SINTEF

TR A7170- Unrestricted

Report

Small-scale biomass CHP recommendations for Norway

Author(s)
Øyvind Skreiberg

SINTEF Energy Research
Thermal Energy
2011-12-16

SINTEF Energi AS
SINTEF Energy Research

Address:
Postboks 4761 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 73597200
Telefax:+47 73597250

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

Report

Small-scale biomass CHP recommendations for Norway

KEYWORDS:
Biomass
CHP
Small-scale
Recommendations
Efficiency
Economy
Cost-efficiency

VERSION
1

DATE
2011-12-16

AUTHOR(S)
Øyvind Skreiberg

CLIENT(S)
KRAV project consortium

CLIENT'S REF.

PROJECT NO.
16X80702

NUMBER OF PAGES/APPENDICES:
29

ABSTRACT
This work deals with evaluations of different possible cost-effective small-scale CHP solutions based on biomass for the Norwegian market. Many CHP technologies and systems exist today, and can easily be proposed as candidates for introduction and/or widespread use in the Norwegian market. However, today they may be far from cost-effective given the current energy market and framework situation. These constraints can, however, change relatively fast. Hence, it is important to evaluate the feasibility of small-scale CHP technologies and systems in this perspective. What will the most promising small-scale CHP technologies based on biomass be in the near to medium term future? What are the limiting factors? What can be done to speed up the introduction of small-scale CHP solutions based on biomass in the Norwegian market? And, finally, what are the research needs, if any, connected to this? This work evaluates and discusses these aspects, and sheds some light on the challenges connected to commercial introduction of small-scale CHP solutions based on biomass in the Norwegian market. General recommendations are given (Chapters 2.3 and 3.3.) regarding size, capacity and utilization, choice of CHP or not CHP, balancing heat and power, choosing the right technology, industrial systems, own electricity consumption, and operational problems. Specific recommendations (Chapters 8.3 and 10) are given regarding Norwegian conditions and choice of conversion technologies and CHP technologies. Combustion and steam turbines dominate today, but this situation can change in the future depending on framework conditions improvements and technology development.

PREPARED BY
Øyvind Skreiberg

SIGNATURE

CHECKED BY
Mette Bugge

SIGNATURE
Mette Bugge

APPROVED BY
Lars Sørum

SIGNATURE
Lars Sørum

REPORT NO.	**ISBN**	**CLASSIFICATION**	**CLASSIFICATION THIS PAGE**
TR A7170	978-82-594-3500-2	Unrestricted	Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
Version No. 1	2011-12-16	

Table of contents

APPENDICES

1 Introduction

The biomass for bioenergy use in Norway is about 15 TWh and the Norwegian government aims at doubling the bioenergy use in Norway from 14 TWh in 2008 to 28 TWh in 2020[1]. Close to half of the bioenergy use today is in the point heating area (mainly wood stoves and closed fireplaces) and half of the increase was expected to come in this area. Bioenergy use in the wood processing industry was not expected to increase much, and the remaining bioenergy increase was expected to come mainly in the district heating sector. Electricity from biomass (bioel) was not a focus in the bioenergy strategy. Bioel has been generated for a long time both in the wood processing industry (using processing residues), in municipal solid waste (MSW) combustion plants (the biomass originating fraction of it), in landfill gas plants and in anaerobic digestion plants (using agricultural, animal, human or food residues), while bioel from ordinary biomass (e.g. wood chips) has not yet been introduced. However, bioel from demolition wood has been produced for a few years in one plant in Norway. Hence, the common view on bioel is that it is only feasible if the fuel comes with a gate fee (MSW), if the fuel is available anyway as residues (wood processing industry) or at a very low cost (demolition wood). However, this is expected to change as the framework conditions improve, e.g. through the planned introduction of green certificates for bioel in the Norwegian market in 2012[2].

Hence, it is important to evaluate the optimum combinations of biomass fuels, biomass conversion technologies and biomass CHP technologies in light of the Norwegian framework conditions, to assess the market possibilities for biomass CHP in Norway. Especially interesting is the small-scale bioel segment, with the potential of making distributed solutions for heating more widespread available through CHP. However, typically it is the small-scale segment that is least cost-efficient, i.e. the economy of scale factor comes into play and many of the available small-scale technologies are less mature in connection with biomass. This work is connected to the competence building project KRAV (Enabling small-scale biomass CHP in Norway; 2008-2012), funded by the Research Council of Norway, SINTEF Energy Research and five industry partners. Small-scale is defined as less than 10 MW fuel input in the KRAV project, but for scale effect evaluations units up to 10 MWel is included in this work.

2 Conversion technology options

Any bioel generation demands a conversion of the biomass to something (energy carrier) that can be directly used for the bioel generation. Combustion, with subsequent heat transfer to a medium that can drive a turbine or an engine is dominating today. Steam is the most common working medium, in steam turbines, and to a much smaller extent in steam engines. However, also organic oil vapor can be a working medium, as in an Organic Rankine Cycle (ORC), and air, helium or hydrogen can be working mediums in a Stirling engine and air and helium can be working mediums in a hot air turbine. Producing a combustible gas from the biomass instead introduces several important advantages with respect to the downstream CHP technology choices, such as increased electricity (el) efficiencies, especially compared to steam as working medium in the small-scale CHP segment. The combustible gas can be produced via gasification (syngas) or anaerobic digestion (biogas or landfill gas), for bioel generation in gas turbines, micro gas turbines, gas engines or fuel cells. In pyrolysis different fractions of bio-oil, gas and charcoal can be produced, and all these fractions can potentially be used for bioel generation. Biocarbon can e.g. be used in a carbon fuel cell. The maturity of the conversion technologies differs. Combustion is a well established and fully commercial biomass conversion technology, while gasification can still not be considered as fully commercial for biomass, despite intensive research and demonstration programs for a number of decades. Gasification is inherently more complex than combustion, and biomass is a more complex fuel to handle compared to coal. Pyrolysis can also still not be considered fully commercial for biomass, and the aim of pyrolysis is usually not subsequent el generation, but bio-oil or charcoal production. Anaerobic digestion is commercially available and is widely used.

---

[1] Bioenergistrategien, 2008, http://www.regjeringen.no/nb/dep/oed/tema/fornybar-energi/bioenergistrategien.html
[2] Regjeringen.no, 2009, http://www.regjeringen.no/nb/dep/oed/pressesenter/pressemeldinger/2009/overgangsordning-for-elsertifikatmarkede.html?id=587253.

2.1 Conversion technology comparisons

Combustion, gasification, pyrolysis and anaerobic digestion are conversion technologies that can be applied to convert the solid biomass to one or several energy carriers that can be used in a power production unit. Within the different conversions technologies there are several to many different technology options, depending mainly on plant size and fuel properties. Going through the different conversion technologies in detail is out of the scope of this report, and has been done previously in the KRAV project[3].

In this report a direct comparison of the different conversion technologies are relevant, with respect to scale, fuel options, advantages and disadvantages, commercialization status, efficiency, economy and cost-efficiency, see Table 1 to Table 3 and Figure 1.

Table 1 ***Conversion technology comparisons - Combustion.***

	Grate furnaces	BFB furnaces	CFB furnaces
Scale	200 kW to 50 MW	5-100 MW	20-550 MW
Fuel options	Fuel and particle size flexible	Fuel flexible. Particle size limitation (<80 mm)	Fuel flexible. Particle size limitation (<40 mm)
Advantages	- Low investment costs for plants <20 MWth - Low operating costs - Low dust load in the flue gas - Less sensitive to slagging than fluidized bed furnaces	- No moving parts in the hot combustion chamber - NOx reduction by air staging works well - High flexibility concerning moisture content and kind of biomass fuels used - Low excess oxygen (3–4 vol%) raises efficiency and decreases flue gas flow	- No moving parts in the hot combustion chamber - NOx reduction by air staging works well - High flexibility concerning moisture content and kind of biomass fuels used - Homogeneous combustion conditions in the furnace if several fuel injectors are used - High specific heat transfer capacity due to high turbulence - Use of additives easy - Very low excess oxygen (1–2 vol%) raises efficiency and decreases flue gas flow
Disadvantages	- Usually no mixing of wood fuels and herbaceous fuels possible (only special constructions can cope with such fuel mixtures) - Efficient NOx reduction requires special technologies (combination of primary and secondary measures) - High excess oxygen (5–8 vol%) decreases efficiency - Combustion conditions not as homogeneous as in fluidized bed furnaces - Low emission levels at partial load operation require a sophisticated process control	- High investment costs, interesting only for plants >20 MWth - High operating costs - Reduced flexibility with regard to particle size (<80 mm) - Utilization of high alkali biomass fuels (e.g. straw) is critical due to possible bed agglomeration without special measures - High dust load in the flue gas - Loss of bed material with the ash without special measures	- High investment costs, interesting only for plants >30 MWth - High operating costs - Low flexibility with regard to particle size (<40 mm) - Utilization of high alkali biomass fuels (e.g. straw) is critical due to possible bed agglomeration - High dust load in the flue gas - Loss of bed material with the ash without special measures - High sensitivity concerning ash slagging

[3] Roger Khalil, Øyvind Skreiberg, Lars Sørum. Småskala kraft/varme anlegg - Teknologistatus. SINTEF Energy Research report TR A6773.

Commercialization status	Fully commercial	Fully commercial	Fully commercial
Efficiency	Fair	Good (low O_2)	Very good (very high carbon burnout, very low O_2)
Economy	Good in a certain scale range	Good above a certain scale	Good above a certain scale
Cost-efficiency	Potentially good	Potentially good	Potentially good

Table 2 ***Conversion technology comparisons – Combustion and anaerobic digestion.***

	Underfeed stokers	Pulverized fuel combustion	Anaerobic digestion
Scale	50 kW to 2 MW	5-15 MW	Small (individual farms) to large (landfills)
Fuel options	Particle size limitation (<50 mm)	Pulverized fuel	Any digestible fuel
Advantages	- Low investment costs for plants - Simple and good load control due to continuous fuel feeding and low fuel mass in the furnace - Low emissions at partial load operation due to good fuel dosing	- Low excess oxygen (4–6 vol%) increases efficiency - High NOx reduction by efficient air staging and mixing possible if cyclone or vortex burners are used - Very good load control and fast alteration of load possible	- Gives a methane rich gas - Fuel flexible
Disadvantages	- Low flexibility in regard to particle size - Suitable only for biomass fuels with low ash content and high ash-melting point (wood fuels) (<50 mm)	- Particle size of biomass fuel is limited - High wear rate of the insulation brickwork if cyclone or vortex burners are used - An extra start-up burner is necessary	- Slow process - Only a part of the fuel can be digested - Gas cleaning is needed before use
Commercialization status	Fully commercial	Fully commercial	Fully commercial
Efficiency	Fair	Good	Poor (solid residue)
Economy	Good in a certain scale range	Good in a certain scale range	Good
Cost-efficiency	Potentially good	Potentially good	Good (residues as fuel)

Table 3 ***Conversion technology comparisons - Gasification.***

	Fixed bed	Fluidized bed	Entrained flow
Scale	10 kW to 10 MW	5-100 MW	>50 MW
Fuel options	Particle size limited (<50 mm)	Particle size limited (<6 mm)	Pulverized fuel (<1 mm preferred)
Advantages	- Simple and reliable design - Capacity for wet biomass gasification - Favorable economics on a small scale	- Short residence time - High productivity - Uniform temperature distribution - Low char and/or tar contents - High cold gas efficiency - Reduced ash-related problems	- Very low in tar and CO_2 - Feedstock flexible - High exit gas temperature - Slagging operation - Potentially very high carbon conversion - Low methane content – well suited for syngas production

Disadvantages	- Long residence time - Non-uniform temperature distribution - High char and/or tar contents - Low cold gas efficiency - Low productivity - Fuel blockages in gasifier throat - Corrosion in gasifier throat - Gas leakages and explosions	- High dust load in syngas - Favorable economics from medium to large scale	- Low in CH4 - if upgrading to SNG is wished for - Extreme feedstock size reduction needed - Complex operational control - Carbon loss with ash if not optimally operated - Ash slagging if not optimally operated
Commercialization status	Early commercial	Early commercial	Early commercial
Efficiency	Fair	Good	Very good
Economy	Poor	Poor	Poor
Cost-efficiency	Poor	Poor	Poor

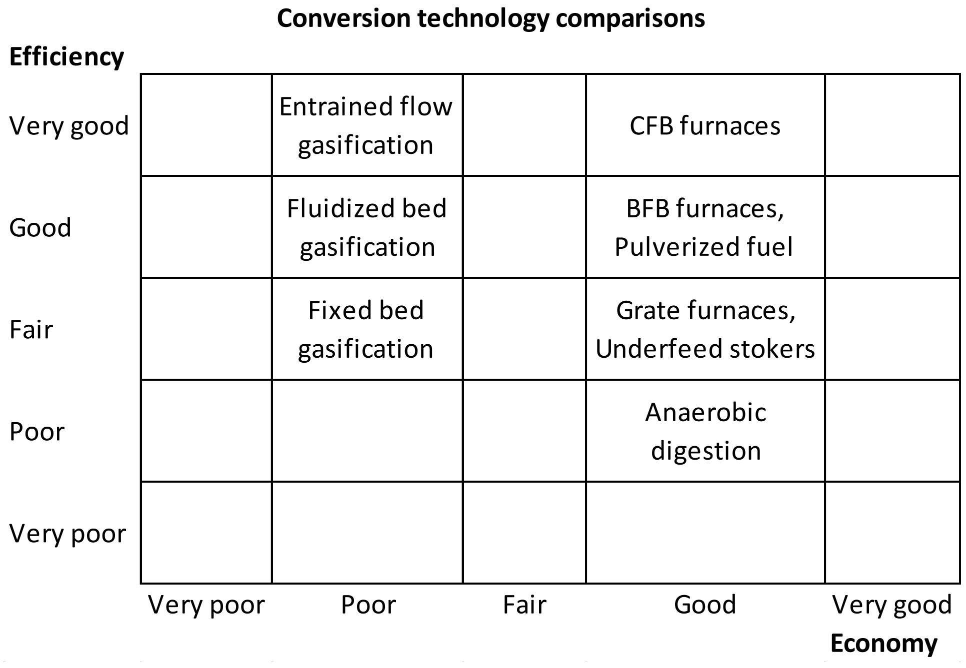

Figure 1. ***Conversion technology comparisons. Efficiency versus economy.***

2.2 Conversion technology improvement potentials

The conversion technology improvement potentials vary, depending on both development status and fuel options.

Obviously, **combustion** of biomass can be considered as a commercial conversion technology. However, there are biomass fuels, especially agricultural and forestry residues, that demand more of the combustion technology than high quality biomass fuels do. Hence, the improvement potential lies mainly in ensuring an optimum conversion of so-called problematic or low-quality biomass fuels in existing combustion technologies. This demands adaption of these existing combustion technologies rather than development of new ones. The need for adaption is mostly connected to the ash amount and properties, causing slagging, sintering, agglomeration, fouling, corrosion and increased emissions. In addition fuel handling and feeding can be a challenge depending on the fuels' physical properties. Fuel upgrading is an option to circumvent problematic physical properties of the fuels. Drying and densification (to pellets or briquettes) are possible non-thermal fuel upgrading options, while torrefaction and carbonization are possible thermal fuel upgrading options giving a solid fuel with improved fuel properties. Fuel mixing or additives are options for improving the fuel ash composition, i.e. decreasing the negative effects of problematic ash elements like alkali metals and chlorine. However, fuel upgrading adds an additional cost which must be justified through other reduced costs (investments, operation and maintenance) and/or efficiency improvements. Small-scale combustion technologies, not having economy-of-scale benefits and also less economic possibilities regarding advanced process monitoring and control and secondary flue gas cleaning options, have a disadvantage compared to medium- to large-scale combustion technologies.

Gasification converts the solid fuel to a combustible gas, giving a fuel which is easier to combust in a downstream unit (burner, engine or turbine) or which can be electrochemically converted in a fuel cell. Having the fuel in gas form also gives advantages with respect to the achievable el efficiency in a downstream CHP technology, especially at small-scale, and the gas can e.g. be cleaned before combusting it, i.e. the gas volume that needs to be cleaned is much smaller than the corresponding flue gas volume after complete combustion with air as oxidant. Pressurizing the gasification process is also possible, with additional efficiency advantages. As for combustion, several gasification technologies exist. Why gasification is not widely applied today? Biomass is a complex solid fuel, and a gasification process is inherently more challenging to control than a combustion process, and especially at pressurized conditions. This adds extra complexity and costs to the conversion plant and puts higher demands on the fuel quality. Gasification must still be regarded as an immature conversion technology when it comes to biomass, simply because biomass is a heterogeneous (both physically and chemically) and hence a difficult fuel. Gasification of coal is much easier in comparison.

Pyrolysis is an option for combined primary product and energy production. Besides being an integral process of a biomass combustion process, pyrolysis is used for producing either bio-oil or charcoal as the main product. The non-primary products are used for sustaining the endothermic conversion process and the excess can be used for energy production. The bio-oil is mainly useable as a fuel in a decoupled combustion process. The challenging properties of bio-oil make upgrading it for transport purposes unattractive. Charcoal, however, have several uses, but again a decoupled combustion process is the main area of use.

Anaerobic digestion is a well known and easily controllable conversion process, for making a CH_4 rich gas for stationary or transport use. The produced gas needs upgrading for transport use and demands an easily degradable material. However, in the case of anaerobic digestion the fuel properties are not as important as for the other conversion technologies. In principle it is possible to use enzyme additives to break down the not easily degradable fractions of also lignocellulosic biomass relatively fast, however, this is still in an early stage of research. Methods like steam explosion can also be used to break down the fibrous structure of a lignocellulosic feedstock.

2.3 Conversion technology recommendations

The following general recommendations can be given for conversion technologies to be coupled with CHP technologies:

- select the proper plant size
- select the proper conversion technology for your fuel and CHP technology
- or adapt (can be costly) an existing conversion technology if your fuel is very special
- or adapt the fuel to your conversion technology (drying, homogenization, densification, fuel mixing, additives, thermal upgrading)
- ensure maximum fixed carbon conversion (except for pyrolysis if charcoal is the primary product)
- reduce thermal losses in the conversion technology
- use the produced energy in an optimum way (heat, steam, el, secondary fuel)

- avoid operational problems like slagging, sintering and agglomeration causing plant downtime
- control fouling and corrosion to reduce O&M costs and connected plant downtime
- control emission by primary measures if possible

3 CHP technology options

Steam turbines, steam engines, gas turbines, micro gas turbines, hot air turbines (externally fired gas turbines), gas engines, ORC, Stirling engines and fuel cells are CHP technology options. Alone, most of them are commercially available, but in a biomass CHP system, i.e. coupled to a biomass conversion technology, they are either commercially available, in a demonstration phase or in a research and development phase. The most used (dominating) CHP system for biomass is combustion and steam turbine, while steam engine is a commercial alternative in the small-scale segment. Also gas engines run on gas from landfills or anaerobic digestion are commercially available. Gasification based CHP systems for biomass are, however, not fully commercially available, despite some claiming their specific system to be. This is due to technical/operational challenges related mainly to the gasification process and the control of this, reducing their reliability and availability, and high cost, due to their complexity. The commercial aspects of ORC, Stirling engine, hot air turbines and fuel cells are very dependent on framework conditions, and only ORC can be said to be commercially available, and only in a market which is strongly supporting bioel generation (high feed-in tariffs or green certificates). Figure 2 shows the development status of the main upgrading technologies, biomass to heat technologies and biomass to power & CHP technologies. Pelletisation is regarded as the only commercial biomass densification process and combustion as the only commercial biomass to heat technology. For biomass to CHP technologies the only commercial technologies are combustion and steam cycle, direct co-firing and steam cycle and 1-stage anaerobic digestion and gas engine.

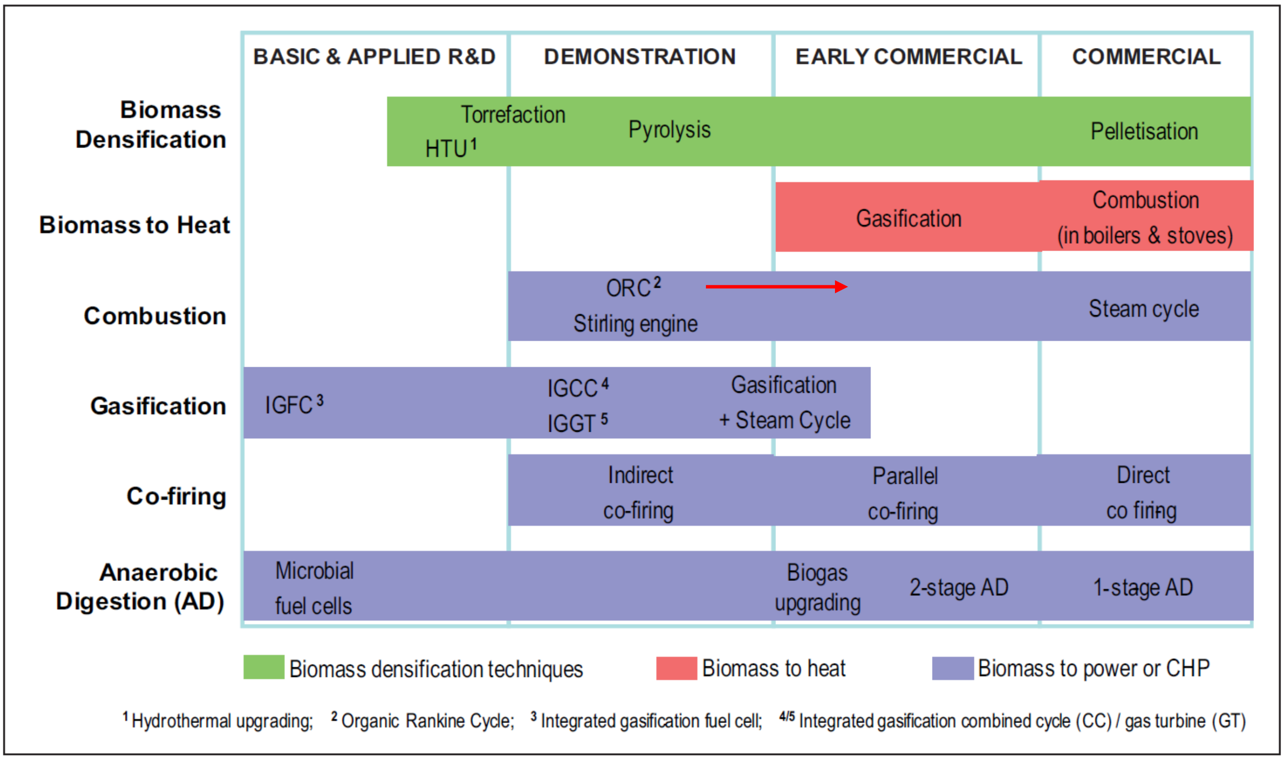

Figure 2. ***Development status of the main upgrading technologies (green), biomass to heat technologies (red) and biomass to power & CHP technologies (blue).*** [4]

[4] IEA BIOENERGY: ExCo: 2009:06.

3.1 CHP technology comparisons

Different CHP technologies can be applied to convert the heat or gas generated in the conversion technology to el and useful heat. Within the different CHP technologies there are for some of these several technology options, depending mainly on plant size and heat transfer principle. Going through the different CHP technologies in detail is out of the scope of this report, and has been done previously in the KRAV project [3,5].

In this report a direct comparison of the different CHP technologies are relevant, with respect to scale, cycle / medium / heat transfer principle, advantages and disadvantages, commercialization status, efficiency, economy and cost-efficiency, see Table 4 to Table 6 and Figure 3.

Table 4 ***CHP technology comparisons.***

	Steam turbines	Steam engines	Gas turbines	Micro gas turbines
Scale	50 kW to 500 MW	0.3 kW to 2 MW	500 kW to 250 MW	30-250 kW
Cycle / medium / heat transfer principle	Rankine / steam / external	Rankine / steam / external	Brayton / flue gas / none (direct)	Brayton / gas / none (direct)
Advantages	- Mature, proven technology - Broad power range available - Separation between fuel and thermal cycle, enabling the use of fuel containing ash and contaminants - High pressures and temperatures can be applied enabling high efficiencies for large plants - Co-firing of fossil fuels and biomass is possible to enable high efficiency	- Suitable for low power ranges - Saturated steam can be used - Efficiency almost independent of partial load - Steam extraction at different pressures possible due to modularity	- High reliability - Low emissions - High grade heat available - No cooling required	- Small number of moving parts - Compact size and light weight - Low emissions - No cooling required
Disadvantages	- Only limited efficiencies are reached in small, decentralized plants due to investment and technology limitations - High specific investment for low power ranges - High operation costs for small and medium plants - Low part-load efficiencies - Variations in fuel quality lead to variation of steam and power production - Superheater temperature (and therefore efficiency) can be limited due to high temperature corrosion and fouling, especially due to alkali metals, chlorine, and sulphur - High-quality steam is necessary	- Traces of oil in expanded steam for older engines - Maximum power output per steam engine is limited - High levels of vibration and noise	- Require high pressure gas or in-house gas compressor - Poor efficiency at low loading - Output falls as ambient temperature rises	- High costs - Relatively low mechanical efficiency - Limited to lower temperature cogeneration applications

[5] Øyvind Skreiberg, Kristian Lien. Evaluations of biomass CHP technologies in a Norwegian context. SINTEF Energy Research report TR A6809.

Commerciali-zation status	Fully commercial	Fully commercial	Demonstration for biomass	Demonstration for biomass
Efficiency	Good	Poor	Good	Good
Economy	Good	Fair	Poor	Poor
Cost-efficiency	Good	Fair	Fair	Fair

Table 5 ***CHP technology comparisons.***

	Gas engines	ORC	Stirling engine	Hot air turbine (Externally fired gas turbine)
Scale	10 kW to 75 MW	400 kW to 3 MW	1- 100 kW	20 kW to 1 MW
Cycle/medium/ heat transfer principle	Otto or Diesel / gas / none (direct)	Rankine / organic oil vapor / external	Stirling / air, helium or hydrogen / external	Brayton / air or helium / external
Advantages	- High power efficiency with part-load operational flexibility - Fast start-up - Relatively low investment cost - Can be used in island mode and have good load following capability - Can be overhauled on site with normal operators - Operate on low-pressure gas	- High cycle efficiency - Very high turbine efficiency (up to 90%) - Low mechanical stress of the turbine due to low peripheral speed - Low RPM of the turbine allowing direct drive of the el generator without reduction gear - No erosion of blades, thanks to the absence of moisture in the vapor nozzles	- External heat source drives the engine - Fuel quality is less important - Few moving parts gives lower maintenance costs - External combustion gives better emission control possibilities - Low noise	- Turbine components are isolated from combustion products - El efficiency is acceptable even at small sizes - Long maintenance intervals, high availability - Ideal for cogeneration plants (CHP) due to high exhaust temperatures
Disadvantages	- High maintenance costs - Limited to lower temperature cogeneration applications - Relatively high air emissions - Must be cooled even if recovered heat is not used - High levels of low frequency noise	- High investment cost - Limited experience with biomass - The working medium can catch fire and is poisonous - Low pressure gives low el efficiency	- Low el efficiency with biomass - Sealing challenges - High investment cost - Corrosion on high temperature heat exchanger - Slow heat-up and not suitable as stand-by power unit	- Expensive - Heat exchanger is exposed to high temperature, aggressive combustion gases - Partial load decreases efficiency
Commercialization status	Fully commercial	Early commercial for biomass	Demonstration for biomass	Applied R&D
Efficiency	Good (based on gas input)	Fair	Fair	Fair
Economy	Good	Fair	Poor	Poor
Cost-efficiency	Good	Fair	Poor	Poor

Table 6 ***CHP technology comparisons.***

	Gas fuel cells	Carbon fuel cell	BIGCC	SOFC-GT
Scale	5 kW to 2 MW	Not established (at a basic R&D stage)	10-300 MWth	Not established (SOFC limited)
Cycle/medium/heat transfer principle	None / electrons / none	None / electrons / none	Brayton and Rankine / gas and steam / none (direct) and external	None and Brayton / electrons and gas / none and none (direct)
Advantages	- Low emissions and low noise - High efficiency over load range - Modular design	- Use carbon rich solid material as fuel - Very high el efficiency possible (80%) - Operates at 700°C, good for CHP - No reforming necessary - Humidified air as oxidant	- High el efficiency possible using the heat in the gas turbine flue gas to produce steam	Very high el efficiency possible using the pressurized SOFC off-gas in a gas turbine
Disadvantages	- High costs - Low durability and power density - Fuels requiring processing unless pure hydrogen is used	- Complex - Fuel carbon purity dependence - At a basic R&D stage	- Fully commercial concept for natural gas with 60% el efficiency possible. However, the biomass gasification step is the weak link - Pressurized gasification process with high temperature gas cleaning needed to maintain a high el efficiency	- SOFC running biomass gasification gas is still in a development stage - SOFC is very expensive
Commercialization status	Demonstration for biomass	Basic R&D	Demonstration for biomass	Basic R&D
Efficiency	Very good	Very good	Very good	Very good
Economy	Very poor	Very poor	Poor	Very poor
Cost-efficiency	Very poor	Very poor	Fair	Very poor

BIGCC: Biomass Integrated Gasification Combined Cycle. SOFC-GT: Solid Oxide Fuel Cell - Gas Turbine

CHP technology comparisons

Efficiency (el)					
Very good	Carbon fuel cell, Gas fuel cells, SOFC-GT	BIGCC			
Good		Gas turbines, Micro gas turbines		Steam turbines, Gas engines	
Fair		Stirling engine, Hot air turbine	ORC		
Poor			Steam engines		
Very poor					
	Very poor	Poor	Fair	Good	Very good
					Economy

Figure 3. ***CHP technology comparisons. Efficiency (el) versus economy.***

3.2 CHP technology improvement potentials

The CHP technology improvement potentials vary, depending on both development status and fuel options.

Steam turbines: Very far developed technology and very small el efficiency improvements can be expected. The higher the steam temperature and pressure the higher el efficiency can be achieved. Intermediate heating and cooling steps in increasing numbers can further increase the el efficiency. For problematic fuels the steam temperature is a limiting factor, due to corrosion risk. Hence, development of cost-effective materials that can reduce corrosion and hence increase the steam temperature is important.

Steam engines: Very far developed technology, with very limited improvement potential.

Gas turbines: Very far developed technology for natural gas or diesel as fuel, but biomass gasification gas can also be used, with reduced el efficiency, and the gasification gas needs to be cleaned. The improvement potential lies mainly on the biomass gasification side, i.e. producing a high heating value gas with stable composition and reduced gas cleaning needs.

Micro gas turbines: Far developed technology, with el efficiency penalty due to small scale. The improvement potentials are as for gas turbines.

Gas engines: Very far developed technology, which runs very well on natural gas. Use of biomass gasification gas, with reduced heating value and gas cleaning needs, results in reduced el efficiency and increased maintenance needs.

ORC: Very far developed technology. It employs external heat transfer to closed thermal cycle at moderate temperatures. Up-scaling to larger units is a key development effort.

Stirling engine: Far developed technology. It employs external heat transfer to closed thermal cycle at relatively high temperatures. The improvement potential lies mainly on the heat transfer side, especially using biomass, i.e. avoiding fouling on the high-temperature heat exchanger.

Hot air turbine (Externally fired gas turbine): Less developed technology. It employs external heat transfer to closed thermal cycle at high temperatures. The improvement potential lies mainly on the heat transfer side, especially using biomass, i.e. avoiding fouling on the high-temperature heat exchanger.

Fuel cells: Several types of fuel cells exist, where most can be said to be well developed. However, fuel cells are inherently sensitive to impurities in the fuel gas. Hence, gas cleaning of biomass derived gas is needed. Solid Oxide Fuel Cells (SOFC) are maybe most interesting (high el efficiency and high off-gas temperature), but high temperature gas cleaning is then needed. A carbon fuel cell is an alternative, but is still in an early stage of research. The improvement potential lies mainly in reducing the gas cleaning needs (improved gas quality) and developing improved fuel cell stack materials that tolerate higher levels of impurities.

Combined CHP systems: Combining e.g. a gas turbine cycle and a steam turbine cycle to achieve very high el efficiency is possible (biomass integrated gasification combined cycle, BIGCC). It is also possible to combine a SOFC with a gas turbine (SOFC-GT) for high el efficiency. The improvement potential is as for the standalone CHP technologies, together with improved/optimized system configurations.

CHP systems in general: There is a general improvement potential connected system configurations optimization. The optimum system configuration depends on many factors, and the configuration giving the highest el efficiency may not be very cost-effective.

The above mentioned improvement potentials are mainly connected to fuel related aspects, and not to the CHP technology itself. This is why the final CHP concept to be studied in the last two years of the KRAV project has been "**Optimum fuels, fuels mixtures and fuel combinations for biomass CHP concepts in Norway**".

3.3 CHP technology recommendations

The following general recommendations can be given for CHP technologies coupled with conversion technologies:

An important study[6] on the practical performance of CHP systems was carried out in the EU Altener programme, and was reported in 2006. The aim of the study was performance comparison and recommendations for future CHP systems utilising biomass fuels. Their conclusions can be summarised as follows:

Big is beautiful: For plants in operation one observes higher efficiency, lower own consumption and better availability for the larger plants, which means that larger plants perform significantly better in fossil fuel substitution and in operational economic performance. Larger plants also show lower investment cost relative to the size of the plant. Hence, for the resources given (capital, biomass, manpower) the bigger the plant, the more renewable energy is produced. However, the biomass CHP systems are limited by the biomass availability and the size of the heat market they can be connected to. For biogas and landfill gas engine systems the size dependency is less significant than for other commercially competing technologies of today. Market development and series production might bring down future capital costs for small-scale systems.

Capacity and utilisation: There is a general tendency that the CHP plants are built with a too high capacity, i.e. a low utilisation factor. Selecting the right size of a CHP system is a challenge due to seasonal variations and the price of el versus heat, and if relevant estimation of the future heat demand.

CHP or not CHP: Depending on incentives and other factors, CHP may not be very beneficial, resulting in low utilisation of the heat. Biogas and landfill gas plants may only to a limited extent utilise the heat, and gate fees for e.g. animal manure and economic incentives favouring el generation may give less focus on heat utilisation in such plants. However, as long as some heat is utilised, they are still CHP plants. A similar situation can occur for large waste incineration plants, if the heat customers are too few, and therefore not all the heat is utilised. Due to gate fees economical operation is still possible.

Balancing heat and power: El should be the most valuable product from an efficiency viewpoint, however, for industrial plants (steam and process heat), and for plants located where renewable heat has a high value (e.g. Nordic countries) the value of el and heat may become more balanced.

[6] Evald A, Witt J. Biomass CHP best practice guide, 2006, http://bio-chp.dk-teknik.dk/cms/site.aspx?p=802

Choosing the right technology: Many biomass CHP technology options exist, giving different el efficiencies. Incomes from el sales must be balanced against the additional costs of the el generation part of the plant. Hence, optimising the el efficiency will be very important, and steam cycles are very sensitive to the scale of operation in this respect.
Industrial systems: Industrial systems are often built to provide industrial processes with steam and process heat, often with one specific customer in mind. Hence, focus on optimum el efficiency in industrial CHP plants is often less prioritised.
Reducing own consumption: A CHP plant's own el consumption may consume a significant part of the el generated by the plant. The net el generated in a plant is what you can sell, and depends on the choice of CHP technology and the el need of auxiliary equipment in the plant. Modern plants are more efficient than old ones. For CHP technologies with a relatively low gross el efficiency, a very large fraction of that el may be needed within the plant.
Operational problems: Operational problems are connected to fuel related effects as sintering, fouling and corrosion, and fuel moisture content variations. Due to the operational problems the el efficiency decreases and the O&M costs increase, significantly influencing the total economy of the plant.

See Chapter 10 for more specific recommendations.

4 Biomass resources in Norway and fuel considerations

A realistic Norwegian biomass for bioenergy potential is about 33 TWh/yr, and includes woody biomass, agricultural residues, biogas and biomass originating waste fractions. The about 15 TWh bioenergy use today consists of about 50% wood logs/chips/pellets, 35% wood residues in industry, 10% MSW and 5% others (2009). The use of agricultural residues and biogas (in others) is limited, but increasing. Table 7 shows the Norwegian annual biomass potential of increase and its estimated costs, according to NVE[7]. About half of this is estimated to be available at a cost below 30 øre/kWh (1 Euro = 8 kr = 800 øre). About 50% of the MSW can be regarded as biomass. The use of biomass for energy purposes is very modest compared to Sweden and Finland, partly due to Norway's topography and resource base, settlement pattern and different taxation policy on alternative energy carriers (fossil fuels and hydro el).

Table 7 ***The Norwegian annual biomass potential of increase. Assembled from NVE, 2010.***

	TWh	øre/kWh	Range
Straw	1.3	13	(10-16)
GROT (branches and tops)	4.8	17	(15-18)
Forest thinnings	3.2	26	(21-30)
Biogas - Sewage sludge	0.3	15	(11-19)
Biogas - Animal manure	2.5	37	(28-46)
Biogas - Household waste	0.8	69	(28-110)
Biogas - Industrial waste	1.4	78	(46-110)
Wood for wood logs/chips	2.5	25	(0-50)
Wood from cultivated landscape	0.7		
Wood from clearings	0.45		
Cereal residues	0.08		
Sum	**18.03**		

Regarding biomass fuels utilization, guiding values and guiding ranges for elements in biomass fuels and ashes for unproblematic thermal utilization are given in Table 8.

[7] NVE, 2010, Tilgangen til fornybar energi i Norge, NVE Rapport 2/2010. Available at www.nve.no.

Table 8. ***Guiding values and guiding ranges for elements in biomass fuels and ashes for unproblematic thermal utilization.*** [9]

Element	Guiding concentration in the fuel wt% (d.b.)	Limiting parameter	Fuels affected outside guiding ranges	Technological methods for reducing to guiding ranges
N	< 0.6	NO_x emissions	Straw, cereals, grass, olive residues	Primary measures (air staging, reduction zone)
	< 2.5	NO_x emissions	Waste wood, fibre boards	Secondary measures (SNCR or SCR process)
Cl	< 0.1	Corrosion	Straw, cereals, grass, waste wood, olive residues	– fuel leaching – automatic heat exchanger cleaning – coating of boiler tubes – appropriate material selection
	<0.1	HCl emissions	Straw, cereals, grass, waste wood, olive residues	– dry sorption – scrubbers – fuel leaching
	< 0.3	PCDD/F emissions	Straw, cereals, waste wood	– sorption with activated carbon
S	< 0.1	Corrosion	Straw, cereals, grass, olive residues	See Cl
	< 0.2	SO_x emissions	Grass, hay, waste wood	See HCl emissions
Ca	15–35	Ash-melting point	Straw, cereals, grass, olive residues	Temperature control on the grate and in the furnace
K	< 7.0	Ash-melting point, depositions, corrosion	Straw, cereals, grass, olive residues	Against corrosion: see Cl
	–	Aerosol formation	Straw, cereals, grass, olive residues	Efficient dust precipitation, fuel leaching
Zn	< 0.08	Ash recycling, ash utilization	Bark, woodchips, sawdust, waste wood	Fractioned heavy metal separation, ash treatment
	–	Particulate emissions	Bark, woodchips, sawdust, waste wood	Efficient dust precipitation, treatment of condensates
Cd	< 0.0005	Ash recycling, ash utilization	Bark, woodchips, sawdust, waste wood	See Zn
	–	Particulate emissions	Bark, woodchips, sawdust, waste wood	See Zn

Explanations: Guiding values for ashes related to the biomass fuel ashed according to ISO 1171–1981 at 550°C; analytical method recommended for ash analysis: pressurized acid digestion and inductively coupled plasma mass spectometry (ICP) or flame atomic absorption spectometry (AAS) detection; N and S analysis recommended: combustion/gas chromatographic detection; Cl analysis recommended: bomb combustion/ion chromatographic detection. d.b. = dry basis.

In addition to a pure fuel, harvesting of the fuel may introduce additional inert and/or reactive components, depending on their properties and the conversion process conditions. Soil and gravel may be introduced into the conversion process together with the fuel, especially if low-quality fuels like GROT (branches and treetops) and roots are used. The challenges connected to this may only be mechanical and also result in an increased bottom ash amount. However, at high enough temperatures also thermal effects may be seen and ultimately they may become reactive components. On the other side, the use of additives may enhance the properties of low-quality biomass fuels, but may also influence the conversion process and increase the ash amount. Drying of biomass is in general beneficial with respect to conversion process efficiency. Use of waste heat may be cost-effective for drying purposes (e.g. drying of garden waste), but this will be case specific.

5 Current biomass CHP and planned CHP in Norway

The current biomass CHP production in Norway, for 2009, is given in Table 9. An annual power to heat ratio is calculated together with an annual el utilization factor and the corresponding full load hours per year. Also the steam turbine/engine installation year is given. A total installed effect of 136 MWel equals maximum 1193 GWhel annual el production capacity. The mean annual power to heat ratio is 0.12 and the mean annual el utilization factor is 0.34, corresponding to 3019 full load hours per year.

Table 9. ***The current biomass CHP production in Norway. Assembled from Norheim et al., 2011.***

Biomass CHP in Norway	Installed turbine/engine effekt	Power production 2009	Heat production 2009	Annual power to heat ratio	Annual el utilisation factor	Full load hours per year	Turbine/ engine installed year
	MWel	GWhel	GWhth	-	-		
Wood processing residues	82	159	2262	0.07	0.22	1939	
MSW	46	167	903	0.18	0.41	3630	
Waste wood	2	15	65	0.23	0.86	7500	
Landfill gas	10	41	61	0.67	0.47	4100	
Biogas	6	29	unknown		0.58	5044	
Sum total	**136**	**411**	**3291**	**0.12**	**0.34**	**3019**	
Södra Cell Tofte	50	159	1378	0.12	0.36	3180	1971 (10 MWel) 1980 (40 MWel)
Norske Skog Saugbrugs, Halden	10	0	335		0.00	0	1968
Norske Skog Skogn	10	0	349		0.00	0	1967
Norske Skog Follum	12	0	200		0.00	0	1970
Sum wood processing residues	**82**	**159**	**2262**	**0.07**	**0.22**	**1939**	
Solør Fjernvarme, Kirkenær	2	15	65	0.23	0.86	7500	2008
Sum waste wood	**2**	**15**	**65**	**0.23**	**0.86**	**7500**	
EGE Klemetsrud, Oslo	10	70	200	0.35	0.80	7000	1986
BIR, Bergen	10	35	130	0.27	0.40	3500	2000
Tafjord Kraftvarme, Ålesund	5	23	100	0.23	0.53	4600	2009
BioEl, Fredrikstad	5.5	18	130	0.14	0.37	3273	2008
Forus Energigjenvinning, Stavanger	2.8	14	60	0.23	0.57	5000	2002
Nordmøre Energigjenvinning, Averøya	2.2	5	70	0.07	0.26	2273	2000
FREVAR, Fredrikstad	0.7	0	210		0.00	0	1984
Senja Avfall, Sørreisa	0.3	2	3	0.67	0.76	6667	2007
Sum MSW	**46.5**	**167**	**903**	**0.18**	**0.41**	**3591**	
VEAS	2.3	13			0.65	5652	
FREVAR	0.36	2.4			0.76	6667	
MOVAR	0.07	0.3			0.49	4286	
Kongsberg	0.14	0.8			0.65	5714	
Ecopro	1.25	6.1			0.56	4880	
Mjøsanlegget	0.63	2.2			0.40	3492	
IATA	0.33	1			0.35	3030	
HRA AS	0.33	1.25			0.43	3788	
HIAS IKS	0.25	1.5			0.68	6000	
Sum biogas	**5.66**	**28.55**			0.58	5044	
Landfill gas total	**10**	**41**	**61**	**0.67**	**0.47**	**4100**	

Note: Norske Skog plants were not in operation in 2009 due to technical problems. Senja Avfall is the only steam engine CHP plant.

The planned (from 2010) biomass CHP production in Norway is given in Table 10. A total planned effect of 118.3 MWel equals maximum 1036 GWhel annual el production capacity.

Table 10. ***The planned biomass CHP production in Norway. Assembled from Norheim et al., 2011.***

Planned biomass CHP in Norway	Installed turbine/engine effekt	Power production	Heat production	Annual power to heat ratio	Annual el utilisation factor	Full load hours per year	Turbine to be installed year
	MWel	GWhel	GWhth	-	-		
Wood processing industry	**20**	**120**	**0**		**0.68**	**6000**	
BIR, Bergen	10	60	0		0.68	6000	2010
Returkraft, Kristiansand	11.5	95	255	0.37	0.94	8261	2010
Eidsiva, Hamar	6.8	40	150	0.27	0.67	5882	2011
EGE Klemetsrud, Oslo	10	60	0		0.68	6000	2011
Sum MSW combustion	**38.3**	**255**	**405**		**0.76**	**6658**	
Fiborgtangen, Skogn	15	100	170	0.59	0.76	6667	2012
Sum gasification	**15**	**100**	**170**	**0.59**	**0.76**	**6667**	
Eidsiva, Gjøvik	5	30	0		0.68	6000	2013
Statkraft Varme, Ranheim	20	120	0		0.68	6000	2015
Others	20	120	0		0.68	6000	until 2020
Sum district heating	**45**	**270**	**0**		**0.68**	**6000**	
Sum total	**118.3**	**745**	**575**		**0.72**	**6298**	
An additional 6 GWhel and 8 GWhth from landfill gas is estimated together with 10-20 GWhel from biogas							

Note: The estimate of the additional future (until 2020) district heating CHP potential (Others in the table) was made by Norheim et al.[8] based on district heating license applications. They assumed plants with at least 10 MWth delivered effect, and with a potential of 2 MWel production in such a plant. Assuming 6000 full load hours per year this gives 12 GWhel per 2 MWel. According to the license applications 70-100 MWth effect was applied for, giving 14-20 MWel potential and 84-120 GWhth. The higher estimate has been used here.

A relatively small increase in el production from biogas is estimated. Biogas, or the methane part of it, also has an alternative value as transport fuel. The amount of landfill gas will later decrease with time as the resource becomes more and more depleted. Bioel production in connection with future carbon capture and storage (CCS) has been discussed as a possibility[5], as they also need significant amounts of heat. Bioel production in 2nd generation biofuels plants is another future possibility.

6 Scale considerations

Big is beautiful is an expression that can be used for many CHP plants. In this connection it means that there are significant economy of scale benefits both connected to the conversion technology and the CHP technology and the overall plant performance. The economy of scale benefits relates to the higher energetic performance of larger plants and less investments costs and less O&M costs per kWh heat and el produced. Examples of scale effects are given below:

[8] Norheim A, Eikrem T O, Bernhard P, Sollesnes G, Bugge L, 2011, Mulighetsstudie biokraft, Norsk Energi. Available at www.enova.no.

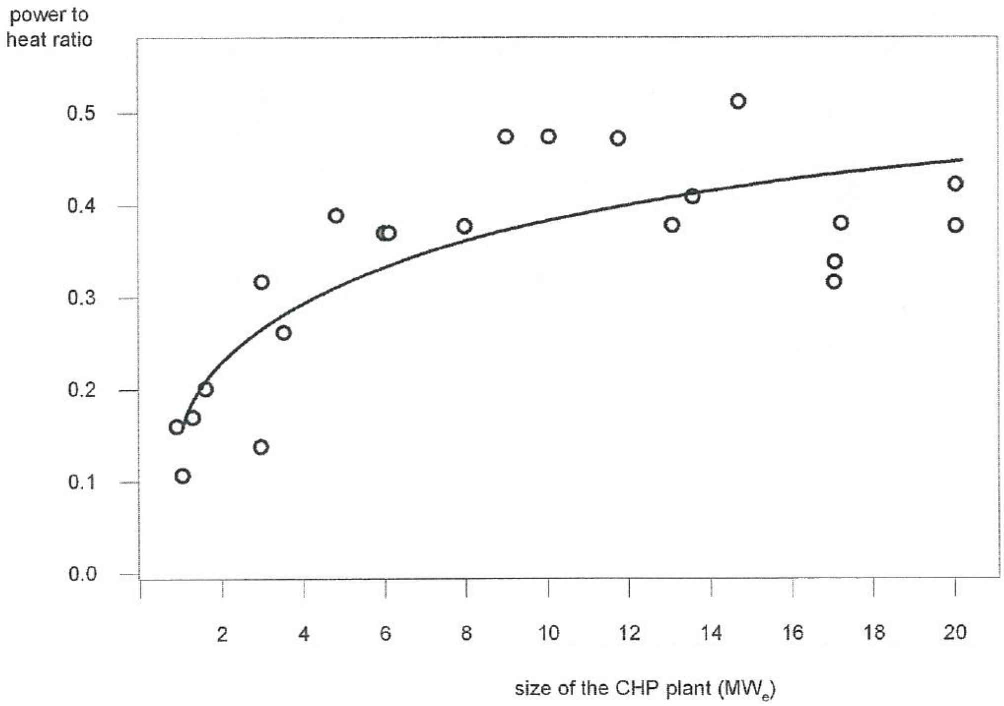

Figure 4. ***Power-to-heat ratio as function of the plant size of biomass-fuelled CHP plants in Finland and Sweden with 1–20MWe.*** [9]

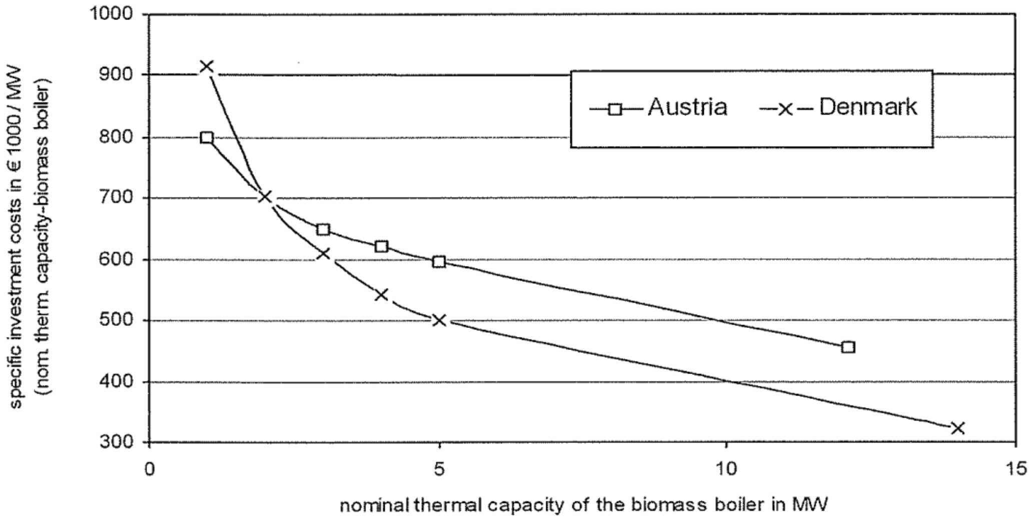

Figure 5. ***Specific investment costs for biomass combustion plants in Austria and Denmark as a function of biomass boiler size.*** [9]

Explanations: Data related to biomass grate furnaces, investment costs include: biomass grate furnace for woodchips, hot water fire-tube boiler, back-up boiler (fuel oil), fuel storage, fuel-feeding system, flue gas cleaning (ESP), stack, buildings, hydraulic and el installations, engineering and construction costs (network of pipes is not included); price level June 2006.

[9] Handbook of Biomass combustion and co-firing, 2008, edited by Sjaak van Loo and Jaap Koppejan, ISBN: 978-1-84407-249-1.

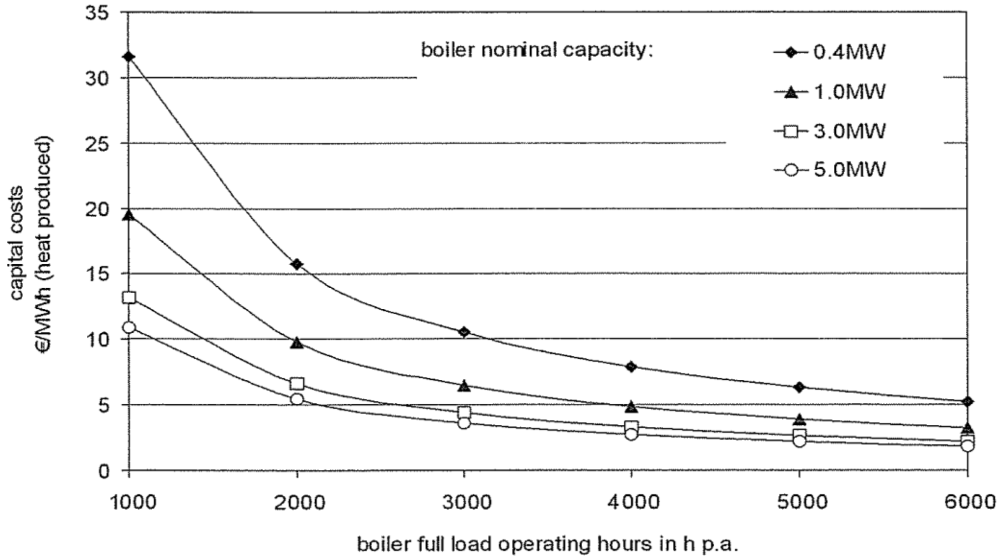

Figure 6. ***Specific capital costs for biomass combustion systems as a function of boiler capacity and boiler utilization.*** [9]

Explanations: Biomass moving grate furnace (including hot water fire-tube boiler, fuel feeding and stack), interest rate 7% p.a., lifetime 20 years, calculations according to VDI Guideline 2067; price level June 2006.

7 Framework conditions

In Table 9 and Table 10, no bioel is generated or planned based on high quality biomass fuels, from wet wood chips and up. The use of GROT (branches and treetops) has been considered for planned CHP plants in the district heating sector, but has so far not been utilized (at a fuel price of 15-18 øre/kWh). The reason is simple; lack of profitability.

The current framework conditions for bioel are:

- The value of the produced el is controlled by the Nord Pool el price, where the level varies significantly through the year with a price mostly below 40 øre/kWhel but with peak prices higher than 50 øre/kWhel
- In addition to the Nord Pool price the consumer has to pay an el grid fee, which varies depending on connection to a high voltage grid (2-3 øre/kWhel) or a low voltage grid (20-25 øre/kWhel)
- Green certificates or feed-in tariffs for bioel do not exist (but a common Swedish-Norwegian certificate market is planned from 2012, with an expected certificate price of 25 øre/kWhel)
- Enova (www.enova.no) supports, since 2009, the erection of bioel through their New Technology program (with up to 50% investment support)
- The Research Council of Norway supports fundamental research and development connected to CHP technologies, and other national and regional organizations are supporting industrial development etc.

The main difference between Norway and other countries where bioel has been generated from high quality biomass fuels for years is the lack of direct support per kWhel produced, i.e. green certificates or feed-in tariffs. However, also several other aspects, to be discussed later, are working against a widespread expansion of bioel in Norway.

8 Economy and cost-efficiency

If the price is high enough, at the level of timber for the wood processing industries (26-29 øre/kWh), producers of wood chips will be able to produce the amount needed in biomass CHP or biomass power plants in the near to medium term future. However, the fuel cost needs to be considerably lower, even for the commercial and well proven CHP technologies, to make it a profitable business. The example given in Table 11 illustrates this by calculating the production cost of bioel in a 2 MWel back-pressure steam turbine plant, with an overall efficiency of 80% and a power to heat ratio of 0.33 (2 MWel/6 MWth) using a timber price of 26 øre/kWh. The fuel cost alone per kWhel produced is close to the Nord Pool el price level.

Table 11. ***The production cost of bioel in a 2 MWel back-pressure steam turbine plant.***

	MWel	2
Distric heat - Back pressure turbine	h/yr	6000
kr/kWel	Boiler	10000
kr/kWel	Turbine	7736
kr/kWel	Other	5321
kr/kWel	Sum	23057
øre/kWhel	Capital	36
øre/kWhel	Fuel	32.50
øre/kWhel	O&M	7.9
øre/kWhel	Sum	77

The simplest way of comparing the profitability of bioel is to compare the average production cost for e.g. 20 years and a selected interest rate (typically 7%) to the sales price of the el, including green certificates and other potential el price benefits. If the produced el is partly or fully used internally in the CHP plant and a connected process industry, an additional benefit, in the form of no grid fee on el that otherwise would have to be purchased, will improve the CHP plant profitability. Data input for the calculations have been collected from Norheim et al.[8], IEA Task 32[10] and US EPA[11]. A calculation setup was made in Excel and the different data input was used to calculate the el production cost (øre/kWhel).

8.1 Calculation assumptions

The following assumptions were made:

Fuel price (øre/kWh): MSW: 0, biogas: 0; industrial wood processing residues used within the industry: 0; dry wood chips: 23, wet wood chips: 20, demolition wood: 6(-12), bark: 3(-10).

Operating hours: MSW plant: 5000; Biogas plant: 5500, District heating plant: 6000, Industry plant: 8000

Interest rate: 7%. Repayment time: 20 years

Key data used in the calculations for the different CHP systems are given in Table 12. Logarithmic curve fitting has been used to estimate data for effects between the “From” and “to” limits stated in the references. For “Other” percentages are stated in Norheim et al.[8], and for IEA and US EPA data 30% has been used if applicable. The total efficiency is used to calculate the fuel price per kWhel produced. O&M costs for the CHP technology were only stated by Norheim and US EPA. For IEA data the O&M costs were assumed.

8.2 Calculation cases

Production cost calculation cases are made for different CHP technologies and scales, and fuels (as defined for the specific plant), as shown in Figure 7, and are compared to the expected near future Nord Pool el price and with addition of green certificates (set to 25 øre/kWhel) and internal use benefit (set to 3 and 25

[10] IEA Task 32, 2011, Minutes of the workshop State-of-the-art technologies for small biomass co-generation, 7 October, 2010, Copenhagen, Denmark. Available at www.ieabcc.nl

[11] US EPA, 2007, Biomass combined heat and power catalog of technologies. Available at www.epa.gov.

øre/kWhel for respectively a high voltage and a low voltage grid), and a CHP technology investment support set to a corresponding 10 øre/kWhel. The figure clearly shows the influence of the technology choice and the fuel choice, and the importance of green certificates. Performing a sensitivity analysis the production profitability is most sensitive to the investment cost and the fuel price. Calculation results are shown in Figure 8 and Figure 9 for the investment cost and the fuel price, respectively.

Table 12. ***Key data used in the calculations for the different CHP systems.***

			Investment costs (kr/kWel)					
	MWel		Conversion tech.		CHP tech. or all		Other	Fuel
	From	to	From	to	From	to	-	-
Biogas - Gas engine	0.05	1			11218	4478	10 %	Biogas
MSW - Back pressure turbine	0.5	10	1075	705	10102	4988	50 %	MSW
Steam turbine w. steam boiler	1	10	10000	10000	6800	2800	30 %	Wet wood chips
Industry - Back pressure turbine	0.5	10	10000	10000	10102	4988	30 %	Wet wood chips
Industry - Back pressure turbine	0.5	10	10000	10000	10102	4988	30 %	Demolition wood
Industry - Back pressure turbine	0.5	10	10000	10000	10102	4988	30 %	No cost fuel
Industry - Condensation turbine	0.5	10	32000	32000	11584	6000	30 %	Wet wood chips
Industry - Condensation turbine	0.5	10	32000	32000	11584	6000	30 %	No cost fuel
Distric heat - Back pressure turbine	0.5	10	10000	10000	10102	4988	30 %	Wet wood chips
Distric heat - ORC	0.2	3	10000	10000	16001	6400	30 %	Wet wood chips
Distric heat - Stirling engine	0.035	0.5			47999	24000		Wet wood chips
Distric heat - Steam engine	0.15	1			25997	13000		Wet wood chips
Steam syst. w. LT-CFB gasifier	6	40	13601	7128	12340	7483	30 %	Bark
Gas engine w. staged gasifier	0.2	1			72865	32000		Wet wood chips
Gas engine w. downdraft gasifier	0.15	1.2			32001	28000		Dry wood chips
Gas engine w. updraft gasifier	1	5			48000	32001		Wet wood chips
Gas engine w. indirect gasifier	2	5.5			52000	46500		Wet wood chips
Gas engine w. BFB gasifier	6				44800			Dry wood chips
Gasifier + Microturbine	0.1	0.25	22840	19714	8100	6600	30 %	Wet wood chips
Gasifier + Gas turbine	1	10	14984	7128	7200	3600	30 %	Wet wood chips
Gasifier + MCFC	0.25	2	19714	12619	30600	17400	30 %	Wet wood chips

				Fuel and O&M costs (øre/kWhel)				
	Total eff.	El. eff.	h/yr	Fuel		O&M		Data from
	-	-	-	From	to	From	to	-
Biogas - Gas engine			5500	0		15		Norheim
MSW - Back pressure turbine			5000	0		12.1	3.0	Norheim
Steam turbine w. steam boiler	80 %	20 %	8000	25		10.0	3.0	IEA
Industry - Back pressure turbine	80 %		8000	25		12.1	3.0	Norheim
Industry - Back pressure turbine	80 %		8000	7.5		12.1	3.0	Norheim
Industry - Back pressure turbine	80 %		8000	0		12.1	3.0	Norheim
Industry - Condensation turbine	25 %	25 %	8000	80		12.1	3.0	Norheim
Industry - Condensation turbine	25 %	25 %	8000	0		12.1	3.0	Norheim
Distric heat - Back pressure turbine	80 %		6000	25		12.1	3.0	Norheim
Distric heat - ORC	87 %	17 %	6000	22.99		14.8	6.6	IEA
Distric heat - Stirling engine	88 %	18 %	6000	22.73		20.1	12.1	IEA
Distric heat - Steam engine	80 %	10 %	6000	25		15.7	10.0	IEA
Steam syst. w. LT-CFB gasifier	80 %	25 %	6000	3.75		8.7	3.0	IEA
Gas engine w. staged gasifier	85 %	30 %	6000	23.53		14.8	10.0	IEA
Gas engine w. downdraft gasifier	75 %	25 %	6000	30.67		15.7	9.4	IEA
Gas engine w. updraft gasifier	80 %	23 %	6000	25		10.0	5.1	IEA
Gas engine w. indirect gasifier	80 %	25 %	6000	25		7.9	4.8	IEA
Gas engine w. BFB gasifier	75 %	28 %	6000	30.67		4.5		IEA
Gasifier + Microturbine	0,62-0,59	0,252-0,288	6000	32.26	33.90	9.0	7.2	US EPA
Gasifier + Gas turbine	0,68-0,73	0,219-0,312	6000	29.41	27.40	6.0	3.6	US EPA
Gasifier + MCFC	0,65-0,7	0,43-0,46	6000	30.77	28.57	25.8	19.8	US EPA

SINTEF

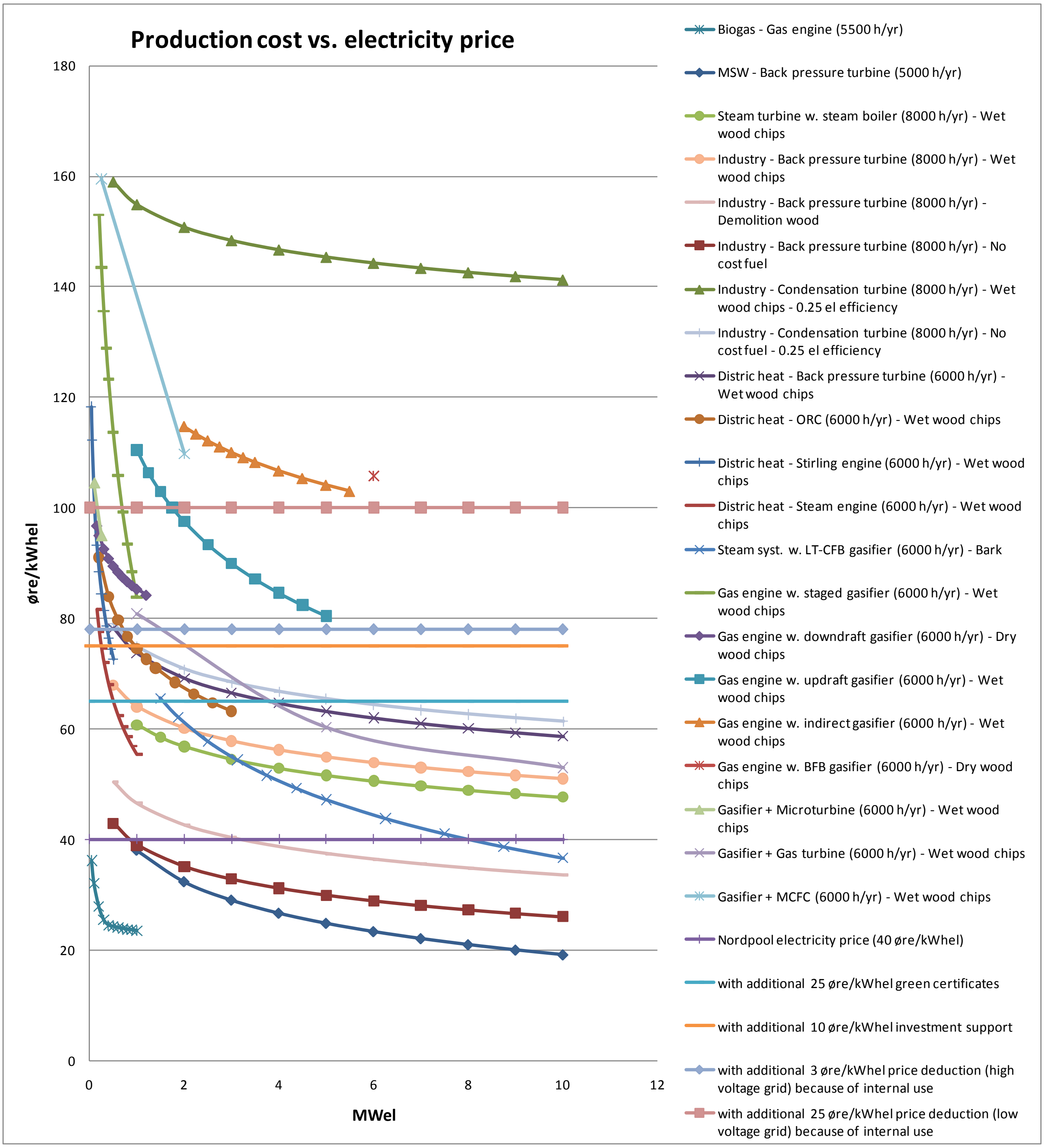

Figure 7. ***Production costs calculation cases for different CHP technologies and scales, and fuels. MCFC: Molten Carbonate Fuel Cell***

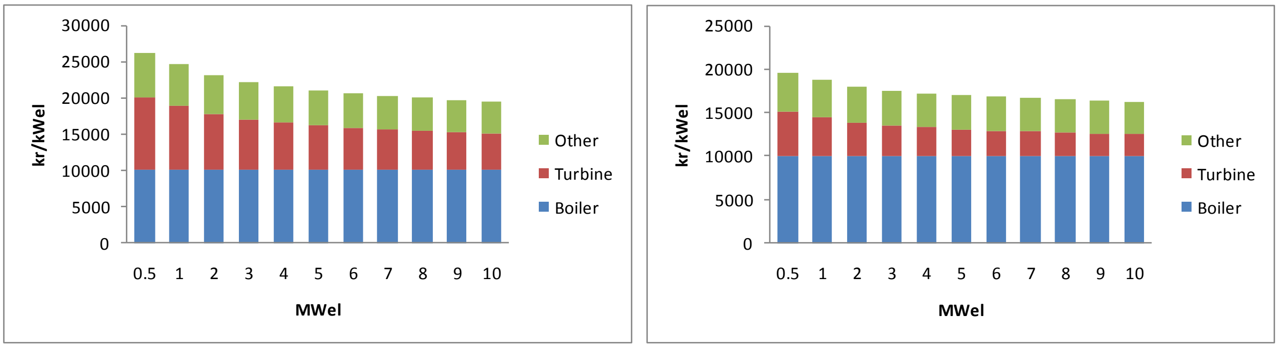

Figure 8. ***Production costs calculation cases for district heating plant with back pressure turbine with wet wood chips as fuel (20 øre/kWh). Investment cost sensitivity (left side: no investment support; right side: 50% turbine investment support)***

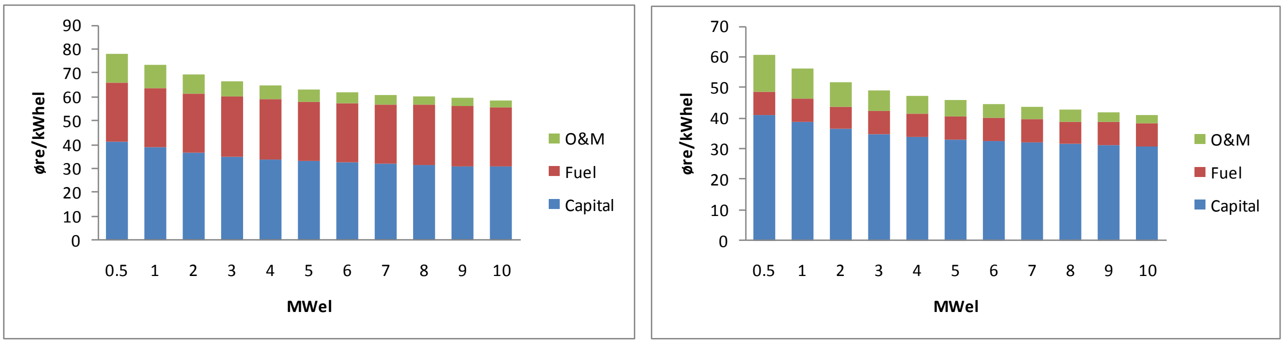

Figure 9. ***Production costs calculation case for district heating plant with back pressure turbine. Fuel cost sensitivity (left side: wet wood chips, 20 øre/kWh; right side: demolition wood, 6 øre/kWh)***

8.3 Results comparisons

From Figure 7**,** Figure 8 and Figure 9 the following conclusions can be drawn:
- Only the MSW-back pressure turbine, biogas-gas engine, industrial processing residues-back pressure turbine and demolition wood-backpressure turbine combinations are profitable without any support to the el price
- Only low-quality woody fuels (residues) are profitable in industrial plants with back pressure turbine
- Maximizing the full load operating hours per year is in general extremely important
- In district heating plants based on woody fuels, high heat utilization degree is essential. They will not run when the heat cannot be sold
- El, and heat, production is most beneficial when it is for internal use
- Power production only in a condensation turbine is not an option
- Gasification based CHP technologies are not yet cost-effective for the Norwegian market, but gasification in combination with a boiler and a back-pressure steam turbine seems to be the best option. And, a gasification plant is as shown in Table 10 planned at Fiborgtangen, Skogn, with investment support from Enova
- Stirling engine and fuel cells are not cost-effective for the Norwegian market
- Steam engine and ORC are small-scale CHP options, if green certificates are implemented
- Improved framework conditions are the key to significantly increased bioel generation in Norway

9 Biomass CHP in a national energy perspective

The possibly increasingly important role of bioenergy in the national energy strategy can only be achieved if this is made possible by and in the energy market. Hence, it must be economically beneficial to convert biomass to energy, for heat, CHP and/or power production. A doubling of the biomass use for energy purposes within 2020 compared to 2008 is a big ambition, which hardly can be achieved without also a significant focus on biomass CHP and maybe also biomass power. The only alternative use of our unused forest resources and residues are for biofuels production through 2nd generation biodiesel and ethanol production processes. These are still in an early research stage.

10 Recommendations

Below, recommendations are given regarding conversions technology choices, CHP technology choices and Norwegian market possibilities depending on framework conditions.

10.1 Biomass conversion technologies

The choice of gasification has in principle some benefits, but the calculations show that the benefits are not sufficient when taking the whole picture into account. The investment costs need to be reduced and the maturity of the gasification technologies needs to be improved. This is also the case for pyrolysis. This leaves combustion as by far the main commercial conversion process, with anaerobic digestion being a commercial conversion process for easily digestible organic residues.

10.2 Small-scale biomass CHP solutions

With the definition of small-scale as up to 10 MWth, a steam turbine based CHP plant is today the best solution. For biogas from anaerobic digestion a gas engine is the best solution. However, biogas has also an alternative use, for transport purposes, and this might be the preferred future use of biogas.

10.3 Micro-scale biomass CHP solutions

There is, as explained earlier, a rather limited CHP potential connected to larger district heating plants in Norway. By utilizing micro-scale CHP solutions the picture becomes very different, with many distributed CHP plants supplying local heating networks or even single houses with heat and el. In this way the biomass use for CHP can become very significant in the Norwegian bioenergy market. For this to happen, new CHP solutions based on e.g. small ORC units and Stirling engines needs to become significantly less expensive, or (as is the case in some European countries) the value of green certificates needs to become significantly higher. For micro-scale CHP, no real cost-effective options, except gas engines in combination with biogas, exist today for the Norwegian market.

10.4 Norwegian market possibilities depending on framework conditions

What will the most promising small-scale CHP technologies based on biomass be in the near to medium term future in Norway?

With today’s framework conditions: Steam turbine in the near term future and maybe gasification and boiler + steam turbine or gas engine in the medium term future. With additional improved framework conditions: Steam engine and ORC in the near term future and Stirling engine in the medium term future.

What are the limiting factors in Norway?

- Lack of profitability
- Heat market number and sizes: The heat market will control the number of full time operating hours. Process industry is the obvious choice for a CHP plant, but the number of possible new plants is rather limited. For district heating, the heat from the CHP plant must cover the base load. This will in many areas conflict with MSW as base load. Norway has a small and distributed population. District heating networks are expensive, and the number and size of the heat customers will be determining for the plant size. A limited amount of further district heating plants of significant size can be identified. Hence, the size of the CHP plants needs to decrease, which is not beneficial from a cost-efficiency perspective
- Investment costs and risks: High capital costs, and profitability very dependent on el price, interest rate level and framework conditions. Hence, it becomes risky business for an investor
- Fuel price and supply: The maturity of the Norwegian biomass fuel market cannot be compared to e.g. our neighboring Nordic countries. If you are willing to pay a high price for the fuel the availability is unproblematic. For low-quality woody biomass fuels, production and logistics systems does not exist in larger scale. The Norwegian forest industry does not see a demand that justifies industrial scale production of these fuels (e.g. GROT, with a potential of about 4.8 TWh/yr for a price of 15-18 øre/kWh[7]
- El price and variations in this
- International competition: Biomass fuels, and MSW, are today a commercial commodity. Transport costs limit the geographical distribution of low-quality biomass fuels, but in some cases (as for MSW, with a gate fee) differences in framework conditions might lead to economic justification of long distance transport, to other countries
- Framework conditions: Any external factor that influences directly or indirectly the economics of biomass CHP is a framework condition. These framework conditions can be economical or political. Any framework conditions that are implemented to support biomass use for energy purposes must have a long-term horizon. Green certificates are planned introduced in Norway from 2012, and will be a very important positive framework condition. Investment support to CHP plants from Enova is another positive framework condition. For MSW the Norwegian so-called combustion fee was a negative framework condition, also contributing to export of MSW to Sweden. This fee has now been removed
- Political climate: The debate regarding introduction of green certificates in Norway has been ongoing for 10 years. Whatever positive framework conditions that are implemented, they need to have a long-term character, i.e. they should be independent of political climate. Short-term and insecure arrangements are not beneficial. Bioenergy plants are long-term investments!

Today, the el production capacity in several of the CHP plants shown in Table 9 are far from utilized, for different reasons. Using data from Norheim et al.[8], the calculated annual el utilization factor for industry plants in Sweden becomes 0.56 (40 plants), while it was 0.36 for the one, from four in total, wood processing residues plants producing el in 2009 in Norway. For CHP plants not defined as industry plants, except biogas plants, the factor becomes 0.34 (74 plants) compared to 0.41 for MSW plants and 0.86 for the only waste wood combustion plant in Norway. For biogas plants the factor becomes 0.45 (33 plants) compared to 0.58 for biogas plants and 0.47 for landfill gas plants in Norway. From this no conclusion can be drawn regarding lower annual el utilization factor in Norway compared to Sweden.

What can be done to speed up the introduction of small-scale CHP solutions based on biomass in the Norwegian market?

- Improved framework conditions
- Focus on optimizing possibilities in biomass CHP planning
    - Optimized CHP plant with respect to steam and heat needs internally and at customer locations
        - Proper plant sizing and technology selection
        - Cover internal heat, steam and el needs
        - Heat and steam distribution distances

- Use own fuel (no or low alternative value) and/or local fuel
    - Plan for fuel flexibility if possible
    - Produce fuel in one plant (e.g. briquettes), which can be supplied to a plant elsewhere
    - Use own, and experienced, industry process personnel in the operation of the CHP plant
- Strong(er) support schemes for micro CHP introduction / technology demonstration
- Technology development for Norwegian conditions and fuels, and support for this

In a CHP plant, both fuel flexibility and energy flexibility is beneficial. Also in a regional or national perspective energy flexibility is wished for. Security of supply is a key issue, and this is also connected to el grid transmission capacity. Hence, distributed el generation is beneficial, relaxing the pressure on long distance transmission lines and grid investment needs, and also reducing el transfer losses. Bioel is renewable el, and contributes to a reduced greenhouse gas effect. It should therefore be in a national interest to more strongly support biomass use for energy purposes, including bioel.

And, finally, what are the research needs, in addition to those mentioned in sections 2.2 and 3.2, if any, connected to this?
Obviously, research is a long term effort to develop and refine technologies, and is very often characterized by slow progression. The different CHP technologies are in different stages of development, and this can clearly be seen in the calculated el production cost. The most mature technologies, like steam turbines, have limited improvement potential, and limited cost-efficiency improvements can be expected. However, coupled to a conversion system and a specific fuel, very significant improvements can be made for the whole CHP system. The key to significantly improved cost-efficiency for mature el generating technologies lies in optimum biomass conversion systems/boilers for low-quality biomass fuels. As shown in Figure 9 fuel cost is a key factor. Being able to utilize low-quality biomass without increasing the investment costs and the O&M costs accordingly, is a key research task today. In the long run the costs of today's not mature CHP technologies will decrease as the research efforts continue and experience accumulates. The unit costs will of course decrease as the number of produced units and producers is increased.

11 Conclusions

The Norwegian government aims at doubling the bioenergy use in Norway from 14 TWh in 2008 to 28 TWh in 2020. Today we are at 15 TWh. The bioel production in Norway was about 411 GWhel from an installed capacity of 136 MWel, corresponding to an annual el utilization factor of 0.34. The bioel is produced in steam turbines (except for one steam engine) and gas engines (biogas, landfill gas). Towards 2020 the planned and estimated increased el production capacity amounts to about 120 MWel. No bioel is produced from high quality biomass fuels, from wet wood chips and up, it is too expensive. About 18 TWh of additional biomass is estimated to be available for energy purposes, where about half at a cost of less than 30 øre/kWh. With today's el price level and the future expected level (40 øre/kWhel), only low cost biomass fuels can be utilized for el production, if no direct support is given to bioel production. A common Swedish-Norwegian green certificate market is planned from 2012, with an expected certificate price of 25 øre/kWhel. This will significantly improve the bioel production possibilities. Lack of profitability is the main barrier for widespread introduction of bioel production in Norway. Enova gives since 2009 investment support to introduction of new technologies through their New Technology program, with up to 50% investment support, which is an important driver for future increased bioel production.

In this work calculations and evaluations have been carried out, showing the production cost for bioel in different CHP systems of a size up to 10 MWel. What will the most promising small-scale CHP technologies based on biomass be in the near to medium term future in Norway? With today's framework conditions: Steam turbine in the near term future and maybe gasification and boiler + steam turbine or gas engine in the medium term future. With additional improved framework conditions: Steam engine and ORC in the near term future and Stirling engine in the medium term future.

The cost-efficiency of the CHP solutions depends on a number of factors, and investment costs and fuel costs are very important. The investment costs per unit el production capacity increase with decreasing unit size, which works against small-scale (and micro) CHP plants. However, for an optimum plant configuration and location, utilizing all possible benefits and synergy effects, and with sufficient bioel support, small-scale (and micro-scale) biomass based CHP can have a cost-effective future in Norway.