BIOHEAT APPLICATIONS IN THE EUROPEAN UNION: AN ANALYSIS AND PERSPECTIVE FOR 2010

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EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

EUR 21401 EN

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http://ie.jrc.cec.eu.int/

http://www.jrc.cec.eu.int/

Luxembourg: Office for Official Publications of the European Communities, 2004

ISBN 92-894-8730-5

Printed in The Netherlands, Institute for Energy – JRC IE, PR&Communication

Cover: The Tamsweg district heating plant in the Salzburg region of Austria; Source: European Commission, Directorate-General for Energy and Transport, http://europa.eu.int/comm/energy/res/sectors/doc/bioenergy/combustion_cocombustion/024bm_333_95.pdf,
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PREFACE

The objective of the Sustainable Energy Technologies Reference and Information System (SETRIS) of the Directorate-General Joint Research Centre – European Commission is to collect, harmonise and validate information on sustainable energy technologies and perform related techno-economic assessments to establish, in collaboration with all relevant national partners, scientific and technical reference information required for the debate on a sustainable energy strategy in an enlarged EU, and in the context of global sustainable development.

This study has been executed in the context of SETRIS and aims at performing a techno-economic analysis of various bioenergy applications for heat generation in the EU in the near- to medium-term, concentrating on the 2010 time horizon. This includes a critical review of a large number of literature sources on the subject, complemented by the author's analysis. Marc Steen, David Baxter and Fred Starr (Joint Research Centre – Institute for Energy) are thanked for their contribution with comments, remarks and suggestions.

GUIDANCE FOR THE READER

In addition to the briefings in the "Executive Summary" and the "Conclusions" chapters, each analytical chapter contains a summary box at the end. A summary figure of the relative advantages and disadvantages of different fuel and technology options, considered from the point of view of (bio)heat generation, is also included before the chapter's summary box. The bibliographic indexes of the data and information sources or of the sources, where more data and/or information can be found on a certain issue or subject are given in brackets [].

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LIST OF USED ABBREVIATIONS

CAP – Common Agricultural Policy (of the European Union)
CHP – combined heat and power (generation)
d – dry (basis)
EC – European Commission
EU – European Union, (European) Community
EU-15 – the member states of the EU until 30 April 2004
EU-25 – the member states of the EU by the end of 2004
EUR, € – Euro
g – gram
G – Giga
GCV – gross calorific value
GHG – greenhouse gas(es)
GIEC – gross inland energy consumption
k – thousand
kg – kilogram
km - kilometre
l – litre
J - Joule
LCA – life-cycle analysis
m – metre, mili
M – million, Mega
m2 – square metre
m3 – cubic metre
NCV – net calorific value
NMS-10 – the 10 new member states of the EU as from 01 May 2004
REP – renewable energy pathway
toe – tonne oil equivalent
USD, $ - United States Dollar
w – weight (basis)
W – Watt
Wh – Watt-hour
WTW- Well-To-Wheel

ENERGY CONVERSION FACTORS

	GJ	Gcal	toe	MBtu	MWh
GJ	1.0000	0.2388	0.0239	0.9478	0.2778
Gcal	4.1868	1.0000	0.1000	3.9683	1.1630
toe	41.8680	10.0000	1.0000	39.6832	11.6300
MBtu	1.0551	0.2520	0.0252	1.0000	0.2931
MWh	3.6	0.8598	0.0860	3.4121	1.0000

Source: Unit Converter, International Energy Agency (IEA) – Organisation for Economic Development and Co-operation (OECD), http://www.iea.org/dbtw-wpd/Textbase/stats/unit.asp

μ – 10^{-6}

m – 10^{-3}

Kilo – 10^{3}

Mega – 10^{6}

Giga – 10^{9}

Tera – 10^{12}

Peta – 10^{15}

AVERAGE ENERGY CONTENT OF SELECTED FUELS, USED IN EU STATISTICS

Net Calorific Value	Kilograms oil equivalent (kgoe)
Hard coal	0.411-0.733
Hard coke	0.681
Brown coal	0.134-0.251
Black lignite	0.251-0.502
Peat	0.186-0.330
Brown coal briquettes	0.478
Light fuel oil	1.010
Heavy fuel oil	0.955
Petroleum coke	0.750
Gross Calorific Value	**Kilograms oil equivalent (kgoe)**
Natural gas	0.0215
Biomass	0.024
Electricity	0.086

Source: European Commission, Statistical Office of the European Communities (EUROSTAT), http://europa.eu.int/comm/eurostat/

EXECUTIVE SUMMARY

The European Union (EU) is heavily dependent upon energy imports. The EU is also a large emitter of greenhouse gases (GHG), which contribute to global warming and climate changes. Securing the energy supply in an environmentally-friendly way is therefore a prime objective of the EU energy and environmental policies. In this context, the European Commission (EC) considers renewable sources of energy as a core tool for simultaneously achieving these policy objectives. Hence, target shares for market penetration of renewable energies by 2010 have been set up in the EU – 12% of gross inland energy consumption, 21% of electricity generation and 5.75% biofuel of all petrol and diesel, used in transport. Amongst the different renewable energy sources, biomass has the largest potential to contribute to these policy goals, followed by wind energy and then, far behind – by other renewable energy sources.

Biomass can be employed for various energy purposes – generation of electricity, production of transport fuels, etc. Biomass can also be used for heating, which is in fact its first ever known energy application. Nevertheless, so far the progress in bioheating is lagging behind the progress in bioelectricity and transport biofuels in the EU. Yet, a large share of biomass contribution to the renewable energy targets of the EU is supposed to come from the heating sector. Thus, the under-performance of bioheating appears to be a key point of concern in the Community's efforts towards reaching the 2010 renewable energy targets.

The goal of this work is to perform a thorough techno-economic assessment of biomass applications for heat generation. This includes a critical review of a large number of literature sources, complemented by the author's analysis. The time horizon of the study is near- to medium-term, focusing on the period up to 2010. The analysis covers the 25 members states of the EU by the end of 2004 (EU-25). Where needed, the EU-25 scope is split up between the old (before 1 May 2004) 15 and the new (after 1 May 2004) 10 member states – EU-15 and NMS-10 respectively. Two types of feedstock are considered – woody [firewood, short rotation forestry, residues (sawdust, shavings, thinning residues, etc.) and waste, demolition material] and herbaceous [dedicated energy crops and residual biomass (straw)]. The fuels analysed are whole trees, firewood, wood chips, wood powder, wood and/or herbaceous pellets and briquettes, dedicated herbaceous material and straw. The combustion concepts considered include direct combustion (small-scale manually and automatically filled burning systems, large-scale batch facilities, various grate combustion systems, including applications for burning whole straw bales), gasification and combined combustion (co-firing) of biomass and fossil fuels. Besides the distinction based on the scale of heat generation, the analysis is examining separately the public heat generation (district heating) and the industrial producers of heat (steam).

Based on the analysis, performed in the study, three core advantages of the use of biomass for heat generation, compared to the alternative applications of biomass and to the utilisation of other renewable and fossil fuels for heat generation in EU-25 by 2010 can be identified:

1. **Strong impact on the security and diversity of the EU energy supply.** With the recent progress in technologies, the heat generation from biomass is roughly two times more energy efficient than the electricity generation from biomass. In addition, for technological reasons efficient power generation typically needs fuels with higher qualities than the average qualities of biomass fuels, and larger scale systems than heat generation. With regard to the production of transport biofuels, the energy efficiency superiority of bioheating seems to be even larger. Hence, by increasing the application of biomass for heat generation, the share of the renewable energies in the EU energy mix would expand faster. Finally, the second largest renewable energy source – wind – is much better suited for electricity generation than for heat generation.
2. **Large environmental benefits.** Owing to carbon dioxide recycling by the vegetation, burning biomass results in negligible (compared to fossil fuels) net emissions of greenhouse gases to the atmosphere. In addition, biomass firing in efficient and well-tuned combustion systems can significantly reduce (compared to coal and heating oil) the emissions of pollutants with impact on the local air quality. This is particularly important for densely populated urban areas, where heat generation should be located as close as possible to the heat consumers, in order to avoid large transmission losses. Another attractive market for bioheating appears to be industrial steam generation for own consumption at the factories of forest, agricultural, furniture and other similar industries. Such plants normally require steam and in parallel – they generate potential biomass fuels along their principal activity as by-products or residues. Due to the required larger scale for efficient electricity generation, compared to heat generation, the available quantities of such by-products or residues are not often sufficient for power generation, but they are enough for steam generation. In addition, electricity can be delivered from remote sources at low distribution losses, in contrast with steam transmission, which is characterised by high distribution losses.
3. **Substantial secondary advantages and synergy benefits with other sectors.** Biomass production creates direct and secondary employment, and business activity in the rural areas, which quite often experience socio-economic difficulties. In such a way it contributes to regional development and social cohesion. In addition, biomass for energy purposes can improve the land management, since biomass for bioenergy is generally less demanding with regard to soil characteristics than conventional agricultural crops. Due to the low energy density of biomass, the transportation, handling and storage costs of biomass are crucial for its competitiveness on the energy market. Hence, the closer to the biomass production the biomass consumption takes place, the lower the total bioenergy costs are. Because of the larger scale units needed for efficient electricity

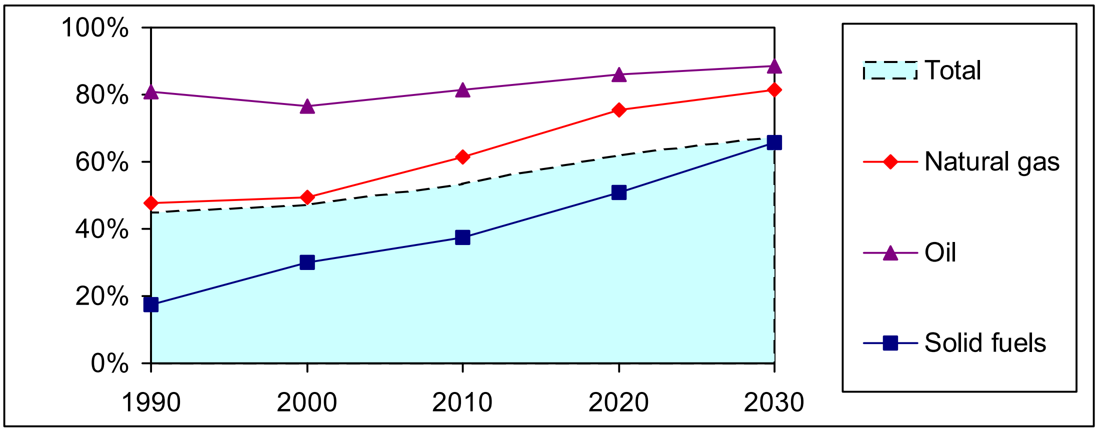
generation and the lower distribution losses, compared to heat, employing a larger part of the locally available biomass resource for heat generation (but not for electricity generation), appears to be more effective within the overall energy system from energy saving, emissions and cost reduction points of view.

The full realisation of the above advantages will need however some additional institutional support. At present, the use of biomass for heating is less covered by dedicated regulatory measures than e.g. bioelectricity and transport biofuels. A specific legislation at EU level, addressing the promotion of bioheating, is not yet available. Partly due to the scarce availability of such legislative measures, large technological, cost and regulatory differences currently exist amongst the EU countries. For the same reason, the data and information availability for bioheating in the EU seems to require additional qualitative and quantitative improvements.

1. BACKGROUND

The 15 states, forming the European Union up to the end of April 2004 (EU-15), are heavily dependent upon energy imports. The share of imports in their gross inland energy consumption (GIEC), currently standing at 50%, could reach 70% by 2030, due to depletion of EU-15's own energy reserves. The EU enlargement, that took place in 2004, is not expected to alter this situation either, because the 10 new member states (NMS-10) are also heavily dependent upon energy imports [45] – Figure 1.

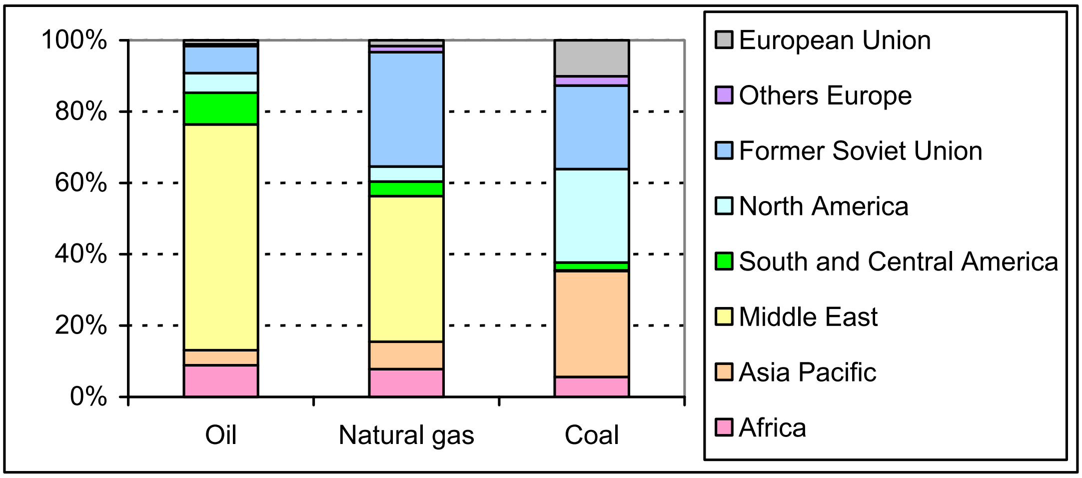
Figure 1
Retrospective (1990-2000) and projected (2010-2030) EU-25 import dependence – total and by main fuels, (%)



Source: Adapted from [53, 54]

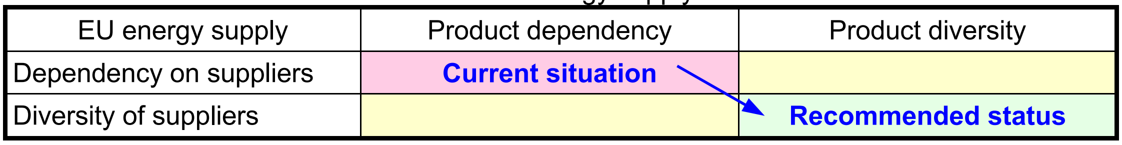
Since world reserves of the main energy sources, imported by the EU – oil and natural gas – are geopolitically concentrated (Figure 2), such an import dependence threatens the security and diversity of the EU energy supply (Figure 3).

Figure 2
Breakdown of proved reserves of oil, natural gas and coal by regions in the world at the end of 2003, (%)



Source: Adapted from [17]

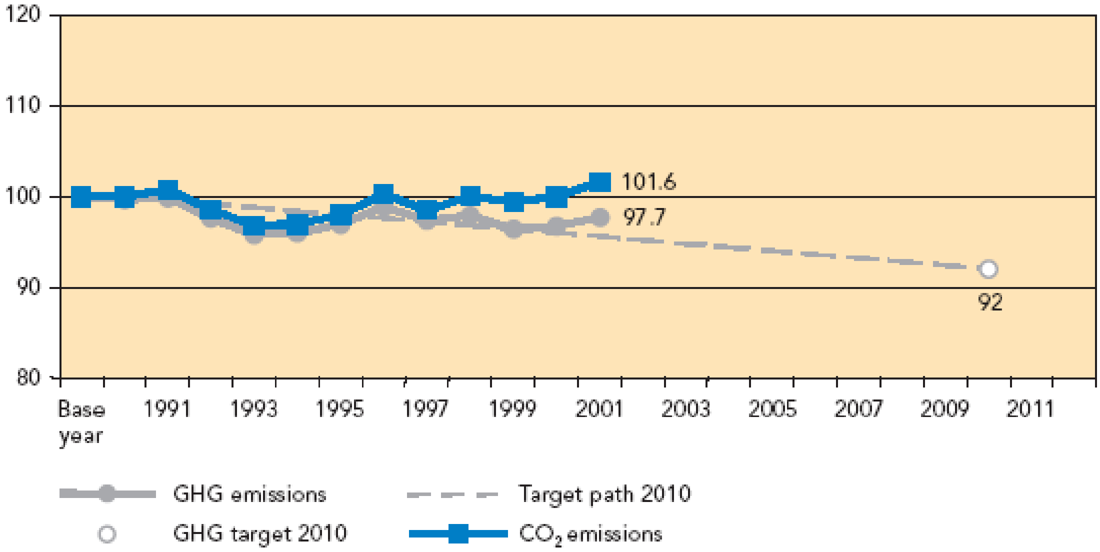
Figure 3
Current and recommended status of the EU energy supply



EU energy supply	Product dependency	Product diversity
Dependency on suppliers	**Current situation**	
Diversity of suppliers		**Recommended status**

In addition, global warming and climate changes, caused by the emissions of greenhouse gases (GHG), recently became a growing concern in the world. For this reason, under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), a number of countries undertook to reduce their GHG, aiming at improving global environment. The EU committed to cut within 2008-2012 its GHG emissions by 8% from the level in 1990. However, the GHG decrease achieved between 1990 and 2001 was 2.3% only, which is 2.1% less than the needed reduction, if a linear regression within 1990-2010 is assumed – Figure 4.

Figure 4
EU GHG emissions over the period 1990-2001, compared to the target for 2008–2012 (Index points, year 1990 = 100)



Remarks: Data exclude emissions and removals from land-use change and forestry. The target path shows how close the actual emissions were to the virtual linear reduction between the base year and the EU Kyoto Protocol target.
Source: [72]

Carbon Dioxide (CO_2) is the key GHG, accounting for 82% of all GHG emissions in the EU in 2001. The delay in the Community's GHG reduction was due mainly to the CO_2 emissions, since instead of declining, they were by 1.6% higher in 2001, compared to 1990 – Figure 4. The intermediate target of keeping the CO_2 emissions by 2000 at their 1990 level was however met – Figure 4 [67, 69, 72, 73].

With regard to the above two concerns, securing and diversifying the Community's energy supply in an environmentally-friendly way is a key objective of the energy and environmental policies in the EU.

Due to the relatively poor internal availability of conventional energy resources, the scope for influencing the energy supply by the EU appears very limited [45]. The reserves to impact the supply are associated mainly with renewable source of energy. The production patterns of the renewable energy sources differ from those of fossil fuels. In addition, the renewable energy sources are CO_2 neutral. In this context, three renewable energy targets have been set up in the EU:

- ✓ 12% of gross domestic energy consumption to be covered by renewables by 2010 [42];
- ✓ 22.1% of electricity generation to come from renewable energy sources by 2010 [76][1];
- ✓ 2.00% by 31 December 2005 and 5.75% by 31 December 2010 of all petrol and diesel, used in transport, measured on energy content basis, to be biofuel [79];

As these policy targets do not provide the same basis for comparison, some room for interpretation is left. The first target addresses gross inland energy consumption, while the second and the third targets refer to the final energy consumption in two sectors.

Based on the latest energy projections, the absolute values of these three renewable energy targets for EU-25 are given in Figure 5.

Figure 5
Renewable energy targets in the EU

EU-25	2005	2010
Projected gross inland energy consumption (Mtoe)	-	1788
RES share (Mtoe)	-	215
Projected electricity generation (TWh)	-	3430
RES share (TWh)	-	720
Projected petrol and diesel consumption transport (Mtoe)	297.2	316.9
Biofuel share (Mtoe)	5.9	18.2

Source: Adapted from [42, 53, 76, 79]

In order to achieve the targets in Figure 5, it is very important to identify the optimal ways of exploiting the available renewable energy potential by sources. The comparison of different renewable energy alternatives and thus, the evaluation of optimal solutions on case-by-case basis, should be based on a systematic approach. This means that the assessment should comprise the whole Renewable Energy Pathway (REP) – from the extraction of feedstock until the final utilisation of energy. The common structure of REP is presented in Figure 6.

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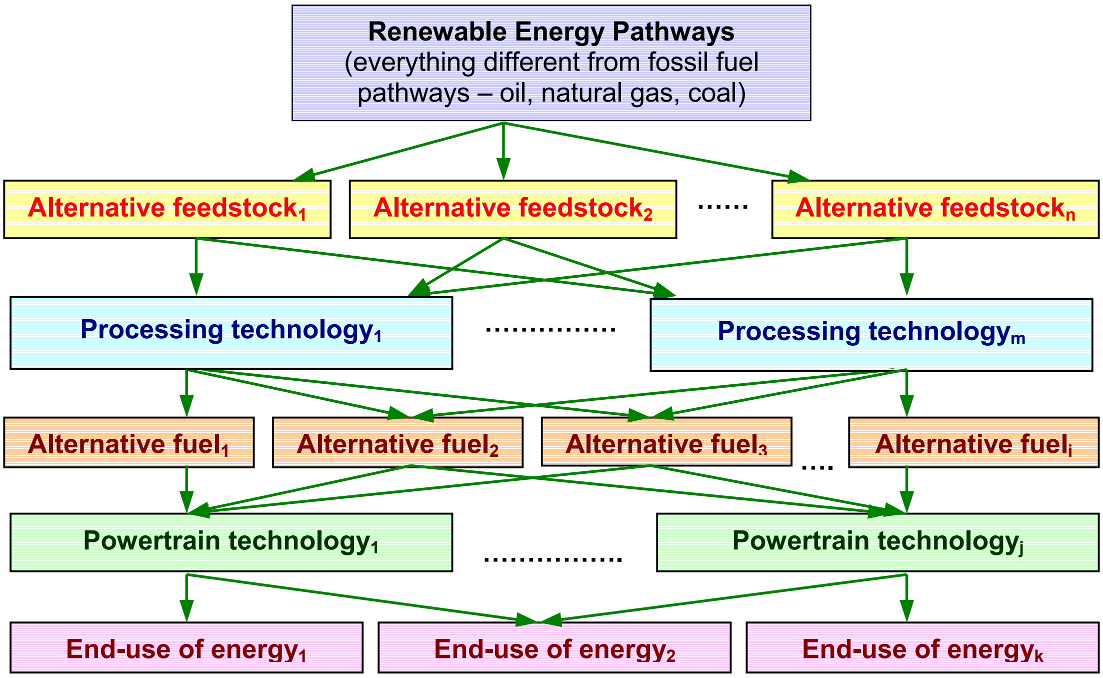
[1] Within the enlarged EU-25, the target drops to 21%, due to lower national targets, negotiated by NMS-10.

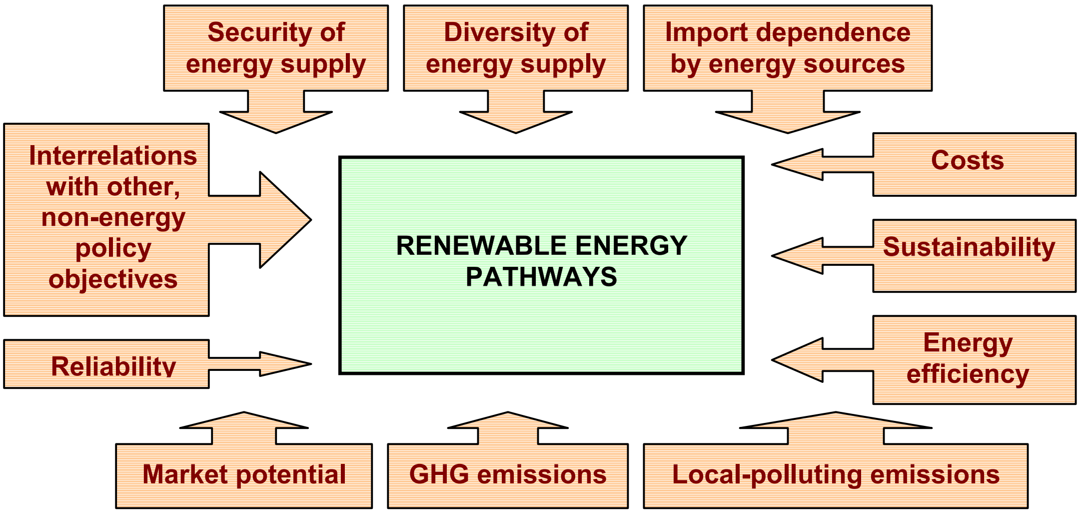
Figure 6
General structure of the renewable energy pathways



The REP structure and hierarchy from Figure 6 can vary on a case-by-case basis. Some REP could be shorter (e.g. in transport, where the last component "End-use of energy" is missing), while other REP could be larger (e.g. the fuels, which are obtained at a certain level, can serve as a feedstock for producing other, more sophisticated fuels).

From a techno-economic point of view, each REP has strong and weak points. Hence, it is not possible to select an ultimate REP, at least with current technologies. The selection of a dedicated REP is normally performed case-by-case, taking into account a number of factors. The common techno-economic criteria to compare and select REP are presented in Figure 7.

Figure 7
Main criteria to assess the suitability of different REP



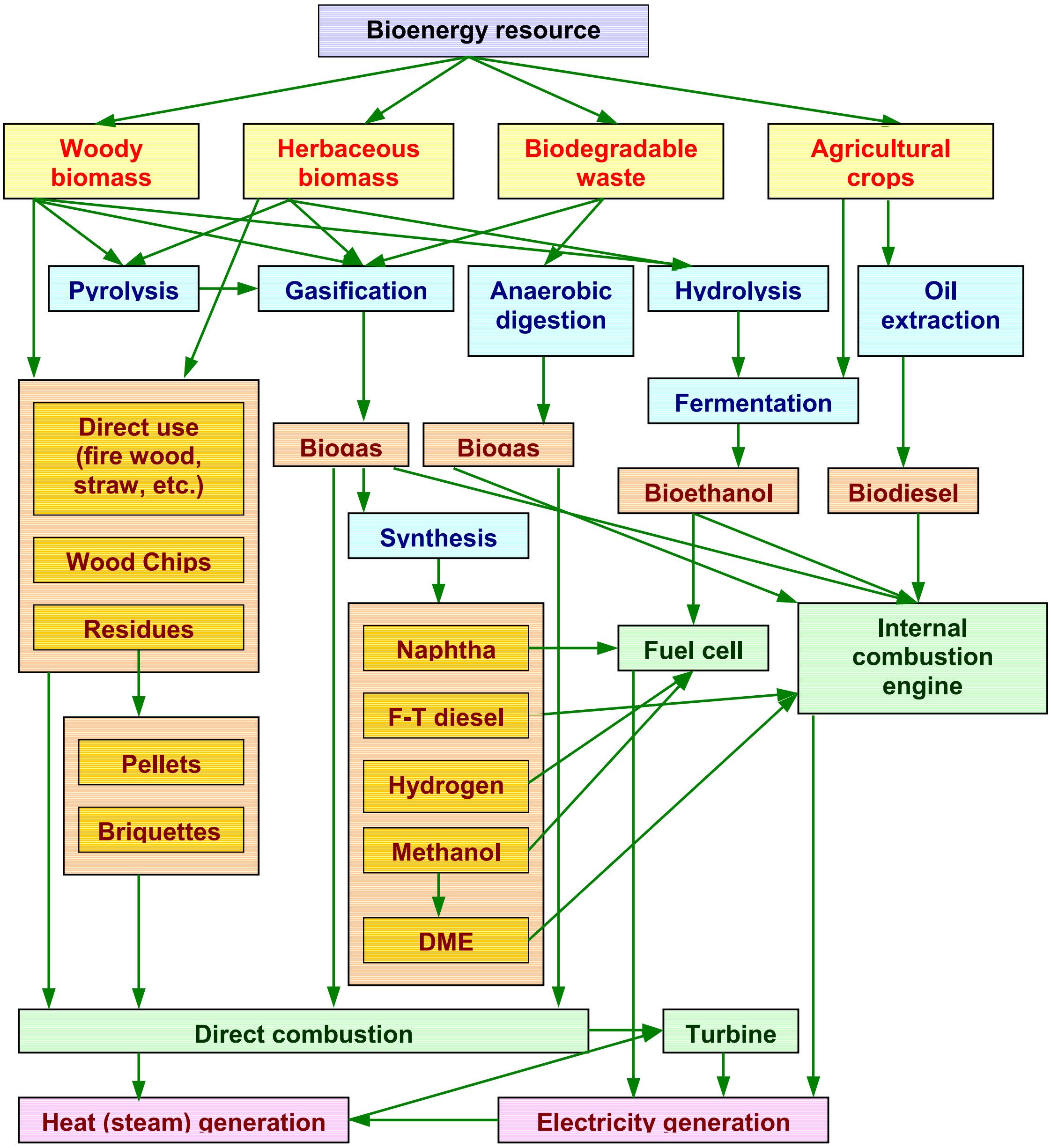
To a certain extent, the criteria from Figure 7 are inter-related and somewhat mutually-contradicting. For instance, a further transformation of a given feedstock may offer lower local-polluting emissions, but at the expense of additional energy losses and costs. Consequently, the selection of REP should take into account simultaneously the combined direct and secondary impacts of these criteria.

The EU is heavily dependent upon energy imports. The EU is also a large emitter of greenhouse gases. Securing and diversifying the energy supply in an environmentally-friendly way is therefore a key objective of the EU energy and environmental policies. The renewable energy sources are seen as a promising tool for achieving these policy goals. The aggregate comparative assessment of different Renewable Energy Pathways (Figure 6) is usually based on the following inter-related criteria: security of energy supply, diversity of energy supply, import dependence by energy sources, energy efficiency, greenhouse gas emissions, local-polluting emissions, costs, sustainability, market potential, reliability and inter-relations with other, non-energy policy objectives.

2. BIOENERGY BASIC FACTS

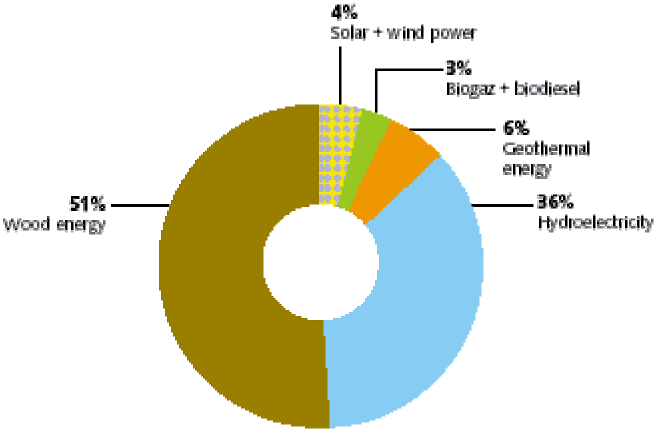
There are several renewable energy sources that can contribute to the achievement of the EU policy targets – hydropower, geothermal power, photovoltaic power, wind power and biomass. Amongst them, biomass is believed to possess the largest unexplored potential by 2010, followed by wind power [16, 42, 45, 53, 123, 128]. In addition, bioenergy shows some specific advantages over other renewable and fossil energies – contribution to all three renewable energy targets, being actually the only renewable source that can fulfil the transport energy target; can be stored; it is more labour-intensive and thus, creates employment especially in the sensitive rural areas, etc. [19, 38, 43, 46, 50, 87, 88, 93, 135, 137, 155, 156, 157, 160, 168, 200, 219]. The feasible alternative REP for biomass are presented in Figure 8.

Figure 8
Most appropriate alternative renewable energy pathways for biomass



The latest data for market penetration of renewable energies in the EU confirm the leadership of bioenergy (Figure 9), which is the second largest renewable energy source after large hydropower [200].

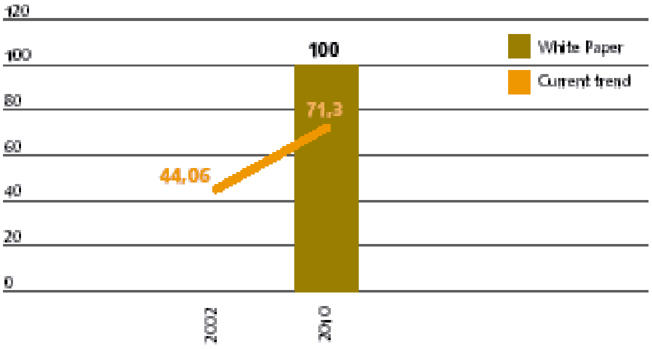
Figure 9
Shares of different renewable energy sectors in the EU in 2002, measured on gross energy production basis[2], (%)



Source: [200], adapted from [33]

Nevertheless, the recent data on penetration of renewable energies in the EU [50] indicate a slower realisation of the bioenergy potential, compared to the preliminary estimates [42]. In order to meet its target, the current annual growth in wood-based energy (2.7% [35]) should be doubled. Although, it should be taken into account that the relative under-performance of the wood energy sector corresponds with a large absolute contribution (44Mtoe) – Figure 10.

Figure 10
Comparison between current rate of wood energy growth and the target in the EC White Paper on the Renewable Energy Sources /COM (1997) 599/ – [42], (Mtoe)



Source: [200], adapted from [33, 35]

The situation in the biogas sector is more worrying, since the present annual growth of about 10% should be more than doubled [33, 34], in order to reach the 2010 target – Figure 11.

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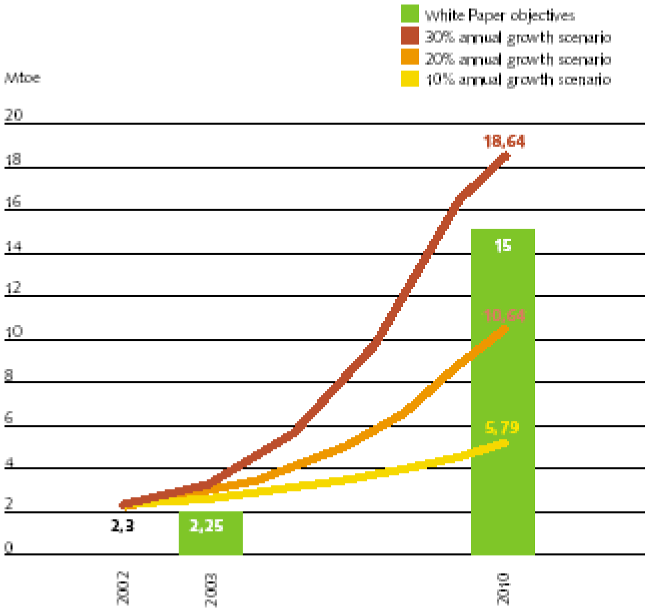
[2] Total gross energy production of renewable energies in the EU for 2002 – 81 Mtoe [200]

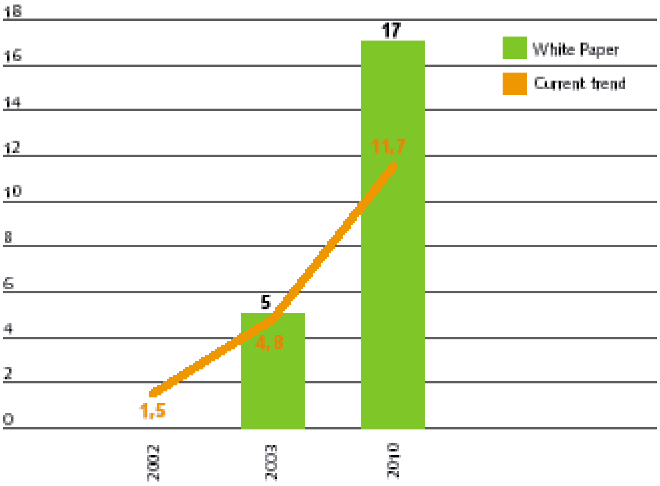
Figure 11
Comparison between current rate of biogas growth (10%), different growth scenarios (20% and 30%) and the target in the EC White Paper on the Renewable Energy Sources /COM (1997) 599/ – [42], (Mtoe)



Source: [200], adapted from [33, 35]

The situation with transport biofuels raises great concerns in the EU. The recent relative increase was impressive, but in absolute terms still little has been done so far – Figure 12.

Figure 12
Comparison between current rate of transport biofuels growth and the target in the EC White Paper on the Renewable Energy Sources /COM (1997) 599/ – [42], (Mtoe)



Source: [200], adapted from [33, 36]

Hence, since bioenergy is to be the major contributor to the achievement of the renewable policy targets of the EU (Figure 13), the delayed bioenergy expansion threatens the overall success in reaching the EU renewable energy goals.

Figure 13
Preliminary estimates for the contribution of various bioenergy sources to the 12% renewable energy target in gross inland energy consumption of the EU by 2010

Feedstock source per annum	Application	2010
Biogas growth 1997-2010	Power and heat generation	15 Mtoe
Agricultural & forest residues growth 1997-2010	Power and heat generation	30 Mtoe
Energy crops growth 1997-2010	Liquid biofuels	18 Mtoe
Energy crops growth 1997-2010	Power and heat generation	27 Mtoe
Bioenergy growth 1997-2010	All applications	90 Mtoe
Total bioenergy in 1997		44.8 Mtoe
Total bioenergy in 2010		135 Mtoe
Bioenergy share in GIEC (1997 forecast)		8.5-8.3%
Bioenergy share in GIEC (2003 forecast)		7.5%

Remarks: Total biogas potential is estimated at 80 Mtoe; Total agricultural and forest residues potential is estimated at 150 Mtoe [42]
Source: Adapted from [42, 50, 53]

Mainly due to the under-performance of bioenergy, at present the feasible renewable share in gross inland energy consumption is estimated to be 10% by 2010 (instead of the targeted 12%), while the renewable electricity share is projected to reach 18-19%, instead of the 21% goal by 2010 [29, 50, 67, 69, 74][3]. It has been therefore concluded that additional policy measures, fostering the market penetration of bioenergy, in particular in the heating sector, are necessary [50, 155, 156].

With regard to the above, the goal of this work is to perform a thorough techno-economic assessment of biomass applications for heat generation in the EU in the near and medium term, concentrating on the 2010 time horizon.

Bioenergy is considered to be the renewable energy source with the largest unexplored potential in the EU (Figure 8). The practical realisation of this potential is however lagging behind the provisional estimates. This may lead to a delayed or only partial achievement of the overall renewable energy targets of the EU. Further efforts and incentives are needed to exploit the feasible potential of biomass as an energy source, in particular in the heating sector.

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[3] The assessment of the progress towards the achievement of the transport biofuel targets is ongoing, according to the stipulations of [79].

3. BIOHEAT BASIC FACTS

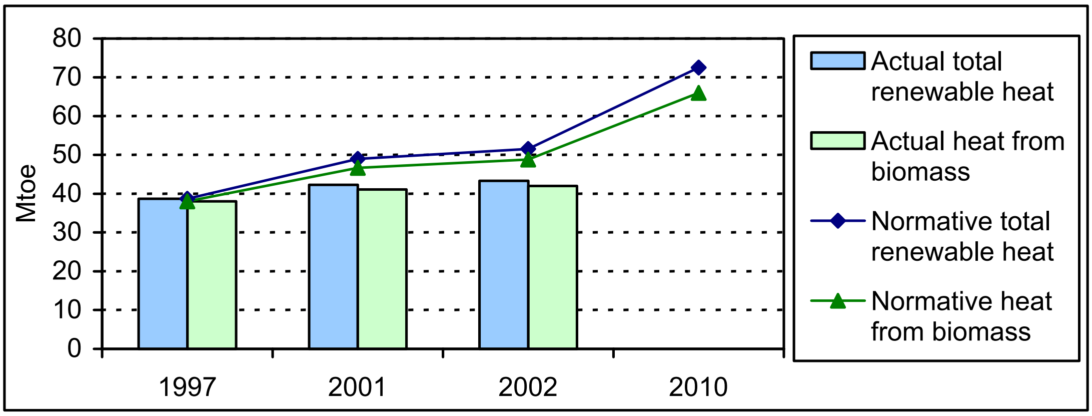
Heating is the largest single end-user of energy, accounting for about 1/3 of total final energy consumption in the EU [45, 202]. A target of 75 Mtoe heat, generated from renewable energy sources by 2010, has been set up for EU-15 [42][4]. With regard to this policy objective, it is of prime significance to identify the niches in the heat market where the renewable energy sources can be successfully introduced or their share can be expanded.

Depending on the type of heat requirements, heat demand can be provisionally classified for:

- Industrial applications –steam generation with a steam temperature above 140ºC;
- Central heating application – for households (including hot water), with usual temperature range between 40ºC and 140ºC;
- Agricultural application – e.g. for greenhouses, where the typically needed temperatures are below 40ºC [20, 45, 48];

Amongst different renewable energy sources, biomass appears to be the most feasible option for heat generation, at least by 2010. It is expected to deliver the major contribution to the 75 Mtoe target for renewable heat – 66 Mtoe (Figure 14 and Annex 1).

Figure 14
Retrospective (1997, 2001 and 2002) and targeted (2010) actual and normative[5] heat generation from renewable energy sources and from biomass, (Mtoe)



Source: Adapted from [50]

Experience with biomass heating is not scarce – burning wood for heating has been known by humanity for millennia. Nowadays, about 85% of all woody biomass, used for energy purposes, goes for heat generation, both on a small-scale (households) and on a large-scale (e.g. district heating) [35] – Figure 15.

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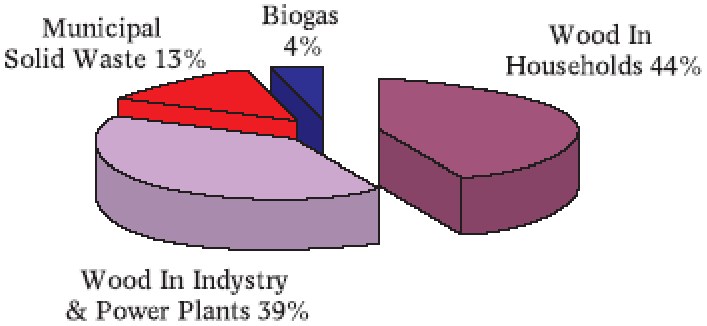
[4] Later updated to 72 Mtoe [62]. An updated scenario for EU-25 is not available yet.

[5] Needed to reach the 2010 target – obtained by linear extrapolation.

Figure 15
Breakdown of biomass application in EU-15 in 2000, (%)



Source: [62]

Despite the bulky share of biomass for heat generation, a dedicated legislation at EU level for promoting bioheating is not available yet. Heat generation from biomass is indirectly influenced by the aggregate target of 12% renewables in gross inland energy consumption, by the directive on the promotion of co-generation of power and heat [84] and by the directive on the energy performance of buildings [78]. Partly due to this lack of dedicated legislation, biomass heat is lagging behind the preliminary defined schedule – Figure 14. The slower progress in bioheat is considered to be a key reason for the under-performance of the EU on the way to the 12% renewables target in gross inland energy consumption by 2010. Without strengthening the support for the renewable energies for heat generation, thus – for bioheat at the first place, the feasible extent of this renewable energy target is thought to be around 10% [50]. For this reason, the implementation of new regulatory measures at EU level, targeting specifically renewable heating and thus – bioheating, has been identified as necessary and urgent [7, 50, 155, 156].

Various types of biomass can be used for heat generation. Some of them, like wood, are well known, while others (e.g. dedicated herbaceous crops) are novel options and little experience is available so far. The feasible biomass REP for heat generation in the EU by 2010, are presented in Figure 16.

Heat generation and in particular bioheat, has some specific characteristics, compared to other energy alternatives and sectors:

- Unlike e.g. electricity generation, heat generation tends to be less centralised, because heat distribution losses are typically high. For instance, an average value of 30% distribution loss is normally taken for district heating. Hence, the more concentrated the heat consumers are, the lower the distribution losses. So, the distribution losses can in first approximation be considered as inversely proportional to the plant size (Figure 17). This means that from the demand side, the size of the heating plant is defined by the nearby availability of heat consumers [4, 19, 20, 109, 130, 135, 168].

Figure 16
Feasible renewable energy pathways from biomass for heat generation

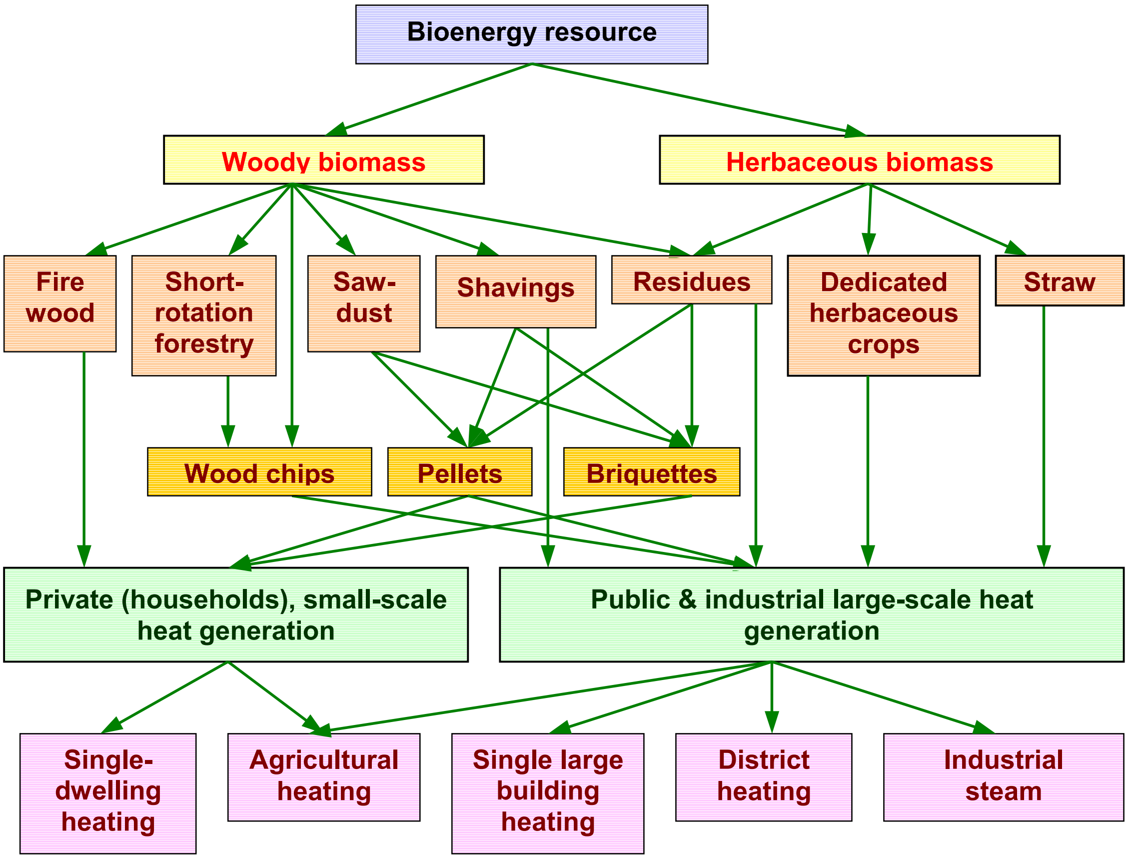
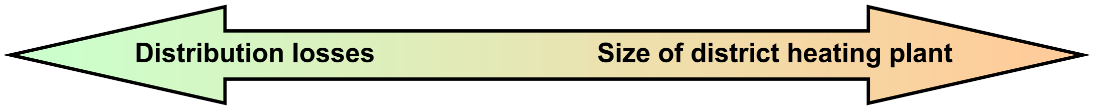


Figure 17
Inverse correlation between heat distribution losses and plant's size

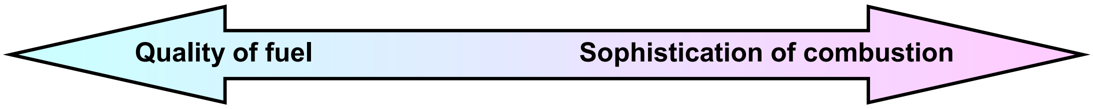


- On the supply side, the size of the plant depends on the nearby availability of feedstock, unlike e.g. the heat generation from fossil fuels. The heating plants, employing biomass, should always be designed based on a careful and thorough assessment of the feasible feedstock availability within a radius of 80-150 km [1, 6, 41, 135, 137, 164, 168, 174].
- Efficient heat generation requires an optimal combination between the fuel and the combustion technology involved. The combustion process should be properly tuned and adjusted according to the properties of the fuel. Conversely, these fuel properties should be guaranteed during different combustion stages. It is also extremely important to ensure a good contact between the oxygen in the air and the fuel. The better the contact is, the faster and more complete (more efficient) combustion. If the fuel is gaseous, it is easy to get the optimum ratio in the fuel & air mixing. The case of solid fuels is however more complicated. If the particle size of the fuel is large, its moisture content – a key factor, influencing the combustion efficiency – will gradually decrease during successive

combustion stages, affecting thereby the combustion tuning. In addition, the moisture content of fuels reduces their energy content expressed by the calorific value, since part of the energy is used for water evaporation. A moisture content of biomass more than 55-60% of total weight makes maintaining an efficient combustion process difficult. Hence, it is often necessary to reduce the particle size of biofuels, especially of those with high moisture content [19, 97].

- In practice, an inverse correlation between fuel quality and the extent of sophistication of combustion technologies is observed (Figure 18). For optimising the combustion process and respectively – the heat generation, relatively simple and thus cheap combustion technologies (e.g. for households use) require better-refined and more expensive fuels. On the contrary, the large-scale sophisticated and expensive combustion technologies used e.g. in district heating and industrial steam generation, can operate efficiently on cheaper fuels with lower quality specifications.

Figure 18
Inverse correlation between the quality of the fuel and the extent of sophistication and refinement of the combustion system



- Detailed assessment of the application of biomass for heating purposes is significantly obstructed by the general lack of data, due to the following reasons:
  - A standardised approach for collecting and classifying bioenergy data is still unavailable both in Europe and worldwide. Bioenergy data are sometimes included in the common category of “renewable energies” or they are reported just as “others”. In the latter case they are usually mixed with the figures for municipal waste.
  - Often the data on biomass for energy purposes do not make a distinction between the utilisation for power generation and for heat generation. As a result, the biomass renewable energy resource sometimes is reported as part of the thermal power generation, i.e. together with fossil fuels.
  - Peat is considered as a fossil fuel at EU level, while in some European countries (e.g. Finland and Sweden) it is classified as a “slowly renewable”[6] biofuel [142].
  - Sound data about the application of biomass for heating in the residential sector are generally not available or are hampered by a very large extent of uncertainty.
  - With regard to EU-25, some data for EU-15 can be found, but they are usually lacking for NMS-10 or in the best case they do not correspond in terms of format and classification to those for EU-15.

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[6] Peat is obtained from biomass that is incompletely decomposed and has been developed in bogs and fens. In Finland and Sweden peat is regarded as a slowly renewable fuel with a long (several thousands of years) renewable cycle. For comparison, the renewable cycle of peat is much shorter than that of fossil fuels – 50-500 million years [138, 142].

- Using alternative (non-EU) sources of information, e.g. [205, 223], does not improve the situation either, as most of these sources apply regional aggregations, which differ from the typical country aggregations in the EU (EU-15, NMS-10 and EU-25).

Considering the above, additional efforts to refine the data collection process, in order to better describe and analyse the bioheat sector, are necessary [50].

The heating sector appears to be the largest energy market for biomass, since there is a number of feasible renewable biomass pathways that fit the requirements of this sector (Figure 16). The progress in bioheating is however lagging behind the preliminary estimates. This delay is seen as a core reason for the under-performance of the EU on the way of reaching the 12% renewables target in gross inland energy consumption by 2010. The delayed progress is considered to be partly due to the lack of specific legislation at EU level targeting the promotion of bioheating.

Bioheating is a complex energy system, since it depends on the simultaneous nearby availability of heat consumers and biomass feedstock. The efficient heat generation requires also an optimum combination between combustion technology and fuel properties. In this context, an inverse correlation between the quality of fuels and the level of sophistication of combustion systems is observed.

4. BIOMASS FUELS FOR HEAT GENERATION

Two core types of biomass for heating can be distinguished – woody and herbaceous (Figure 16). Biomass fuels can be also classified according to other criteria, i.e. cost (relatively cheap / relatively expensive), properties (lower quality, feedstock type and higher quality, end-product type), etc. The main technical specifications of the typical solid biofuels for heating are shown in Figure 19. For comparative purposes, Figure 19 gives also the properties of the key fossil fuels, employed for heat generation – coal and natural gas. Peat is also included, because as already mentioned, some countries in Europe consider it as a slowly renewable biofuel.

4.1. WOODY BIOFUELS

Currently wood is the key renewable energy source (Figure 9) and biomass fuel in the EU (Figure 15). Its dominance in the EU renewable energy mix is expected to continue in the future as well (Figure 10). Thanks to climate advantages, some European countries (mainly Finland and Sweden[7], but also Austria, Denmark, Germany, France, etc.) are amongst the world leaders in the development and the promotion of wood energy [64, 174]. The wood-based fuels comprise all kinds of raw materials from forestry – felling residues, thin cuttings, stem wood, chips, cutter shavings, wood powder, pellets, briquettes, etc. [138].

4.1.1. Whole trees

Whole trees firing takes place in the USA only. Upon harvesting, the whole trees are directly shipped to the plant. Since fresh wood is very wet (about 50% moisture), it is left for about a month in a special storage, where forced drying is applied, so the moisture content drops to about 20-25%. The dried whole trees are burnt in dedicated large-scale furnaces, being just dumped there in regular intervals. The only advantage of the whole tree concept is the avoidance of the handling costs, associated with the reduction of the fuel size. On the other hand, a number of disadvantages is observed – higher transportation costs, due to poorer utilization of trucks' cargo carrying capacity; impossibility of optimising combustion (resulting in low energy efficiency and high polluting emissions), because of varying fuel properties from the periodical addition of fresh material with higher wetness, etc. [97, 164, 168]. Due to these drawbacks, the whole tree concept is not applied anywhere in Europe, so it is not examined in this work.

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[7] For instance, 60% of district heating in Sweden in 2001 was coming from biomass, mainly wood [138].

Figure 19
Main quality specifications of selected fuels

Fuels / properties	Coal	Natural gas	Peat	Peat pellets / briquettes	Wood[8]	Bark	Wood chips	Forest residues[9]	Wood pellets / briquettes	Willow	Straw	Red canary grass	Olive oil residues
Ash, d%	8.5-10.9	0	4-7	1.5-2.5	0.4-0.5	3.5-8	0.8-1.4	1-3	0.4-1.5	1.1-4.0	3-5	6.2-7.5	2-7
Moisture, w%	5-10	0	40-55	10-11	5-60	45-65	20-50	50-60	7-12	50-60	14-25	15-20	60-70
NCV, MJ/kg	26-28.3	48	20.9-21.3	19-19.9	18.5-20	18-23	19.2-19.4	18.5-20	16.2-19	18.4-19.2	17.4	17.1-17.5	17.5-20
Density, kg/m3	1100-1500	n.a.[10]	n.a.	650-700	390-640	320	250-350, 320-450[11]	n.a.[12]	500-780	120[13]	100-170[14]	200[9]	n.a.
Volatile matters, %	25-40	100	n.a.	>70	>70	69.6-77.2	76-86	>70	>70	>70	70-81	>70	n.a.
Ash melting point, t°C	1100-1400	-	n.a.	n.a.	1300-1700	1400-1700	1000-1400	n.a.[15]	>1120	n.a.	800-1000	1100-1200	≈1260
C, d%	76-87	75	52-56	52.4	48-52	48-52	47-52	48-52	48-52	47-51	45-48	45.5-46.1	48.5-49.5
H, d%	3.5-5	24	5-6.5	5.6	6.2-6.4	4.6-6.8	6.1-6.3	6.0-6.2	6.0-6.4	5.8-6.7	5.0-6.0	5.7-5.8	5.4-6.5
N, d%	0.8-1.5	0.9	1-3	1.2	0.1-0.5	0.3-0.8	<0.3	0.3-0.5	0.27-0.9	0.2-0.8	0.4-0.6	0.65-1.04	0.5-1.5
O, d%	2.8-11.3	0.9	30-40	33	38-42	24.3-42.4	38-45	40-44	≈40	40-46	36-48	≈44	34-38
S, d%	0.5-3.1	0	<0.05-0.3	0.10-0.16	<0.05	<0.05	<0.05	<0.05	0.04-0.08	0.02-0.10	0.05-0.2	0.08-0.13	0.07-0.17
Cl, d%	<0.1	-	0.02-0.06	n.a.	0.01-0.03	0.01-0.03	0.02	0.01-0.04	0.02-0.04	0.02-0.05	0.14-0.97	0.09	≈0.1
K, d%	0.003	-	0.8-5.8	n.a.	0.02-0.05	0.1-0.4	≈0.02	0.1-0.4	n.a.	0.2-0.5	0.69-1.3	0.3-0.5	≈1.3
Ca, d%	4-12	-	0.05-0.1	n.a.	0.1-1.5	0.02-0.08	≈0.04	0.2-0.9	n.a.	0.2-0.7	0.1-0.6	9	≈0.7

Source: Adapted from [1, 19, 20, 28, 39, 41, 97, 122, 126, 129, 137, 144, 148, 164, 168, 174, 207, 208, 228]

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[8] Without bark

[9] Coniferous trees with needles

[10] Depends on the aggregate state (compression and temperature)

[11] The first range is for soft wood, the second range – for hard wood

[12] Large variations are possible

[13] Willow chips

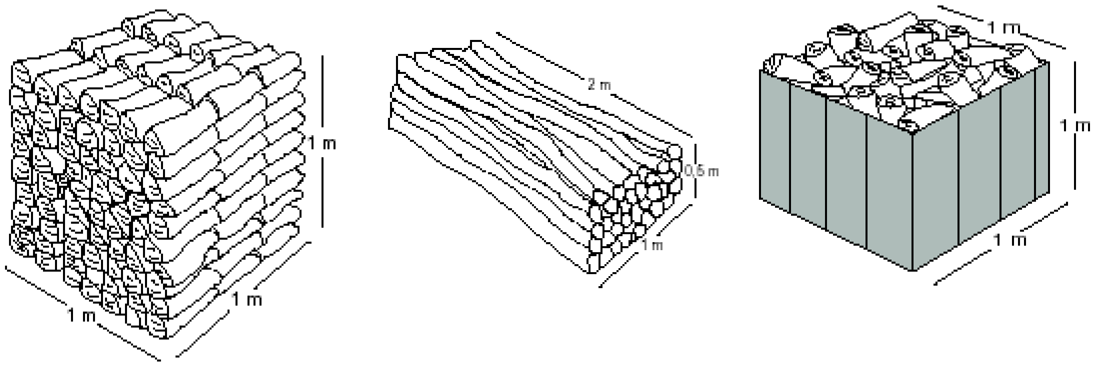
[14] Bales

[15] Large variations are possible

4.1.2. Firewood (fuel wood, wood logs)

Firewood represents forest fuel of trimmed or untrimmed stem wood – Figure 20.

Figure 20
Different shapes of fuel wood; the NCV are given for beach with 20% moisture content



Sawn, split and stacked wood, NCV – 7.6-8.6 GJ.

Stacked whole-tree wood, NCV – about 6.5 GJ.

Loose volume wood, NCV – about 4.8 GJ (40 cm pieces).

Source: [19]

Fuel wood with length of wood pieces less than 50 cm is considered as a short-length wood, while firewood with length more than 50 cm is called pole-length [139]. Burning wood pieces is the first ever known way of heating. It is still used by the households, but its application is declining, because:

- Firewood is relatively expensive, compared to other biofuel alternatives, moreover stem wood can usually find higher value applications, e.g. for pulp and paper production, furniture industry, etc.
- The energy efficiency of fuel wood burners is low (50-60%, compared e.g. to 75-90% for burners on wood chips and wood pellets), while the emissions are high. This is due to the impossibility to optimise the combustion process for firewood, because of the gradually changing fuel properties of the wood pieces.

Conversely, wood (pile) burners are simple, cheap and can handle various particle sizes and types (e.g. wet and dirty) of woody fuels [164]. Nowadays firewood is employed mostly for creating a nice atmosphere in private houses and leisure public locations, rather than for economically or technically justifiable reasons.

4.1.3. Short rotation forestry

Dedicated cultivation of short-rotation (3-30 years) wood species recently got an increasing popularity in Europe. The core wood species, considered in Europe, are willow (Salix) and poplar (Populus) - Figure 21.

Figure 21
Short-rotation forestry – willow and poplar

Willow harvesting in Sweden, [141]   Poplar felling in the USA, [89]

Willow is harvested in 2-4 year intervals, when the shots are of approximately 6 meters of height, normally in the winter, in order to reduce the moisture content. After harvesting, willow stumps are left to coppice and another crop grows in 2-4 years. Poplar needs longer harvest intervals – 8-15 years. Current yields of short-rotation forestry reach 10-15 tonnes per hectare per year that is higher than the wood yields from ordinary forestry. Hence, a smaller land area is needed to obtain the same amount of woody material. A value of 30 tonnes per hectare per year is targeted in the near future. The cultivation of short-rotation forestry is also quite efficient. It requires the energy equivalent of only 4-5% of the final energy content of the biofuel and little fertilising. The core drawback of dedicated woody crops is the much higher cost, compared to various wood residues from thinning, pulp and paper industries, etc. Hence, the reduction of cultivation costs of short-rotation forestry is a main challenge and pre-requisite for its larger penetration in the bioenergy market. Another weak point of woody crops is the typically higher moisture content, compared to firewood – Figure 19. For these reasons, and because of the heterogeneous particle size, which affects transportation costs and the efficiency of the combustion process, short-rotation forestry normally is not used directly as a fuel. In most cases, it is employed as a feedstock for obtaining other, more homogeneous and refined woody fuels, e.g. wood chips [8, 19, 31, 89, 97, 124, 135, 137, 141, 146, 151, 161, 162, 163].

4.1.4. Residual wood

A residual (waste) product can be defined as a material, which is a refuse without objective value within a specific context, otherwise it constitutes a material at the end of its usefulness [6]. Ensuing from this description, a number of woody materials can be included in the group of residues and waste: thinning and logging residues from forest industry (e.g. tops, branches, small size stems), demolition wood, fibreboard residues, railway sleepers, cutter shavings, sawdust, plywood residues, etc. Residual woody material is believed to be a very promising and attractive bioenergy resource, since it is available at much lower and even – no cost, compared to firewood and short rotation forestry. Synergies are also earned with other industries e.g. the regular thinning improves wood yields and quality, and prevents forest fires. However, it is often not possible to use directly residual woody biomass for heat generation, due to its heterogeneous composition and properties, e.g. particle size, which make inefficient and difficult the transportation and handling, content of moisture and impurities, etc. Hence, the residual woody biomass is usually employed as an intermediate feedstock for obtaining more refined woody fuels with better qualities – chips, powder, pellets and briquettes [19, 97, 127, 139, 146, 159, 168].

4.1.5. Wood chips

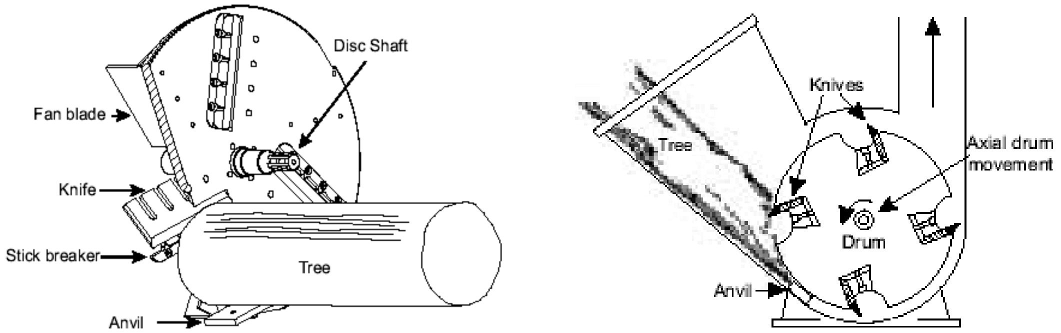
Wood chips (Figure 22) represent chopped with special facilities (chippers – Figure 23) woody material – whole trees (normally soft wood), short-rotation forestry, branches, tops, etc. with usual particle size distribution 5-60 mm.

Figure 22
On the left hand side – wood chips (juxtaposed for comparison to sawdust on the right hand side)

Source: Adapted from [19]

The chips from wood stems are of higher quality and contain fewer impurities, compared to the chips from residual woody material, but they are also more expensive. For stem wood, disc chippers are usually employed, since they produce more uniform chips (within the range 12-35 mm) than drum chippers (10-50 mm). Conversely, mostly drum chippers are used for residual woody biomass, because they are less sensitive to feedstock particle size differences and contaminants. The larger and less uniform chips from residual wood are more suitable for large-scale (industrial) utilisation, while the smaller and more refined chips from stem wood are more appropriate for small-scale (households) application [1, 19, 28, 137, 139, 146].

Figure 23
Typically used wood chippers



Disc chipper Drum chipper

Source: [19]

Wood chips are gaining an increasing popularity as a fuel option, due to the following advantages:

- Chipping allows the use of various residual woody materials, which otherwise are not suitable for handling or firing, due to different and/or not appropriate properties (e.g. too dissimilar or too large particle size, high moisture content). By combining different woody feedstocks, it becomes possible to compensate to a given extent the poorer fuel qualities of a given feedstock with the better fuel properties of another feedstock.
- Chipping gives a homogeneous woody fuel with better-guaranteed and more stable fuel qualities. As already mentioned, the homogeneity and the guaranteed fuel specification are key preconditions for energy efficient and low-emissions combustion.
- Chipping is very energy efficient, as it requires the equivalent of only 1-3% of the energy content of the woody biomass. The energy cost for wetter feedstocks is lower, due to the lower internal friction [97, 138].
- Chips are less expensive than other processed woody fuels, made out of residues, e.g. pellets and briquettes [1].

However, the production and handling of wood chips presents some potential problems:

- Chipping allows more complete utilisation of woody biomass. On the other hand, the reproduction of forests and the maintenance of high wood yields require leaving in the soil part of the nutrients (mainly nitrogen, phosphate and potassium), contained in wood. A more complete utilisation of the forest resource means also a larger removal of nutrients. If this process if not carefully controlled, it can result not only in reduced wood yields, but also in destroyed biodiversity and deserted areas. It is therefore of prime significance to find the right balance between the short-term yields and the long-term fertility of forest soils. In practice, achieving such a balance is relatively easy, since the largest part of the woody biomass (i.e. biofuel) is bound in stems, while the majority of nutrients are contained in needles and branches. Hence, after felling, the whole trees are often left on the ground for a couple of months. During this period, the needles and small branches fall down, due to gradual drying [19, 87, 89, 125, 137, 139, 146, 215].

- When chipping fresh wood (e.g. short-rotation forestry, tops, etc.), its moisture content, respectively – the wetness of chips can be very high (45-55%). As already mentioned, at such high moisture levels combustion is unstable and inefficient, so the wetness should be reduced. There are three ways of decreasing the moisture content of wood and wood chips, which can be used also consecutively to optimise the financial and energy costs:
    - Natural drying of woody raw material: When the whole trees are left on the ground so the needles and the small branches to be left in the forest, a parallel drying of stems also occurs. If the trees are felled between January and March, when the moisture content of wood is normally the lowest, and then are left for the summer to dry, the moisture content can naturally go down from 50-55% to 35-45%.
    - Natural drying of wood chips: Wood chips can be stored out-of-door (in the summer) or in-door (in the winter) nearby the heating plant for further drying. The summer out-of-door storage is preferred, since it is cheaper – due to the low bulk density of chips (Figure 19) they need large drying spaces. The reduction of wetness is similar to that of the natural drying of whole trees – from 50% to about 30%. Outdoor storage of biomass fuel with moisture content of less than 30% is however not recommended, since it can get wetter, due to rainfall. The height of the wood chips piles should be no more than 7-8 metres, due to the natural heating of the inner parts of the pile (up to 60°C), which may lead to self-ignition.
    - Forced drying of wood chips: Dedicated drying of woody biomass at heating plants should be generally avoided, since it reduces the energy efficiency of plants and increases costs. Thus, as much as possible natural drying is recommended. When natural drying is not sufficient and/or heat, which otherwise will be lost, is employed for drying (heat from flue gas re-circulation, from condensation units, etc.), the application of forced drying is justifiable. In the latter case, it contributes to a more complete utilisation of the total heat generated. Using part of the heat, generated in the furnace, for preheating does not increase the overall energy efficiency and hence is pointless, as this heat will be anyhow employed for steam generation. In any case, the cost calculations should always take into account the additional capital and running costs, juxtaposing them to the additional benefits incurred [1, 19, 97, 134, 137, 144, 146, 167].
- Besides the advantages of natural drying, leaving trees and chips in out-of-door storages may introduce some negative aspects – natural biological decomposition, insect infection (especially for soft wood species) and respective weight loss. The rate of biological degradation can be sometimes rather high, in particular for wet material in the beginning of the storage period – up to 5% per month for fresh chips or bark, later on getting down to 1-2%. The decomposition rate depends also on the particle size – the larger the particles, the lower the rate. In order to prevent large weight losses from insect infections, trees left on the ground for natural drying should be regularly inspected [1, 19, 97, 129, 137, 146].

4.1.6. Wood powder, pellets and briquettes

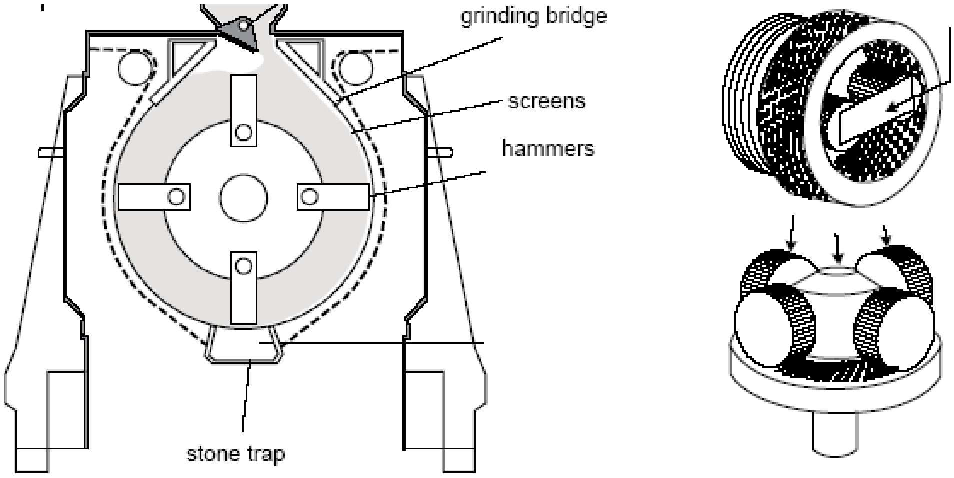
Another option to use various types of residual woody material is via its powdering and then optionally – producing pellets or briquettes from the wood powder (Figure 24).

Figure 24
From left to right - wood pellets, wood powder and wood briquettes

Source: [144]

Wood powder is fine shredding of woody biomass – the particle size of wood powder is below 3 mm, usually – about 1 mm [19, 139]. Wood powder is produced by milling various woody materials. Drum mill (Figure 25) is the most used type of mill, because it is robust, reliable and can process feedstock of various quality (including with impurities) and particle size.

Figure 25
Technologies for producing wood powder and wood pellets



Hammer mill – the most used mill for producing wood powder

Flat circular (up) and annular matrix (down) for pelletising wood powder

Source: Adapted from [97]

When demolition wood is employed as feedstock, a removal of the metallic contaminants may be necessary (with magnets), before the material enters the hammer mill. A preliminary reduction of the particle size can be needed, if they are longer than 50 cm. Wood powder can be also obtained directly – sawdust (Figure 22) from sawmills [19, 41, 97, 139, 144, 168, 228].

Wood powder can be used straight as a fuel, however its direct application poses a number of handling issues. For this reason, wood powder finds a limited direct application in practice, only in some industrial-scale facilities. In order to overcome the difficulties with handling, wood powder is normally used to produce pellets and/or briquettes – Figure 24.

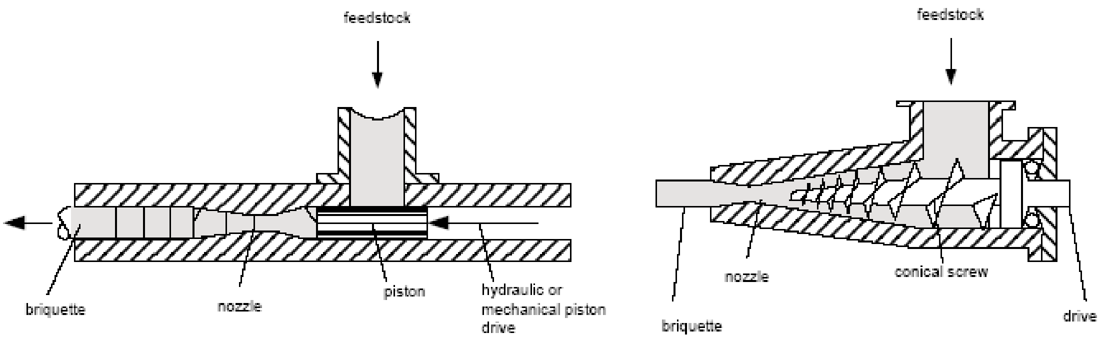
In terms of properties, wood pellets and briquettes are almost identical. Their major difference is the particle size – pellets' length is normally 10-30 mm at 8-12 mm of diameter, while briquettes are of 10-40 cm length at 2-12 cm of diameter.

Pellets are produced by way of forcing wood powder through a matrix (Figure 25) under high pressure, followed by cooling down (from 90-95°C to ambient temperature) for durability and stability. Binding agents (e.g. starch, molasses, natural paraffin, plant oil, etc.) usually are not added, because pellets keep their shape owing to the lignin content of wood, which has sticking properties. The well-defined and maintained moisture content of the woody feedstock – within the range of 8-12%, is an important condition for successful pelletising. Both higher and lower wetness are undesired – a lower moisture content may lead to lignin burning, while a higher wetness may prevent hardening. So, a forced drying of the woody feedstock for pelletising may be required in some cases. At the end, pellets are screened for fine particles, which may cause problems, especially in small-scale burning systems [19, 41, 97, 144].

The energy efficiency of pellet production is lower than that of chips. If dry raw material is used, the energy costs may reduce to that of chips – 1.5-2% of the energy content of pellets. If such drying is necessary, the energy costs may raise up to 7-13%. An additional 10% can be spent for preliminary crushing of the raw material, if needed [41, 97].

Compared to pellet production, the briquette technology is relatively simpler. Wood powder is pressed in special facilities (Figure 26), giving the briquettes shape and then cooled down for stability and durability. Similar to pellets, the wetness is an important parameter for successful briquettes manufacturing – it should be about 10-15% [19, 41, 97, 144].

Figure 26
Technologies for producing briquettes from wood powder



Source: [97]

Compared to other woody fuels (firewood and chips), pellets and briquettes have the following advantages:

- Better defined and guaranteed fuel properties. In fact, firewood (including short-rotation forestry) and chips can be regarded as feedstock, rather than as a fuel, while the case of pellets and briquettes is the opposite.
- Pellets and briquettes usually have much lower moisture content than firewood and chips (Figure 19), that makes them quite appropriate for small-scale simplified heating systems (see Figure 18).
- The higher bulk density of pellets and briquettes, compared to firewood and chips (Figure 19) permits longer economically efficient transportation (up to 200 km [7, 41]).
- The pelletising and briquetting technologies allow highly efficient energy utilisation of wood waste and residues, which otherwise cannot be utilised.

Conversely, pellets and briquettes are more costly than chips and in some cases – firewood. Furthermore, in order to maintain their fuel properties, pellets and briquettes always require in-door storage that increases their total costs.

Considering the above facts and the inverse correlation from Figure 18, it can be concluded that wood chips appear more appropriate for large-scale industrial applications, while wood pellets and briquettes are better suited for small-scale (households) utilisation. Briquettes seem particularly suitable to replace firewood. Pellets of low quality, which do not meet the requirements of the small-scale heating systems, can be employed for industrial use [41].

4.2. HERBACEOUS BIOFUELS

At present, woody feedstock is the leading biofuel for heat generation in the EU. Herbaceous biomass is lagging far behind woody biomass [174]. Nonetheless, it is widely believed that the energy potential of herbaceous biomass is promising, because most of it represents in fact residual material from agriculture (straw), available at relatively low cost. In addition, the dedicated cultivation of energy crops can be considered in the framework of the Common Agricultural Policy (CAP) of the EU. The energy crops may contribute to sustainable rural development and to a more market-oriented CAP, as well as they may facilitate the incorporation of NMS-10 in the CAP mechanisms [79, 197].

4.2.1. Herbaceous energy crops

Growing dedicated herbaceous crops for energy purposes is a relatively novel practice, being more at an experimental stage, rather than representing a large-scale practice [124]. For that reason, complete information about various impacts of growing energy crops is still scarce.

There are several herbaceous energy species, currently considered in Europe – miscanthus, red canary grass and switch-grass (Figure 27).

Figure 27
Red canary grass, grown in Sweden (left hand side) and switch-grass plantation in the USA (right hand side)

Source: Adapted from [141]

Source: Adapted from [161]

Miscanthus is an attractive option, since growing requires low quantities of fertilisers and pesticides, while the yield can reach 15 tonnes of dry matter per hectare per year. Red canary grass gives about two times lower yields per hectare per year (5-7 tonnes), without needing crop rotation for approximately 10 years. It fits well the climate conditions of Nordic countries, which are the leaders in the development and the application of bioenergy. Compared to short-rotation forestry, herbaceous crops have lower moisture content (Figure 19) and under certain conditions can be slightly cheaper. On the other hand, herbaceous crops have some disadvantages, compared to woody biomass: lower bulk density, higher ash content, lower calorific value (due to lower carbon content[16]), larger content of undesirable compounds causing corrosion (potassium, chlorine, sulphur) and increasing emissions (sulphur, nitrogen), lower ash melting point (Figure 19). For these reasons, burning herbaceous energy crops requires precise combustion control, which is economically feasible only for large-scale industrial applications [8, 20, 39, 55, 97, 135, 144, 150, 152, 161, 162].

4.2.2. Residual herbaceous biomass (straw)

Various kinds of straw (Figure 28) are the major, if not the only, residual herbaceous material for energy application. As it is a residual product, the availability of straw for heating purposes is driven by the cereals market forces and regulations, and does not have an autonomous market behaviour. In addition, farms use internally significant quantities of straw – as bed material for livestock, grain drying, etc. Part of straw is also chaffed and returned back to the field, as a natural fertiliser for soil amelioration.

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[16] Carbon, hydrogen and sulphur increase calorific value, while nitrogen, oxygen and ash decrease calorific value [97].

Figure 28
Straw collection and baling

Collection of straw, left in the swaths Big straw bale of 500 kg.

Source: Adapted from [20]

Similar to herbaceous crops, straw has typically lower moisture content than woody biomass. Conversely, it has a lower calorific value, bulk density, ash melting point and higher content of ash, corrosive and polluting elements (Figure 19). Nonetheless, the last two drawbacks of straw can be relatively easily overcome by leaving the straw on the field for a while (Figure 28, left hand side). In such a way, rainfall "washes" straw naturally from a large part of potassium and chlorine. Alternatively, fresh straw can be directly shipped to the heating plant, where it is washed by dedicated facilities at moderate temperature (50-60°C). However, due to washing, the initially low moisture content of straw becomes slightly higher in both cases. In both cases also, the content of corrosive components is reduced, but not completely taken out. Hence, similar to herbaceous energy crops, straw appears more appropriate for large-scale industrial applications, where sophisticated combustion controlling equipment can be economically introduced than for small-scale application. The only feasible exception from this rule is the own use by the agricultural farms, since in this case the fuel is available at almost "zero" cost.

In order to reduce handling costs, straw is usually baled (Figure 28, right hand side) before being shipped to the heating plant. The weight and the size of bales depend on the baling equipment and on requirements of the heating plant. The weight may vary from about 10 kg to about 500 kg, while the density increases up to 100-170 kg/m3 [20, 97].

4.2.3. Herbaceous pellets and briquettes

The production of pellets and briquettes from herbaceous material, mainly straw, is a recent technology. The production techniques and the particle size of straw pellets and briquettes are similar to those of wood pellets and briquettes (Figure 24, Figure 25 and Figure 26). However, due to the lower calorific value and density of straw, straw pellets and briquettes have lower energy content and weight than wood pellets and briquettes – around 16 MJ/kg at about 550 kg/m3. In order to prevent clinker formation, some kaolin is added to straw pellets, which increases the ash content (up to 8-10%), as well as some molasses (to improve stability and durability). The advantages of straw pellets and briquettes over the direct use of straw are the much higher density and the better-defined fuel qualities. Their weak point versus straw is the increase in costs, due to the pelletising and briquetting. Straw pellets and briquettes are better suited for industrial applications, rather than for households' appliances, due to the poorer fuel properties, compared to wood pellets and briquettes. For this reason, there are also ongoing experiments for producing pellets and briquettes from mixed raw materials – straw and woody feedstock. Mixing is seen as an opportunity to earn synergy benefits by combining different fuel properties [20, 141, 144, 228].

4.3. OTHER BIOMASS FUELS

In theory, some agricultural products (oilseed crops, some cereals, e.g. oats) could be directly burnt to generate heat. However, this option appears not quite appropriate in practice. After burning oilseeds, a huge amount of oil is left on the bottom of the boiler, which leads to risks of fire and malfunctioning [20, 97]. Regular and costly cleaning is therefore needed. In addition, oilseeds find much more attractive alternative applications both for food and energy purposes (oil extraction for producing biodiesel) [141]. Last, but not least, it is slightly sensitive to justify food burning when there is a shortage of food in many regions in the world.

Various residues from food and agricultural industries can be considered for energy purposes as well, under certain conditions. For example, residues from olive oil production could be an interesting fuel option, since only about 20% of olives' weight is oil – the rest can be burnt. Nevertheless, olive oil residues pose a number of challenges, mainly related to the high alkali content (Figure 19), leading to corrosion. A potential solution of this problem is their combined combustion at relatively low concentrations (10-25%) with coal. In any case, further research and work are needed to prove the viability of this combustion option[17] [39, 97].

4.4. SUMMARY

Based on the analysis, performed in the previous sections, Figure 29 summarises the relative suitability of different solid biofuels for heat generation in small-scale and large-scale facilities.

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[17] A more complete discussion on the combined combustion of different fuels is enclosed in chapter 7.

Figure 29
Relative suitability of different solid biofuels for small-scale and large-scale application

Fuels / applications	Small-scale application	Large-scale application
Whole trees	– –	0
Firewood	0	–
Wood chips	+	+ +
Wood powder	–	+
Wood pellets	+ +	+
Wood briquettes	+ +	–
Herbaceous biomass and straw	–	+ +
Straw pellets and briquettes	–	+ +
Agricultural products	–	–
Agriculture & food industry residues	– –	+

Legend: (– –) Not possible; (–) Not appropriate; (0) The penalties are compensated to a given extent by the advantages; (+) Appropriate; (++) Very appropriate;

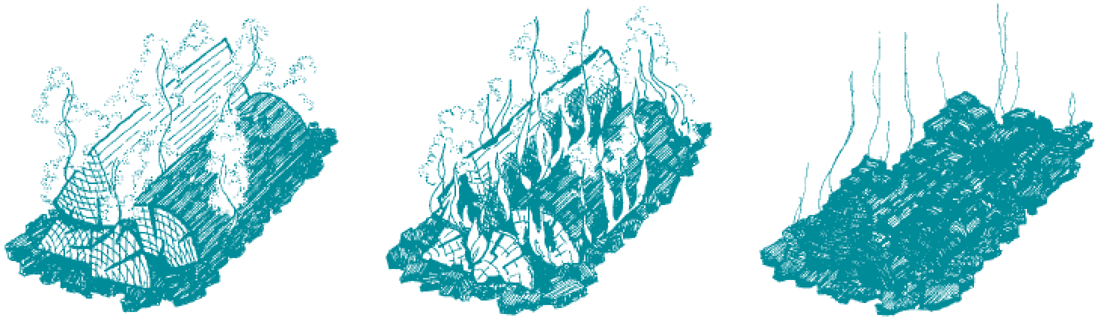
There is a large variety of solid biofuels that can be employed for heat generation (Figure 19). Amongst these, woody biofuels account for the larger part of heat generation, while herbaceous fuels find much smaller application (Figure 29), due to poorer fuel properties. Wood briquettes and pellets are most appropriate for small-scale appliances, while firewood represents a far poorer alternative. For large-scale applications, wood chips from short-rotation forestry and residual wood appear to be the best options, followed by pellets and wood powder. Burning whole trees seems to bring more disadvantages than benefits. All herbaceous feedstocks (energy crops and straw) and fuels (pellets and briquettes) seem better suited for large-scale systems than for small-scale facilities. Various residues from agriculture and food industry can also be considered under certain conditions.

5. BIOMASS COMBUSTION

5.1. GENERAL OVERVIEW

The combustion of solid fuels is a complex process, consisting of four successive stages – Figure 30. First, fuel is dried, i.e. the contained therein moisture is evaporated. Hence, the lower the moisture content of fuel is, the smaller the amount of energy, spent on evaporation and the higher the combustion efficiency. For these reasons, as mentioned in section 4.1.5, biomass fuels are often pre-heated (dried) before being burnt. On the next step, fuel is pyrolysed and after that – gasified. Both pyrolysis and gasification represent thermal degradation (de-volatilisation) of fuel. The difference between these two processes is that pyrolysis is carried without the addition of oxidising agent, while gasification needs such an agent (usually air, but in some cases also pure oxygen or steam). Pyrolysis produces mainly tars and chars, while the output from gasification is predominantly gaseous (CO, CO_2, H_2O, H_2, CH_4, etc.). At the final stage – combustion, various energy products, obtained from pyrolysis and gasification – tars, chars and gases, are completely oxidised [97].

Figure 30
Stages of solid biomass combustion



Drying Pyrolysis and gasification Charcoal combustion

Source: [127]

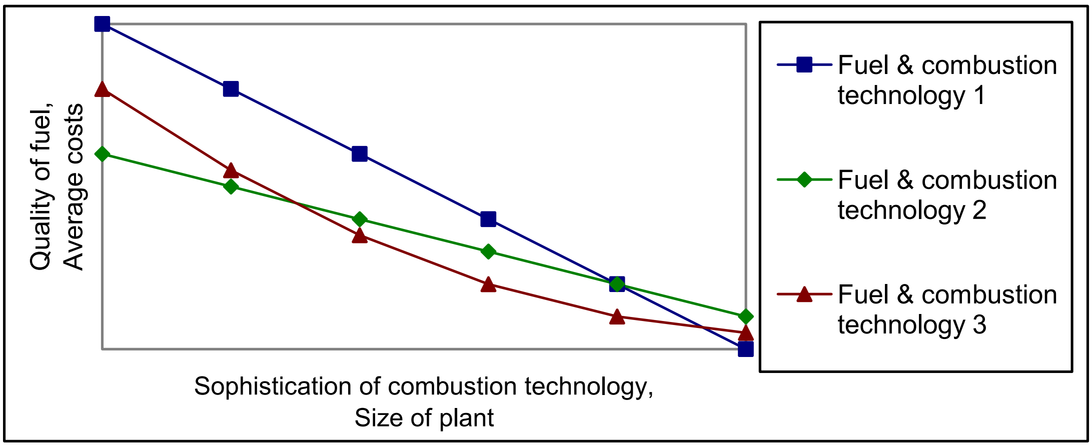
The efficiency of the overall combustion process depends on a number of factors – sufficient: temperature, residence time, mixture (homogeneity) of the fuel, and availability of oxidising agent. If some of these are not available in sufficient quantities and/or proportions, combustion becomes unstable and/or poorer, i.e. less efficient, with higher emissions.

Burning biomass imposes some specific requirements compared to fossil fuels, due to its properties (Figure 19). Because of the higher moisture content of biomass, the amount of energy, spent for drying, is larger than for coal. As a result, the temperatures and the energy efficiency of biomass combustion tend to be lower. The lower temperatures are due also to the lower calorific value of biomass, compared to coal. This also means that larger quantities of biomass than coal are needed to get the same energy output. Conversely, extremely high temperatures when burning biomass are not recommended. Biofuels and especially –

herbaceous biomass, contain more alkali metals (mainly potassium and sodium) than coal. Alkali metals lower the ash melting point and upon reaction with chlorine, also contained in biomass, have a strong corrosive effect on heat exchangers. Thus, when herbaceous biomass is employed for steam generation, the steam temperature should be kept below 450°C. For woody fuels, this temperature limit is higher – up to 500°C, but still lower than that for coal – 540-580°C, since woody biomass also contains more alkali elements than coal. On the other hand, the higher volatility of biofuels means that less char is left after combustion, compared to coal. The same is also valid for the ash – less ash is left after biomass combustion than from coal burning. Due to the high volatility, most biomass ash is bottom ash, while mainly fly ash (about 80% of total ash) is left from coal combustion. The high volatility of biomass also requires the oxidising agent to be supplied above the fuel bed (secondary air), where the gases are burnt, rather than under the fuel bed (primary air) [19, 39, 97, 143, 164, 174][18].

Figure 17 and Figure 18 already indicated some correlations between different parameters of bioheat application and combustion, however several additional functions can be identified – Figure 31.

Figure 31
General correlations between fuel quality, average heat generation cost, level of sophistication of combustion technology and size of plant



The complexity of combustion technology is directly proportional to the size of plant. As already pointed out, the introduction of expensive sophisticated controlling equipment is economically feasible only at a large-scale. Based on Figure 18, with increasing the size of plant lower quality fuels can be employed. As a result, the average costs of heat generation normally also go down, as the saved fuel costs compensate the increase in investment costs. In this context, it is sometimes claimed that the economy of scale is preceded by economy of

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[18] The purpose of this work is to make an easy-to-understand techno-economic analysis of bioheating, rather than to look at the very specific technical aspects of bioheat components, e.g. biomass combustion technologies. Thus, only the most important facts, related to biomass combustion, are considered in this chapter. For more detailed information on selected items, other publications from the attached bibliographical list can be referred to.

numbers (learning curve) [6]. This means that first more heating plants that use biomass should get to the market, in order to establish the fuel supply, transportation and handling chains. Finally, the reduction in fuel quality requirements and average costs may not follow the same trend in different combustion systems. Depending on the specific particularities, the reduction can be faster or slower (fuel & combustion technologies 1 and 2 from Figure 31), as well as not linear (fuel & combustion technology 3 from Figure 31).

5.2. SMALL-SCALE COMBUSTION

The simplest biomass burning system is the standard open fireplace. Nowadays, this combustion concept is almost abandoned, because of its very low energy efficiency (below 10-12%), and high dust and CO emissions. Due to the very large amount of excess air needed (λ[19]>3), open fireplaces may reach even negative energy efficiency (the energy input is larger than the energy output) when the outdoor temperature is below 0°C. Therefore, at present the application of open fireplaces is motivated by other, non-energy reasons, e.g. creating a nice atmosphere [19, 96, 97, 174].

Currently a great variety of small-scale combustion facilities (with typical heat output of 6-25 kW, up to 50kW for multi-family houses) is available that can be classified according to different criteria. The mode of fuel in-feed (manual or automatic) is an appropriate parameter for their distinction. Figure 32 shows a modern small-scale biomass burner of each type: a manually-filled firewood stove with electronic combustion control and an automatically-filled pellet burning facility.

Manually-filled stoves release heat by way of radiation and convection to the surroundings. The combustion is of downdraft[20] type, i.e. the combustible gases pass down through a lined chamber, where the final combustion takes place at high temperatures. Besides firewood, the manually-filled stoves may use also briquettes. Burning chips and pellets in such facilities is not appropriate, because of their small particle size and high bulk density. The manually-filled stoves are equipped with a water storage tank to accumulate the heat from one complete fuel portion, supplied to the furnace. The storage tank also allows more stable combustion. If there is no storage tank, the fuel wood properties will change after introduction of a new fuel portion, which will result in unstable combustion and in high emissions and corrosion, due to the variations in the flue gas temperatures.

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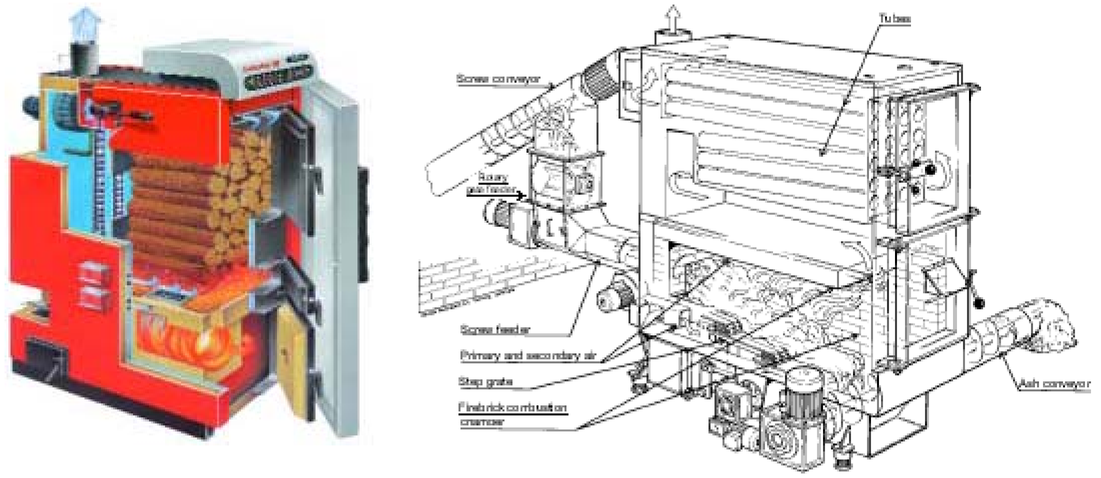
[19] The simple explanation of "λ" is that this parameter indicates the ratio between the supplied amount of air and the optimum amount of air that is needed for combustion.

[20] The circulation of the primary airflow determines the type of the stove. Apart from the downdraft, the air circulation can be also updraft, cross-draft and "S"-type draft [97].

Figure 32
Manually-filled downdraft firewood stove with electronic control of combustion and a separate chamber for the secondary combustion (on the left hand side), and automatically-filled pellet burning system (on the right hand side)



Source: [96]

Source: [19]

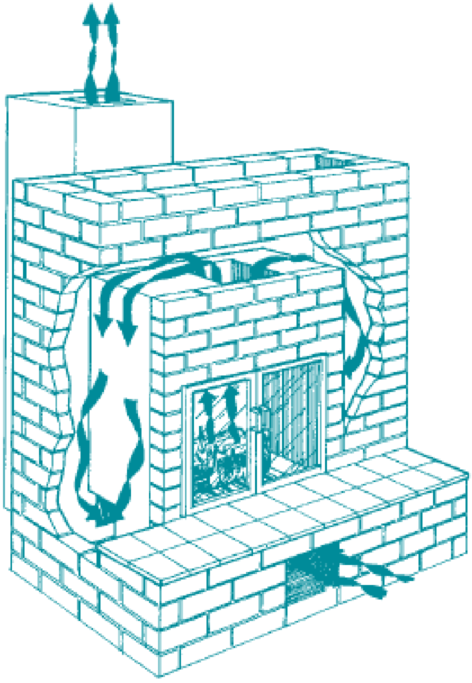
The combustion air is introduced through inlets in the gate of the furnace and is preheated. The flue gases move backward on the way to the chimney. An exhaust fan is added at the back of the stove to correct the pressure in the combustion chamber. The ash is taken out either from a removable grate, placed in the centre of the firebox hearth, or from an ash box, placed under the grate, or directly from the hearth.

The cost of downdraft stoves is about 50% higher than the cost of open fireplaces. On the other hand, the excess air requirements of stoves are lower – $2.1<\lambda<2.3$, and the combustion is more stable. Hence, the energy efficiency of stoves is much higher – about 70% for fresh wood with about 50% moisture content [19, 96, 97].

With the aim of increasing the energy efficiency of the stove, it is often connected to a water storage tank of 1-5 m3 to obtain hot tap water via heat exchange. In this case, before being released to the chimney, the hot flue gases pass first through tubes, forming a convection unit (well seen in the upper section of the automatic pellet burner in Figure 32). The tubes are equipped with spirals as to increase the heat exchange with the boiler water.

Another way to increase the energy efficiency of stoves is by adding a heat storing option – Figure 33. Here, the stove is equipped with an inert heat-storing jacket (typically of soapstone), which slowly accumulates and releases heat. Hence, after the combustion is over, the stove continues to release heat for a certain period of time (normally up to 1 day, maximum 2 days). Heat-storing stoves are suitable for countries where the outdoor temperatures are constantly low and thus, heating is required during the whole day. The main disadvantage of heat storing stoves is their much larger weight, due to the heat-storing jacket, which reaches several hundreds of kilograms.

Figure 33
Heat storing stove



Source: [127]

The automatically-filled pellet-burning systems for small-scale application (Figure 32) are a relatively novel heating option for households. Besides pellets, these facilities can burn also wood chips and even straw. The potential drawbacks of chips versus pellets are the lower density (larger storage space needed) and the typically higher moisture content. Conversely, chips tend to be cheaper than pellets. In the case of straw, both bulk straw and straw bales first have to be finely shredded and then the well-chopped straw can be fed to the furnace. The fuel is supplied from a dedicated pellet or chips silo to the step grate in the combustion chamber by a screw feeder. The fuel output of the screw conveyor is flexible and can be adjusted to the actual heat needs. Owing to the inclination of the step grate, the fuel is gradually combusted and the ash is pushed towards the ash chute, where another screw conveyor takes it out. Because of the design of the grate, the inlet and outlet conveyors, pellet burners cannot run on fuels with large particle size, e.g. briquettes or wood logs. The principle of heat and hot water generation is the same as that of downdraft stoves, described above.

The automatically-filled pellet systems have some advantages over downdraft stoves. Because of the more homogeneous fuel mixture, the combustion is better optimised and the energy efficiency can reach 90%. The emissions of CO and hydrocarbons, ensuing from poor combustion, are also lower, but NOx and dust emissions are still high. On the other hand, because of their more sophisticated design, pellet burners tend to be more expensive than conventional downdraft stoves [7, 9, 19, 20, 41, 97, 126, 127, 147, 150, 151].

5.3. LARGE-SCALE COMBUSTION

5.3.1. Batch combustion

As stated in section 4.1.1, burning fuels with large particle size in batch-type furnaces is not recommended because of low energy efficiency and high polluting emissions. However, this combustion approach still finds application for some fuels.

The first option is when piled wood (similar to firewood) is burnt. In this case, batch firing basically represents a larger-scale wood log stove – Figure 32. The combustion concept and the fuel in-feed are almost identical. They show the same advantages as downdraft stoves – simplicity, low capital and installation costs, ability to handle wet and dirty fuels. Conversely, pile burners have low efficiencies (50-60%), cycling operation (due to the ash removal) that is difficult for controlling and thus – for optimising, and increased corrosion. As a result, currently pile burners find little application for large-scale heat generation [164].

A more viable alternative of batch combustion is the utilisation of straw bales, especially for farm heating. The comparative advantages of straw bales are the elimination of the shredding equipment and costs (as the straw bales are directly fed into the combustion chamber) and the typically lower moisture content that allows better and more stable combustion. The volume of straw in-feeds to the combustion chamber depends on the boiler output – from 1 medium to 3-4 big bales. Electronic control equipment is widely used to monitor various combustion parameters – the amount of excess air and its distribution between the primary and the secondary combustion zones, flue gas temperatures, etc. Owing to the electronic controlling facilities, the combustion takes place at low excess air levels ($\lambda \approx 1.5$). However, when a new portion of fresh straw bales is fed, the combustion may not be optimum in the beginning, when the straw drying takes place. In order to maintain stable combustion and to optimise the heat output via keeping the combustion at maximum load, batch furnace systems for straw bales are often equipped with a water storage tank, similar to that of stoves. The volume of the tank is function of the rough proportion of 60-80 litres per kg of straw in the combustion chamber[21]. This allows an increase of the temperature of the water in the storage tank by 30-40°C when combusting a full straw in-feed, unless there is a parallel heat extraction from the storage tank. The combined result of the above improvements in the batch combustion technology is an increase of the energy efficiency up to 75-80% [20, 97].

5.3.2. Grate combustion

At present, grate combustion appears to be the most appropriate combustion concept for biomass. It is simple, reliable, efficient, able to process various, including “difficult” fuels (with

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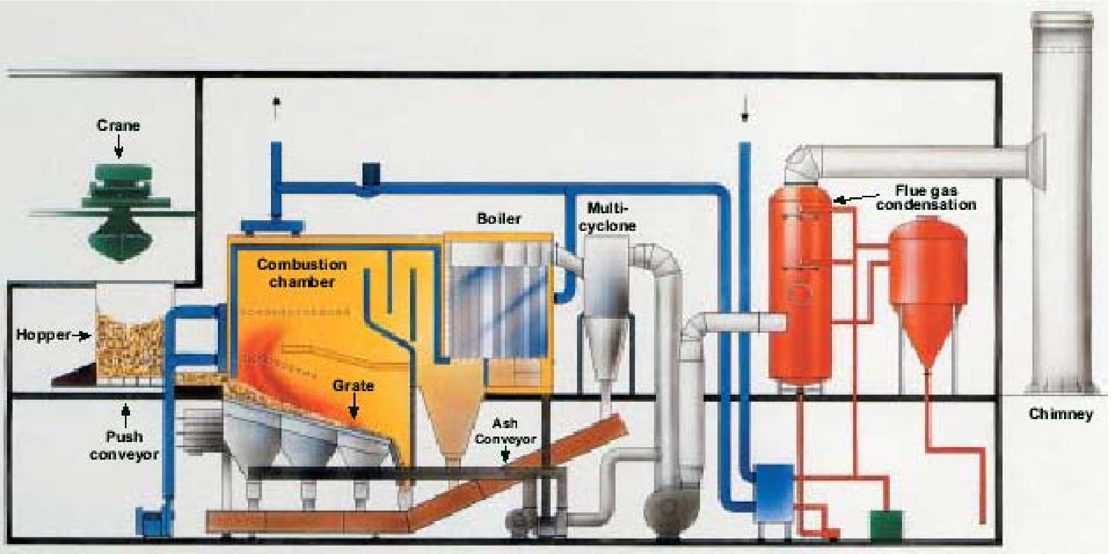
[21] An additional water storage tank can of course be added also to the batch combustion systems running on wood.

high moisture and ash content, dissimilar particle size, etc.), suitable for lower-scale use (0.5-20 MW), convenient for cycling and partial load operation, cost competitive. In exchange, the efficient functioning of grates requires proper sizing, homogeneity and good mixing of fuels. For these reasons, grates are suitable for simultaneous combustion of fuels with different properties, e.g. woody with herbaceous. However, some undesirable side effects, e.g. intensive fouling and slagging, can be observed in such cases [19, 20, 39, 96, 97, 124, 129, 133, 143, 146, 168, 174]. Various grate combustion systems have been developed over the years – fixed inclined, travelling, vibrating, etc.

In the fixed inclined grate systems, carefully measured portions of fuel are fed within well-defined periods of time into the combustion chamber. There, because of natural gravitation, the fuel bed is gradually moving down on the inclined surface of the grate. In such a way, the fuel is successively drying and de-volatilising. At the end of the grate, the char is burnt out and the ash is taken out from the combustion chamber. To improve the fuel homogeneity and the mixing with air, respectively – the combustion efficiency, steps are sometimes added on the inclined surface of the grate. The fuel particles turn upside down when passing different grate steps. The outlook of fixed inclined grates is similar to that, presented in Figure 34.

Figure 34
Sketch of a typical district heating plant with inclined grate – the Thyborøn plant in Denmark with 4 MW heat output, running on wood chips, equipped with a flue gas condenser that adds another 0.8 MW heat at 50% moisture content of wood chips



Source: [19]

Like in most biomass combustion concepts, the primary air supply is updraft vice-versa the grate, while the secondary air is supplied above the fuel bed. Due to the reliance on natural gravitation, the fuel particle size should be small enough and the fuel should be well mixed (homogeneous) for complete combustion to occur. Since it is difficult to control accurately the fuel movement and distribution on the grate during different combustion stages via inclination only, the fixed grate combustion concept is generally not considered for large-scale burning systems anymore. However, fixed inclined grates are still applied in smaller scale facilities, because they are simpler, easier for operation and maintenance, and cheaper than other grate designs.

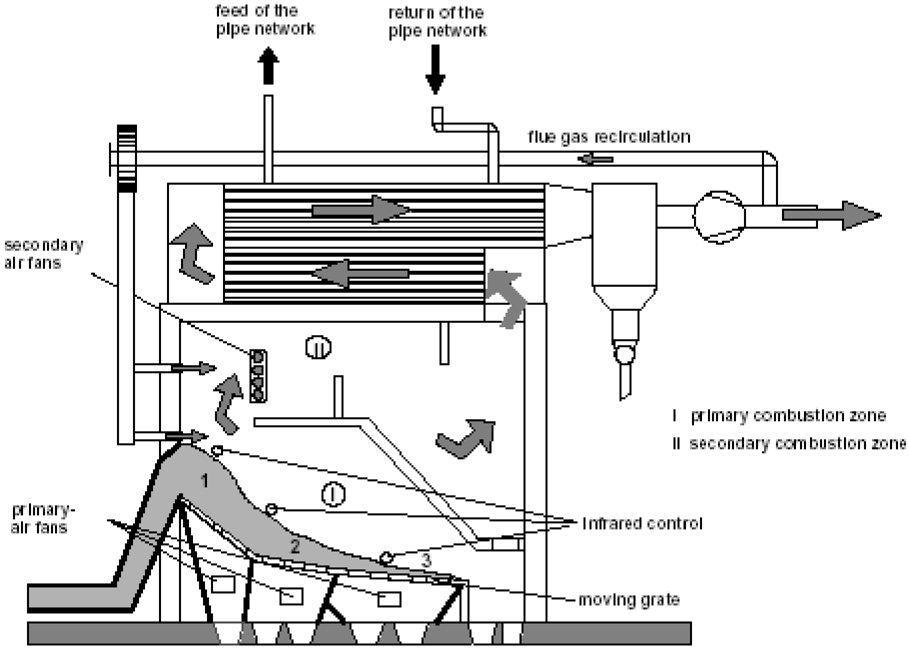
As it can be seen from Figure 34, the grate is not the only component of the combustion system in heating plants. The fuel is first delivered from the storage to the area of the combustion system and then, it is fed into the furnace. In addition, the ash, left after fuel burning, should be removed from the combustion unit. The fuel can be transported from the storage to the combustion unit by wheel loaders (the most simple option, appropriate for small plants), cranes (suitable for bulk material, as shown in Figure 34, and straw bales) and various types of conveyors (belt, tube-rubber, chain, etc.). The fuel can be supplied to the furnace by hydraulic feeders (convenient for wood chips, as it is in Figure 34), screw feeders (for pellets, sawdust), spread or pneumatic stokers (for less homogeneous fuels), conveyors, etc. Most often, the ash is removed from the combustion unit by means of conveyors (screw, belt, etc.). In any case, there is no uniform solution for the fuel delivery system and the selection is made on a case-by-case basis. The governing criteria in this selection are the specifics of the prevailing fuel(s) – particle size, content of moisture and of various harmful substances, and their impact on the elements of the combustion system [19, 39, 96, 97].

Travelling grate is maybe the most widespread biomass combustion technology at present. It is well-proven and has been used for a number of years for coal firing. Opposite to fixed grates, in travelling grates the fuel does not move along the grate, but the grate, made of bars of heat-resistant steel alloys, is moving as an endless chain band – Figure 35. The key advantage of travelling grates over fixed grates is the far better control of combustion, since the residence time of the fuel in different combustion stages does not depend on natural gravitation, but it is regulated by the speed of the grate. Consequently, the combustion efficiency can be increased, due to lower excess air requirements – λ=1.4/1.6 for wood chips and λ=1.2/1.3 for pellets. In addition, cleaning the grate from ash is easier, since the ash is discharged to the conveyor automatically when the chain band turns back at the end of the combustion chamber – Figure 34. Depending on the position of the chain band, two variants of travelling grates are known – horizontal and inclined.

The main advantage of horizontally moving grates is that uncontrolled movement of fuel particles, due to natural gravitation, is avoided. Hence, the thickness of the fuel bed, fuel homogeneity and fuel distribution along the chain band are better controlled. The initially even distribution of the fuel on the chain band is achieved by a simple sliding gate at the inlet of the combustion chamber. In exchange, the horizontally travelling grates require fuels with sufficient homogeneity and small particle size.

The inclined travelling grates combine the principles of fixed and travelling grates – Figure 35.

Figure 35
Modern inclined travelling grate with counter-current[22] combustion, infrared control system for moving speed and for the thickness of the fuel bed, section separation of the grate, flue gas re-circulation and primary air control in different combustion zones (zone 1 – drying, zone 2 – pyrolysis and gasification, zone 3 – char burning)



Source: [129]

There, the fuel transportation, thanks to the moving chain band, is further facilitated by natural gravitation. It is believed that such a design of travelling grates could ensure a more complete burning of fuels, compared to the horizontally travelling grate. It allows fuel particles to continuously turn down on the chain band, which improves mixing, especially for fuels with larger particle size.

Another option to deal with less homogeneous fuels is to use spread-stokers that blow fuel on the chain band, rather than just to pre-load fuel at the beginning of the chain band. The blowing ensures automatic good mixing of the fuel supplied to the furnace. Conversely, spread-stockers cannot guarantee the same extent of evenly distributed fuel along the chain band as the conventional approach does.

In order to avoid overheating, on the way back the chain band is cooled down by the primary air or by water. Air-cooling is usually applied when relatively wet fuels are burnt (wood chips). The heat, recovered in the primary air, is employed in the drying stage of combustion. In such a way, less heat from the direct combustion is consumed for fuel drying, hence – the energy efficiency of the combustion process increases. Water-cooling is normally applied, when relatively dry fuels (pellets) or fuels with low ash melting point (straw) are mostly used. A

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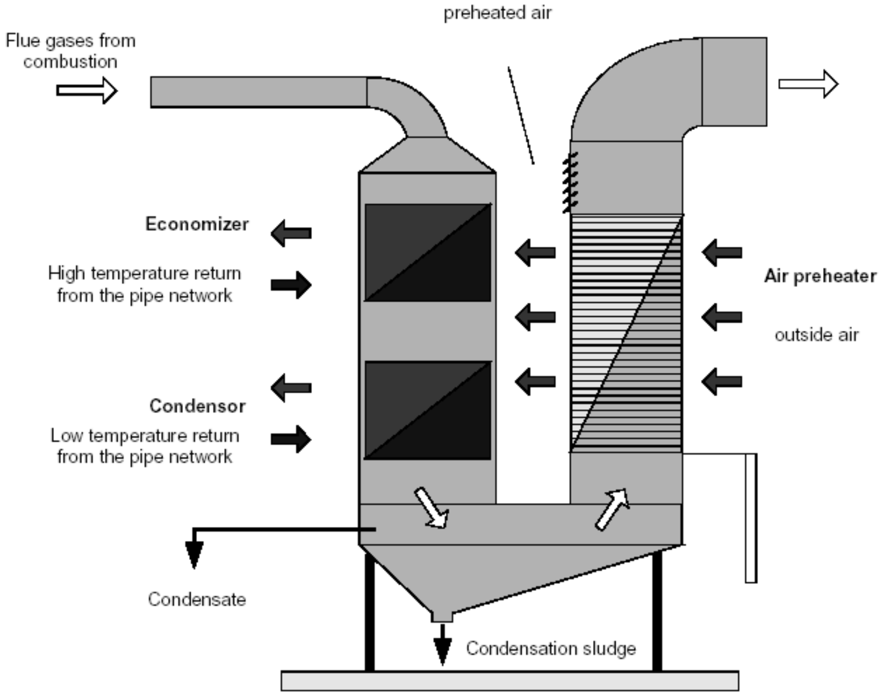
[22] Counter-current combustion is appropriate for wet fuels, since the hot flue gas passes over the whole fuel bed and in such a way facilitates fuel drying. On the contrary, co-current combustion (the hot flue gas leaves the combustion chamber at the end) is applied when mostly dry fuels are combusted, as well as when intensive primary air preheating is available [97].

lower moisture content means that less preheating is needed for optimising combustion. In this case using primary air for cooling may lead to insufficient cooling of the chain band, which may cause its overheating and consequently – intensive wear and tear. Biofuels with low ash melting point need lower combustion temperatures to reduce ash sintering and melting. A heavier cooling of the chain band by water, rather than by air, would diminish the temperatures in the combustion chamber and in particular – of the chain bed, on which the ash melting will be reduced. Nevertheless, in this case no net energy benefits are gained, as it is generally not possible to use the return cold water from the district heating pipeline network. The water that cools down the travelling grate is normally thrown away, which raises environmental concerns with the treatment of the wastewater and the safe discharge of the sludge in a landfill. The latter issue deserves particular attention, in view of the recently introduced legislation in the EU [75], aiming at reducing landfill deposits.

Apart from primary air preheating by the combustion grate, the steam storage tank and the flue gas heat recovery complex (Figure 36) represent other tools for increasing the energy efficiency of heating plants.

Figure 36
Diagram of a flue gas heat recovery complex, consisting of economiser, condenser and air pre-heater



Source: [97]

The reasons for adding a steam storage tank to a heating plant and the way of its use are the same as for the water tank in small-scale applications (section 5.2) and in straw batch burners (section 5.3.1). The storage capacity of the tank depends on the site specifics, mainly on the intensity and on the cyclic variations in the steam consumption. The main advantage of the steam storage tank is its ability to:

- Meet peak heat demand, for which the capacity of the heat plant is not sufficient, thereby avoiding supplementary firing of heating oil.
- Cover low heat demand in a more efficient way by running the plant at maximum load for a certain period of time. The excess heat is stored in the tank and then slowly released to the consumers, instead of continuously running the plant on partial load.
- Cover short shutdown periods, due to small maintenance works or breakdowns, and thus again avoiding a substituting combustion of heating oil.

Conversely, the introduction of a steam storage tank increases capital costs of the plant. It is therefore not reasonable to add such facilities to heat generating plants, which operate with stable heat outputs.

After being employed for steam generation in the boiler (Figure 35), the used flue gas still contains a lot of energy. If this flue gas is directly released to the atmosphere, its remaining energy content is lost. Hence, the remaining heat in the flue gas should be extracted so that its temperature gets as close as possible to that of the ambient air. For this reason, a heat exchange unit is added, where the energy of the used flue gas is transferred to the return cold water from the district heating pipeline web – Figure 36. This unit consists of two parts – economiser and condenser (see also Figure 34). For a more complete energy recovery, the heat from the flue gas is applied also for initial preheating of the primary air in a dedicated air pre-heater. The air pre-heater is introduced at the end of the unit, after the economiser and the condenser, since the water, returning to the boiler pipeline, should have a certain minimum temperature – 70-80°C, to reduce corrosion of boiler tubes. Finally, at the end of the heat recovery complex, the flue gas passes through a mist eliminator to protect the rest of the heat generation system (tubes, chimney) from condensation and corrosion.

Flue gas heat recovery is of particular importance when wet fuels are burnt. Since a lot more energy is spent during the drying combustion stage for moist fuels than for dry fuels, much more energy would be therefore lost, if no flue gas heat recovery was applied for such wet fuels. It is generally perceived that the flue gas heat recovery is cost and energy effective, when the moisture content of fuels exceeds 30-35%, the boiler output is larger than 2 MW and the temperature of the return water is below 60°C. The heat recovery efficiency is directly proportional to the moisture content of fuels and it is inversely proportional to the temperature of the ambient air and of the return pipeline water – Figure 37. For these reasons, the energy efficiency gains vary widely, but in most cases they fall within the range of 10-30%.

Figure 37
Dependence of the heat recovery rate on the moisture content of fuels and on the temperature of the ambient air and of the return pipeline water

When relatively wet fuels are burnt, air preheating by the flue gas and by the returning chain band is sometimes not sufficient to ensure the needed pre-drying. In such a case, the walls of the combustion chamber are isolated with refractory linings. The linings act as a screen, allowing higher combustion temperatures and heat radiation onto the fuel. On the contrary, when relatively dry fuels are burnt, the radiation linings are of no utility and may have even a negative impact on combustion. Raising too much the combustion temperatures may lead to intensive slagging and fouling, especially when herbaceous fuels are fired. In such a case, water-cooling of the walls of the combustion chamber can be introduced [19, 20, 28, 96, 97, 118, 127, 129, 135, 151, 164, 168, 200].

5.3.3. Other combustion concepts

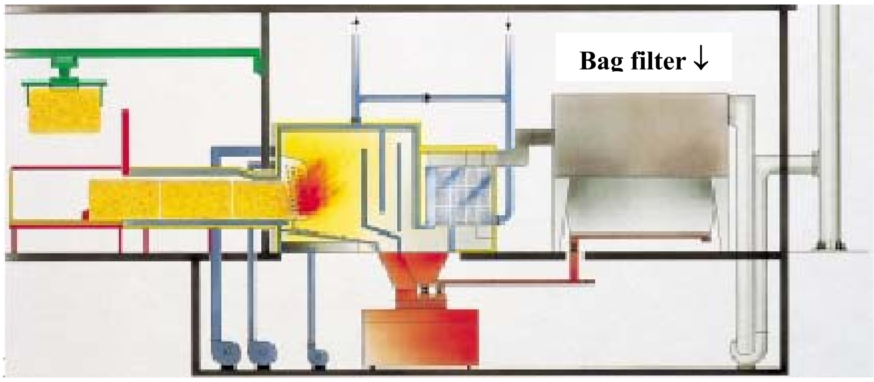
Vibrating grates represent another combination of fixed and travelling grates. The grate is again inclined, but good mixing of the fuel and its gradual sliding down on the grate is ensured by regular vibrations in the grate's width within short periods of time [97, 168]. The advantages of vibrating grates are better fuel handling in the furnace (compared to fixed grates) and less moving parts, which implies lower maintenance costs (compared to travelling grates). On the other hand, vibrating grates have larger dust emissions and poorer combustion than travelling grates.

Underfeed stokers represent a novel combustion approach, applied mainly for wet wood fuels with particle size up to 50 mm and low ash fraction, e.g. wood chips. The fuel is supplied to the combustion chamber by screw conveyors from beneath to a rotating grate. As a result, a good fuel mixing is achieved with simple technology that allows easy control of the fuel supply and partial load operation. The system is suitable for small- and medium-scale (up to 6 MW) heat generating facilities [96, 97, 118, 129].

As mentioned in section 4.1.6, due to sophisticated handling, wood powder is used mostly as a feedstock for producing pellets and briquettes. Nonetheless, wood powder can be also fired directly in dedicated dust burners. There, wood powder is blown at high velocity into the combustion chamber by pneumatic spreaders, together with the primary air. Because of the small particle size, little excess air is needed (λ=1.3/ 1.5) and the combustion process is quick and efficient. Conversely, dust burners pose a number of requirements. The fuel should have moisture content less than 20% and particle size below 20 mm. The walls of the combustion chamber should be water-cooled, due to the high energy density of the fuel and the respective high combustion temperatures. Since efficient combustion of powder needs sufficiently high temperatures in the combustion chamber, a preheating burner operated by fossil fuel is needed at start-up. The most important drawback of dust burners is the intensive erosive wear and tear of the insulation bricks inside the combustion chamber, due to the high velocity injection. For these reasons, as well as because of the complexity of the wood powder handling, dust burners are not widely used for heat generation. They find little application, mainly for small and medium scale (2-8 MW) facilities [97].

The last combustion option, described in this chapter, is applied only to big straw bales – the cigar-type burner – Figure 38.

Figure 38
Sketch of a district heating plant with cigar burner for big straw bales, equipped with bag filter (for noise considerations, most noisy mechanisms – fans, hydraulic engines, etc., are placed in the basement)



Source: Adapted from [20]

Here, the big bales of straw are not shredded, but directly burnt in the furnace. In such a way, the large costs for the bales breaking up are saved. The bales are delivered by a crane on a conveyor that slowly pushes them in line to the combustion chamber. In order to stabilise combustion, before being fed to the furnace, each bale is preheated in a dedicated chamber. In the preheating chamber, the bale is ignited by the fuel that is already there. When the bale becomes dry and starts to burn, it is pushed further to the inclined inlet of the furnace. By gradually pushing the bale forward, it burns from the front end. The amount of fuel, delivered to the furnace, is controlled by the speed of the conveyor. The combustion air is supplied to the furnace via nozzles, placed in the inclined inlet of the chamber. The ash is collected by sliding down on an inclined grate towards the bottom of the chamber. Since straw tends to cause high slagging and fouling, the temperatures in the combustion chamber should be kept below 900°C. For this reason, the walls of the furnace are water-cooled and a heat exchange system is used for the inclined ash-collecting grate [20, 97, 129].

5.4. SUMMARY

Based on the analysis, performed in the previous sections, Figure 39 summarises the relative suitability of different small- and large-scale direct combustion technologies for solid biofuels from the point of view of heat generation.

Figure 39
Relative suitability of the typical small-scale and large-scale direct combustion technologies for solid biofuels from the point of view of heat generation

	Firewood	Wood chips	Wood powder	Pellets	Briquettes	Straw
1. Open fireplace	0	–	–	–	0	–
2. Manual stove	+	–	–	–	+	–
3. Automatic burner	– –	+	–	+ +	– –	+
4. Batch combustion	0	– –	– –	– –	–	+
5. Fixed inclined grate	– –	+	–	+	–	–
6. Travelling grate	– –	+ +	–	+ +	–	+
7. Vibrating grate	– –	+	–	+	–	+
8. Underfeed stoker	– –	+	–	+	– –	–
9. Dust burner	– –	– –	+	– –	– –	–
10. Cigar burner	– –	– –	– –	– –	– –	+ +

Note: Combustion systems (1-3) are suitable for small-scale applications, while combustion systems (4-10) are appropriate for large-scale facilities.
Legend: (– –) Not possible; (–) Not appropriate; (0) The penalties are compensated to a given extent by the advantages; (+) Appropriate; (++) Very appropriate

The efficiency of the combustion process is a complex issue that depends on a number of factors – quality of fuel, combustion process design, etc. As a general rule of thumb, less complex combustion systems require higher quality fuels (Figure 39). Sophisticated electronic control equipment can improve significantly the performance of combustion units, even at a small-scale.

The small-scale facilities are less efficient than the large-scale systems, due to economies of scale. The automatic systems using pellets and in fewer cases – using straw, are the efficiency leaders in the small-scale sector. However, the performance of conventional manually-filled stoves on firewood or briquettes has recently improved significantly.

For large-scale applications, the travelling grate technology, using wood chips, pellets or straw, appears to be the preferred choice for burning solid biofuels, followed by other grate modifications – fixed inclined grate, vibrating grate or underfeed stokers. The batch combustion of biomass is generally not regarded as a suitable large-scale option, although one of its variants – the cigar-type burner of whole straw bales, has proven its viability.

6. BIOMASS GASIFICATION

The key driving force for the development of gasification technologies for solid fuels is electricity generation. The possibility to obtain liquid transport fuels via gasification (entrained flow gasifiers) however attracts lately a growing interest as well[23].

In the conventional steam-cycle power plants with grate furnaces, heat is transformed into steam. The steam passes through a turbine, which is connected to a power generator. The typical electric efficiency of modern plants of such type is 40-45% [136]. In the gasification-type power plants, the fuel is not directly burnt, but it is first gasified at temperatures of 800-1100°C. After cleaning from tars, chars and other undesirable substances, the combustible gas is burnt and the clean hot flue gas is passed through a gas turbine[24]. After passing the turbine, the still sufficiently hot flue gas is used to generate steam that is employed in a steam turbine. The advantages of gasification-based power generation, compared to grate combustion steam-based generation, are:

- Potentially increased electric efficiency, due to doubling the power-train capacity – two (gas and steam) turbines instead of just one (steam) turbine. Passing the hot flue gas from a grate furnace combustion through a gas turbine is not feasible, since it contains a lot of contaminants that can damage the turbine. Nonetheless, at present the electric efficiency of gas & steam-cycle power plants is still similar to that of only steam-cycle power plants – about 40-45%. This is due to the impossibility of useful utilisation of the low-quality heat, released during gasification, and to the more sophisticated design of the process, involving more energy transformations, respectively – higher energy losses.
- Potentially better environmental performance of power plants, because of cleaner combustion, through prior purification of the combustible gas. On the other hand, obtaining combustible gas with sufficient cleanliness for application in gas turbines is the biggest technological and cost challenge in the whole gas-cycle power concept. It is disputable whether the preliminary cleaning of the combustible gas is more cost-effective than the cleaning of the flue gas from conventional grate combustion.
- Great fuel flexibility – the modern large-scale bubbling (normally more than 15-20 MW) or circulating (usually above 30-40 MW) fluidised bed gasifiers can process various types of solid feedstock – coal, biomass, waste, etc[25] – with no or only negligible adjustments of the gasification process [27, 87, 97, 129, 130, 147, 164, 168, 174]. This advantage is of special interest for the household's waste, which is heterogeneous by origin [124].

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[23] The entrained flow gasification is not considered in this work, since it is a sophisticated and expensive technology that is not economically feasible for heat generation.

[24] In small-scale facilities, where the efficiency of gas turbines is very low, the combustible gas is burnt in an internal combustion engine.

[25] The subject of this work is not to perform an analysis of power generation, so the description of different power generation options does not pretend completeness.

The gasification combustion concept for biomass became lately quite a topical issue in the EU. Nevertheless, sometimes the feasibility of biomass gasification is slightly over-estimated, tending to directly extrapolate the results from experimental or small-scale facilities to real conditions. Based on the above, gasification seems to have limited utility for heat generation from solid biomass, unlike e.g. the generation of bioelectricity:

- First of all, doubling the turbine capacity is totally irrelevant to heat generation.
- The questionable benefits from the preliminary cleaning of the combustible gas are even more doubtful in the case of biomass. In theory, a combustible gas that is cleaned from corrosive alkali and chlorine elements of the herbaceous feedstock and to a lesser extent of the woody biomass, can be used for reaching higher steam temperatures (up to 500ºC), compared to the grate furnace firing (about 450°C). Nonetheless, getting sufficient corrosion-preventing purity of the combustible gas appears to be extremely difficult in practice. It involves highly energy-intensive and expensive processing, whose success in cleaning is still questionable [97]. On top of that, achieving such temperatures for heat generation is pointless. Even the users of the highest quality heat – the industrial consumers – normally require temperatures, being lower at least by factor of 3. Raising the steam temperatures to such levels is useful only for power generation.
- Thanks to the good fuel mixing, the advanced and most widespread gasification concepts – fluidised bed systems – tend to show lower CO and NOx emissions than grate furnaces. On the contrary, fluidised bed technologies have higher dust and particulate emissions, compared to grate furnaces [97, 168].
- In order to be cost-effective, fluidised bed gasifiers need a minimum output of 15-20 MW. Such a size is fine for power generation, but is not suitable for district heating plants that use biomass – see Figure 17 and the other explanations in section 3 [129, 146, 147, 174]. Considering the typical size of the biomass district heating plants – from 1 to 15 MW, with an average of 3-4 MW [19, 20, 38, 130, 146], it becomes obvious that using the fluidised bed concept for district heating is not the most convenient option.
- Fluidised bed gasifiers have low efficiency when operated on partial load, due to the fixed energy cost needed to create the fluidising environment inside the gasifier. Thus, fluidised bed gasifiers are not appropriate for variable load (cycling operation), which is a usual case for heat generating plants.
- The highly efficient gasification technologies of fluidised bed-type are inflexible, having a long start-up period (up to 15 hours [97]).
- The fluidised bed technology is associated with higher investment and operating costs than conventional grate furnaces [6, 143, 168]. The running costs increase further due to the requirement for small particle size of fuels (below 80 mm for bubbling and below 40 mm for circulating fluidised bed [97]) and of bed materials (silica sand). Periodically, bed material should be added to the gasifier to compensate for losses [6, 174].
- An important, sometimes overlooked weak point of fluidises bed gasification is that the use of the biomass ash as a soil fertiliser is not possible, since it is mixed with bed

material. Additional costs are therefore incurred due to the replacement of the biomass ash with other nutrient substances to maintain soil fertility. Additional costs are also incurred along the safe discharge of the used bed material in landfills [6], as waste incineration has become a growing concern in the EU [75].

- The fluidised bed gasifiers are still less reliable than grate furnaces. For experimental installations, reliability is not of prime significance. Nevertheless, it is a key issue for commercially operated plants, which face a strong competition from the alternative, highly reliable heating plants on fossil fuels [6, 124, 168].

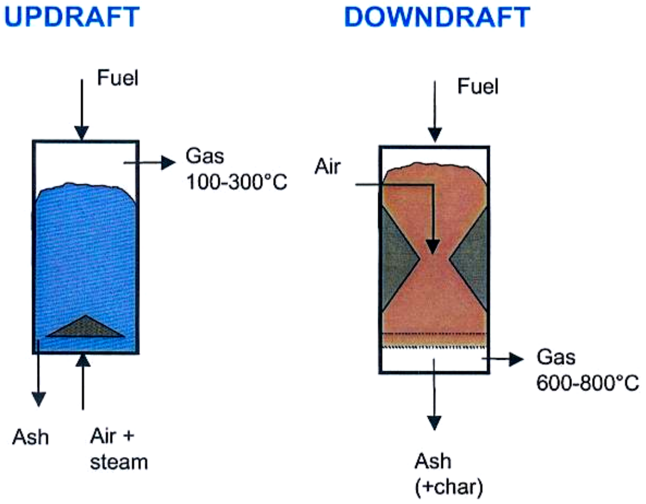
The strong and weak points of the most widespread gasification technology – the fluidised bed type – for heat generation from biomass, compared to the alternative grate combustion, are summarised in Figure 40.

Figure 40
Summary of the strong and weak points of gasification for heat generation from biomass vice-versa conventional grate combustion

Advantages of gasification over grate combustion with high relevance for heat generation	Advantages of gasification over grate combustion with little relevance to heat generation	Disadvantages of gasification vice-versa grate combustion from the point of view of heat generation
• Ability to process various (including mixed) feedstock	• Potential increase of the power generation efficiency • Potential generation of higher quality steam • Potential better environmental performance	• Higher investment and operating costs • Economically efficient at a larger scale than the usual scale needed for heating plants • Inefficient operation on partial load • Difficult cyclic operation • Low reliability • No possibility for recycling the biomass ash • Waste treatment concerns • Strict requirements for the particle size of fuels and of bed materials • Adequate gas cleaning still problematic

Amongst different gasification technologies, there is however an option, which under certain conditions might be appropriate for heat generation from biomass. This gasification concept is the fixed-bed gasification, in its two basic variants – updraft and downdraft (Figure 41). Its potential suitability comes from the simplified design, respectively lower capital costs, and the smaller size of efficient operation. The updraft gasifiers are more appropriate for the scale 1-10 MW, while the downdraft gasifiers can be used even on a micro-scale – from 10 kW to 1 MW [6].

Figure 41
Principle schema of updraft and downdraft fixed-bed gasifiers



Source: [130]

In updraft gasifiers, different combustion stages – drying, pyrolysis, gasification and char combustion – follow each other. The products of pyrolysis are taken out of the gasifier before entering the gasification zone, so they contain a lot of tars and oils. For the generation of electricity and for the synthesis of liquid fuels, such a high contamination of tars and oils is problematic. For heat generation however, the contamination can be accepted, since the tars and the oils are subsequently decomposed during combustion of the pyrolysis products.

In downdraft gasifiers, the fuel flows co-currently through the hot combustion and the gasification zones, so most tars are oxidized and decomposed. The product gas, consisting mainly of CO, H_2, CH_4, CO_2 and N_2, is relatively clean, with low content of tars and oils, and can be directly burnt for generation of heat (steam).

The average heating values of the main components of the combustible gas from biomass gasification are given in Figure 42. The proportion amongst these components and hence, the heating value of the combustible gas, depends on a number of factors, e.g. moisture content of feedstock, oxidising agent used, etc. When air is employed as oxidising agent, which is the conventional approach, the gross heating value of the combustible gas normally ranges between 4 and 7 MJ/m3. The net heating value is slightly lower, due to the hydrogen and methane content [6, 28, 97].

Figure 42
Average heating values of the main combustible gases, obtained from gasification of biomass

Average heating values, (MJ/m3)	CO	N_2	H_2	CH_4	N_2
Gross heating value	12.6	0.0	12.8	39.8	0.0
Net heating value	12.6	0.0	10.8	35.8	0.0

Source: Adapted from [90]

Despite both updraft and downdraft fixed bed gasifiers overcome part of the disadvantages of fluidised bed gasifiers, they still show some weak points, which keep their efficient application for heat generation doubtful. Fixed bed gasification requires a well-sized biomass feedstock with high quality specifications – moisture content less than 45%, ash content less than 10%, ash melting point not less than 1190°C and enough high bulk density to guarantee a stable fuel flow. All these pre-conditions narrow significantly the scope of potential raw materials, limiting it basically to high-quality woody biomass only. All herbaceous biomass, saw dust, crushed bark, demolition wood, heterogeneous waste, etc. in fact cannot be employed in fixed bed gasifiers [6]. On the other hand, it is rather questionable whether fixed bed gasifiers are the best technological option to utilise the limited availability of high quality woody biomass. In any case, most drawbacks of fluidised bed gasifiers versus grate combustion for the purposes of heat generation from Figure 40 are also applicable to fixed bed gasifiers.

Figure 43
Relative suitability of different gasification technologies for processing solid biofuels from the point of view of heat generation /Note: No very appropriate gasification for heat generation!/

	Fire-wood	Wood chips	Wood powder	Bio-waste	Pellets	Briquettes	Straw
Entrained flow	– –	–	–	–	– –	– –	–
Circulating fluidised bed	– –	–	–	–	– –	– –	–
Bubbling fluidised bed	– –	–	–	0	–	– –	–
Updraft fixed bed	– –	0	+	–	– –	– –	–
Downdraft fixed bed	– –	0	0	–	– –	– –	–

Legend: (– –) Not possible; (–) Not appropriate; (0) The penalties are compensated to a given extent by the advantages; (+) Appropriate; (++) Very appropriate;

Biomass gasification appears more appropriate for power than for heat generation. The only gasification option, which seems suitable for heat generation, is fixed bed gasification (Figure 43). Nonetheless, even the application of this gasification concept for heat generation is questionable, since it does not offer significant advantages over direct combustion systems, but involves additional complexities and costs.

7. COMBINED COMBUSTION OF BIOMASS AND FOSSIL FUELS

7.1. GENERAL DESCRIPTION OF COMBINED COMBUSTION

Combined firing (co-firing) is often described as a simultaneous combustion of different fuels in the same burner or as a parallel combustion of different fuels for the same boiler. Co-firing is considered primarily for large-scale heating plants, rather than for small-scale heat facilities. The key advantages of co-firing over separated combustion are:

- Lower capital costs – when co-firing fuels with similar physical and chemical properties, a partial or full synergy use of the same fuel handling and firing infrastructure is possible.
- Fuel diversity – the feasible biomass availability is restricted by its low calorific value and the need of its availability nearby the heating plant. Adding another fuel to biomass can allow increasing the heat output, if needed, and can earn economies of scale.
- Reduction in local-polluting emissions, because of the lower content of polluting substances in biomass, compared to fossil fuels (Figure 19), or due to synergies between properties of different fuels. This advantage can be of particular relevance for district heating plants, located in densely-populated residential areas [164, 168, 174].

7.2. TYPES OF BIOMASS CO-FIRING WITH FOSSIL FUELS

7.2.1. Gasification and gas co-firing

Biomass and fossil fuels in various proportions are gasified and the resultant combustible gases are burnt together. This option basically represents a combined firing of gases, rather than of solid fuels. As discussed in chapter 6, for a number of techno-economic reasons the whole gasification concept has little relevance to heat generation. The simultaneous firing of different combustible gases is therefore not considered in this work any longer[26].

7.2.2. Biomass-based combustion with fossil fuel super-heating complementation

In this case, biomass is the principal fuel, while a fossil fuel is employed as a complement. The suitable fossil fuels are natural gas (if a natural gas pipeline connection is available), light and heavy fuel oil. Coal can also be used, but the complications, associated with its logistics and environmental performance, may obstruct this option. Again, this co-firing concept is normally used in power plants, where high steam temperatures are needed, hence it is only briefly described. To reach such high temperatures, the steam, generated by the primary biomass firing, can be further heated by a secondary combustion of a fossil fuel in the so-called super-heater. The fossil fuel super-heater is separated from the biomass furnace, as

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[26] The same applies also to the application of “clean coal” technologies and fuels.

well as the boilers for the primary and for the secondary super-heated steam. Hence, this is more a kind of consecutive, rather than a simultaneous co-firing.

7.2.3. Biomass-based combustion with fossil fuel compensating complementation

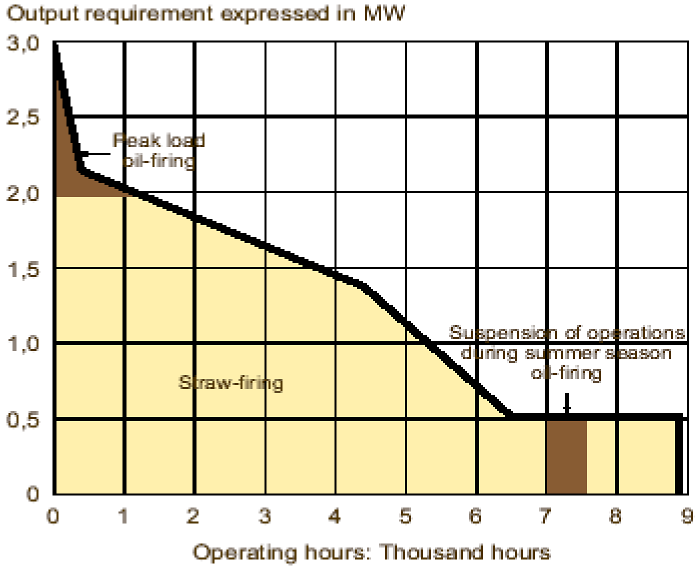
Here biomass is again the principal fuel, but co-firing with fossil fuels is introduced to compensate for the lower calorific value of biomass. As already mentioned, on equal terms this means that more biomass (in terms of weight and volume) than fossil fuel should be employed for the same heat output. For various reasons, e.g. insufficient feasible biomass availability, limited storage space at the heating plant, etc., the existing heat demand might not be met solely by burning biomass. In this case, steam can be first generated from biomass and then complemented by a secondary firing of fossil fuels. Nonetheless, building a heating plant that uses biomass must always be preceded by a thorough assessment of the availability of feedstock and the handling issues. The introduction of a complementary firing of fossil fuels to ensure the normal performance of the heating plant should be considered as a secondary solution, rather than as a designed-in technological component. It can be justified only by an unexpected substantial cutback in feedstock supply. Otherwise, it is better to go for a co-firing option, where biomass is used as a complementary fuel, while the heat generation relies mainly on fossil fuels. Natural gas, light or heavy fuel oil are again the preferred options for the secondary complementary fossil fuel firing, rather than coal. The latter introduction of a coal burner could be constrained especially in residential areas. There, problems might come from the lack of storage space, concerns about increased local-polluting emissions, road traffic intensity and associated noise. The last two points ensue from the lower calorific value of coal, compared to light and heavy fuels oil, which involves a larger number of truckloads [168].

The above scenario must not be mixed with the usual and in some cases even necessary complementary firing of fossil fuels in biomass-based heating plants. Small amounts of fossil fuel, typically heating oil, are widely used as a fuel complement in purely-biomass based heating plants to facilitate start-up, to compensate temporal shortages or breakdowns in biomass supply, to cover occasional extremely high winter loads or low loads during summer maintenance, etc. – Figure 44 [20, 97, 168]. Such type of combined combustion of biomass and fossil fuel should not be regarded as a weakness in the design of biomass heating plants.

7.2.4. Fossil fuel-based combustion with biomass complementation

Here, heat generation is based on fossil fuel(s), while biomass is used as a complementary fuel. Opposite to the previous variants, in this case the preferred basic fossil fuel for combined firing with biomass is coal, rather than natural gas, light or heavy fuels oil. Natural gas is a highly-efficient and clean fossil fuel. Its advantages ensue from its high calorific value,

Figure 44
Annual duration curve of fuel inputs for an exemplary 3 MW heating plant with 2 MW straw-fired boiler for basic heat generation and complementary firing of heating oil for compensating peak loads and maintenance periods (yellowish sectors – straw inputs, brownish sectors – heating oil inputs)



Source: [20]

chemical composition – high hydrogen-to-carbon ratio (4:1) that reduces CO_2 and CO emissions, and the lack of components with potential local-polluting impact (nitrogen and sulphur). Its gaseous aggregation state makes direct simultaneous firing with biomass extremely difficult, almost impossible. Generating first heat from natural gas and then super-heating it by biomass does not make sense from a technical point of view, since biomass causes corrosion of heat exchangers at high steam temperatures. Similar arguments can be stated also for light and heavy fuel oil, with the exception of the local-polluting impact, where some modest gains from biomass combustion might be obtained. However, achieving small reductions in local-polluting emissions at the expense of extremely high costs does not appear reasonable. Conversely, the co-firing coal with biomass for heat generation appears promising. Hence, the following analysis deals with this co-firing option only.

Biomass can be burnt with coal in ratios of up to 25%, i.e. 1/4 biomass and 3/4 coal. Higher biomass concentrations tend to have substantial impacts on the combustion process, which then would require major modifications in the combustion system and even a switch to gasification [164, 174]. Within the 25% biomass limit, three combustion approaches are applied.

In the first option, coal is simultaneously co-fired with biomass at low concentrations (2-5%). Here, biomass is mixed with coal at the inlet to the coal mill. The coal & biomass suspension is transported to the furnace and burnt without any further particular treatment, metering or controlling [39, 52, 97, 148, 164, 174]. The key advantages of the simultaneous co-firing coal with biomass are:

- Economy of capital costs, thanks to the synergy use of the available infrastructure at the plant.
- Simultaneous reduction of SO_2 emissions, ensuing from the sulphur content of coal, and of the corrosion impact of the alkali components of biomass, due to the chemical reaction between the sulphur and the alkali elements.
- Because of the higher calorific value and the lower moisture content of coal, the biomass component in the mixed fuel can be of lower quality, compared to that required for pure biomass combustion. In such a way, the better coal properties compensate the poorer biomass qualities.
- The highly efficient flue gas cleaning installations of the large-scale coal plants, which are not economically feasible in the lower-scale purely biomass plants, are used for purifying the biomass flue gases [1, 20, 39, 97, 174].

Sometimes two additional benefits are attributed to biomass co-firing with coal. Nevertheless, these two benefits come from the biomass application itself, rather than from combined firing with coal. These two benefits are the reduction in nitrogen oxide (NOx) and GHG emissions:

- NOx emissions from co-firing biomass and coal are lower, compared to pure coal combustion, because of the lower nitrogen content of biomass (Figure 19). Nonetheless, if biomass is fired alone, thereby reducing the use of coal, the final NOx emissions will be roughly equal to those obtained when co-firing the same amount of biomass with coal. The impact of biomass co-firing with coal on NOx formation is still unclear. Some results indicate that NOx decline when biomass is mixed with coal, while others affirm the opposite [39, 164, 174].
- Co-firing biomass with coal reduces GHG emissions, compared to burning pure coal, thanks to the much lower net CO_2 emissions from biomass. The reductions ensue from the CO_2 recycling ability of biomass[27]. It should be however kept in mind that GHG are a global, rather than a local concern. If biomass is fired alone, in such a way reducing the use of coal, the final GHG impact is equal to the case of co-firing the same amount of biomass with coal. Hence, combined firing of biomass and coal itself does not lead to an automatic reduction in GHG emissions.

Conversely, simultaneous co-firing of coal and biomass has some inherent drawbacks, which may preclude its practical application:

- Simultaneous co-firing stands for blending different fuel properties. First, this means that the combustion process cannot be optimised to any of the fuels involved. Second, due to the fuel properties blending, slagging and fouling become more severe, compared to separate firing of either fuel. This is caused by the already mentioned reaction between

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[27] A more complete discussion on carbon dioxide (CO_2) and GHG is available later on in section 10.1.

the alkali components in biomass and the sulphur in coal. Both processes are more pronounced for herbaceous biomass than for woody biomass, due to the higher alkali content of the former [20, 39, 97, 164, 168, 174].

- A core drawback of simultaneous combustion of biomass and coal is the impossibility of recycling both biomass and coal ashes, respectively as a soil nutrient and as an ingredient for concrete production. While for the mixed biomass & coal ash for fertiliser purposes the explanation is quite obvious[28], the reason for the production of concrete is slightly different. The prevailing legislation in the EU allows using only pure coal ash in concrete production. The alkali components of biomass, deposited in the mixed coal & biomass ash, could have a negative impact on the concrete properties. They may react to flint stone particles in the gravel aggregate, with which the cement is mixed during concrete manufacturing. This may result in absorption of water from the surroundings, leading to a volume expansion, formation of cracks, triggered by freezing and thawing. On top of that, the chlorine content of biomass is problematic because it may cause corrosion of the reinforcement bars [97]. Hence, the only solution for mixed coal & biomass ash is deposition in landfills [20, 75, 174].
- Simultaneous handling and burning biomass with coal may lead to increased running costs, caused by possible malfunction of the fuel feeding systems and by boiler damage, due to the presence of corrosive biomass components [39, 97].

In the second option, coal is again co-fired with biomass, but the biomass share is larger (5-25%). Here, biomass is still burnt in the same furnace with coal, but biomass pre-treatment, handling and metering is separated from those of coal. This is needed, since at high biomass fractions, biomass fuel properties and input should be already well controlled and measured. For ensuring good and stable combustion, particular attention should be paid to the particle size distribution and moisture content. Biomass should be well shredded before mixing with pulverised coal in the furnace. The recommended size for the biofuel particles is about 2 mm for wood and around 5-6 mm for straw. The moisture content should be below 25%. Compared to low-concentration biomass co-firing, this option is associated with higher capital costs. Conversely, the increase in running costs is assumed to be lower, due to reduced risks of malfunction of the fuel handling systems. The diversity of fuel supply impacts are also greater, since more coal is replaced by biomass. In any case, this co-firing concept basically does not differ from the low-concentration option. The drawbacks of the low-concentration biomass co-firing are fully valid for higher shares of biomass co-firing. Hence, higher-concentration biomass co-firing with coal does not seem to bring many additional benefits, compared to the low-concentration option [20, 52, 97, 133, 148, 164, 174].

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[28] Putting mixed biomass & coal ash in the soil would have more a poisonous impact, representing in fact a landfill deposition.

In the third option, coal is co-fired with biomass at high concentrations (5-25%) in parallel, but not simultaneously. Here, biomass is pre-treated, handled and burnt in dedicated furnaces, separately from coal. Hence, a mixture of hot flue gases from coal and biomass, rather than a physical mixture of the two fuels is employed to generate steam. The key disadvantage of this concept, compared to simultaneous co-firing, is the larger capital costs. The additional capital cost for simultaneous co-firing is about \$50-100 per gross kW biomass, while for parallel co-firing it is about \$200-300 per gross kW of biomass[29]. Conversely, parallel co-firing offers a major advantage – the bottom biomass and coal ashes can be recycled as a fertiliser and as a concrete additive respectively[30]. The benefits for coal are however less pronounced, because unlike biomass, bottom ash represents a minor part of total coal ash, whose majority is fly ash. Last, but not least, coal fly ash is generally preferred as a concrete additive, than the coal bottom ash [20, 39, 52, 97, 148, 164, 174].

7.3. SUMMARY

Based on the above reasons, Figure 45 summarises the strong and weak points of co-firing biomass, while Figure 46 presents the relative suitability of different biomass co-firing options, depending on the type of fossil fuel application – main or complementing.

Figure 45
Summary of the strong and weak points of co-firing biomass with fossil fuels for heat generation compared to pure biomass combustion

Advantages of co-firing biomass with coal over pure biomass firing with high relevance for heat generation	Advantages of co-firing biomass with fossil fuels over pure biomass firing with little relevance for heat generation	Disadvantages of co-firing biomass with fossil fuels compared to pure biomass firing from the point of view of heat generation
• Reduction in the capital costs for fuel handling • Fuel diversity • Reduction in the SO_2 emissions from coal, especially when co-firing herbaceous biomass • Potential reduction of the corrosion influence of the biomass alkali elements, especially for herbaceous biomass	• Ability to obtain higher steam temperatures	• Increase in running cost, due to more intensive wear and tear of handling facilities, increased slagging and fouling, corrosion, etc. • Combustion process can be optimised to the properties of neither of the co-fired fuels • Recycling both coal and biomass ashes is not possible in most cases

Apart from the pure techno-economic conclusions from Figure 45 and Figure 46, the role of biomass co-firing with coal can be seen in a slightly different perspective. Low-concentration co-firing biomass with coal can be used as an introductory step for biomass as a fuel for heating plants, operating so far on coal only. In such a way, heating plant operators may

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[29] This means that if the biomass fraction is e.g. 10%, the additional total capital cost per sized fuel output will be \$5 to \$30 per kW [86, 158, 164].

[30] Coal fly ash is still mixed with biomass fly ash, so it is not possible to use it for concrete production.

Figure 46
Advantages and disadvantages of different options for co-firing biomass with fossil fuels for heat generation /Note: No significant benefits!/

		Woody biomass	Herbaceous biomass	Bio-waste
Coal	Simultaneous	–	–	–
	Consecutive	0	0	0
	Parallel	0	+	0
Natural gas	Simultaneous	– –	– –	– –
	Consecutive	0	0	0
	Parallel	– –	– –	– –
Light / Heavy Fuel Oil	Simultaneous	– –	– –	– –
	Consecutive	0	0	0
	Parallel	–	–	–

Legend: (+ +) Significant benefits; (+) Moderate benefits; (0) No benefits; (–) Moderate penalties; (– –) Significant penalties, not possible;

(not!) get a positive experience with biomass as a fuel. If the trial is successful, the already established biomass supply chains and handling systems can be gradually expanded to a higher replacement share of coal via parallel co-firing, or even to a switch to a purely biomass-based operation. Nevertheless, this introductory approach can be restricted by the generally declining application of coal as an energy source in the EU[31]. In any case, biomass co-firing with coal should be considered mainly as a way of promoting biomass application, rather than as a long-term strategy.

The combined combustion (co-firing) of biomass with fossil fuels (mainly coal) is a convenient tool for introducing biomass to the large-scale heat generation market. Initially a small, but gradually increasing portion of biomass can be simultaneously burnt with coal. Later on, the simultaneous combustion can be replaced by a parallel firing, which appears to be more efficient and more environmentally-friendly – Figure 46.

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[31] A more complete discussion on the trends in fuel utilisation for heat generation is presented in chapter 9.

8. COMBINED HEAT AND POWER GENERATION FROM BIOMASS

The combined generation of power and heat (CHP) recently became quite a topic within the EU context. It is seen as a feasible option to increase the energy efficiency and to improve the environmental performance of the power generation sector [48, 84].

In conventional condensing-type power plants, the exhaust steam from the turbine is cooled down in a condenser by water at ambient temperature. Hence, a large part of generated heat is simply lost.

In the standard CHP concept with so-called "back-pressure" turbines, the exhaust steam is used for heating. For this purpose, the exhaust steam should however possess sufficient pressure and temperature, depending on the particular heat requirements (e.g. typically 90-120°C and 1-6 bar for residential heating [6, 20]). The power efficiency of condensing-type power plants, which generate only electricity and thus are optimised only for electricity, is therefore higher (by at least 10% on average [6]) than the power efficiency of back-pressure plants, which generate both electricity and steam. The electricity-to-heat ratio is fixed (typically about 0.45 [84]), defined by the exhaust steam output of the turbine. Normally, the power efficiency of CHP plants supplying district heating is higher than that of CHP plants supplying industrial heat, because the pressure and the temperature requirements of industrial consumers usually are higher than those of district heating.

The only difference between the conventional back-pressure CHP concept and the advanced CHP concept, which uses so-called "extraction-type" turbines, is that some additional steam can be extracted directly from the turbine, if such a demand exists. Hence, the electricity-to-heat ratio is variable and it can be adjusted to the particular needs of customers [6, 9, 28, 37, 189].

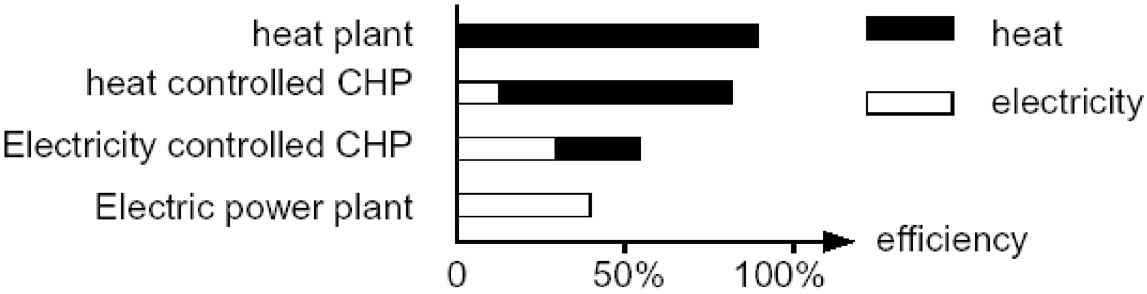
The main characteristics of these three plant concepts are summarised in Figure 47

Figure 47
Main characteristics of different (power and CHP) plant concepts

Parameters / plants	Condensing-type power plant	Back-pressure CHP plants	Extraction-type CHP plant
Generation	Electricity	Electricity and steam (heat)	Electricity and steam (heat)
Optimisation versus	Electricity	Electricity or heat	Electricity or heat
Electricity to heat ratio	-	Fixed	Variable

Figure 48 illustrates the overall energy efficiency gains of CHP plants, compared to purely power generating plants.

Figure 48
Typical efficiencies of alternative power and/or heat generating plants



Source: [97]

Figure 48 indicates that if a heating plant is retrofitted to a CHP plant, its energy efficiency decreases. This is due to the technologically lower efficiency of power generation, compared to heat generation. In most cases CHP plants represent either retrofitted power plants, or dedicatedly designed plants. In the case of power plants, the CHP extension usually is easier in relatively new or less populated urban areas. Establishing a pipeline network for heat distribution in densely populated areas can be associated with extremely high costs, if feasible at all [4, 6]. Adding power option to an existing heating plant, especially run on biofuels, is not very common because power generation poses much tougher technological requirements, e.g. purity of the combustible gas, pressure, steam temperature, etc., than heat generation. Hence, from a technical point of view CHP plants can be regarded as power plants, whose energy efficiency is increased by a useful utilisation of the residual steam. A detailed analysis of the CHP concept is therefore not performed herein, since it would be dealing mainly with power generation, rather than with heating. The attention is paid just to the CHP aspects, which are relevant to heating.

Apart from the obvious advantages of the CHP concept, it contains also some disadvantages and potential threats, which might partly or completely offset the energy efficiency gains under certain conditions, described here below.

Besides CHP plants represent power plants with a by-product heat option to increase energy efficiency, in fact heat is the governing parameter in the CHP design concept, rather than electricity. The smooth operation of CHP plants and their electric efficiency actually depend on a constant heat demand in time. If the heat demand declines, the exhaust steam output from the turbine should be reduced pro-rata, thus the electric output will be proportionally reduced as well. The installation of a steam storage tank or the use of extraction-type turbines solves the problem partly, only in case of variations in heat demand of short duration. The alternative option to the storage tank is to go back to the conventional condensing-type power generation. In such a case however, the CHP energy efficiency benefits are lost. Additional penalties are also incurred, due to investments in idle or under-used heat facilities. Last, but not least, the technological design of the CHP plant may completely or partly prevent the switch to condensing-type operation. For this reason, CHP is generally considered more appropriate for industrial steam use than for district heating, since the heat demand of the former normally is much more stable than that of the latter. The heat demand by the residential sector is quite poor in the summer – about 10% of the winter demand, only for hot water, plus another 30% for distribution losses on average. Thorough quantitative and qualitative assessment of the realistic heat demand nearby the CHP plant is therefore a key point in the decision-making process whether to go for the CHP option (either by building a new plant, or by retrofitting an existing power plant) or not [4, 19, 20, 37, 48, 130, 168, 189].

Apart from the quantitative and qualitative analysis of the realistic heat demand nearby the CHP plant, the price difference between electricity and heat can also play a major role in the decision whether it is worth to build a CHP plant or not [4, 130]. The possible combinations of price differences between electricity and heat with plant concepts are summarised in Figure 49.

Figure 49
Indicative comparison of different CHP options (comparisons with pure power and/or pure heat plants are not considered)

	Large price difference between electricity and heat	Small price difference between electricity and heat
Building a new CHP plant, optimised versus electricity output	+ +	– –
Building a new CHP plant, optimised versus heat output	– –	+ +
Retrofitting an existing power plant to a CHP plant with a small heat output	+	–
Retrofitting an existing heat plant to a CHP plant with a small electric output	+	–

Legend: (++) Most probably appropriate; (+) Can be appropriate; (–) May not be appropriate; (– –) Most probably not appropriate

Hence, the financial gains from adding or increasing the power output should always be juxtaposed to the respective financial losses from eliminating or reducing the heat output and vice-versa, i.e. adding or increasing the heat output at the expense of cutting or reducing the electricity output (Figure 48). The benefits and the losses should be calculated on cumulative basis, taking into account the reimbursement of investment costs[32]. Finally, adding a co-generation option to a purely heating or power plant means also a more sophisticated plant planning and management (two products, instead of just one), but for the same reason – increased market flexibility as well.

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[32] The reimbursement of the cumulative investment costs can be identified by a simple cost-benefit business calculation that takes into account the projected cash flow, amortisation rate, period of return on investments and discount rate. The purpose if this work however is not the performance of such business calculations, so the issue is not assessed.

In case biomass is employed as a fuel for CHP, there is an additional factor that should be taken into account: the availability of a stable and sufficient biofuel supply in terms of both quantity and quality within a reasonable distance from the CHP plant [6, 169]. For this reason, CHP plants that run on biomass normally are smaller than those using fossil fuels. They can be even smaller than pure power plants that employ biomass, because of the larger distribution losses for heat, compared to electricity [6]. Hence, as the most suitable customers for bio-based CHP plants appear to be factories, which may generate biomass fuels as a by-product or as residues from their core activity – agricultural farms, sawmill, the plants of pulp and paper industries, etc. Biomass CHP plants are also a convenient option for remote and/or off-grid consumers, since there the competition with the generally more efficient heat and/or power centralised plants on fossil fuels is respectively softer or does not exist [4, 140].

Despite the above complications, associated with biomass fuels, their application in CHP plants is one of the most promising options to achieve simultaneously a substantial efficiency improvement in bioenergy utilisation and a great reduction in emissions. For these reasons, recently the use of biomass fuels in CHP plants increased significantly [4, 85]. Renewable energy sources (mainly biomass) already account for 13% of all fuel inputs to CHP in EU-15 [48, 157, 200]. The penetration of renewable energy sources for CHP generation in NMS-10 is however lagging far behind EU-15 and accounts for about 1% of all fuel inputs only [24]. Hence, NMS-10 appear to have large unexplored reserves for further increase of the application of biomass fuels in CHP[33] [157].

Summarising the above, Figure 50 presents the strong and weak points, the opportunities and threats (SWOT analysis) of biomass CHP plants biomass versus purely power and purely heat generating plants that run on biomass or fossil fuels. The SWOT comparative analysis is performed from the point of view of heat generation, the impacts on power generation being not taken into account.

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[33] A more detailed discussion on biomass potential for heat generation in EU-15 and NMS-10 is proposed in the next chapter 9.

Figure 50
SWOT analysis of biomass-based CHP generation, compared to purely power and purely heat generating plants that run on biomass or fossil fuels, from the point of view of heat generation

Strong points	Weak points
• Higher total energy efficiency of the plant • Lower GHG emissions per energy unit generated • Lower local-polluting emissions per energy unit generated • Certain flexibility in the power-to-heat ratio is possible	• Mandatory simultaneous availability of concentrated feedstock supply and heat demand nearby the plant • More sophisticated energy system – two plants in one • Less flexible energy system, compared to pure power and pure heat plants • Reduced separate electric and heat efficiencies, compared to pure power and pure heat plants respectively
Opportunities	**Threats**
• Quite appropriate for industrial users of power and steam, which are in the same time fuel suppliers – agricultural farms, pulp and paper factories, sawmills, etc. • Suitable for off-grid generation of electricity for relatively small remote consumers and for district heating in regions with relatively fresh climate • Diversified market risk – two products, instead of one • Appropriate to increase the energy and cost efficiency of existing power plants	• Over-estimated or unstable heat demand • Disruptions in supply or shortage of sufficient feedstock nearby the plant • Competition from larger, more efficient (due to economies of scale), pure power or pure heating plants • Penalties for not meeting electricity quotas generation, if any

Combined heat and power generation is a way of improving energy efficiency and environmental performance of the energy sector. The key factor for a successful performance of the CHP plants is the nearby existence of sufficient and stable heat demand. In case of a biomass CHP plant, there is an additional important factor – the nearby availability of sufficient biomass resource in terms of quantity and quality – Figure 50.

9. SECURITY AND DIVERSITY OF ENERGY SUPPLY

It is widely recognised that biomass contributes to the security and diversity of the EU energy supply. This is due to the difference between the reserves, production and supply patterns of biomass and those of fossil fuels. Bioenergy tends to be produced internally within the EU, while the majority of fossil fuels are imported from a small number of countries (Figure 2). Under the most pessimistic assumption, part of biomass may come from import, e.g. from the Former Soviet Union, mainly in the form of final products or half-finished materials, rather than as feedstock, due to the transportation costs. But even in this case, there will be still a positive contribution to the security of supply, while the diversity of supply benefits might be, under certain conditions, slightly reduced (Figure 51, compared to Figure 3).

Figure 51
Positioning of biomass (bioheat) within the EU energy supply

EU energy supply	Product dependency	Product diversity
Dependency on suppliers	🟥	**Most pessimistic case**
Diversity of suppliers	🟨	**Business-as-usual case**

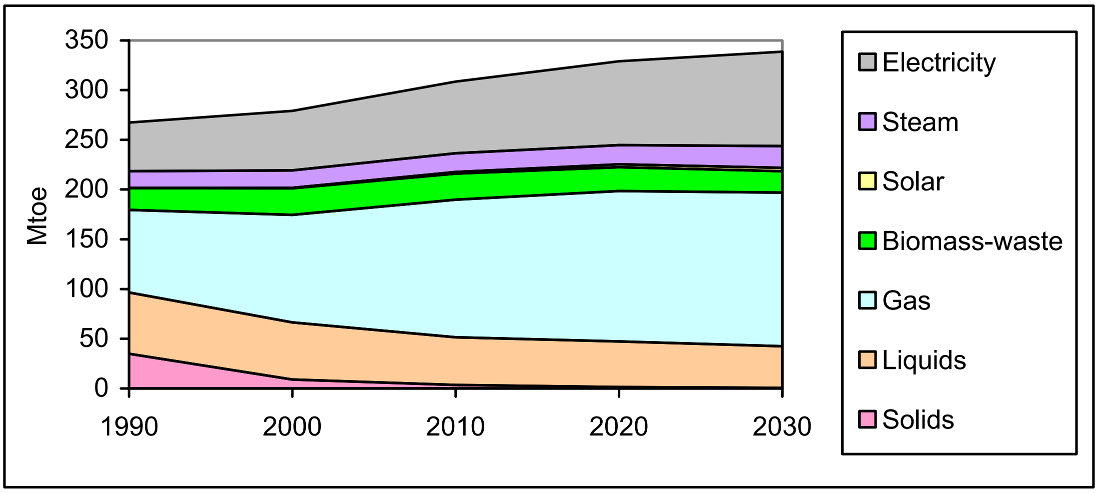
The analysis of the impacts of bioheat generation on the total heat consumption and thus – on the security and diversity of the EU energy supply seems however to be quite a challenging task. The reason is that it is generally very difficult to realistically assess the amount of heat use. The problem comes from the lack of coherent and validated statistical data, especially for NMS-10, but also from the inherent constraints in calculating the energy inputs and outputs for small-scale generating units – Figure 52.

Figure 52
Relative extent of feasibility to identify the energy inputs and outputs for heat generation in EU-25, split up by countries (EU-15 and NMS-10) and scale of heat generation

Scale / countries	EU-15	NMS-10
Small-scale generation and use	**Difficult**	**Extremely difficult**
Large-scale generation and use	**Feasible**	**Feasible**

With regard to small-scale heat generation and use, mainly in households, the identification of how much energy out of the total final energy consumption is employed for heating purposes is a common and well-known problem in statistics and energy balances. The problem comes from the fact that it is extremely difficult to calculate with a satisfactory certainty how much heat households are generating. Indeed, except electricity (and then even not all electricity), the other elements in the households' final energy consumption (Figure 53) are used exclusively for heating.

Figure 53
Retrospective and projected final energy consumption in the residential sector of EU-25 by fuels within 1990-2030, (Mtoe)



Source: Adapted from [53]

Also the final heat consumption is difficult to calculate, because the efficiencies of different households' heat generating units vary widely[34]. On top of that, even the rough estimates of the amount of heat, generated by the households from biomass, are quite vague. In fact, it is almost impossible to identify precisely how much biomass is self-produced or just collected by the households, without any interaction with the market. This problem is of particularly high relevance in the rural areas, where the largest part of bioheat generation and consumption takes place. The aforementioned uncertainties in the residential sector have a substantial impact on the breakdown of total final energy consumption by fuels. Households account for a large share in total final energy consumption in EU-25 (about 1/4), while their actual share in final heat demand appears to be even larger.

Considering the above reasons, the analysis in this chapter concentrates on the large-scale heat generation, i.e. distributed heating and industrial auto-producers of steam[35].

The heat market situation in EU-25 differs significantly from country to country due to a number of factors, e.g. climate conditions, fuel availability, established supply chains, etc. Despite these country specifics, major differences in heat situation are observed between EU-15 and NMS-10.

In the beginning of '90s, distributed heating accounted for the largest share in total heat generation in the NMS-10. With the start of the economic reforms, a great deal of these large-scale, but at the same time – inefficient heating facilities, was shut down. The closure of centralised heating plants in NMS-10 was also driven by the reduced demand of residential

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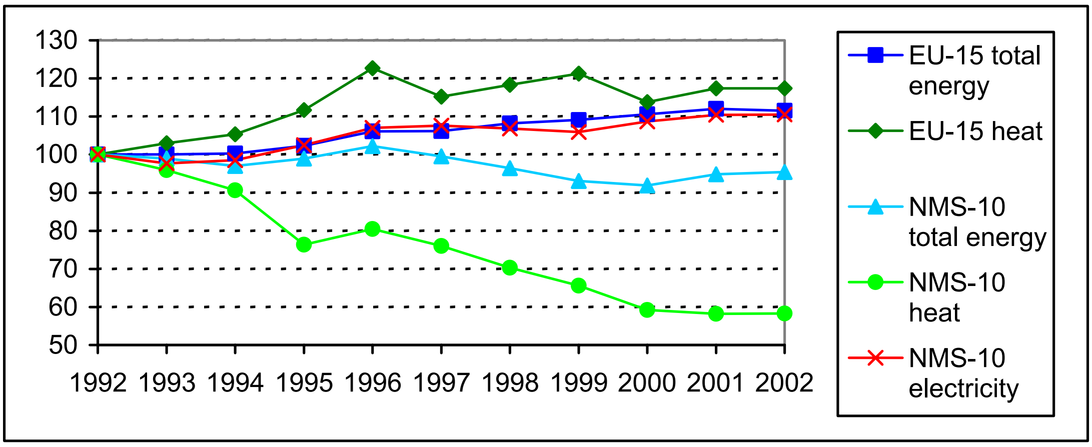
[34] See section 5.2
[35] Distributed heating incorporates are users of heat which do not have own heat (steam) generation, e.g. district heating consumers. On the contrary, the industrial auto-producers of steam are all factories, which generate by themselves the steam they consume.

and industrial users, due to the economic changes during the transition period. As a result, the relative decline in final heat consumption was much larger than the relative reduction in total final energy consumption (Figure 54). Despite this huge cutback, about 40% of heat needs in NMS-10 are still covered by district heating [23, 24, 48, 109]. Hence, steam demand still represents about 10% of the total final energy demand in the NMS-10 – a drop from 16% in the beginning of '90s [201, 205].

Figure 54
Indexes of final consumption of total energy, heat and electricity in EU-15 and NMS-10 over the period 1992-2002, (Index points, year 1992 = 100)

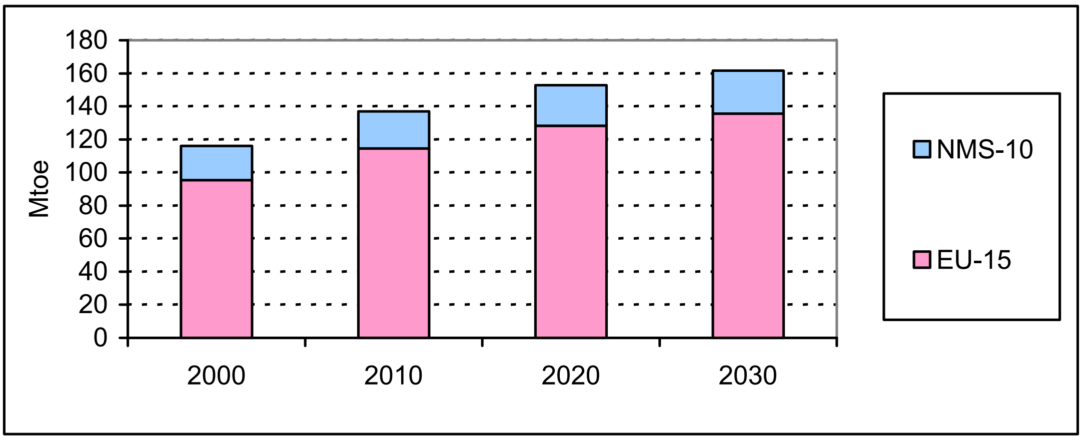


Source: Adapted from [201, 205]

In EU-15, where such substantial economic transformations didn't take place, the trends in total final energy demand and final heat demand were not so much pronounced. Total final energy consumption grew slightly, along with the economic growth, but at a lower rate [45, 54, 59, 68]. The relative increase in heat demand was larger than that in total final energy consumption, primarily during the first half of '90s, remaining basically unchanged thereafter (Figure 54). The stability in the EU-15 heat demand was due mainly to the fact, that heat requirements were already met. District heating does not represent a major heating option in EU-15. Its share in total heat demand is estimated to be about 10% [23, 24, 43], while its share in total final energy demand is stable – about 2% over the past decade [201, 205]. However, within EU-25 in absolute terms EU-15 account for a much wider share in the total distributed steam consumption than NMS-10, due to the larger overall energy use. For the same reason, the proportion between EU-15 and NMS-10 in total steam demand within EU-25 is not likely to change much in the future (Figure 55).

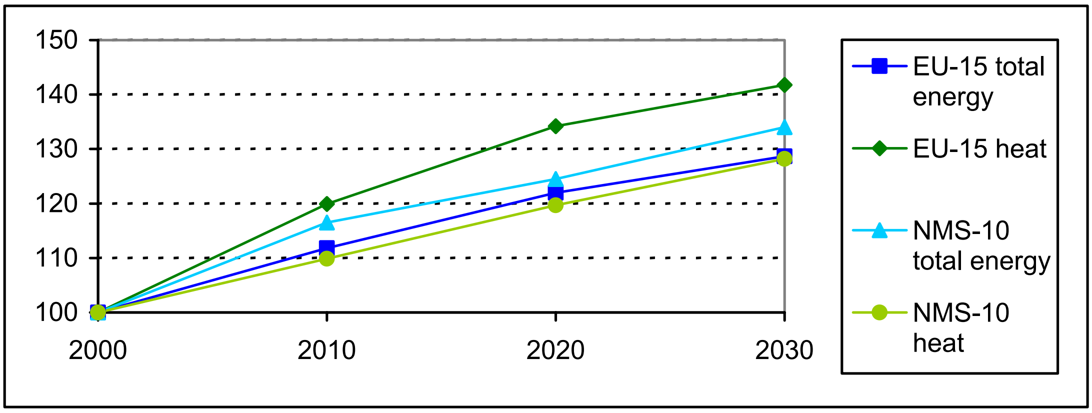
The baseline projections for the future (Figure 56) do not predict substantial differences from the prevailing trends. Heat demand will increase slightly faster than total final energy demand in EU-15, while the opposite trend will be observed in NMS-10. Nonetheless, both total final energy and heat consumption in NMS-10 will recover from the huge decline between 1990-2000 and the gap between them will get narrower.

Figure 55
Retrospective (2000) and prospective (2010, 2020, 2030) total steam demand in EU-15, NMS-10 and cumulative in EU-25, (Mtoe)



Source: Adapted from [53]

Figure 56
Index of the prospective final energy demand and final steam demand in EU-15 and NMS-10 within 2000-2030 (Index points, year 2000 = 100)

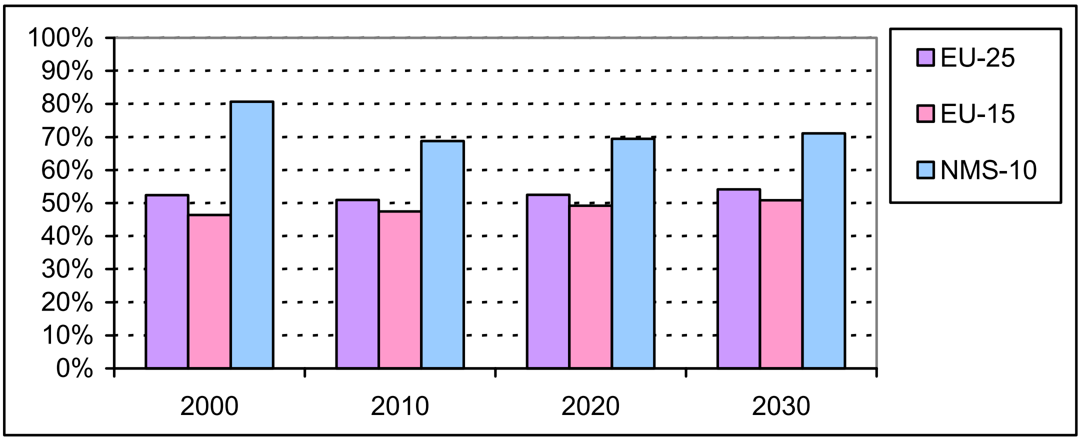


Source: Adapted from [53]

The growth in final energy demand in NMS-10 will be faster than in EU-15, while for heat the opposite is projected. The aggregate trends in EU-25 will follow the trends in EU-15, again due to the much larger share of EU-15 in both total final energy consumption and heat application, compared to NMS-10.

A significant distinction between EU-15 and NMS-10 exists also in respect of the breakdown between the types of steam users (Figure 57). Currently, the industrial auto-producers slightly dominate the overall steam consumption in EU-15. In the long-term, the difference between industrial auto-producers and distributed steam users will reduce. On the contrary, in NMS-10 distributed steam consumption is far ahead from the steam auto-production, despite the big drop after 1990. The leading position of distributed heating ensues also from the relatively larger reduction in the demand for processing steam, due to the substantial cutback in industrial output [109].

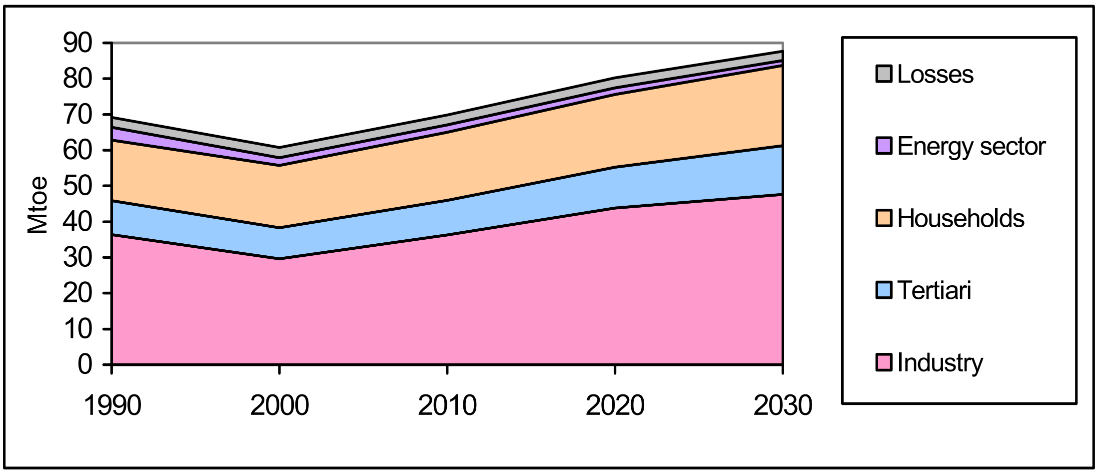
Figure 57
Retrospective (2000) and prospective (2010, 2020, 2030) share of distributed steam use in EU-25, EU-15 and NMS-10 /steam auto-producers fill the remaining percentage up to 100%/, (%)



Source: Adapted from [53]

Despite the projected industrial recovery in NMS-10, distributed steam consumption will remain the key component in total steam demand. Moreover, the techno-economic performance of district heating is expected to improve gradually. Within EU-25, the industrial users will continue to dominate the distributed steam consumption in EU-25 – Figure 58. Nevertheless, the importance of households and of the tertiary sector will progressively increase both in absolute and relative terms.

Figure 58
Distributed steam use in EU-25 by sectors (without auto-producers) within 1990-2030, (Mtoe)



Source: Adapted from [53]

The growth in households' steam demand is assumed to come mainly from the reduction in the average households' size and the respective increase in the number of households (Annex 2), resulting in a less efficient use of heat. The impact of the ageing population will be negligible, due to the expected increase of the average retirement age [30, 59, 60, 61, 63][36].

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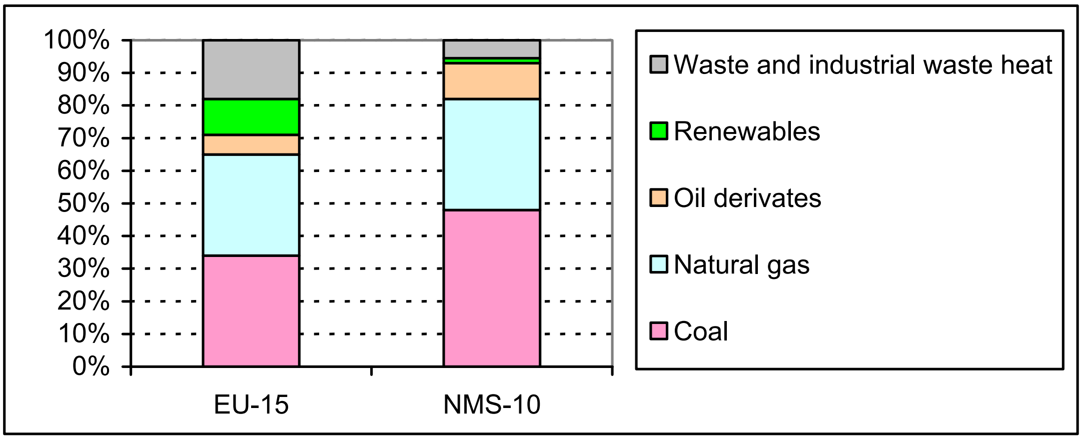
[36] On average, retired people stay for longer periods at home, rather than in large public buildings or just outside.

The improved performance of distributed steam generation is supposed to come partly from the switch to better fuels. In this aspect, however, again important differences between EU-15 and NMS-10 are observed – Figure 59.

Figure 59
Breakdown of fuel inputs for district heat generation in EU-15 and NMS-10 in 2001, (%)



Source: Adapted from [23, 24]

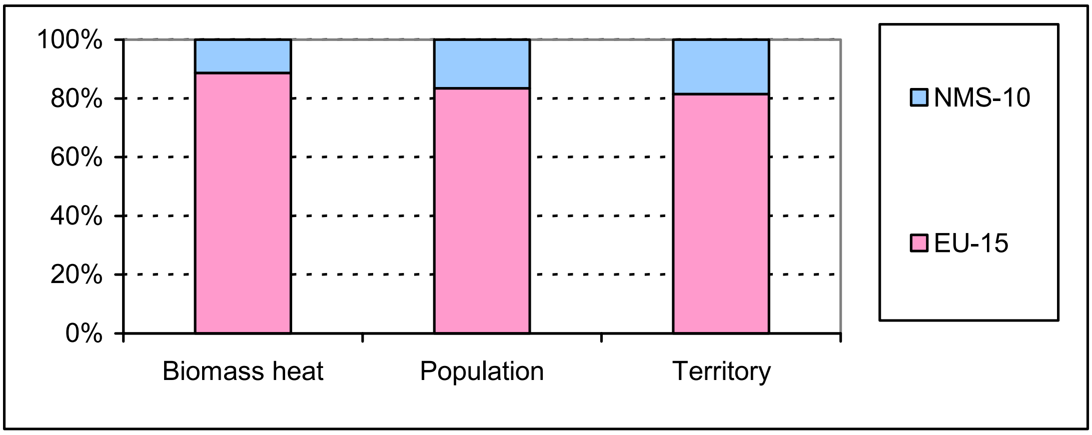
In EU-15 the role of coal in district heating is steadily decreasing, in part due to greater use of natural gas and especially of renewable sources of energy and waste. In NMS-10 coal is still the dominant fuel source, although gradually replaced by natural gas. Using natural gas is seen as most appropriate for improving the performance of distributed steam plants [24, 30, 109]. Heating oil accounts for a large part of steam generation in MNS-10 as well. This is a major drawback, due to the high oil import dependence of NMS-10, being even larger than that of EU-15 (95% versus 77% respectively in 2001). The utilisation of renewable energy sources and waste for steam generation is still little known.

With regard to the above analysis, the following conclusions about the feasible positioning of bioheat on the aggregate EU-25 steam market can be drawn:

- Bioheat could gain greater penetration in the distributed steam sector, rather than in the sector of steam auto-producers. This follows from the expected larger growth in the former sector for EU-15 (Figure 57). In NMS-10, this comes from the clear dominance of distributed steam in total steam consumption (Figure 57). On the other hand, steam auto-producers always try to make use of the existing fuel supply and handling infrastructure, built already for their core activities. Bioheat can be therefore considered mainly for industrial auto-producers, that at the same time generate biomass fuels – pulp and paper plants, agricultural farms, sawmills, etc. [140].
- NMS-10 possess a larger potential of increase in heat demand than the EU-15, because their heat needs are still unsatisfied, due to the huge decline in 90's (Figure 54). The option of meeting the additional heat consumption with biomass in NMS-10 is further strengthened by their lower population densities (Annex 3) and less explored bioheat

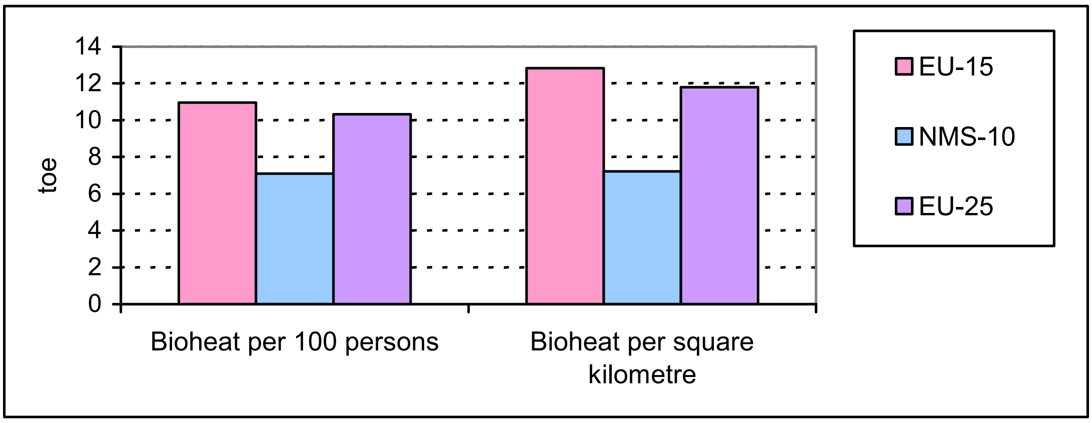
potential (Annex 1). Figure 60 indicates that within EU-25, EU-15 (with lower population and territory shares) has a larger share in bioheating than NMS-10. As a result, the bioheat application, both per capita and per square kilometre, in EU-15 is much larger than in NMS-10 – Figure 61.

Figure 60
Percentage allocation between EU-15 and NMS-10 within EU-25 (EU-25 = 100%) of biomass heat application, population and territory in 2001



Source: Adapted from [51, 54, 59]

Figure 61
Relative bioheat application – per 100 persons and per square kilometre – in EU-15, NMS-10 and EU-25 in 2001 (toe)

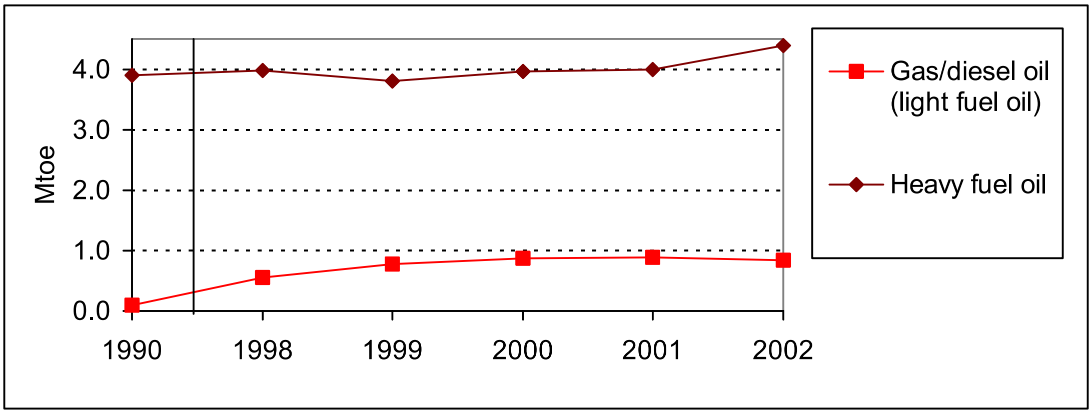


Source: Adapted from [51, 54, 59]

- The gradual phase-out of coal as an energy source for heat generation gives a chance for a larger penetration of bioheat. As mentioned in chapter 7, initially biomass can be co-fired with coal to facilitate the transition. Again, the reserves for such coal-to-biomass switch are greater in NMS-10, because the share of coal in heat generation of EU-15 has been already substantially reduced – Figure 59.
- Where well-developed networks of natural gas pipelines are available, the penetration of bioheat is significantly obstructed. Natural gas is a clean fuel that is getting increasingly popular and can earn great economies of scale. Hence, biomass is not yet competitive in general to natural gas, at least in the near to medium-term [46, 135, 174].

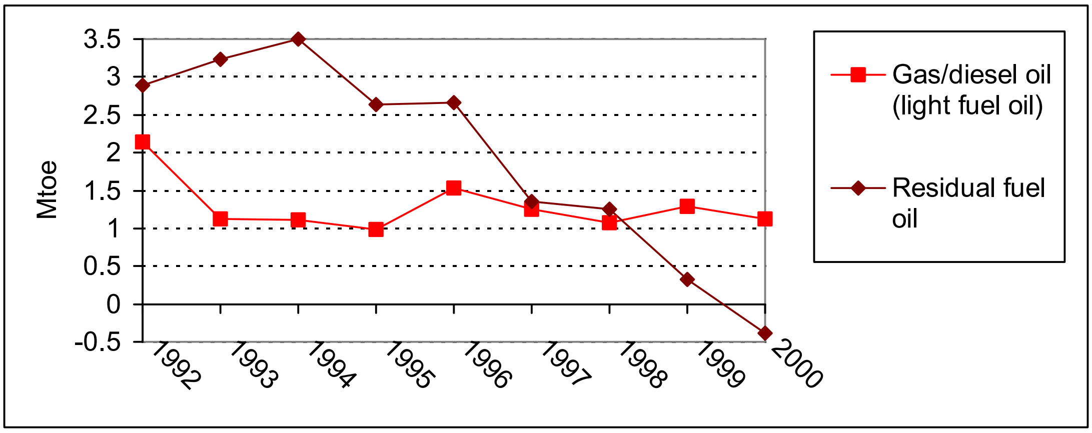
- The relations between heating oil and biomass for steam generation are more complex. As stated in section 7.2.3, biomass heating plants consume small quantities of heating oil as a fuel complement for various reasons – Figure 44. The use of light and heavy fuel oil for steam generation in EU-15 (Figure 62) was already reduced significantly – Figure 59. In NMS-10, the share of light heating oil is still quite large (Figure 59) and some reserves for its reduction have to be available[37] – Figure 63. Additional benefits from the substitution of light and heavy fuel oil will also occur in terms of lower SO_2, since both fuels have high sulphur contents – 0.2% and up to 3.5% on mass basis respectively [21, 22].

Figure 62
Retrospective (1990 and 1998-2002) use of light fuel oil and heavy fuel oil for heat generation in CHP and district heating plants in EU-15, (Mtoe)



Source: Adapted from [91, 105, 108, 201]

Figure 63
Net imports of gas/diesel oil (light fuel oil) and residual fuel oil (heavy fuel oil) in NMS-10 over the period 1992-2000, (Mtoe)



Source: Adapted from [201, 205]

As already stated, from a statistical point of view it is quite challenging to quantify the actual share of heat in the final energy consumption of households. So, it is difficult also to quantify

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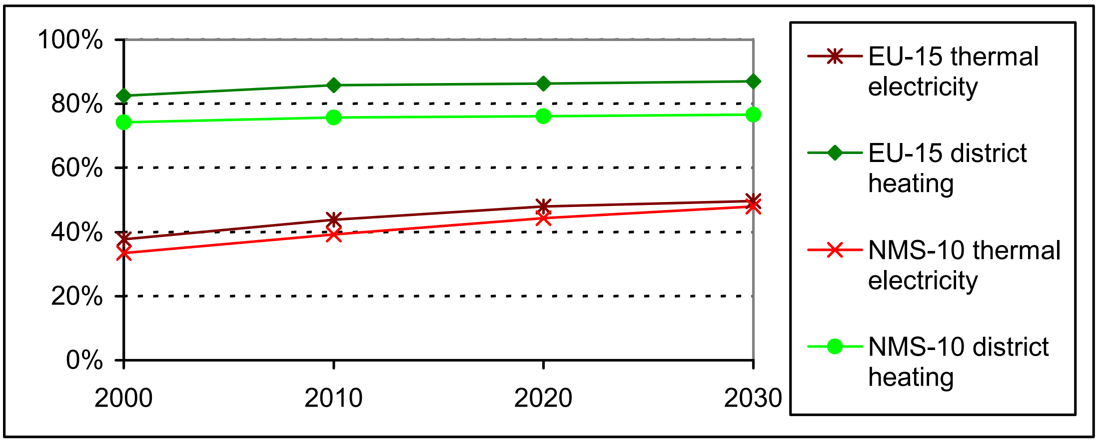
[37] Retrospective statistical data about the quantities of light and heavy fuel oil, used for heat generation in NMS-10 were not found.

the contribution of biomass to the households' heating. Nonetheless, the feasible capability of biomass to substitute coal, natural gas and light heating oil[38] follows the already identified patterns for the large-scale steam generation (distributed steam and auto-producers). The last component in the households' final energy consumption – electricity – should also be taken into consideration, when assessing the alternatives for small-scale generation of heat[39].

Detailed and coherent data about the residential heat, generated from electricity, in EU-15, NMS-10 and EU-25 are generally not available. It is however assumed that on average up to 10% of dwellings in EU-15 use electricity for heating [41, 99, 205]. In NMS-10 this share could be larger, due to the huge closure of district heating facilities in the '90s. An indirect proof for this hypothesis is the growth in electricity demand over the period 1992-2002, while total energy demand and heat consumption declined (Figure 54). In most cases, heat generation from electricity is considered as an extremely inappropriate option. All feasible alternatives for its substitution, including biomass-derived heat, should be therefore explored as much as possible. The basics for this are:

- For technological reasons, electricity generation is about twice less energy efficient than heat generation (Figure 48) and this ratio is not expected to change in the future either [7] – Figure 64;

Figure 64
Retrospective and prospective thermal[40] electricity and steam generation efficiencies in EU-15 and NMS-10 within the period 2000-2030, (%)



Source: Adapted from [53]

- In EU-25, the growth in electricity consumption was larger than the growth in total energy use and this is projected to remain also in the future. The largest contributors to the electricity growth were the households and the tertiary sector – a situation, which is not expected to change in the future either (Figure 65). Households are a key consumer of electricity, responsible for about 1/4 of total final electricity demand in EU-25.

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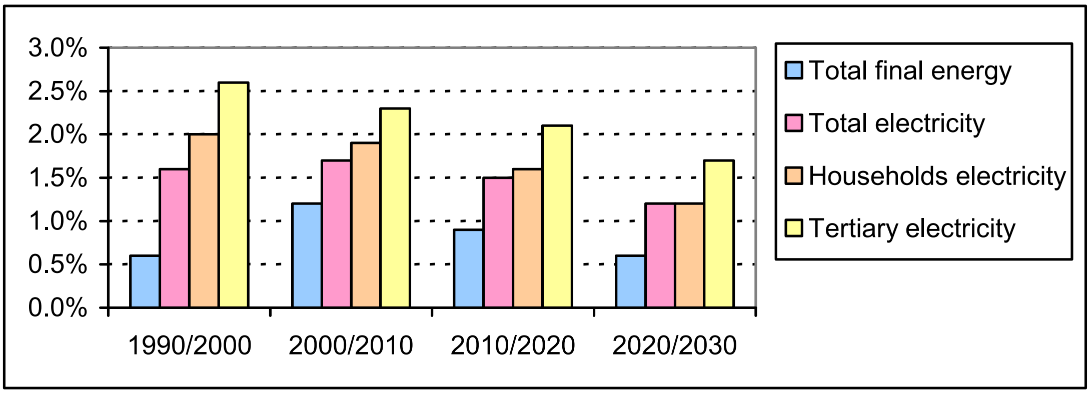
[38] Heavy fuel oil is not used for households heating, due to handling and combustion constraints.
[39] On a large-scale, electricity is generally not used for heat generation any longer.
[40] Electricity generation based on fuel inputs (nuclear, coal, natural gas, etc.) – not including hydro and wind power.

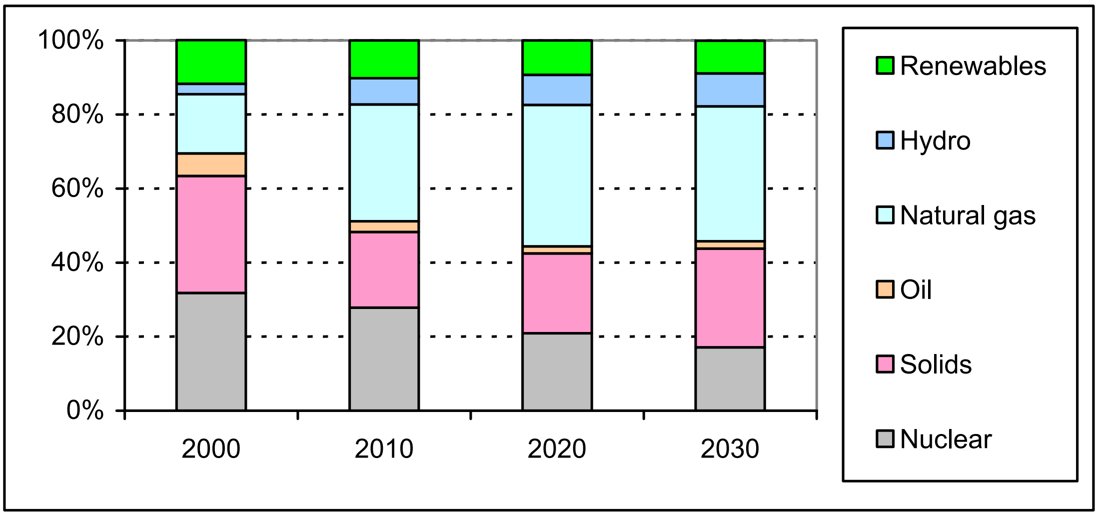
Figure 65
Average annual growth in final energy consumption, total electricity demand, electricity consumption of households and of the tertiary sector in EU-25 within 1990-2030 (%)



Source: Adapted from [53]

- A clear trend of increasing the share of electricity, generated from natural gas, is recently observed in EU-25. The growth rate of natural gas-derived electricity will intensify further in the future not only in the EU (Figure 66), but also world-wide [53, 58, 91, 166].

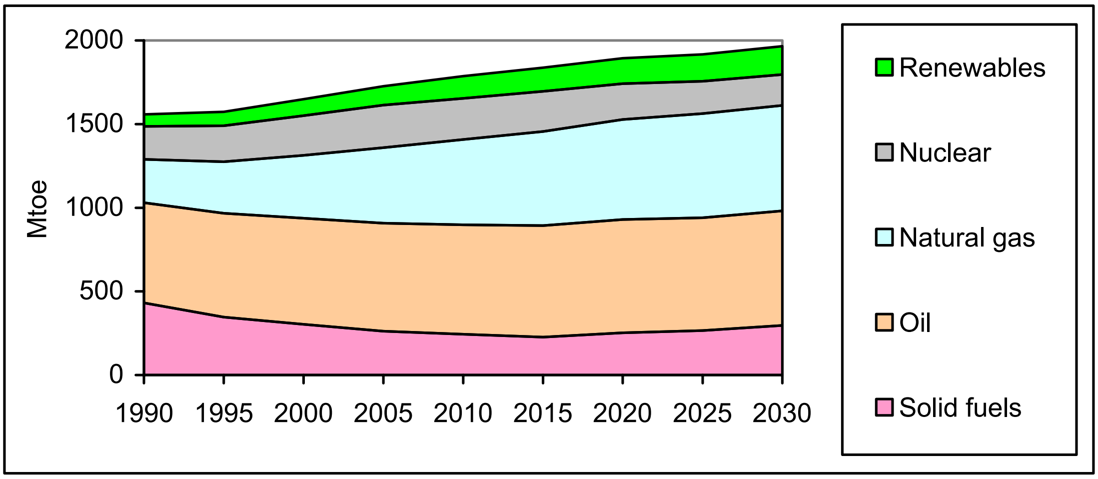
Figure 66
Breakdown of the electricity generation by fuel inputs in EU-25 by 2000, 2010, 2020 and 2030, (%)



Remarks: Hydro includes geothermal power, renewables include biomass and wind
Source: [53]

- Electricity generation accounts for about 40% of gross inland energy consumption in EU-25. The latter is projected to grow slightly, mainly driven by natural gas for power generation – Figure 67 [53, 58, 91, 166]. As a result, the natural gas import dependence will increase noticeably and will push up respectively the EU total energy import dependence (Figure 1). In parallel, this will bring negatives in terms of diversity of the Community's energy supply as well, due to the geopolitical concentration of the majority of world oil and natural gas resources (Figure 2).

Figure 67
Gross inland energy consumption of EU-25 within 1990-2030, (Mtoe)



Source: Adapted from [53]

Summarising the above, it becomes obvious that replacing as much as possible heat, generated from electricity, by other types of heat will have a direct positive impact on the EU security and diversity of energy supply [67]. Last, but not least, reducing the overall electricity demand by switching from electricity-heat to e.g. bioheat, will assist in reaching the renewable policy objectives in the EU:

- Directly – to the 21% share of renewable electricity [76], by simply reducing the pressure on electricity demand;
- Indirectly – to the 12% gross inland energy consumption from renewable energy sources [42], by using the available renewable resource in a more efficient way (Figure 64);

Nonetheless, in some particular cases electricity could be a suitable option for generation of heat. Such situation might arise in countries, where the electricity generation is based on hydro or nuclear power exclusively, whose installed capacity exceeds the electricity demand. Hydropower differs from thermal power in terms of its relatively constant output and inefficient operating on partial load. In order to be economically effective, the operation of nuclear plants requires also full load, due to the governing share of fixed costs in their total costs. The share of fuel costs for nuclear power plants, compared to thermal power plants on coal or natural gas, is negligible. Hence, if there is an excess availability of hydro or nuclear power generating capacities, using electricity for heating could be reasonable from the point of view of efficient operation of these power facilities. For hydropower, such a scenario is definitely sound. In the case of nuclear power, however, it might be slightly questionable whether this was appropriate, considering the concerns about nuclear safety.

Summarising the above thoughts, Figure 68 presents the feasible ways, in which bioheating can contribute to the security and diversity of energy supply of the EU.

Figure 68
Suggested feasible niches for market penetration of bioheat in EU-15 and NMS-10 with regard of optimising the security of energy supply impacts /Note: No any adverse impacts!/

Type of facilities	Use / fuel	EU-15	NMS-10
New Capacities	Industrial users	0	+
	Distributed steam	+	+ +
Substitution	Coal, including co-firing	+	+ +
	Natural gas	0	0
	Light fuel oil	0	+
	Heavy fuel oil	+	+ +
	Electricity	+	+ +

Legend: (+ +) Large potential; (+) Small potential; (0) Negligible or no potential; (–) Small adverse impact; (– –) Large adverse impact;

Using biomass for heating clearly contributes to the security and diversity of energy supply of the EU. In general, bioheat appears more feasible for small-scale heat generation (households) and for distributed steam consumption than for industrial auto-producers of steam. The penetration and further growth potential of bioheat seems larger for NMS-10 than for EU-15. For heat generation, biomass could successfully complement or substitute coal, while its ability to replace natural gas appears negligible. Under certain conditions, biomass can also substitute heating based on light and/or heavy fuel oil, and on electricity. The opportunities to switch from electricity to biomass heating should be carefully assessed, especially in NMS-10 – Figure 68.

10. ENERGY EFFICIENCY AND ENVIRONMENTAL PERFORMANCE

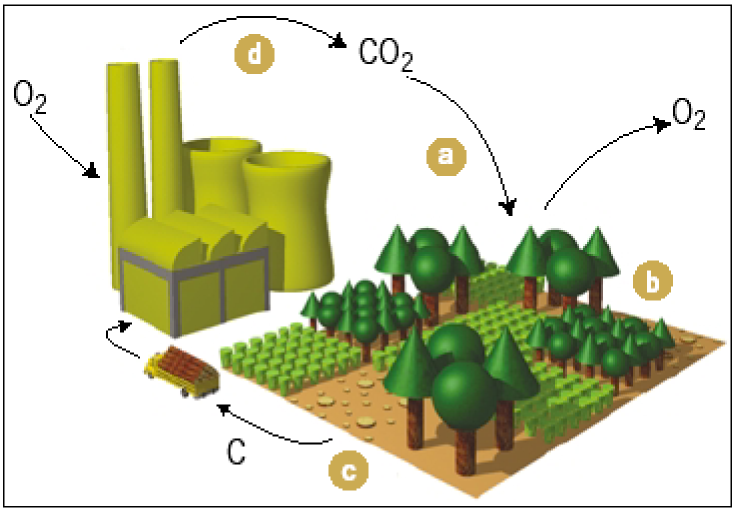
10.1. ENERGY EFFICIENCY AND EMISSIONS OF GREENHOUSE GASES

As stated in chapter 1, the emissions of greenhouse gases (GHG) represent a growing concern in the EU and worldwide. The reason is that the impact of GHG is not localised by areas, but it affects global climate. Hence, if the GHG reduction in one part of the world were achieved at the expense of a larger increase in GHG emissions in another part of the world, the net global GHG balance would be negative. For this reason, GHG emissions are counted along fuel chains (Figure 6), i.e. from the extraction of feedstock till the final use of energy. There are 2 main approaches to quantify GHG emissions. The first one counts only the direct GHG emissions, incurred along fuel chains. This methodology is widely used for assessing energy consumption and GHG emissions in transport – the so-called "Well-To-Wheel" (WTW) analysis. The second one tries to looks at all GHG, associated with fuel utilisation – the so-called "Life Cycle" analysis (LCA). Beside direct GHG emissions, this approach includes also indirect GHG emissions from various types of infrastructure and equipment, needed for the production and the proper use of fuels. In principle, LCA is expected to give a more complete picture of GHG emissions than WTW. Nevertheless, in practice it is quite challenging to define the LCA scope, i.e. which components should actually be taken into account. Hence, the WTW approach appears more appropriate, as it gives results with a lesser extent of uncertainty than the LCA methodology.

As mentioned in chapter 1, the main GHG is carbon dioxide (CO_2). Other important GHG are methane (CH_4) and nitrous oxide (N_2O). The amount of CO_2 emissions from fuel combustion depends on the quantity of carbon that is employed in the combustion process. Higher fuel consumption or combustion of fuels with larger carbon chains increases CO_2 emissions. However, in the case of biomass the GHG balance is slightly different. The CO_2, released during biomass combustion, is later on absorbed by other plants, which need it for their growth, so biomass is <u>generally</u> CO_2 neutral – Figure 69. The "general", but not "full" neutrality of biomass is due to the small amount of fossil fuel that is consumed in the biomass cycle – for cultivation, transportation, etc. Nevertheless, <u>the amount of this fossil energy as a share in gross (bio)energy output, is modest – typically between 2% and 4%</u> [31, 87, 97].

The efficiency of different heating systems varies widely – from almost 0% for open fireplaces to more than 90% for modern large-scale district heating plants with flue gas condensation units (chapter 5). Hence, estimating with a satisfactory extent of accuracy the energy use and the GHG (CO_2) emissions along various biofuel chains for heat generation is extremely difficult, if feasible at all, since the combustion stage accounts for more than 85% of total energy use and GHG emissions along fuel chains. This hindrance is strengthened by the high site-dependence of bioenergy, in particular on transportation and handling.

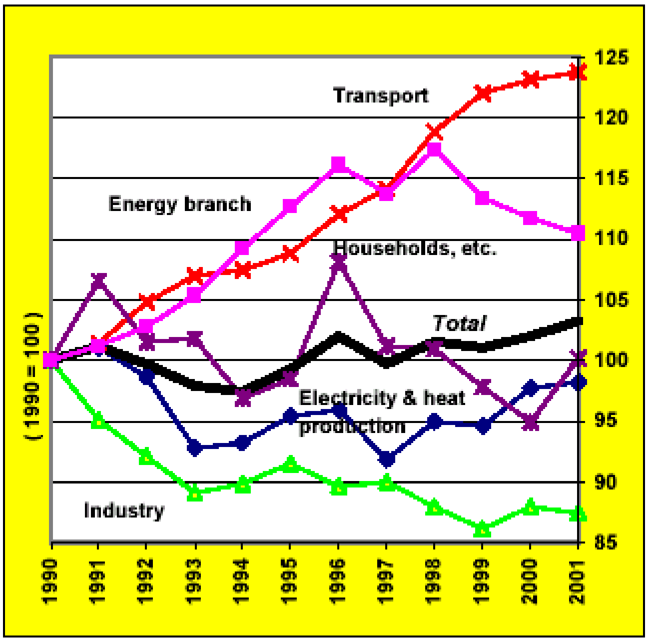
Figure 69
Mechanism of the closed CO_2 cycle of biomass



Legend: a) CO_2 is captured by the growing crops and forests; b) Oxygen (O_2) is released and carbon (C) is stored in vegetation; c) Biomass (carbon) is harvested and transported to the combustion plant; d) The combustion plant burns biomass, releasing CO_2 to the atmosphere, that is captured by the vegetation;
Source: [87]

Hence, calculations of energy efficiency and GHG (CO_2) emissions for bioheat pathways are extremely scarce. Some general patterns can be however identified. As Figure 70 indicates, the CO_2 emissions from power and heat generation in the EU sharply decreased in the first half of '90s, however again a steady growth has been registered after 1997.

Figure 70
CO_2 emissions from fossil fuels in EU-15 by sectors over the period 1990-2001, (Index points, year 1990 = 100)



Source: [54]

The downward trend in the CO_2 emissions was due exclusively to the switch to less polluting fuels (mainly from coal to natural gas) and the larger penetration of renewable energy sources – Figure 67. The efficiency improvements had a smaller contribution to the reduction of the CO_2 emissions. The upward trend was caused by fast growing electricity consumption – Figure 54. Nonetheless, the cumulative impact of these two trends was positive, since a net reduction in the CO_2 emissions from power and heat generation was achieved in 2001, compared to 1990 – Figure 70. The other GHG pollutants – CH_4 and N_2O do not represent a major concern any longer, as a substantial reduction in their emissions has been achieved between 1990 and 2001: -20.4% in CH_4 and -15.8% in N_2O [67, 68, 69, 71, 72][41].

The hopes for future reductions in CO_2 and consequently – in GHG emissions are associated notably with a larger penetration of the renewable energy sources. In this context biomass will be the most important contributor, at least in the near- to medium-term, thanks to its dominance in the renewable energy mix (Figure 9) and the closed CO_2 cycle (Figure 69). Particular attention should be paid to the residential sector, where significant CO_2 cutbacks might be achieved by increasing the efficiency of the small-scale heating and by a larger application of biofuels [67, 69].

10.2. LOCAL-POLLUTING EMISSIONS

The local-polluting emissions incorporate a range of chemical substances with various impacts on air quality, health, materials, etc. Some of the important local-polluting compounds are carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic components[42] (NMVOC) and various particulate matters (PM).

Within the period 1990-2001 the EU achieved substantial reduction in the emissions of local pollutants: -63.6% in SO_2, -40.2% in CO, -29.4% in NMVOC and -25.8 % in NOx. [72]. Similar to the GHG emissions, this large decrease in the local-polluting emissions was primarily achieved by fuel switch, triggered by stricter emission regulations [77] and control. Currently local pollutants are already under control and hence, they represent a relatively smaller concern than GHG emissions. Despite these attainments, there is still a room left for further cutbacks. Because of their nature and impact, such an additional decrease is of particular importance for densely populated urban areas. Regardless of the significant improvements, the energy sector remains a major emitter of local pollutants, in particular of SO_2. The high SO_2 emissions push up the corresponding cumulative emissions of gases with acidifying potential [SO_2, NOx and ammonia (NH_3)] and of fine particulate matters (PM_{10} – SO_2, NOx and various primary particulates from fuel combustion) – Figure 71 [65, 66, 68, 69, 70, 72].

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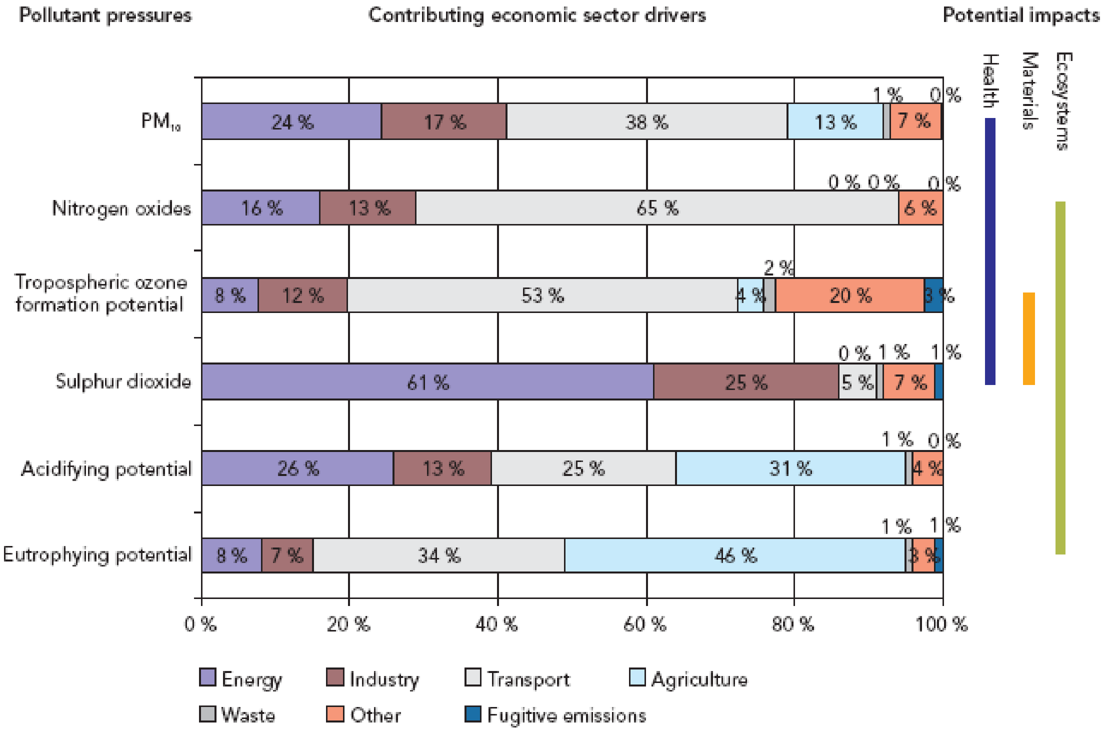
[41] See Figure 4, where the growth in CO_2 emissions exceeds the growth in total GHG emissions

[42] Various organic compounds, made up predominantly of carbon and hydrogen.

Figure 71
Shares of different sectors in selected local-polluting emissions in EU-15 in 1999



Source: Adapted from [65]

CO is a combustible gas – Figure 42. CO emissions do not depend on the fuel burnt, because they result from inefficient and incomplete firing – a useful product is in fact not utilised. Thus, CO emissions should be kept as low as possible. This can be easily achieved with appropriate control of the combustion process – combustion temperatures above 850°C, well-measured excess air supply, etc. [8, 31, 97, 126, 168]. The situation of NMVOC is identical to that of CO, as NMVOC are also combustible gases. Hence, high NMVOC indicate incomplete combustion.

SO_2 emissions entirely depend on the sulphur content of fuels. In general, SO_2 emissions do not raise concerns when biomass is fired, due to its negligible sulphur content, compared to coal – Figure 19. In addition, thanks to the high volatility of biomass, a large part of biomass sulphur is captured in the bottom ash and thus – not released to the atmosphere. The extent of sulphur capture varies between 40% and 90%, rising with the increase of the alkaline compounds in biomass, which react with sulphur and retain it[43]. As a result, replacing coal with biomass in heat generation offers a large potential for SO_2 savings and for further cutback of SO_2 emissions in the EU energy sector – Figure 71. On the other hand, from a SO_2 emissions point of view biomass is a worse alternative than natural gas, which does not contain any sulphur – Figure 19 [28, 129].

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[43] The same capturing process is also valid for chlorine (Cl) and Cl-related (hydrogen chloride – HCl) emissions. Cl emissions come from the Cl content of fuels, mainly of herbaceous biomass. Thanks to the reaction with the alkali compounds (Na and/or K), 40-90% of Cl is trapped in the bottom ash [19, 20, 97].

The amount of sulphur, which is not captured in the bottom ash and is released to the atmosphere, can be reduced further. Sulphur is a combustible compound that increases the calorific value of fuels. Hence, high SO_2 emissions can also indicate incomplete combustion. Similar to the CO case, increasing combustion temperatures decreases SO_2 emissions. If the flame temperature is not high enough, part of the sulphur is released to the atmosphere with the flue gas in the form of dust particles, upon reaction with the alkali compounds (K and Na) of biomass. Besides sulphur, other dust particles originate from reactions between alkali compounds and chorine (Cl). For these reasons, various dust-retaining facilities are applied, the most typical of them being multi-cyclones and bag filters.

Multi-cyclones (Figure 34) are used for primary separation of coarse dust particles (particle size larger than 5 μm, with separation efficiency up to 90%) from the flue gas by centrifugal turbulence in vertical tubes. Depending on the fuel, they can reduce dust concentrations in the flue gas from 1000-2000 mg/m3 to 200-500 mg/m3. The key advantages of multi-cyclones are simple design and maintenance, low cost, high operation temperatures (above 1300°C) and ability to process high dust loads. Conversely, their main drawbacks are sensitivity to variable and partial dust loads, and potential condensation of tars inside the cyclone, which obstructs the collection of the dry ash [19, 20, 97].

Bag filters (Figure 38) are used for further cleaning of the flue gas from fine particles and consist of a filter, placed in a closed construction, which the flue gas passes through. In such a way, bag filters can retain very small particles (particle size less than 1 μm) at an extremely high efficiency – about 99%. As a result, bag filters can bring dust concentration down to 10-50 mg/m3. Bag filters are, however, quite humidity- and temperature-sensitive and typically can process flue gas with temperature up to 250°C. Similar to multi-cyclones, problems with tar condensing are possible, as well as a relatively frequent (every 2-3 years) replacement of the filtering component is often needed [19, 20, 97].

In any case, both multi-cyclones and bag filters are considered as relatively inexpensive tools for efficient cleaning of the flue gas from dust particles in large-scale heat generation. Hence, they are widely used in district heating plants [19, 20].

Electrostatic filters and dust scrubbers represent other techniques for flue gas cleaning from dust particles. However, both techniques find smaller application than multi-cyclones and bag filters in heat generating plants, mainly due to higher capital costs. In electrostatic filters, dust particles are first electrically charged. Then, they pass through an electric field where they stick to the electrodes. The captured dust is removed periodically from the electrodes via vibration. Electrostatic filters have similar performance like bag filters – efficient collection of fine particles, plus some small advantages, e.g. higher operating temperatures (up to 480°C) and potentially lower maintenance costs. In scrubbers, the flue gas passes through a water wall, which retains dust particles. Hence, scrubbers collect simultaneously gases (SO_2, HCl, NO_2) and dust. On the other hand, there are problems with wastewater cleaning, wet ash disposal, corrosion and freezing at low temperatures [19, 20, 97].

The situation of NOx emissions is more complex. Part of them result from the nitrogen content of fuels – fuel nitrogen. Here, biofuels possess comparative advantages over fossil fuels, due to their lower nitrogen content. Usually, fuel-derived NOx emissions prevail in total NOx emissions at low flame temperatures – 800-1100°C. Another and even – larger part of NOx comes from the nitrogen in the excess air that is supplied to the combustion chamber – thermal nitrogen. Nitrogen from the air reacts with the oxygen (O_2) that comes also with the excess air to the combustion chamber. As a result, NOx are formed – mainly NO and much less NO_2 (in proportion 90%/10%). Unlike fuel NOx, thermal NOx prevail in total NOx at flame temperatures above 1100°C. There are several ways to reduce thermal NOx emissions:

- The amount of thermal NOx emissions depends on the amount of excess air (λ), supplied to the combustion chamber. The lower the excess air is, the lower the NOx emissions[44]. Hence, optimising combustion by keeping the excess air supply as low as possible is a way of reducing thermal NOx emissions. Alternatively, one may inject oxygen instead of air, but this is far more expensive and cost ineffective for heat generation.
- NOx emissions increase with the increase of the fuel residence time in the combustion chamber. Hence, using high-quality fuels (with small particle size, low moisture content, high calorific value, etc.) whose combustion is fast, leads to low NOx emissions.
- Thermal NOx emissions grow with the increase of the flame temperature. Up to 1300°C, the growth in NOx emissions is linear with the raise in the temperature. Above 1300°C, the growth in NOx emissions becomes faster (exponential). Due to high moisture content and low calorific value, the combustion temperatures for biomass typically do not reach 1300°C. Nevertheless, NOx formation below 1300°C is still relevant to biomass firing. Flue gas re-circulation is a way of reducing combustion temperatures, if necessary. Here, part of the flue gas is returned back to the combustion chamber – Figure 35. As a result, the amount of oxygen in the combustion chamber is reduced, substituted by inert gases from the flue gas – N_2, CO_2. The flame temperature is lowered, since more heat is absorbed by these inert gases. Due to the specifics of the combustion process, this leads to a reduction in NOx, since at low flame temperatures mainly pure N_2 is formed, rather than NOx. Pure N_2 does not raise concerns, since it is exactly how it has been brought from the air to the combustion chamber. Before being put back to the combustion chamber, the flue gas should be cleaned from dust particles to avoid dust deposition in the re-circulating lines. Hence, it has to be extracted after passing a bag filter. Flue gas re-circulation is not suitable for cyclic operation, due to the condensation of the flue gas in the re-circulating lines and the ensuing corrosion.

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[44] Nitrogen is the main component of air – more than 78% on volumetric basis. Oxygen accounts for another 21%, while all other components (CO_2, H_2, etc.) fill the remaining less than 1% [221].

- NOx emissions can be reduced by injecting ammonia (NH_3) or carbamide $[CO(HN_2)_2]$ to the furnace. By reacting with those substances at strictly defined temperatures, NO and NO_2 are transformed to N_2 and water. With the addition of expensive catalysts (platinum, titanium or vanadium oxides), the required temperature is about 250°C for NH_3 and 400-450°C for $CO(HN_2)_2$. If no catalysts are used, the needed temperatures range within 850-950°C. The temperature defines the NOx removal, since at higher temperatures NO, but not N_2, is formed, while at low temperatures the reaction simply does not occur.

The emissions of many pollutants (N_2O, CO, NMVOC, PM) decline with increasing the combustion temperature. Trade-offs are therefore observed between NOx and most other emissions, including a nitrogen trade-off (NOx/N_2O). By controlling excess air supply, combustion temperatures and residence time, NOx emissions can be successfully kept low. In this context, staged-air combustion is a way of achieving simultaneous reduction in the emissions from incomplete combustion and NOx. In staged-air combustion, the gas de-volatilisation and the gas burning phases take place in different sections of the combustion system and so, they can be optimised separately [8, 19, 20, 39, 97, 129, 168].

Similar to GHG emissions, local-polluting emissions depend very much on the level of sophistication of combustion systems. Local pollutants depend even more on the quality and tuning of burning facilities. If biomass is fired in inappropriate or poor combustion systems, the emissions of local pollutants can be even higher than the emissions from e.g. coal burning in modern and well-tuned facilities. Thus, bioenergy should not be regarded as environmentally friendly by definition.

The control equipment for local-polluting emissions is expensive, causing a significant increase in capital costs. Hence, such systems are implemented mainly for large-scale heat generating facilities, while their utilisation in small-scale systems is modest or simplified. Nonetheless, these costs are a major issue even for the large-scale heating plants, since the feasible heat generation is inherent with much smaller scale than e.g. power generation. However, biomass has the potential to improve significantly the local air quality, provided the heat generation units are equipped with adequate emission control equipment. This advantage deserves particular attention in densely populated urban areas, where local air-quality raises serious concerns [8, 19, 20, 39, 97, 168, 174, 200].

10.3. SUSTAINABILITY AND OTHER ENVIRONMENTAL ISSUES

Two types of ash from solid fuel combustion are formed – bottom and fly ash. Bottom ash is accumulated on the floor of the combustion chamber. It is often mixed with impurities (sand, stone), which can lower the ash melting point and can foster slagging. As stated in section 5.1, bottom ash usually accounts for the major share in total ash deposition from biomass combustion (60-90%), due to the high biomass volatility[45]. Unlike bottom ash, fly ash leaves the furnace with the hot flue gas. It is either collected by various dust cleaning facilities (multi-cyclones, bag filters), or it is released to the atmosphere through the chimney. Fly ash is normally sub-classified in cyclone ash – coarse particles, trapped in multi-cyclones, and filter ash – fine particles, retained by bag or electrostatic filters. If woody biomass is burnt, cyclone fly ash prevails, while when herbaceous biomass is fired, mainly filter fly ash is obtained.

The great advantage of biomass ash is that it represents a useful by-product. Instead of being dumped in a landfill like most coal ashes, bio-ash is used as a soil fertiliser, thus avoiding air, soil and water pollution from landfill deposition. Bio-ash can be employed as a fertiliser because most nutrients, contained in biomass, are not lost during combustion, but captured in the ash. By returning the bio-ash back to the field, where it originated from, the renewable energy cycle (Figure 69) is completed, since the nutrients in bio-ash are usually sufficient to guarantee the growth of the new plants. The only exception from this rule is nitrogen. Part of fuel nitrogen is released during combustion as NOx, thus the nitrogen balance should be re-established. This can be easily achieved by adding some nitrogen fertiliser to the soil. Another advantage of biomass ashes is that all of them contain alkali substances, due to the biomass composition, which prevent soil acidification.

The ash composition fully depends on the type of biomass that is burnt. Since various kinds of biomass have different composition, so do bio-ashes. In order to maintain the nutrients' balance of the soil, it is not recommended to use mixed ashes from various feedstocks. So, woody biomass ash should be spread in forests, while herbaceous bio-ash should be returned back to the fields where the herbaceous feedstock came from. By not mixing different biomass ashes, exactly the components, which have been extracted, can be returned back to the same fields [19, 97, 125, 135, 145, 149, 168, 228].

Besides the chemical composition of biomass ashes, the bio-ash degradation period and the frequency of the bio-ash addition to the soil are other important considerations for sustainability. The growth period of forests is long, hence – the degradation period of woody bio-ash should also be long otherwise the nutrient balance in the forest would be destroyed. Before being returned to the soil, bio-ash should be hardened in the form of granules to ensure slow degradation. The biomass ash addition to the soil should be also carefully dosed. The frequency of ash addition should be not less than every 5 years for herbaceous crops and not less than 10 years for wood species on average. The total quantity of spread dry ash should not exceed 7-7.5 tonnes per hectare per forest rotation (about 100 years), while for herbaceous crops the recommended dose is 0.75-1 tonne per year per hectares [19, 97, 125, 138].

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[45] With the exception of sawdust and wood powder, where mainly fly ash is left [97, 149].

Mainly bottom bio-ash is used as fertiliser. The reason is that most heavy metals, contained in biomass (especially in wood), are bound in the filter ash. The higher content of heavy metals in woody biomass, compared to herbaceous species, comes from the longer cultivation period of wood. The difference in the concentration of heavy metals between woody and herbaceous biomass varies between 3 and 20 times [97]. Even larger differences can appear in bio-ash from residual wood, depending on where the residual wood originates. Hence, filter ash from (woody) biomass firing is normally disposed in landfills, while bottom and cyclones fly ashes are used as fertiliser. Nonetheless, this is not regarded as a serious drawback, as the greater part of soil nutrients (85-95%) is bound in the bottom ash [19, 20, 87, 97, 125, 138, 139, 149].

10.4. SUMMARY

Figure 72 summarises the relative environmental advantages and disadvantages of biomass application for heat generation, compared to fossil fuels. Figure 72 indicates that biomass in heat generation earns significant environmental benefits, especially compared to coal.

Figure 72
Relative environmental advantages and disadvantages of biomass application for heat generation, compared to fossil fuels /Note: No significant penalties!/

	Coal	Heating oil	Natural gas
GHG emissions, of which:	+ +	+ +	+ +
CO_2 emissions	+ +	+ +	+ +
Local-polluting emissions, of which:	+ +	+	–
CO and NMVOC emissions	0	0	–
SO_2 emissions	+ +	+	–
NOx emissions	+	+	–
Particulate (dust) emissions	+	0	–
Soil protection	+ +	0	0
Water protection	+ +	0	0
Sustainability & recycling	+ +	+ +	+ +

Legend: (+ +) Significant benefits; (+) Moderate benefits; (0) Similar performance; (–) Moderate penalties; (– –) Significant penalties;

Using biomass for heat generation earns significant GHG benefits compared to fossil fuels, due to the CO_2 recycling. Biomass may also improve significantly the local air quality by large cutbacks in SO_2 emissions and to a lesser extent – in NOx emissions. The extent of the air-quality advantages of biomass use over fossil fuels however strongly depends on the quality of combustion systems. If biomass is burnt in non-suitable combustion systems, it can earn relative air pollution penalties, compared to fossil fuel burning in proper systems. Biomass offers significant benefits in terms of water and soil protection, compared to coal, by avoiding landfill depositions, because of the possibility of recycling bio-ash as a soil fertilizer – Figure 72.

11. COST ANALYSIS

The cost analysis of bioheat applications deserves particular attention, since costs have a major impact on prices and thus – on the market penetration of bioheating.

Despite the fact that wood heating has been well-known for centuries, biomass heating as a modern technology is relatively immature. Not so long ago, mainly households were using biomass for heating in low-efficient systems. Only in the last decade bioheating became competitive to the heating systems based on fossil fuels, thanks to significant improvements in energy efficiencies, emissions and costs. As a result, heat generation from biomass started to be considered also for large-scale applications. Nevertheless, like all immature technologies, the bioheat market is not yet well developed and differs significantly from country to country – Annex 1. A large part of these differences is due to the high site-dependence of bioenergy and in particular of bioheating. Because of this high site-dependence and of the limited cross-border heat exchange (constrained by the huge transmission losses), the heating sector is not subject of a uniform tax treatment in the EU [26]. Hence, large cost and price differences are observed amongst the EU countries, which makes the identification of aggregate conclusions about the average bioheat costs at EU level difficult [1, 2, 6, 7, 8, 16, 51, 127, 151, 168].

The total bioheat costs are split up in two groups – fixed costs and variable costs.

Fixed costs incorporate the costs of all types of equipment along different energy pathways, required for heat generation from biomass fuels (Figure 16). Besides combustion units, this category includes various facilities, needed during the production, handling, transportation, storage and processing of raw materials, fuels and ashes. On average, the fixed costs of biomass applications for heat generation tend to be higher than the fixed costs for heating with fossil fuels [7, 64, 135, 153]. This is due to the:

- Biomass properties – biomass has lower energy density than fossil fuels. Hence, biomass has larger costs for transportation, storage, handling, etc. per energy unit, compared to fossil fuels. The issue with the larger storage space needed may become particularly important in densely populated residential areas, where little spare room is usually available and its cost (price) is high [20, 41, 168, 170].
- Economies of scale – as a result of the above point, the economically effective availability of biofuels around heating plants is typically lower than that of fossil fuels. The feasible extent of increasing the scale of heat generation from biomass is therefore lower than that from fossil fuels, <u>if</u> a respective nearby heat demand exists (see Figure 17).
- Economy of numbers – the infrastructure and supply chains for fossil fuels are already in place, established and paid back over a number of years. However, this is not the case

with biomass fuel infrastructure in many EU countries, where it should be built from scratch. Thus, the initial investments for bioheat could be substantial [174].

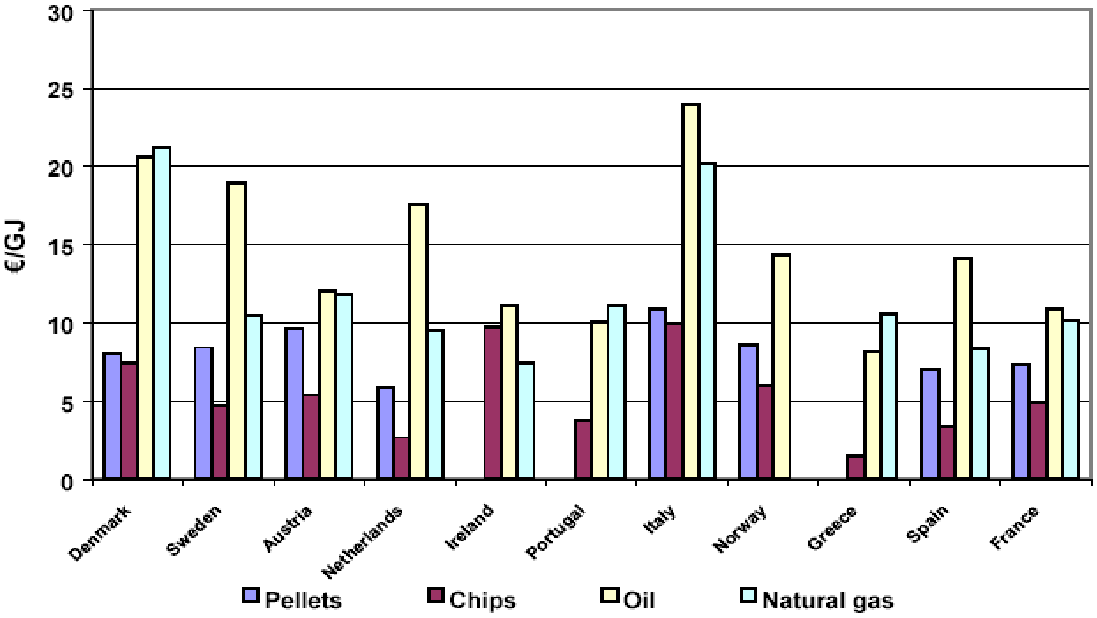
- Higher investment risk – the return on investment for biomass infrastructure and supply chains could be more risky. Most current taxation frameworks are designed with regard to the properties of fossil fuels. Thus, in order to be competitive to fossil fuels, various immature technologies like biofuels often need preferential tax treatment. However, it is not sure either whether the extent of such tax preferences will be maintained, or for how long they will last. Hence, the risk surcharge in the investment calculations for biomass supply chains is by definition larger than that for fossil fuels infrastructure [7,168].

The higher fixed costs of biomass heating plants, compared to the heating facilities on fossil fuels, have a couple of implications. First of all, the design of biomass heating systems should be as much as possible simplified, aiming at optimising the balance between capital costs and performance parameters. Hence, the application of some sophisticated and expensive plant modules, e.g. for a more complete flue gas cleaning or more efficient combustion, which are widely used for systems that use fossil fuels, may not be suitable for biomass heating systems.

In addition, in order to compensate the higher fixed costs in the total cost calculations and thus to become competitive to the fossil fuel heating systems, the heating installations for biomass need either tax preferences, or lower variable costs. From a point of view of the regulatory authorities, if the fixed cost surcharge is compensated by tax reductions, the heat consumption should be low, in order to limit the loss from uncollected taxes. Such an approach would be appropriate for regions with a short heating season, modest or variable heat requirements (e.g. the Southern part of Europe [7]) or expensive biomass production. If the fixed cost surcharge is compensated by lower running costs, as high as possible heat use should be targeted, because the reimbursement of the fixed cost surcharge will be accelerated. Opposite to the first case, this approach would be appropriate in regions with long heating season, large and stable heat requirements (e.g. the Northern part of Europe) or cheap biomass production. As the tax considerations do not meet the scope of this work, only the second option is further assessed.

Cheap production of biomass is a key factor for low variable costs of biomass heating systems, since fuel costs are the major component in the variable costs. To a certain extent, the cost of the fuel is influenced by the capital costs. For instance, wood pellets are typically more costly, thus – more expensive than wood chips (Figure 73), because they require more processing, respectively – more equipment. From the point of view of fuel costs, biomass feedstock can be provisionally spit into two major groups – cheap and expensive.

Figure 73
Fuel prices for wood pellets, wood chips, heating oil and natural gas for small-scale heating in selected European countries in 2001, (EUR/GJ)

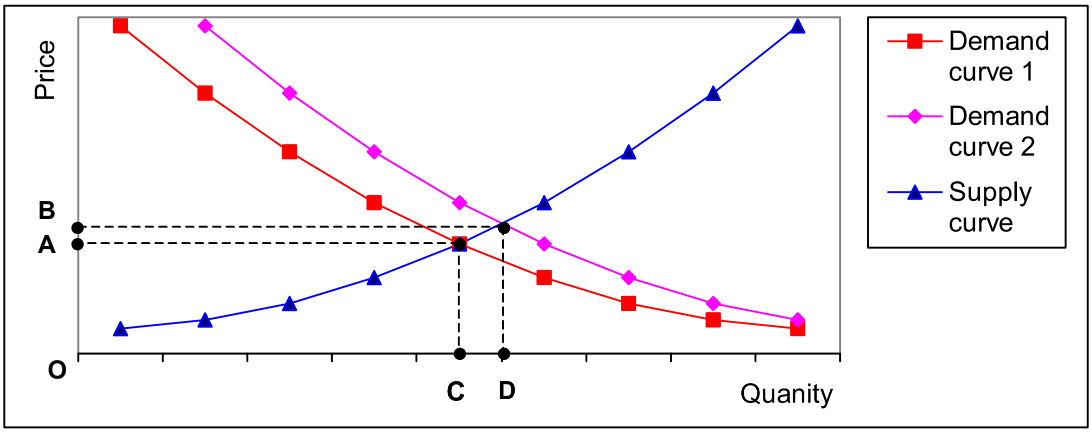


Source: [7]

The “cheap” group comprises various types of biomass residues (shavings, sawdust, thinning and logging material, demolition wood and sometimes – straw) and their derivates (e.g. chips, powder, in some cases – pellets). The “expensive” group includes dedicated agricultural and herbaceous crops, short-rotation forestry and round wood, their derivates (chips, pellets and briquettes) and sometimes firewood. Obviously, all bioenergy users aim first to get as much as possible cheap feedstock, rather than expensive. So, strong competition is observed amongst different players in the bioenergy field for the access to the cheap biofuels. This competition sometimes does not favour either the optimum utilisation of the cheap biomass resource, or the development of the bioenergy industry as a whole. In this context, the recent large growth in the bioenergy application in the EU in fact came mainly from the more complete utilisation of the available “cheap” bio-resource. On the other hand, the efforts for improving production technologies for the “expensive” biomaterial and thus – reducing its costs, were lagging noticeably behind the growth in the “cheap” feedstock application. As a result, increasing and even maintaining the recent expansion trends in biomass application in the EU might become more challenging, due to a gradual depletion of the “cheap” bio-resource and the ensuing need for switching to “expensive” biofuels [1, 8, 51, 126, 133, 135, 146].

In contrast to the above, it is often stated that the availability of “cheap” biomass at almost no cost will even increase, since the rate of residual biomass generation will increase with the growth of forest, agricultural and other related industries. This statement however disregards the economic fundaments of the price formulation, resulting from the interaction between demand and supply – Figure 74.

Figure 74
General economics correlation between supply, demand and price



From an economic point of view, waste or residue is a product that is of no utility only within a specific context. This means that for such products there is no demand, so the respective price on the market is zero (position O in Figure 74). However, if such a demand appears (OC in Figure 74), residues become tradable goods and they get a price on the market (OA in Figure 74), which reflects the equilibrium between demand and supply. If the demand for such goods increases fast (from OC to OD in Figure 74), so that the supply is not able to respond, the price is simply moving up (from OA to OB in Figure 74). Therefore, it is not correct to assume that waste and residues are cheap by definition. Their price depends on the applications they may find, including for non-energy purposes. If other customers appear, the price may increase in addition, since the demand curve from Figure 74 will move further to the right. Last, there are always some costs, associated with waste and residues processing – for collection, transportation, screening, shredding, milling, etc [6, 168].

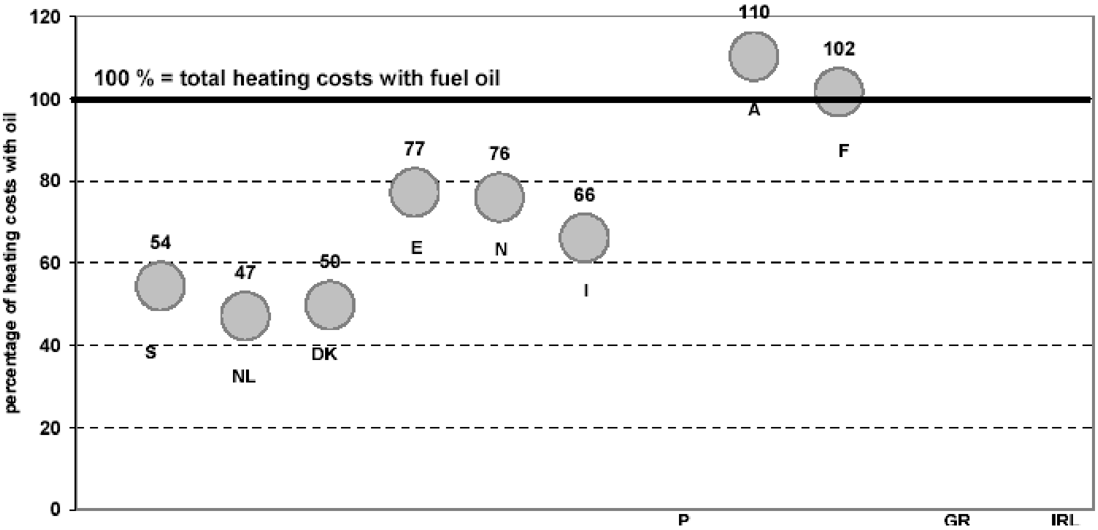
Assessing and predicting biofuel costs with a satisfactory extent of accuracy can be further constrained by various regional or external factors. Three examples are listed below:

- At present straw is used as biofuel in few EU countries (mainly Denmark and Germany). Any direct extrapolations from the Danish and the German cost values to other EU countries would not be appropriate, since the agricultural, climate, etc. conditions in Denmark and Germany are quite different from those e.g. in the Southern part of Europe [20, 97, 174].
- The prices of some biomass fuels, e.g. straw, herbaceous energy crops, etc. do not have an autonomous behaviour, as they depend on other factors – agricultural policy, weather conditions, yields, other prime non-energy land and biomass applications, etc.
- It is nearly impossible to draw any, even rough estimates about costs and prices of firewood that is widely used in households. A large part of this fuel wood never reaches the market, because it is simply collected or self-produced by households [128].

As a proof of the above examples, the wide cost and price differences amongst different EU countries are illustrated by Figure 73. Figure 73 indicates not only large absolute differences between maximum and minimum fuel prices (e.g. approximately 5 times for wood chips), but also relative – in price proportions between different fuels (e.g. pellets are not necessarily a lot cheaper than their fossil fuel alternatives).

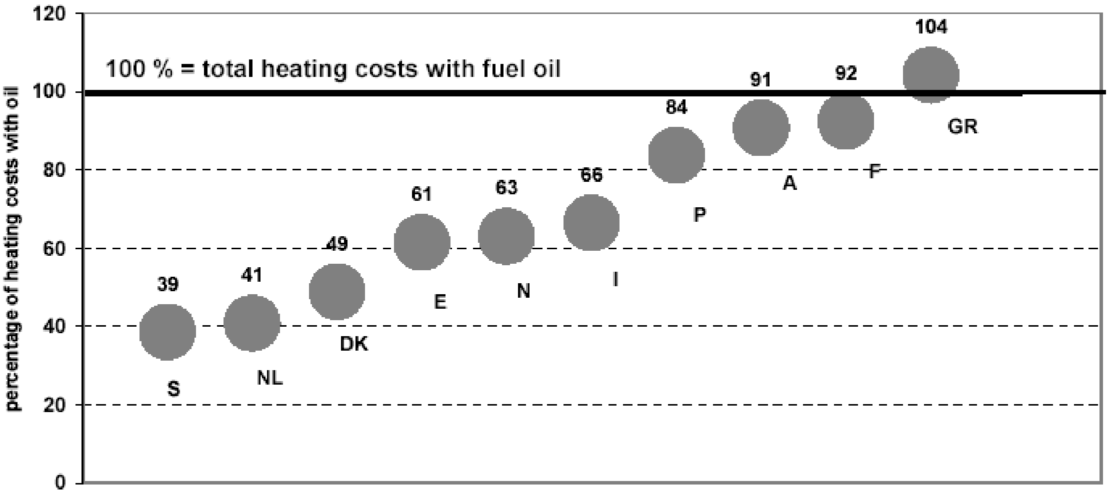
The combination between wide differences in bioheat investment and fuel costs results in a quite dispersed picture of total costs for heat generation from biomass in Europe. For example, the difference in total heating costs with wood pellets amounts to a factor of 2 – Figure 75, while for wood chips it reaches 2.5 – Figure 76.

Figure 75
Comparison of the relative heating cost with wood pellets, compared to heating with fuel oil as a baseline in selected EU countries in 2001, (%, heating oil = 100%)



Source: [7]

Figure 76
Comparison of the relative heating cost with wood chips, compared to heating with fuel oil as a baseline in selected EU countries in 2001, (%, heating oil = 100%)



Source: [7]

With the gradual development of the EU bioheat market, these large differences in total costs are supposed to get narrower. Nevertheless, Figure 77 is trying the present a concise picture of the prevailing costs of the typical biofuels for heat generation, compared to their fossil fuel analogues.

Figure 77
Relative comparison of the prevailing fixed, variable and total costs of the typical biomass technologies and fuels vice-versa their fossil fuel analogues

Fuels / Costs	Fixed Costs	Variable Costs		Total Costs	
		Residual feedstock	Dedicated feedstock	Residual feedstock	Dedicated feedstock
Firewood	–	+ +	– –	+	– – / –
Wood chips	–	+ +	0 / –	+	+ / 0
Pellets and briquettes	–	+	–	+ / 0	–
Herbaceous biomass	–	+	–	+ / 0	–

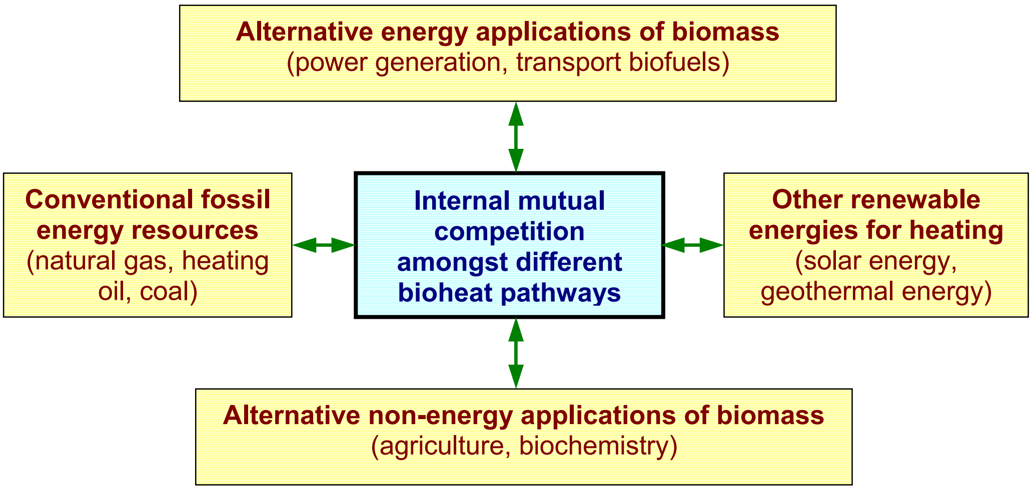
Legend: (– –) Much higher cost; (–) Higher cost; (0) Similar cost; (+) Lower cost; (++) Much lower cost;

Despite biomass heating being well-known for centuries, it is still a relatively immature technology in terms of large-scale market commercialisation. As a result, wide cost and price differences are observed amongst the EU countries. In general, the equipment costs of biomass heating are higher, while the fuel costs are lower, compared to the fossil fuel heating. Hence, the competitiveness of bioheating vice-versa fossil fuel heating depends on the extent the lower fuel costs can compensate the higher equipment costs. This extent is a function of a number of factors – severity of climate, tax incentives to promote bioheating, etc. In addition, this also means that the design of bioheating systems should be simplified, compared to the design of heating facilities that run on fossil fuels. All in all, bioheating appears to be a cheaper long-term, but not short-term, alternative of heating with fossil fuels – Figure 77.

12. MARKET ASPECTS

Various applications of biomass for heat generation (Figure 16) compete simultaneously with other fuel options for heat generation and with other applications of biomass – Figure 78.

Figure 78
Energy alternatives and alternative applications of bioenergy, competing bioheat



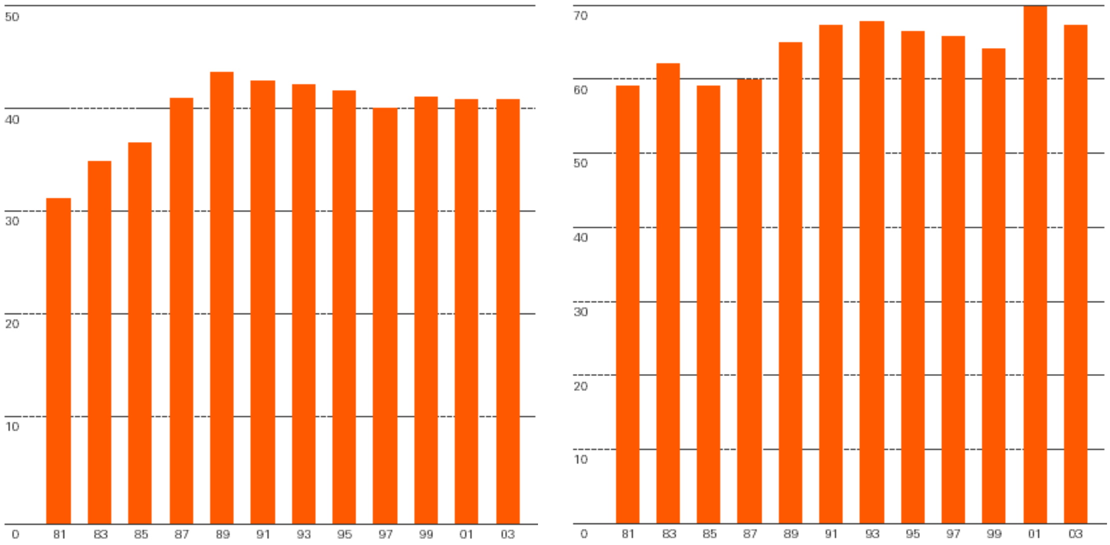
As already thoroughly discussed in chapter 9, heat generation from biomass faces strong competition from heat generation from fossil fuels, especially in periods of low fossil fuel prices [1, 6, 8, 93, 157]. The modern and efficient biomass heating is a relatively new technology, where large room for further improvements is still left in all aspects: fuel production and fuel properties, pre-treatment, logistics (storage, handling, transportation, etc.), combustion and in particular – reliability. Like all new technologies, it faces the typical "chicken-and-egg" problem – a reliable supply cannot be established without an existing demand and the demand cannot be created without an existing reliable supply. On top of that, if the bioheat trial has not been successful, any further market implementation of bioheating most probably will face even bigger resistance and obstacles [7, 11, 13, 14, 15, 165, 168]. Unlike bioheating, using fossil fuels for generation of heat is a mature, well-proven and continuously improved technology, which earns significant economies of scale. For this reason, most current taxation and price-regulatory frameworks are designed with regard to fossil fuels. As a consequence, the relative advantages of biomass as an energy source, e.g. contribution to security of energy supply and to GHG abatement, etc. are not yet (fully) implemented in the taxation regimes. The external costs of fossil fuels (e.g. increasing GHG emissions and energy import dependence) are not fully reflected in the regulatory acts of a number of EU member states either [7, 57, 93]. Strong political and financial incentives, supporting (directly or indirectly) bioenergy utilisation [75, 76, 77, 79, 83], have been introduced only recently [7, 41, 52, 156].

Biomass faces extremely tough competition in particular from natural gas (Figure 68). Compared to biomass, natural gas benefits from the typically much larger-scale of production and distribution, which earns significant economies of scale. It has also easier handling (e.g. no need of storage space) and application mode [6, 9]. Finally, natural gas is also perceived as a clean fuel, because of the negligible local-polluting emissions, compared to biomass, and of the low CO_2 emissions, because of its low carbon-to-hydrogen ratio (1:4). The ongoing opening of the natural gas markets in the EU [81] is expected to give further strength to natural gas on the EU energy market by lowering its prices. Hence, biomass appears not to be competitive in heat markets, where well-developed natural gas distribution networks are available.

Similar predictions can be made also for electricity. Like for natural gas, the ongoing process of opening the electricity markets in the EU [80] most probably will reduce electricity prices. In such a way, the electricity markets opening may further constrain the penetration of biomass in the EU heat market, since people will get more incentives for switching to heating with electricity.

The same is also more or less valid for the competitiveness of biomass versus heating oil. This situation is not likely to change substantially, since world reserves of oil (but also of gas) are still abundant, at least in the near to medium future, and new discoveries are continuously being made, hence world security of oil and gas supply is extended – Figure 79.

Figure 79
Development of the "reserves to production" (R/P) ratio[46] for oil and natural gas in the world within 1981-2003, (years)



Oil

Natural gas

Source: Adapted from [17]

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[46] The R/P ratio represents the length of time (in years), obtained when the reserves at the end of the year are divided by the production in that year. The quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions, are taken as reserves in the R/P ratio calculation [17].

On the other hand, such an availability of conventional energy sources gives a certain time credit to the bioenergy technologies for further improvement. Progress in CO_2 capture and sequestration technologies may have also a strong negative impact on the development of renewable energies and in particular – on bioenergy in the short- to medium-term.

As a result, the only fossil fuel, against which biomass seems to be currently competitive, is coal, due to the generally poor environmental performance of coal firing technologies. Precisely because of this reason, the coal share in the EU energy mix tends to decline, at the expense of cleaner fuels, mainly natural gas (Figure 67 and Figure 59, together with the following explanatory paragraph). Thus, it turns out that with current regulatory frameworks the prospects for further large penetration of biomass on the heat market are not very promising, at least in the near term, since the penetration would be constrained by the poorer biomass competitiveness versus natural gas. An additional, but very important limitation for a larger bioheat market penetration is the already mentioned lack of any specific measures at EU level that promote bioheating. As a result, such measures are generally lacking at a country level as well.

The lack of regulatory mechanisms, promoting bioheat application, has also a negative impact on bioheat competitiveness on the gross renewable energies market and on its bioenergy segment in particular. Apart from heat generation, the limited bioenergy resource can be alternatively employed for electricity generation and/or production of transport fuels – Figure 8. Both these alternative applications of bioenergy enjoy a well-defined institutional support at EU and national level [76, 79]. As a result, the progress in bioheating is lagging far behind the progress in bioelectricity and to a lesser extent – in transport biofuels [50].

The alternative bioenergy applications are not the only bio-based factor that can hinder bioheat growth. Bioenergy and biomass should always be considered within a broader framework of policy objectives and priorities. It is widely agreed upon that the land availability is the core factor that defines the amount of the feasible biomass potential. The available land can be however used for a number of purposes. The Common Agriculture Policy (CAP) secures the food supply of the EU – a core element in the EU strategy for sustainable development. Thus, a substantial part of the available land is, by definition, reserved for this purpose. In this context, the CAP regulations ensure also a reasonable profit for farmers. The non-food and non-energy land production (flowers, pharmaceutical plants, wood for construction, etc.) normally has higher value than bioenergy production, thus – it is more competitive on the land market. The bio-refinery concept – production of various bio-products (biochemistry), receives growing attention and importance worldwide. In brief, the allocation of biomass resources for heat generation competes on the overall biomass and land market with a number of alternative applications. The bioenergy sector also affects different socio-economic factors, e.g. land use, visual changes of landscape, impacts on biodiversity, etc. Hence, bioenergy appears to be a complex and difficult to manage system, which involves a number of variable parameters [5, 6, 87, 89, 93, 107, 119, 124, 131, 165, 174, 197].

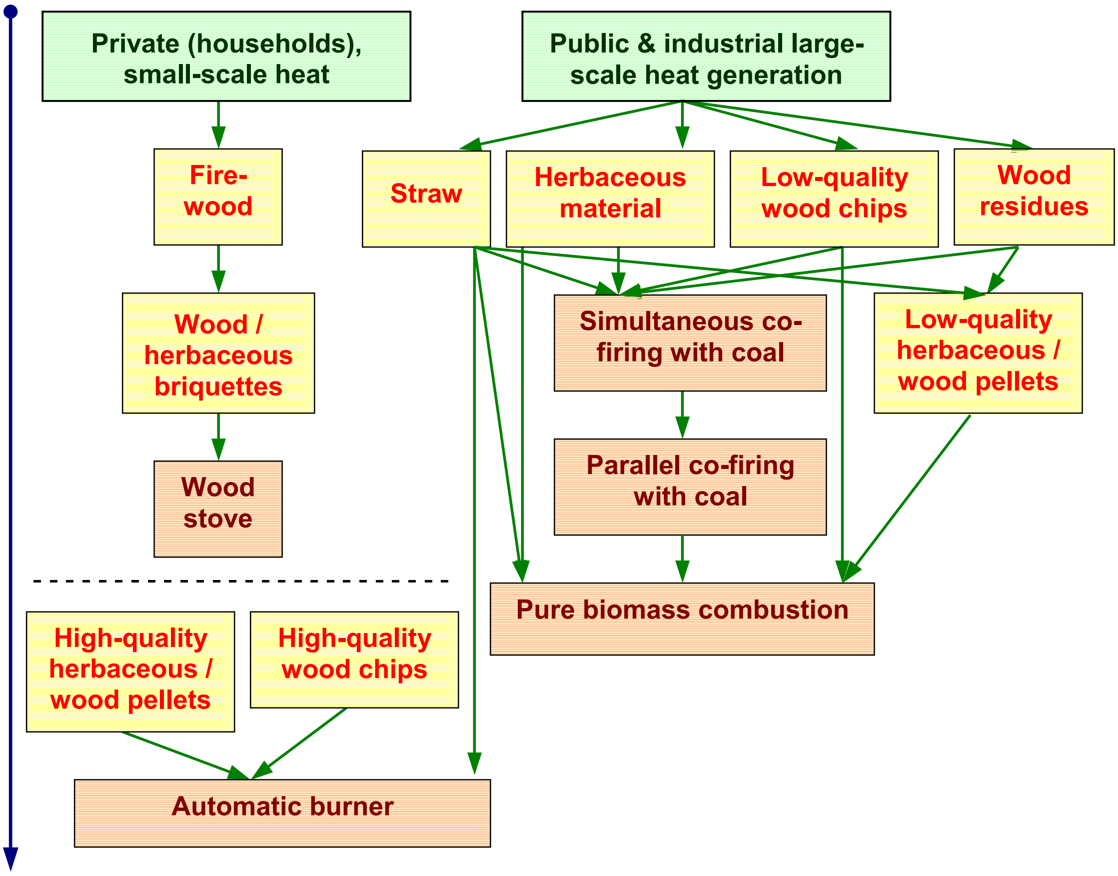
Despite the fact that bioenergy is considered to be the renewable energy source with the largest growth potential up to 2010 and even – beyond 2010, other renewable energies seem to be quite convenient for heat generation on selected markets. For instance, thanks to the large number of sunny days per year, solar energy appears particularly well-suited for heat purposes in the Southern parts of Europe. Conversely, large-scale biomass heating in such countries does not seem very appropriate. The low annual load (heating hours per year) results in very long reimbursement period for the large capital costs, inherent to biomass heat generation. The penetration of biomass in the heat market can be also strongly constrained in regions, where natural geothermal heat at almost no costs is available.

As Figure 16 already indicated, there are multiple options in which the available land and biomass resource for heat generation can be explored. Based on the analysis, performed in the previous chapters, it becomes obvious that each bioheat pathway has its strong and weak points in specific contexts. It is therefore not possible to identify an ultimate bioheat pathway, at least with current technologies. The comparative competitiveness of different bioheat pathways and the selection of the optimum ones should be performed on a case-by-case basis, taking into account the criteria from Figure 7.

Based on the analysis from the previous chapters, several evolutionary pathways for the penetration and the promotion of biomass on the heat market of the EU can be suggested – Figure 80.

On a small-scale, firewood is already widely used for heat generation, especially in rural areas. The driving forces for using firewood are its low, almost zero cost (in rural regions) and its contribution to creating a nice and cosy atmosphere (in urban areas) by the visibility of the flame in the open fireplaces. Nevertheless, burning firewood still remains generally inefficient, despite recent improvements in fuel wood combustion technology. This is due mainly to the varying properties of wood logs both before and during combustion. On top of that, in many occasions the woody material, transformed into firewood, can find other, more appropriate or higher value applications, e.g. in the furniture industry. Hence, using fuel wood for heat generation should be generally considered as a fading option from energy, environmental and cost point of view. In the manually-filled stoves and in the open fireplaces wood logs can be successfully replaced by biomass briquettes. Briquettes, made out of residual woody and/or herbaceous feedstock, have much better and stable fuel properties than fuel wood and thus ensure more efficient combustion at lower emissions. In addition, the psychological sense of pleasure is not lost, since the flame is still seen. If the visibility of the flame is not an important issue, it appears more appropriate to substitute manually-filled stoves and especially the very

Figure 80
Suggested evolutionary bioheat pathways



low-efficient open fireplaces by automatic burning systems. Thanks to the dedicated equipment, that controls fuel in-feed, combustion process, emissions, etc., automatic combustion systems are able to provide high energy-conversion efficiencies at very low emissions. In addition, the automation offers the customers the advantage of easier handling and much higher flexibility in heat outputs, compared to the manually-filled stoves. Conversely, the automatic burning systems require another class of fuels. Typically they operate on pellets, produced from dedicated (not residual) woody and/or herbaceous feedstock. The application of high-quality wood chips, obtained from woody material, is also possible, but less popular, at least at present.

On a large-scale, there are more options for burning biomass for heat generation, compared to the small-scale. Because of the economy of scale, industrial combustion systems can afford the implementation of more sophisticated controlling equipment, compared to the small-scale facilities. As a result, industrial systems can run on a wider range of fuels, which have lower quality characteristics and hence – are cheaper. These fuels include woody or herbaceous residues and/or waste (wood shavings, sawdust, demolition wood, wood powder, straw, etc.), wood chips or wood/herbaceous pellets of lower quality, made from residues and/or waste, various other biomass material (e.g. herbaceous energy crops, short rotation forestry, etc.). If biomass enters an already established heat market, its penetration could be facilitated by initial simultaneous co-firing with coal, rather than going straight for a pure biomass burning. Co-firing a small amount of biomass with coal is associated with low commercial risk, since it does not involve immediate investments. Later on, if the biomass trial is successful, the biomass share can be continuously increased, which consecutively will support the gradual establishment and development of a dedicated biomass fuel supply and handling infrastructure. Along with the increase of biomass share, simultaneous co-firing can be transformed into a parallel combustion of biomass and coal. At the end, if the biomass expansion is successful and welcomed by the local population and authorities, coal can be phased out and the whole heat generation may switch to biomass only. In such a case, further improvements in the performance of biomass heat generation are feasible, since the combustion process can be fully optimised towards the properties of biomass, rather than being just balanced between the fuel characteristics of coal and biomass. Thanks to this optimisation, the range of the appropriate biomass fuels can be expanded further, including e.g. lower quality pellets, made from woody and/or herbaceous waste and residues. Such kind of pellets would improve further the energy and emission performance, due to the better fuel properties, compared to e.g. wood chips, straw, residues, etc. On the other hand, the full and complete realisation of these advantages of pellets is generally not possible in the co-firing concept, because the combustion system cannot be exactly tuned according to their fuel characteristics.

Summarising the above thoughts, as well as the market aspects, discussed in the previous chapters, Figure 81 presents briefly the key strengths, weaknesses, opportunities and threats (SWOT) of biomass application for heat generation in the European context.

Figure 81
SWOT analysis of bioheating

Strengths	**Weaknesses**
Environmentally-friendly Security and diversity of energy supply Reduction of the energy import dependence Possible storage	More expensive technology Immature, not well-refined technology
Opportunities	**Threats**
Public support Job creation Implementation of stricter environmental regulations and standards	Public support Lower prices of conventional fossil energy sources Keeping the fossil-based taxation approach

The utilisation of biomass for heat generation faces a strong competition from fossil fuels, other renewable energy sources and alternative, energy and non-energy applications of biomass. In addition, various bioheat options compete with each other, since all they tend to show some advantages and disadvantages in specific contexts. Hence, a number of trade-offs between various criteria for assessment – energy efficiency, environmental performance, costs, etc. – are necessary. As a result, with the current state of technologies, it is not possible to identify an ultimate bioheat alternative and the selection of the optimum bioheat option is always performed on a case-by-case basis – Figure 80.

13. CONCLUSIONS

Based on the analysis, performed in the previous chapters, the following conclusions can be drawn about the application of biomass for heat generation in the EU by 2010:

- ✓ Amongst different renewable energy sources, bioenergy has the largest potential for contribution to the security and diversity of energy supply of the EU. A major share of this potential should come from the use of biomass for heat generation. Unfortunately, the biomass utilisation for heat generation is still lagging behind other energy applications of biomass, which slows down the Community's progress towards achieving the target for 12% renewable energy sources in gross inland energy consumption by 2010.
- ✓ Bioheating faces strong competition from natural gas and heating oil, but it is competitive with coal. The utilisation of biomass for heat generation also competes with other, energy and non-energy applications of biomass, and with other renewable energies.
- ✓ Within EU-25, bioheating has currently a larger penetration in EU-15, compared to NMS-10. Conversely, the additional penetration potential of biomass for heat generation seems to be larger in NMS-10 than in EU-15, especially in the residential (district heating) sector. The reserves for additional expansion of bioheating in EU-15 appear to be located mainly in the industrial sectors (including co-generation of electricity and steam), which generate biomass fuels as by-products or residues.
- ✓ The economically efficient heat generation from biomass is a complex energy system, where both the availability of sufficient heat demand and biomass resource should be located nearby the heat generating facility.
- ✓ There are two main types of biomass feedstock, which can be employed for heat generation – woody and herbaceous material. The utilisation of herbaceous feedstock is generally associated with more technological constraints than the utilisation of woody feedstock. In this context, the proper performance of small-scale heat generation facilities normally requires higher quality biofuels, while the large-scale heat generation systems can operate on lower quality biofuels.
- ✓ Biomass fuels earn significant reduction of GHG emissions and soil protection benefits.
- ✓ When employed in modern and well-tuned combustion facilities for heat generation, various biomass fuels can earn significant reductions in the emissions of local pollutants. Conversely, when employed in poor systems, biofuels may lead to emission penalties. Thus, bioenergy should not be perceived as environmentally-friendly strictly by definition.
- ✓ High quality wood and/or herbaceous pellets, followed by high-quality wood chips and straw, all of them employed in automatically-filled burning systems, seem to be the optimum fuel & combustion system for small-scale heat generation. Another efficient option is burning wood and/or herbaceous briquettes in manually-filled stoves. The application of firewood in manually-filled stoves and in particular – in open fireplaces, appears to be the least efficient option.

- ✓ Burning low-quality wood chips, followed by low-quality wood and/or herbaceous pellets in travelling grate combustion systems appear to be the most appropriate option for large-scale heat generation. Firing whole straw bales in dedicated “cigar” burners seems also a viable alternative. Another, but less attractive option, is the direct combustion of various wood and herbaceous residues. The batch combustion of firewood, as well as the gasification combustion concept, appear to be the least convenient alternatives.
- ✓ The simultaneous combined combustion of biomass and coal, with gradual increase of the biomass fraction and then – transformation to parallel co-firing and pure biomass combustion, seems to be an appropriate penetration and growth strategy for biomass on the heat market.
- ✓ The fixed costs of bioheating are typically higher than the fixed costs of heat generation from fossil fuels. On the contrary, the variable costs of bioheating tend to be lower than those of heating with fossil fuels. Altogether, the total bioheating costs appear to be lower in the long run, compared to the total cost for heating with fossil fuels, provided there is sufficient heat demand. Large cost and price differences are however observed amongst different EU countries.
- ✓ With current technologies, it is not possible to identify an ultimate heat generation fuel & combustion system, because a number of trade-offs have to be made between energy efficiency, environmental performance and costs. The selection of the optimum bioheat fuel & combustion systems should be therefore performed on a case-by-case basis.

Summarising the above conclusions, Figure 82 presents the relative ranking of biomass applications for heat generation versus the alternative utilisation of fossil fuels.

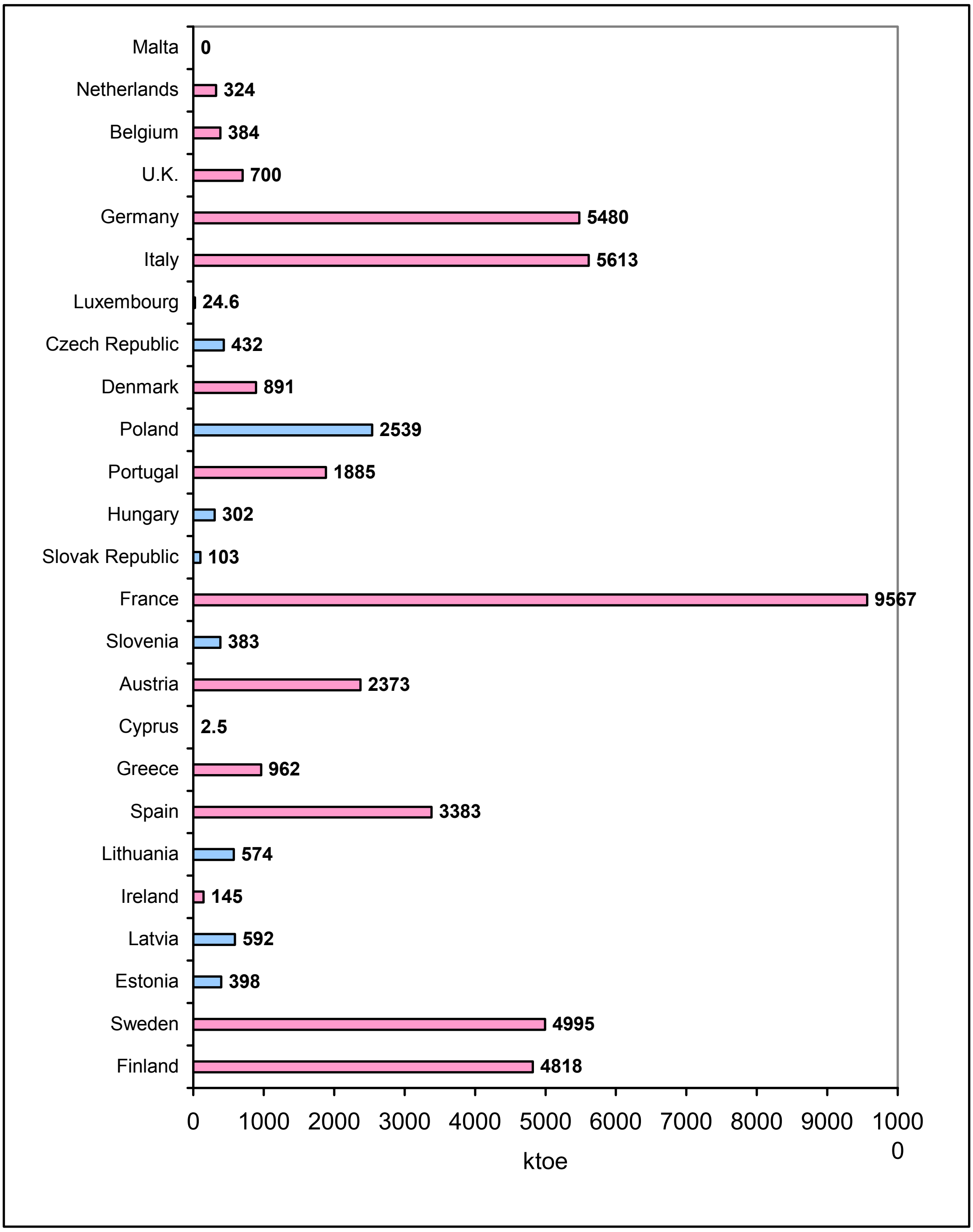
Figure 82
Relative ranking of biomass applications for heat generation versus the alternative utilisation of fossil fuels in the short term (up to 2010) and long term (beyond 2010) /Note: No significant penalties!/

Criteria	Short-term prospective	Long-term prospective
Security of energy supply	+	+ +
Diversity of energy supply	+	+ +
Import dependence by energy sources	+	+ +
Energy efficiency	–	0
GHG emissions, global warming and climate changes	+	+ +
Local-polluting emissions	+	+ +
Costs	0	+
Market penetration	+	+ +
Sustainability, ecology, biodiversity	+	?
Interactions with other policy objectives (e.g. rural development, employment, sustainable agriculture)	+	+ +

Legend: (+ +) Significant advantages; (+) Moderate advantages; (0) Similar performance; (–) Moderate penalties; (– –) Significant penalties; (?) Not clear yet;

14. ANNEXES

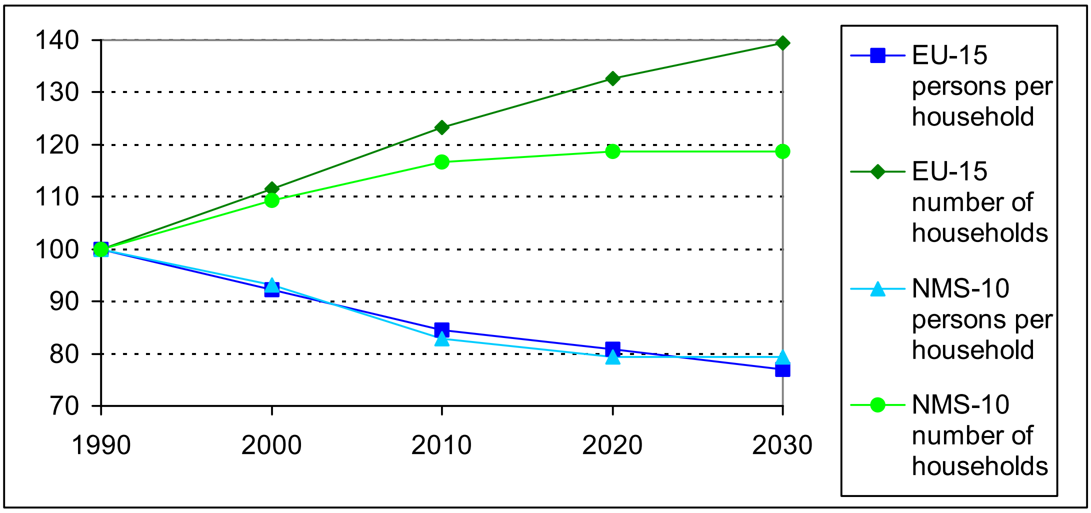
Annex 1
Biomass for heat application in the countries of EU-25 in 2001, (ktoe)



Remark: The countries are listed according to their population density (see Annex 3)
Source: Adapted from [51]

Annex 2

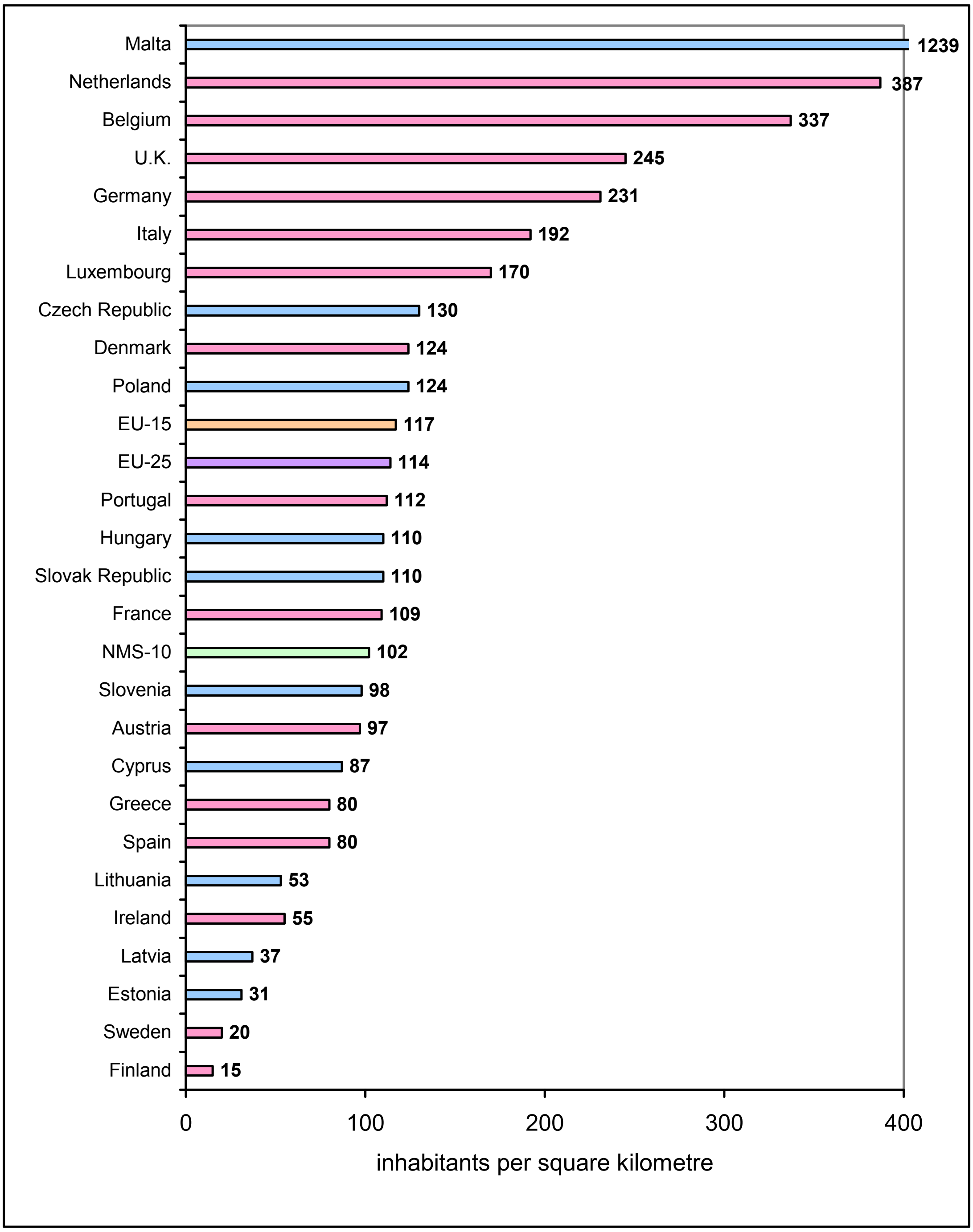
Index of the retrospective and prospective number of persons per household and of the number of dwellings in EU-15 and NMS-10 within 1990-2030, (Index points, year 1990 = 100)



Source: Adapted from [53, 59]

Annex 3

Population densities in EU-25 by countries in 2001, (persons per square kilometre)



Source: Adapted from [54, 59]

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EUR 21401 EN – BIOHEAT APPLICATIONS IN THE EUROPEAN UNION: AN ANALYSIS AND PERSPECTIVE FOR 2010

B. KAVALOV and S. D. PETEVES

Luxembourg: Office for official Publications of the European Communities

2004 – 122 pp. – 21 x 29.7 cm

Scientific and Technical Research series

P2004/221

ISBN 92-894-8730-5

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ISBN 92-894-8730-5
9 789289 487306