layers, in ambient air, in lakes, streams or seawater. Also waste heat from industrial processes can directly or in connection with heat recovery be utilized as heat source.

This technology sheet covers compressor heat pumps only, not absorption heat pumps.

**Input**

A heat source (e.g. ambient air, water or ground, or waste-heat from an industrial process) and energy to drive the process. Typical Danish temperatures are 0-18 $^{\circ}$C as ground temperature and 5-10 $^{\circ}$C as groundwater temperature. Compressor heat pumps are driven by electricity or engines, whereas absorption heat pumps are driven by fuels.

**Output**

Heat.

**Typical capacities**

The capacity of small heat pumps is 0.5 to 25 kW heat output. Large heat pumps are available from 25 kW to 3-5 MW heat output, but also larger than this.

**Regulation ability**

The use of heat pumps can be very beneficial for the overall electricity system in converting electricity to heat at high efficiencies in times of surplus electricity generation. This feature becomes increasingly valid, when more intermittent renewable energy generators are entering the system.

Small heat pumps have previously been operated in on/off-mode, but recently some air/air and liquid/water heat pumps have been introduced with regulation ability; typically 30-150%. In ten years time, a regulation of 10-200% is expected. Regulating up to 150-200% is only possible for shorter intervals, but could be used for peak demand. It does however shorten the lifetime of the heat pumps.

Large heat pumps are usually regulated continuously and instantly. In starting from cold, electricity consumption is full load instantly.

**Research and development**
The phasing out of the ozone depleting refrigerants CFC and HCFC from the heat pump market has been agreed internationally. The heat pump industry has introduced refrigerants, which are not ozone depleting. These are among others hydrocarbons (propane, butane and iso-butane), carbon dioxide, and water. The use of these refrigerants does not decrease the energy efficiency, on the contrary if anything. It is primarily the so called HFC refrigerants that has been developed to replace the CFC and HCFC refrigerants, but the HFC's contribute to global warming and therefore work has been initiated in order to make sure that these also are phased out.

Besides the further development of environmentally neutral refrigerants it is expected that technology development will focus on:

- Increase the efficiencies of all types of heat pump systems.
- Heat pumps combined with direct solar heating.
- Use of wind power, photovoltaic electricity and biomass as input energy.
- Use of heat pumps combined with combined heat and power production.
- Optimise the benefits for the overall electricity system of using heat pumps.
- Further development of heat pumps driven by natural gas.

**Advantages/disadvantages compared to other technologies**
A general advantage of heat pumps is, that the heat pump is able to utilize energy at a low temperature level. Additionally the heat pump is flexible concerning use of renewable energy, waste and surplus heat. The combined utilization of a heat source at a low temperature level and the use of for example gas as driving power enables a more effective resource utilization compared with conventional heat production technologies.

Compared with traditional heating technologies, heat pumps are relatively expensive in investments costs. However, this is counterbalanced with considerable savings in operating costs.

**Environment**
Harmless refrigerants are currently replacing the former previous refrigerants at large scale.

As heat pumps need drive energy (electricity, oil or gas), the environmental impact from using heat pumps stems from the production and use of the drive energy.

**Special remarks**
This technology sheet does not cover heat pumps using geothermal heat as heat source. For this purpose, refer instead to technology sheet no. 53. The data for 'hot' heat pumps is based on a heat source of 40°C; otherwise the average outdoor temperatures is used as heat source. If other heat

sources are used e.g. in connection with decentralised CHP systems the plants the COP values would be considerably higher. This could be heat sources such as flue gas cooling, heat from intercooler or waste heat from gas engines.

Concerning financial data mentioned in the data sheets, the span of investment costs and O&M costs is expected to cover the future. Investment costs are not expected to fall and O&M costs may increase slightly in the future.

**Reference**
Danish Technology Institute, 2003, 2004 & 2005

**Data for electric heat pumps:**

| Technology | Very large heat pumps, electric (heat source: ambient temperature) | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generation capacity for one unit (MW heat) | **50 - 100** | | | |
| Coefficient of performance                (A) | | | | |
|   - liquid/water | 3.5-4.2 | 5 | 5 | 1 |
|   - air/water | 3.2-4 | 5 | 5 | 1 |
| Forced outage (%) | 0 | 0 | 0 | 1 |
| Planned outage (weeks per year) | 0 | 0 | 0 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 1 |
| Construction time (years) | < 1 | < 1 | < 1 | 1 |
| **Environment** | | | | |
| Refrigerants                (C) | partly neutral | neutral | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW heat)        (E) | 0.6-1.5 | 0.6-1.3 | 0.6-1.3 | 2 |
| Total O&M (€/MW heat per year)        (D) | 1000-3000 | 1000-3000 | 1000-3000 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.)        (B) | | | | |
| Minimum load (% of full load) | | | | |

**References:**
1 Danish Technology Institute. September 2004
2 York Refrigerants, personal communication Dec. 2004

**Remarks:**
A The technology in 2004 is a two-step ammonia heat pump. The quoted COP's assume outdoor temperatures as heat source and 55 C as outlet temperature. As a rule of thumb, every extra degree on the heat source adds 4-5% to the COP. The COP's are values measured over a year. The span is due to variations in types of installations.

B Electricity consumption regulates instantly from cold to full load

C From 2010 it is assumed that $CO_2$ is used as refrigerant

D Large heat pumps will typically contain a turbo compressor, which is almost maintenance free. O&M costs therefore only need to be calculated for the rest of the system.

E These costs include pipes, electrical system, construction etc. The heat pumps alone would cost between 0.3 and 0.6 M€/MW heat.

| Technology | Hot very large heat pumps, electric (heat source 40 C) | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generation capacity for one unit (MW heat) | **50 - 100** | | | |
| Coefficient of performance (A) | | | | |
| - liquid/water | 6.3 | 6.3 | 6.3 | 1 |
| Forced outage (%) | 0 | 0 | 0 | 1 |
| Planned outage (weeks per year) | 0 | 0 | 0 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 1 |
| Construction time (years) | < 1 | < 1 | < 1 | 1 |
| **Environment** | | | | |
| Refrigerants (C) | partly neutral | neutral | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW heat) (E) | 0.8-1.7 | | | 1 |
| Total O&M (€/MW heat per year) (excl. electricity) (D) | 1000-3000 | | | 1 |
| **Regulation ability** (B) | | | | |
| Fast reserve (MW per 15 minutes) | full | | | |
| Regulation speed (MW per sec.) | 0.02 | | | |
| Minimum load (% of full load) | 0 | | | |

**References:**

1 York Refrigerants, personal communication Dec. 2004

**Remarks:**

A The technology in 2004 is an ammonia heat pump. The quoted COP's assume 40 C as heat source and 75 C as outlet temperature. To raise the temperature above 75 degrees it is necessary to change from ammonia as refrigerant to hydrocarbons or $CO_2$. This is not a developed technology in this scale. As a rule of thumb, every extra degree on the heat source adds 4-5% to the COP. The COP's are values measured over a year. The span is due to variations in types of installations.

B Heat pumps can be started 5-10 times per hour. Repeated start-ups tears on the equipment. Compared to natural gas fired motors the tear will be the same, but the heat pumps can start up less times per hour.

C From 2010 it is assumed that $CO_2$ is used as refrigerant

D Large heat pumps will typically contain a turbo compressor, which is almost maintenance free. O&M costs therefore only need to be calculated for the rest of the system.

E These costs include pipes, electrical system, construction etc. The heat pumps alone would cost between 0.4 and 0.85 M€/MW heat.

| Technology | Hot large heat pumps, electric  (heat source: 40 C) | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generation capacity for one unit (MW heat) | **5-10** | | | |
| Coefficient of performance                (A) | | | | |
| - liquid/water (55C) | 4.5 | 4.5 | 4.5 | 2 |
| - liquid/water (65C) | 3.9 | 3.9 | 4.3 | 2 |
| - liquid/water (2004: 72C, 2010-15 and 2020-30: 75C) | 3.5 | 3.5 | 4.2 | 1; 2 |
| Forced outage (%) | 0 | | | 1 |
| Planned outage (weeks per year) | 0 | | | 1 |
| Technical lifetime (years) | 20 | | | 1 |
| Construction time (years) | 0.5-1 | | | 1 |
| **Environment** | | | | |
| Refrigerants                                  (D) | partly neutral | | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW heat)        (E) | 0.6-1.1 | 0.6-1.1 | 0.6 | 1 |
| Total O&M (€/MW heat per year) (excl. electricity) (B) | 1000-4500 | 1000-4500 | 1000 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | Full | | | 1 |
| Regulation speed (MW per sec.)           (C) | 0.02 | | | 1 |
| Minimum load (% of full load) | 0 | | | 1 |

**References:**

1 York Refrigerants, personal communication Dec. 2004

2 Danish Technology Institute. January 2005

**Remarks:**

A The technology in 2004 and 2010-15 is a two-step ammonia heat pump. To raise the temperature above 75 degrees it is necessary to change from ammonia as refrigerant to hydrocarbons or CO2. This is not a developed technology in this scale. As a rule of thumb, every extra degree on the heat source adds 4-5% to the COP. The COP's are values measured over a year.

B A typical service contract is estimated 2,000-3,000 €/year, for the larger sizes. Furthermore an overall check is needed for every 10000 hrs of operation costing approximately 1500 euro/MW.

C To raise the temperature from around 10 C average to 72 C it is necessary to have a two step heat pump, which will slow the regulation speed a bit down.

D From 2020 it is assumed that CO2 is used as refrigerant

E These costs include pipes, electrical system, construction etc. The heat pumps alone would cost between 0.3 and 0.6 M€/MW heat.

| Technology | Medium-scale heat pumps, electric (heat source: ambient temperature) | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | | | |
| Generation capacity for one unit (MW heat) | 0.2 - 1.5 | | | |
| Coefficient of performance (A) | | | | |
| - liquid/water (55C) | 4.5 | 4.5 | 4.5 | 3 |
| - liquid/water (65C) | 3.9 | 3.9 | 4.3 | 3 |
| - liquid/water (75C) | 3.5 | 3.5 | 4.2 | 2; 3 |
| Forced outage (%) | 0 | 0 | 0 | 1 |
| Planned outage (weeks per year) | 0 | 0 | 0 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 1 |
| Construction time (years) | < 0.5 | < 0.5 | < 0.5 | 1 |
| **Environment** | | | | |
| Refrigerants (D) | partly neutral | neutral | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW heat) (E) | 0.6-1.1 | 0.6-1.1 | 0.6 | 2 |
| Total O&M (€/MW heat per year) (B) | 3000-6000 | 3000-6000 | 2000-4000 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) (C) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Danish Technology Institute. Personal communication, September 2003

2 York Refrigerants, personal communication Dec. 2004

3 Danish Technology Institute. January 2005

**Remarks:**

A The technology in 2004 and 2010-15 is a two-step ammonia heat pump. The quoted COP's assume outdoor temperatures as heat source. As a rule of thumb, every extra degree on the heat source adds 4-

B A typical service contract is estimated 2,000-3,000 €/year, for the larger sizes. Furthermore an overall check is needed for every 4000 hrs of operation costing approximately 1500 euro/MW.

C Electricity consumption regulates instantly from cold to full load

D From 2020 it is assumed that $CO_2$ is used as refrigerant

E These costs include pipes, electrical system, installation etc. It does not include buildings or storage tanks. The heat pumps alone would cost between 0.3 and 0.6 M€/MW heat.

# 51 DISTRICT HEATING BOILER, WOOD-CHIPS FIRED
2004.09.28

**Brief technology description**
Boiler fired by wood-chips from forestry and/or from wood industry.

If the moisture content of the fuel is above 30-35%, flue gas condensation should be employed. Thereby the thermal efficiency usually exceeds 100% (based on lower heating value). The efficiency is primarily determined by the condensation temperature, which is little above the return temperature from the district heating network. In well-designed systems, this return temperature is below 40 $^{o}$C, yielding efficiencies above 110%.

**Input**
Wood chips are comminute wood in lengths 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, and not to the quality.

Existing district heating boilers in Denmark can burn wood-chips with up to 45-63% moisture content, depending on technology. In 1993, the actual moisture content was 42% in average, varying between 32 and 48% (ref. 1).

The wood-chips are often traded in two size qualities, coarse and fine.

**Output**
District heat or heat for industrial processes.

**Typical capacities**
1 - 50 MJ/s.

**Regulation ability**
Typical plants are regulated 25 - 100% of full capacity, without violating emission standards. The best technologies can be regulated 10 - 120%.

**Advantages/disadvantages**

**Environment**
Wood-chips fired boilers produce four sorts of residues: Flue gas, fly ash, bottom ash, and condensate from flue gas condensation.

The fly ash and bottom ash are normally accumulated in the same container and transported to a safe landfill (primarily due to cadmium, lead and mercury).

The condensate water is usually treated for Cadmium, so that the content reaches 3 – 10 grams per 1000 m$^3$. The sludge must be deposited in a safe landfill.

**Research and development**
There is still a need for R&D in the following areas:

- environmentally safe recycling of ashes to forestry; e.g. by pellets to ensure slow release of nutrients
- reduction of aerosols and NOx

**Examples of best available technology**
Danish manufacturers of best available technology are AL-2 Teknik A/S, Eurotherm A/S, Hollensen A/S and Weiss A/S, while the newest operational plants can be visited in the cities of Frederiksværk, Høng, Ry, Nakskov, Vejen, and Lemvig.

**Special remarks**
Straw fired boilers are approximately 20% more expensive than woodchips fired, both in investments and in operation and maintenance. (ref. 3)

**References**
1. Videncenter for Halm og Flis-fyring. anlægs- og driftsdata for flisfyrede varmeværker. May 1994.
2. Videncenter for Halm og Flis-fyring. Træ til energiformål. 1999.
3. Dansk Fjernvarme Forening, September 2004

**Data sheet**

| Technology | District heating boiler, wood-chips fired | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one plant (MW) | 1 - 50 | | | 1 |
| Total efficiency (%) net | 108 | | | 1 |
| Availability (%) | 96-98 | | | 2 |
| Technical lifetime (years) | 20 | | | 1 |
| Construction time (years) | 0.5 - 1 | | | 2 |
| **Environment** (Fuel: wood-chips; LHV 8.8 MJ/kg; 0.5% ash; 0.04% S) | | | | |
| $SO_2$ (kg per GJ fuel) | ~0 | | | 1 |
| $NO_X$ (kg per GJ fuel) | 0.08 | | | 2 |
| Particles (mg per GJ fuel)                          (B) | 14,600 | | | 2 |
| Other residuals, dry ash (kg per GJ fuel) | 1 | | | 2 |
| **Financial data**                          (A) | | | | |
| Specific investment (M€ per MW) | 0.25 - 0.6 | | | 2 |
| Total O&M (% of initial investment per year) | 3 | | | 2 |
| Total O&M (€ per MW per year) | 15000 - 25000 | | | 3 |

**References:**
1    Danish Association of District Heating Companies (DFF), December 2003
2    Elsams og Elkrafts opdatering af Energistyrelsens 'Teknologidata for el- og varmeproduktionsanlæg', december 1997
3    Danish Association of District Heating Companies (DFF), September 2004

**Remarks:**
A    The scale of economy is straightforward: The larger the plant, the lower the specific investments and O&M costs.
B    Calculated from 40 mg/Nm³ assuming this value refers to dry flue gas at 6% oxygen

# 52 DISTRICT HEATING BOILER, GAS FIRED
2004.10.05

**Brief technology description**
The fuel is burnt in the furnace section. Heat from the flames and the exhaust gas is used to heat water (or oil) in the boiler section.
Boilers for district heating have been used for decades. Today most boilers are used for peak-load or back-up capacity.

**Input**
Natural gas, with heavy fuel oil or gas oil as back-up fuel.

**Output**
District heat.

**Typical capacities**
0.5-20 MJ/s.

**Regulation ability**

**Advantages/disadvantages**

**Environment**
The only residue results from scaling.

**Research and development**
It is a commercial technology with insignificant need for R&D.

**References**

# Data sheets

| Technology | District heating boiler, gas fired | | | |
|---|---|---|---|---|
| | **2004** | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| Generating capacity for one plant (MW) | 0.5 - 10 | | | 2 |
| Total efficiency (%) net                 (A) | 97 - 105 | 97 - 105 | 97 - 105 | 2 |
| Availability (%) | 95 - 97 | | | 1 |
| Technical lifetime (years) | 20 | | | 1 |
| Construction time (years) | 0.5 - 1 | | | 1 |
| **Environment** (Fuel: natural gas) | | | | |
| $SO_2$ (kg per GJ fuel) | 0.0003 | | | 3 |
| $NO_X$ (kg per GJ fuel)                 (C) | 0.012-0.017 | | | 3 |
| Particles (mg per GJ fuel) | | | | |
| **Financial data** | | | | |
| Specific investment (M€ per MW)      (B) | 0.05-0.1 | 0.05-0.1 | | 2 |
| Total O&M (% of initial investment per year) | 2 - 5 | 2 - 5 | | 1 |
| Total O&M (€/MW/year) | 1000-5000 | | | 2 |

**References:**

1 Elsams og Elkrafts opdatering af Energistyrelsens 'Teknologidata for el- og varmeproduktionsanlæg', december 1997

2 Danish Association of District Heating Companies (DFF), September 2004

3 Emissions from large gas-fired boilers' (in Danish), Danish Centre for Gas Technology (DGC), 2003

**Remarks:**

A The high efficiencies are due to flue gas condensation

B Investment costs are 0.10-0.13 M€ for a 1 MW plant, 0.33 M€ for 5 MW and 0.47 M€ for a 10 MW plant.

C Low-NOx burnes; 0.030-0.055 kg/kJ if ordinary burners

# 53 GEOTHERMAL ENERGY
2004.12.20

**Brief description**
Geothermal energy is energy located in underground water reservoirs of the earth. In average the temperature of the reservoir increases with 3 ºC per 100 m depth, so at 3000 m the temperature is around 100 ºC.

Heat from this depth can be utilized directly through a heat exchanger. However, from Danish experiences it is economically more attractive to use heat pumps and extract heat from higher reservoirs, typically at 1000-2500 m depth. The heat pumps can either be compressor heat pumps driven with electricity or absorption pumps driven by heat. The assessment of when it is economically and environmentally optimal to use electrical heat pumps or absorption heat pumps depends of the energy source for production of the electricity.

In general terms geothermal energy is divided into the following systems:
- Low temperature (Denmark).
  Heat production from porous sandstone layers, typically 1000-2500 meters below surface. From these reservoirs it is possible to reach temperatures of 30-80 ºC. The geothermal system consists of a production well, heat exchangers and/or heat pumps transferring heat into the district-heating network and a re-injection well returning the cooled water to the same reservoir maintaining the reservoir pressure.
- Middle and high temperature.
Geothermal heat with a temperature level, where generation of both heat and power is possible. The high temperatures are often located in connection with volcanic activity.
- Hot dry rock geothermal energy.
Hot dry rock formations in the depth of 3000-4000 meters below surface is another source of geothermal energy. The technology for utilising the energy is still under development.

**Input**
Hot water from underground reservoirs. Temperatures from 35 to 300 ºC. Typical Danish temperatures are 40-70 ºC. The temperature increases with depth, in Denmark typically 30 ºC per kilometer.

**Output**
Heat for district heating.
Electricity, if temperatures are high.

**Typical capacities**
Typical capacities range from small units utilizing the geothermal energy for heating e.g. swimming pools (0.1 MJ/s) up to huge plants utilizing the geothermal water such as aluminium plants or district heating plants for cities up to 200,000 inhabitants (500-2000 MJ/s).

**Regulation ability**
Making an optimised geothermal energy system the general experience is that the geothermal energy should be used as base load, covering approximately 50% of the total district heat supply. The main reason is economy.

Also for power production the use of geothermal energy will serve as base load.

**Research and development**
Utilizing the Hot Dry Rock technology is still not fully developed. In US, GB, Japan and French Polynesia technicians are trying to utilize the energy in the deeper dry rock laying layers (3000-4000 m). The investigations consist of increasing the extremely small natural fractures to enable water to flow through the rock.

Heat storage is also at the investigation stage. Waste heat from solar plants and incineration plants may in summertime be used for heating the geothermal reservoir temperature. During wintertime it is then possible to increase the energy output from the reservoir. DONG is at the moment running tests for this purpose in Thisted, Denmark.

Better utilization of the geothermal resources could be achieved through lowering the district heating temperatures.

**Advantages/disadvantages compared to other technologies**

Advantages:
- Well known technology
- Cheap running costs and "fuel" for free
- Renewable energy source and environmental friendly technology with low $CO_2$ emission
- High running security and long lifetime

Disadvantages:
- No security for success before the first well is drilled and the reservoir has been tested
- High initial costs
- The best reservoirs not always located nearby cities
- Normally not feasible together with waste incineration

**Environment**
Utilization of geothermal energy is very $CO_2$ friendly.

**Examples of best available technology**
- In Denmark a geothermal energy plant in Thisted has been in operation since 1984. The 45 ºC warm water is boosted by an absorption heat pump for the district-heating network in Thisted. The plant has been operated with only minor technical problems.
- Two investigation wells have been drilled in Copenhagen to the depth of 2500 meters. Here the temperature reaches 73 ºC.

Other possibilities of utilising geothermal energy in Denmark are at Brønderslev, Hillerød, Hjørning, Holbæk, Kalundborg, Kerteminde, Nyborg, Randers, Roskilde, Skive and Aalborg.

Iceland is the country in the world where the utilization of geothermal energy is highest. More than 98 % of the heating for households comes from geothermal energy and the same levels are reached for electricity production. Furthermore, due to the low energy prices, several aluminium factories are located in Iceland. In Iceland a new plant using the Kalina process (the ammonia-water mixture is vaporised with geothermal water, which is cooled from 124 to 80 degree and used in a vapour

turbine) has been established and tested for the last 4 years. This process increases the electrical efficiency of the plant by 20-50 % (Ref. 1).

Other countries with high utilization of geothermal energy are USA, France, Italy, China, Austria, the Philippines, Indonesia and New Zealand.

The cost of producing geothermal heat to a district-heating network in Denmark depends primarily on:
- Availability of aquifer data or costs to obtain such data
- Depth, transmissivity and temperature of aquifers, distance to abnormalities such as faults
- Time dependant values through a normal year for:
  - Limits for the supply of heat and access to driving heat
  - Costs of electricity and absorption heat pump driving heat
  - Distances to connections for clean up water, power, driving heat and heat supply
  - District heating water temperature levels and water flow at connection point

Assuming 6% real interest on a 25 year loan financing a geothermal plant, heat production costs are typically in the range DKK 150-300 per MWh often requiring heat supply in the base load region to a district heating network with an annual heat demand of 500 TJ (140 MWh) or more. The variable costs often constitute around 40% of the total costs (Ref. 2).

The heat production costs vary a lot from place to place and they cannot be calculated from simple general equations. DONG VE has, however, developed tools to assess the costs together with Danish district heating companies interested in cooperation to establish such plants. (Ref. 2)

**Reference**
1) Product description - Geothermal Plants, Husavik Energi
2) DONG 2004

**Data for geothermal heat:**

| Technology | Geothermal heat-only plant with absorption heat pump, Denmark | | | |
| --- | --- | --- | --- | --- |
| | **2004** (A) | **2010-15** | **2020-30** | **Ref** |
| **Energy/technical data** | | | | |
| | | | | |
| Heat generation capacity (MJ/s) | 89 | 300 | 860 | 2;1;1 |
| Annual heat generation (TJ/Year) | 75 | 4500 | 12950 | 2;1;1 |
| Temperature of geothermal heat (degrees C) | 45 | | | |
| District heat forward temperature, winter (C) | 95 | 80 | 80 | 3 |
| Forced outage (%) | 0 | 0 | 0 | 1 |
| Capacity factor | 0.32 | 0.5 | 0.5 | 1 |
| Technical lifetime (years) | 25 | 25 | 25 | 1 |
| Construction time (years) | 4 | 3 | 3 | 1 |
| **Environment**　　　　Fuel: natural gas | | | | |
| Reduction $CO_2$ emissions (tonnes per year) | | 115-337 | | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW heat)　　　(B) (C ) | 1.1 | 0.8 | 0.8 | 3;1;1 |
| Total O&M (€/MWh), electricity excluded | 3.2 | 3.0 | 2.9 | 3 |
| Fixed O&M (€/MW heat per year)　　　(D) | | 13000 | 13000 | 1 |
| Variable O&M (€/MWh)　　　(D) | | - | - | |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | | | | |
| Regulation speed (MW per sec.) | | | | |
| Minimum load (% of full load) | | | | |

**References:**

1 Final report from the Geothermal Committee, Danish Energy Authority, Final draft, March 1998

2 Rambøll, 2004

3 Danish Energy Authority: "Teknologidata for vedvarende energianlæg, Del 1", 1995.

**Remarks:**

A Energy/technical data are from the geothermal plant in Thisted, Denmark, with an apsorption heat pump driven by natural gas

B Costs include heat pump

C DONG has estimated the investment costs based on experience from the plant in Copenhagen to be 1-2.5 ME/MW. The only method to assess the cost at a specific location is to analyse the main parameters influencing the costs and calculate the heat production costs based on these parameters. Capacity and energy dependent costs have, however, been requested and the following indicative cost relations has been established based on the simulation of the heat production costs for 20 plants with first right to production.

D DONG has estimated the O&M costs based on experience from the plant in Copenhagen to be 10000-30000 EUR/MW/year for the fixed O&M and 5-15 EUR/MWh for the variable O&M. Both the MW (capacity) and the MWh are based on the heat extracted from the geothermal water and the heat is assumed transferred to existing district heating networks using heat exchangers and absorption heat pumps. Power losses on CHP plants with steam turbines supplying drive heat to the absorption heat pumps may increase the costs with e.g. 2.5 EUR per MWh, whereas the supply of drive heat from district heating boilers carry no costs as all drive heat is transferred to the district heating network.

# 54 WASTE-TO-ENERGY DISTRICT HEATING PLANT
Draft 2004.10.10

**Brief technology description**
The major components are: A waste reception area, a feeding system, a grate fired furnace interconnected with a hot or warm water boiler, an extensive flue gas cleaning system and systems for handling of combustion and flue gas treatment residues.

The plant is primarily designed for incineration of municipal solid waste (MSW) and similar non-hazardous wastes from trade and industry. Some types of hazardous wastes may, however, also be incinerated.

The waste is delivered by trucks and is normally incinerated in the state in which it arrives. Only bulky items are shredded before being fed into the waste bunker.

**Input**
MSW and other combustible wastes, water and chemicals for flue gas treatment, gas oil or natural gas for auxiliary burners (if installed).

**Output**
Heat as hot (> 120 $^o$C) or warm (<120 $^o$C) water, bottom ash (slag), residues from flue gas treatment, including fly ash. If the flue gas is treated by wet methods, there may also be an output of treated process wastewater.

**Typical capacities**
5-15 tonnes of waste per hour, corresponding to a thermal input in the range 15-50 MW. Plants larger than 15 tonnes/h would typically be designed for combined heat and power.

**Regulation ability**
The plants can be down regulated to 60% of the nominal capacity, but for emissions control reasons they should be operated at base load.

**Advantages/disadvantages**
By incinerating the non-recyclable, combustible waste its energy content is utilised thereby replacing equivalent quantities of energy generated on fossil fuels. Moreover, the waste is sterilised, and its volume greatly reduced. The remaining waste (bottom ash/slag) may be utilised in construction works, and it will no longer generate methane. Consequently, by incinerating the waste, the methane emission generated, when landfilling the same quantity of waste, is avoided.

The disadvantages are that a polluted flue gas is formed, requiring extensive treatment, and that the flue gas treatment generates residues, which are classified as hazardous waste.

**Environmental aspects**
Waste is a mixture of $CO_2$ neutral biomass and products e.g. plastics of fossil origin. A typical $CO_2$ emission factor may be approximately 18 g/MJ for the waste mixture currently incinerated in Denmark. This is based on an emission factor for mixed plastics of 78.7 g/MJ (ref. 2) and assessed 6.6% of mixed plastic in the incinerated waste (ref. 3).

Ecological footprints are: air and water emissions including dioxins as well as solid residues to be disposed of.

**Research and development**
There is a potential of increasing the energy efficiency of waste fired district-heating plants by application of condensation of flue gas moisture.

Further challenges are the amount and quality of the residues (bottom ash, fly ash and flue gas cleaning residue). The continued use of bottom ash for road construction etc. is expected to take place under tightening demands on the contents and leachability of a range of pollutants, including salts, heavy metals and dioxin.

Similarly, the amount of hazardous waste (fly ash and flue gas cleaning residue) may be reduced by optimisation of the overall process. Also, treatment of residues may be further developed for recycling and/or disposal in landfills not dedicated for hazardous waste.

**Examples of best available technology**
Denmark has one of the major international suppliers of Waste-to-Energy district heating plants: Babcock & Wilcox Vølund ApS, Esbjerg, Denmark.

Due to the fact that the Danish energy policy has hitherto focussed on CHP, there are no recent examples of waste-to-energy district heating plants. However, Kolding Forbrændingsanlæg plans to establish such a line, which will be commissioned in 2007.

**Special remarks**
Contrary to other fuels used for energy generation, waste has a negative price and is received at a gate fee. The primary objective of a waste-to-energy plant is the treatment of waste, energy production may be considered a useful by-product.

To comply with European Union requirements (cf. Directive 2000/76) the flue gas must be heated to min. 850 $^{o}$C for min. 2 seconds and the gas must be treated for $NO_x$, dust (fly ash), HCl, HF, $SO_2$, dioxins and heavy metals. If HCl, HF and $SO_2$ are removed by wet processes, the wastewater must be treated to fulfil some specific water emission limit values.

By condensing most of the water vapour content of the flue gas in the flue gas treatment, a thermal efficiency (based on the net calorific value) of around 100% is achievable. At the same time the plant becomes self-sufficient in water.

The solid residues from flue gas and water treatment are hazardous wastes and are often placed in an underground storage for hazardous waste (cf. Council Decision 2003/33).

Recently, the Danish governmental subsidies on electricity produced in e.g. Waste-to-Energy CHP plants have been reduced. Consequently, the plants will now have to sell their electricity at market prices. This decision reduces the incentive to establish new incineration capacity based on CHP in Denmark, which in turn favours the establishment of district-heating Waste-to-Energy plants.

**References**

1. Kleis, H. and Dalager, S.: 100 Years of Waste Incineration in Denmark. Babcock & Wilcox Vølund and RAMBØLL, 2004.
2. Lov om $CO_2$-kvoter, LOV nr.493 af 09/06/2004. (Law of the Danish parliament on $CO_2$-allowance trading, cf. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC)
3. Affald 21, Miljø- og Energiministeriet, 1999, "Waste 21".

## Data sheet

| Technology | Waste to energy district heating | | | |
|---|---|---|---|---|
| | 2004 | 2010-15 | 2020-30 | Ref |
| **Energy/technical data** | | | | |
| Waste treatment capacity (tonnes/h) | 15 | 15 | 15 | 1 |
| Thermal input (MW) | 50.0 | 50.0 | 50.0 | 1 |
| Own consumption (MW-e) | 1.2 | 1.2 | 1.2 | 1 |
| Generating capacity for one unit (MW-e), gross | 0.0 | 0.0 | 0.0 | 1 |
| Generating capacity for one unit (MW-e), net | n.a. | n.a. | n.a. | 1 |
| Total efficiency (%) gross | 87.9 | 98    A | 100    A | 1 |
| Total efficiency (%) net | 85.5 | 95.6    A | 97.6    A | 1 |
| Electricity efficiency (%) gross - 100% load | 0 | 0 | 0 | 1 |
| Electricity efficiency (%) net - 100% load | n.a. | n.a. | n.a. | 1 |
| 75% load | n.a. | n.a. | n.a. | 1 |
| 50% load | n.a. | n.a. | n.a. | 1 |
| Start-up fuel consumption (GJ) | 1080 | 1080 | 1080 | 1 |
| Time for varm start-up (hours) | 12 | 12 | 12 | 1 |
| Cb coefficient | n.a. | n.a. | n.a. | 1 |
| Cv coefficient (40$^o$C/80$^o$C) | n.a. | n.a. | n.a. | 1 |
| (50$^o$C/100$^o$C) | n.a. | n.a. | n.a. | 1 |
| Forced outage (%) | 2 | 1 | 1 | 1 |
| Planned outage (weeks per year) | 3 | 3 | 3 | 1 |
| Technical lifetime (years) | 20 | 20 | 20 | 1 |
| Construction time (years) | 3 | 3 | 3 | 1 |
| **Environment** (Fuel: Waste, 12 MJ/kg, 0.4%S) | | | | |
| $SO_2$ (kg per GJ fuel) | 0.027 | 0.014 | 0.011 | 1 |
| $SO_2$ (degree of desulphurisation, %) | 95.9 | 98.0 | 98.4 | 1 |
| $NO_X$ (kg per GJ fuel), note C | 0.109 | 0.082 | 0.011 | 1 |
| $CH_4$ (kg per GJ fuel) | ~ 0 | ~ 0 | ~ 0 | 1 |
| $N_2O$ (kg per GJ fuel) | ~ 0 | ~ 0 | ~ 0 | 1 |
| Particles (mg per GJ fuel) | 5,500 | 2,700 | 1,100 | 1 |
| Ashes (kg per GJ fuel), bottom ash | 14 | 12 | 11 | 1 |
| Other residuals (kg per GJ fuel) | 1 | 1 | 1 | 1 |
| **Financial data** | | | | |
| Specific investment (M€/MW-e), note B | 1.0 | 0.9 | 0.9 | 1 |
| Fixed O&M (€/MW/year), note B | 49,000 | 44,000 | 43,000 | 1 |
| Variable O&M (€/MWh), note B | 5.1 | 4.5 | 4.4 | 1 |
| **Regulation ability** | | | | |
| Fast reserve (MW per 15 minutes) | n.a. | n.a. | n.a. | 1 |
| Regulation speed (MW per sec.) | n.a. | n.a. | n.a. | 1 |
| Minimum load (% of full load) | 75 | 75 | 75 | 1 |

**References:**

1 Rambøll Danmark, September 2004

**Remarks:**

A    With flue gas condensation
B    Energy reference is heat production
      Total costs are included, including the ones relating to waste treatment
C    NOx emissions are foreseen to be controlled by the SNCR process until 2015,
      and in 2020-30 application of the SCR-process is foreseen.