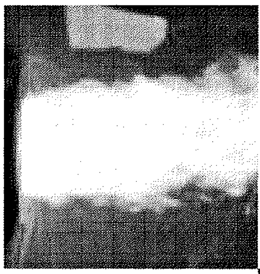

Evaluation of Biomass Combustion based Energy Systems by Cumulative Energy Demand and Energy Yield Coefficient

Thomas Nussbaumer
Michael Oser

Verenum
CH – 8006 Zurich
Switzerland

Final report prepared for

International Energy Agency (IEA)
BioenergyTask 32: Biomass Combustion and Co-firing

and

Swiss Federal Office of Energy (SFOE)

ISBN 3-908705-07-X

Thomas Nussbaumer, Michael Oser: Evaluation of Biomass Combustion based Energy Systems by Cumulative Energy Demand and Energy Yield Coefficient, International Energy Agency IEA Bioenergy Task 32 and Swiss Federal Office of Energy, Verenum press, Version 1.0, Zurich, January 2004

ISBN 3-908705-07-X

Content

1 Abstract

The study presents a method for a comparison of different energy systems with respect to the overall energy yield during the life cycle. For this purpose, the Cumulative Energy Demand (CED) based on primary energy and the Energy Yield Factor (EYC) are introduced and determined for the following scenarios: Log wood, wood chips, and wood pellets for residential heating and – except for log wood – also for district heating. As an alternative to heat production, power production via combustion and utilisation of the electricity for decentralised heat pumps is also regarded. The scenario for power production is valid for both, dedicated power production with biomass or co-firing of biomass. The main difference between these two applications is respected with a variation of the net electrical efficiency.

To enable a reasonable interpretation of the results, the energy demand related to the fuel consumption during plant operation is considered, which is often not the case for figures presented on non-renewable fuels in literature. The calculations are performed once with respect to all fuels used during operation (denoted as CED and EYC), and once with respect to non-renewable fuels only, hence without counting the energy content of the biomass (denoted as CED_{NR} and EYC_{NR}). The evaluation and comparison of both, EYC and EYC_{NR}, enables a ranking of energy systems without a subjective weighing of non-renewable and renewable fuels. For a sustainable energy supply, it is proposed to implement renewable energy systems in the future which achieve an energy yield described as EYC_{NR} of at safely greater than 2 but favourably greater than 5.

A parameter variation is performed for the plant efficiency, the transport distance, the fuel type for drying used for pellet production, and the heat distribution in case of district heat. A visualisation of the sensitivity of these parameters reveals a relevant influence on the ranking of the different scenarios and hence confirms the importance of these characteristics which are identified as key parameters.

For the reference scenarios and for an identical annual plant efficiency of 80%, an energy yield for non-renewable fuels of EYC_{NR} = 13.8 is achieved for log wood, of 13.0 for wood chips, of 9.0 for wood chips with district heating, of 8.3 for eco-pellets produced from saw dust with biomass used for drying, and of approximately 3.3 for wood pellets dried with fossil fuels. If the electricity from power production from biomass is used to drive local heat pumps for heating, similar or even higher energy yields are achievable than for direct heating with wood chips. These results show, that all investigated scenarios based on biomass combustion are reasonable with respect to the overall energy yield. In comparison to heating with fossil fuels, biomass combustion enables CO_2 savings by approximately a factor of 10 for wood chips, eco-pellets and log wood, and by a factor of 4 to 5 for wood pellets, if fossil fuels are used for drying.

The presented evaluation of the different scenarios is proposed as a basis for decisions to choose the most efficient energy systems based on biomass combustion in the future. Further, there is a potential to expand the method to applications for other technologies for biomass utilisation and to other energy sources.

Keywords: Cumulative Energy Demand (CED), Energy Yield Coefficient (EYC), log wood, wood pellets, wood chips, district heat, power production, co-firing, efficiency, transport distance

2 Executive Summary

2.1 Methodology

In the present study, the Cumulative Energy Demand (CED) calculated as primary energy in [TJ_{prim}] is discussed according to three different definitions. The common definition often found in literature does not include the primary energy demand related to the fuel consumption during plant operation. Hence this definition is denoted as CED_{WOF} (for „without fuel") in the present study. However, results given as CED_{WOF} enable only a limited interpretation and are not evaluated here.

In the present investigation, CED includes the fuel consumption for all types of fuel, while for CED_{NR} only non-renewable fuels are accounted for. For a comparison of two different energy systems, it is proposed to evaluate both characteristics, **CED *and* CED_{NR}**. If an energy system is favourable due to both definitions, it can be assessed as definitively favourable, as it consumes less non-renewable fuels *and* less fuel in total. If the two definitions lead to a different ranking, a subjective weighing of non-renewable and renewable fuels is necessary, as one system is related to a lower non-renewable fuel consumption, while the other system leads to a lower consumption of fuels in total. In this case, the assessment can be used as a decision basis, e.g. for an optimisation of the plant size with respect to the transport distance of the fuel. If the optimum value is determined according to both definitions, it can be concluded, that the optimum transport distance is certainly between the lower and the higher of the two figures. This result is valid without the need of a subjective weighing. Hence the proposed method by evaluation of CED and CED_{NR} is advantageous not only in comparison to the application of the conventional definition CED_{WOF}, but also in comparison to an assessment solely based on CED_{NR}.
With division of CED and CED_{NR} by the Cumulative Energy Production (CEP) given as collectible energy in [TJ_{coll}], the dimensionless factors ced and ced_{NR} are derived. The Energy Yield Coefficients (EYC, EYC_{NR}) are then determined as reciprocal values of ced and ced_{NR} respectively. Furthermore, the Energy Payback Time (t_P, $t_{P,NR}$) can be determined. For energy systems based on non-renewable fuels, the following conditions are always valid: $ced_{NR} > 1$, $EYC_{NR} < 1$, and $t_{P,NR} = \infty$.

For renewable fuels $ced_{NR} < 1$, $EYC_{NR} > 1$, and $t_{P,NR} <$ lifetime are possible. For a sustainable energy supply in the future, only renewable energy systems should be developed and implemented, which safely fulfil these conditions, i.e., with a minimum requirement of **$EYC_{NR} > 2$** but with a target value of **$EYC_{NR} = 5$ to 10.**

In the study, the described characteristics are determined by a Life Cycle Analysis (LCA, also Life Cycle Assessment) of the energy conversion processes for different biomass based energy systems. The standard cases are heating with log wood, heating with wood chips with and without district heat, and heating with wood pellets. A parameter study by variation of the plant efficiency from 50% to 100% is performed for these cases. The visualisation of the results in graphs enables a fast comparison of different applications as illustrated for the following exemplary conclusions, which can be drawn from the results.

2.2 Results and Conclusions

The **annual plant efficiency** and the energy consumption for **fuel pre-treatment and transport** are identified as **key parameters** for the energy assessment during the whole life cycle, while the embodied energy for the plant production and disposal is only of minor importance. For district heating plants, the energy density of the heat distribution is an additional key parameter and for pellet production the fuel type used for the drying of the raw material.

The Energy Yield Coefficient for ***non-renewable*** **fuels EYC_{NR}** is only slightly influenced by the plant efficiency, except for wood pellets, if fossil fuels are used for drying.

Table 2.1 gives a summary of the most relevant results for all scenarios in comparison with selected data from literature. Table 2.1 is an extract of Table 6.3 (results from this study) and Table 6.4 (data from literature). It has to be respected, that data from different investigations cannot be compared directly in all cases, since assumptions and boundaries may vary. In the present study, the primary energy for the wood chain is defined by the heating value of the wood mass which is suited for fuel production. Thin branches, needles and leaves, which are left in the forest after harvesting, are not counted as primary energy. In some investigations (e.g. [Kessler et al. 2000], the whole tree is calculated as basis for primary energy. This basis leads to a smaller energy yield. Further, log wood results in smaller energy yield than wood chips due to greater losses of biomass left in the forests. The preferred definition depends on the specific utilisation of the results. The definition used in the present study is sensible for a combined production of log wood and wood chips which avoids additional biomass losses in the log wood chain, if small branches are utilised for wood chip production.

For an annual plant efficiency of 80%, **log wood** achieves an **EYC_{NR} of 13.8**, **wood chips** of **13.0** without district heating and of **9.0** with a properly designed district heating system. **Wood pellets** with a transport distance of 50 km achieve an **EYC_{NR} of 8.3** if the drying of wet saw dust is performed with biomass as fuel (denoted as „eco-pellets), while a value of **3.3** is achieved if the drying is performed with fossil fuels. Hence, a significant improvement of the energy yield of wood pellets is achieved, if renewable energies are used for the drying. The dry raw material is available, a slightly higher EYC_{NR} than for the eco-pellets is achieved (which is not shown in a separate scenario). The results from the present study are in good agreement with data from literature [Kasser et. al 1999, Kessler et al. 2000]. However, the values for EYC_{NR} are higher and the ranking of log wood and wood chips is inverted in comparison to [Kessler et al. 2000] due to the different definition of the primary energy content of wood as described above.

Since heating with light fuel oil or natural gas exhibits an **EYC_{NR} of 0.66 to 0.81**, it can be concluded, that well designed and operated heating plants with wood chips, eco-pellets or log wood enable a **reduction of non-renewable primary energy consumption and fossil CO_2 emissions** respectively by a **factor of 10 and higher**, if wood from a sustainable forestry is used and reasonable transport distances (i.e. 15 – 50 km) are guaranteed. Wood pellets produced with fossil fuels for drying achieve a reduction of fossil CO_2 emissions by a **factor of 4 to 5** in comparison to oil or natural gas. Hence biomass combustion exhibits a significant potential of CO_2 savings in comparison to fossil fuels and it also offers an interesting potential among the renewable fuels.

Table 2.1 Energy Yield Coefficient EYC (which respects non-renewable and renewable fuels) and Energy Yield Coefficient EYC_{NR} (which respects non-renewable fuels only) of different scenarios for heat production with wood (own calculations, above) and comparison with literature data including additional scenarios. For direct heating application, an annual plant efficiency of η_a=80% is assumed. Electricity consumption is rated with η_{ex} =2.5. The reference scenarios 4, 6, 8, 10, 11, 13, and 16 are given in bold. TD = Transport Distance, where driving distance = 2 TD, since an empty return drive is assumed. In addition TD is varied to present the distances which correspond to EYC_{NR}=1 (where 1 stands for 1.000), thus indicating the maximum allowable transport distance. The data from literature are derived from A: [Kessler et al. 2000], B: [Hartmann and Kaltschmitt 2002], C: [Sterkele 2001], D: [Studer & Wolfensberger 1991], E: [Wörgetter et al. 1999].

	No	Scenario	TD [km]	EYC $= ced^{-1}$ [–]	EYC_{NR} $= ced_{NR}^{-1}$ [–]
Heat Production	1	Pellets with district heat dh with 1.5 MWh $a^{-1}m^{-1}$	50	0.580	2.81
Heat Production	2	Pellets w/o dh	5000	0.419	0.88
Heat Production	3	Pellets w/o dh	500	0.613	2.63
Heat Production	**4**	**Pellets w/o dh**	**50**	**0.643**	**3.27**
Heat Production	5	Pellets w/o dh	15	0.645	3.34
Heat Production	**6**	**Eco-pellets w/o dh**	**50**	**0.647**	**8.30**
Heat Production	7	Wood chips, with district heat =0.6 MWh $a^{-1}m^{-1}$	15	0.583	7.89
Heat Production	**8**	**Wood chips, with district heat =1.5 MWh $a^{-1}m^{-1}$**	**15**	**0.658**	**8.96**
Heat Production	9	Wood chips, with district heat =3 MWh $a^{-1}m^{-1}$	15	0.687	9.37
Heat Production	**10**	**Wood chips w/o dh**	**15**	**0.732**	**13.0**
Heat Production	**11**	**Log wood w/o dh, heat storage**	**5**	**0.756**	**13.8**
Heat Production	12	Log wood w/o dh, w/o heat storage	5	0.757	14.0
Power	**13**	**Power plant, 25%el, hp: COP=2.5**	**50**	**0.545**	**10.1**
Power	14	Power plant, 50%el, hp: COP=2.5	50	1.076	16.0
Power	15	Power plant, 25%el, hp: COP=5	50	1.085	18.4
Power	**16**	**Power plant, 50%el, hp: COP=5**	**50**	**2.129**	**27.7**
TD for EYC_{NR}=1	4"	Pellets w/o dh	4186	0.444	1
TD for EYC_{NR}=1	10"	Wood chips w/o dh	2093	0.437	1
TD for EYC_{NR}=1	8"	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	1845	0.415	1
TD for EYC_{NR}=1	13"	Power plant, 25%el, hp: COP=2.5	1555	0.366	1
TD for EYC_{NR}=1	14"	Power plant, 50%el, hp: COP=2.5	3183	0.536	1
Literature Data	A,B,C	Light fuel oil heating (high value with flue gas condensation)			0.66 – 0.72
Literature Data	A,B,C	Natural gas heating (high value with flue gas condensation)			0.73 – 0.81
Literature Data	A	Log wood boiler (η_a=65%, *E_{prim}= tree, **E_{prim}=useful wood)		0.46*	10.1* / 12.1**
Literature Data	A	Wood chip boiler (η_a=65%, *E_{prim}= tree, **E_{prim}=useful wood)		0.51*	11.0* / 12.1**
Literature Data	C	Wood heating			7.1
Literature Data	B	Log wood boiler / Wood chip boiler			4.2 / 4.8
Literature Data	C	Solar heating			4.0
Literature Data	B,D,E	Bio Diesel (Rape Methyl Ester RME, w/o / with by-products)			1.5 / 2 – 3
Literature Data	B	Ethanol from sugar beets in Europe			2.1

With respect to the ***total* fuel** consumption denoted by **EYC** (including the renewable fuels), the ranking of the different energy systems is dominantly influenced by the plant efficiency (Table 6.1, Table 6.2). The reference scenarios for **heating applications** achieve an Energy Yield Coefficient in the range from **EYC = 0.64 – 0.76** (ced = 1.32–1.56) with an annual plant efficiency of 80%. However, a value of ced = 1.5 or EYC = 0.67 is regarded as reasonable with nowadays technology under optimum conditions. The following applications correspond to an identical total energy efficiency with **ced = 1.5 or EYC = 0.67**:

a) **Log wood** boiler with an annual plant efficiency of **70%**
b) **Wood chip** boiler without district heating with an annual plant efficiency of **72.5%**
c) Wood chip boiler with typical **district heating** with an annual plant efficiency of **81%**
d) **Pellet boiler** with pellets from wet saw dust with an annual plant efficiency of **82.5%**.

This comparison shows, that automatic plants can be favourable thanks to higher efficiency. However, the differences between manual and automatic boilers may not justify the implementation of automatic plants in any case. On the other hand, advantages thanks to reduced emissions are not validated in this assessment. Furthermore, the assessment does not consider the fact that wood pellets are often produced as an alternative to saw dust incineration or disposal. For such applications, wood pellets are regarded as a reasonable option, which is not fully accounted for in this comparison. However, the assessment also shows, that wood pellets are not favourable with respect to EYC, if the pellets are produced from native wood with high water content instead of log wood or wood chips, except if waste heat is used for drying. Hence log wood, wood chips with district heating, and wood pellets for decentralised heat production are regarded as useful complementary technologies.

The **transport distance** does not have a major influence, if the fuel distribution is organised with transport distances up to 50 km thus corresponding to 100 km driving distance with empty return drive. However, if long distance transport of the fuel is regarded as an option, e.g. for wood pellets or wood chips, and if the fuel distribution is performed by road transport, the distance and the energy density of the fuel influence the overall assessment significantly. For an annual plant efficiency of 80%, a transport distance of approximately 4200 km for wood pellets and of 1850 km for wood chips with district heating correspond to $EYC_{NR} = 1$, thus indicating the theoretically allowable distribution radius with a positive contribution to the energy balance. Hence longer transport distances are related to a higher primary energy consumption for embodied energy and transportation fuel than finally delivered as collectible heat to the consumer. For a transport distance greater than 607 km, the production and transport of wood pellets becomes favourable in comparison to wood chip production and transport. However, if road transport with distances below 50 km to 100 km are aimed at, the production of wood pellets instead of wood chips is not favourable with respect to energy savings, except if higher plant efficiencies are ascertained.

In addition to the standard cases for heat production in combustion plants, a scenario of **electricity production** is investigated for a net electric efficiency of 25% and 50%. The calculations are valid for biomass based power stations and for co-firing, since the embodied energy is of secondary importance and the higher efficiency of large co-firing plants is be respected in the assumption of the efficiency. To enable a comparison with heating appliances, the utilisation of decentralised heat pumps with an annual Coefficient Of Performance (COP) of 2.5 and 5 is assumed. This leads to four cases with two medium cases with similar results. For the low values of efficiency and COP, an EYC_{NR} of 0.545 results, which is lower than for well operated direct heating applications. Hence power plants according to this scenario are not favourable. However, an EYC_{NR} of 1.08 results for the medium cases and of 2.13 for the best case. EYC_{NR} greater than 2 is thermodynamically possible but not achievable with nowadays technology, while an **EYC_{NR} of 1** is estimated as a realistic value with state-of-the art technology. This corresponds to a **50% higher energetic yield** than typical heating applications and also to the theoretical limit for heating applications without flue gas condensation. Hence the scenario of power production is regarded as an interesting option for future energy systems, as the energy yield can significantly exceed the theoretical limit of direct heating applications. However, it must be respected, that the electric efficiency of nowadays power plants based on steam cycles increases significantly with the plant size, thus leading to longer fuel transport distances. For such applications, the presented method by application of EYC and EYC_{NR} enables an optimisation of the transport distance and plant size. Furthermore, the presented method can be applied for a comparison of different technologies for biomass conversion such as combustion, gasification, and pyrolysis, and it can also be adopted for a comparison of energy systems based on different primary energy sources.

3 Introduction

Biomass combustion is widely applied for heat and power production in a large variety of different technologies. In the long term, supply chains that ensure a high energetic yield will be most promising with respect to economy and ecology.

Nowadays, the efficiency of different conversion technologies are often evaluated and compared. However, a conversion technology such as a log wood boiler, a wood chip boiler or a pellet boiler describes only a single conversion step in an energy chain, which consists of several consecutive process steps. For the efficiency of the whole chain, the embodied energy of the pre and post combustion processes has to be considered which corresponds to harvesting, fuel pre-treatment, plant erection, and disposal of plant and residues. The embodied energy can vary significantly for different fuel types and distribution systems. Hence an assessment method is of interest which enables a comparison e.g. of log wood for residential heating with wood pellets for residential heating and with wood chips for district heating. A comparison of the boiler efficiency only is not sufficient, since there can be a target conflict with respect to the total energy consumption. As example, higher efficiency of a pellet boiler in comparison to a log wood boiler is related to increased embodied energy for pellet production, while higher efficiency of a district heating plant is related to additional embodied energy for the heat distribution system. Hence an objective comparison of log wood boilers, pellet boilers, and district heating plants based on wood chips demands for a Life Cycle Assessment (LCA) for the evaluation of the total primary energy consumption of each energy chain denoted as Cumulative Energy Demand (CED) in [TJ_{prim}]. The Cumulative Energy Demand is often related to the Cumulative Energy Production (CEP, described as secondary energy or collectible energy) thus resulting in a specific value in [TJ_{prim}/TJ_{sec}] or [TJ_{prim}/TJ_{coll}]. This specific value is denoted as ced in the present study.

Results of the specific Cumulative Energy Demand from different scenarios of domestic heating appliances are illustrated in Figure 3.1, which are derived from a recent LCA study of renewable energy systems [Hartmann and Kaltschmitt 2002]. In the study of Hartmann and Kaltschmitt, the energy content of the renewable fuels is not counted for, while non-renewable fuels during plant operation are considered in the calculation. As described in the theory, the factor derived with these assumptions is denoted as ced_{NR} in the present investigation.

The LCA in Figure 3.1 shows a strong correlation between ced_{NR} and the greenhouse gas emissions given in [t CO_2 equivalent/ TJ_{coll}]. This is valid for the investigated scenarios based on heating with oil, gas, and wood, and even with solar energy and heat pumps. As a result from these extensive LCA can be concluded, that the calculation and interpretation of ced and ced_{NR} is well suited for a basic assessment of energy system.

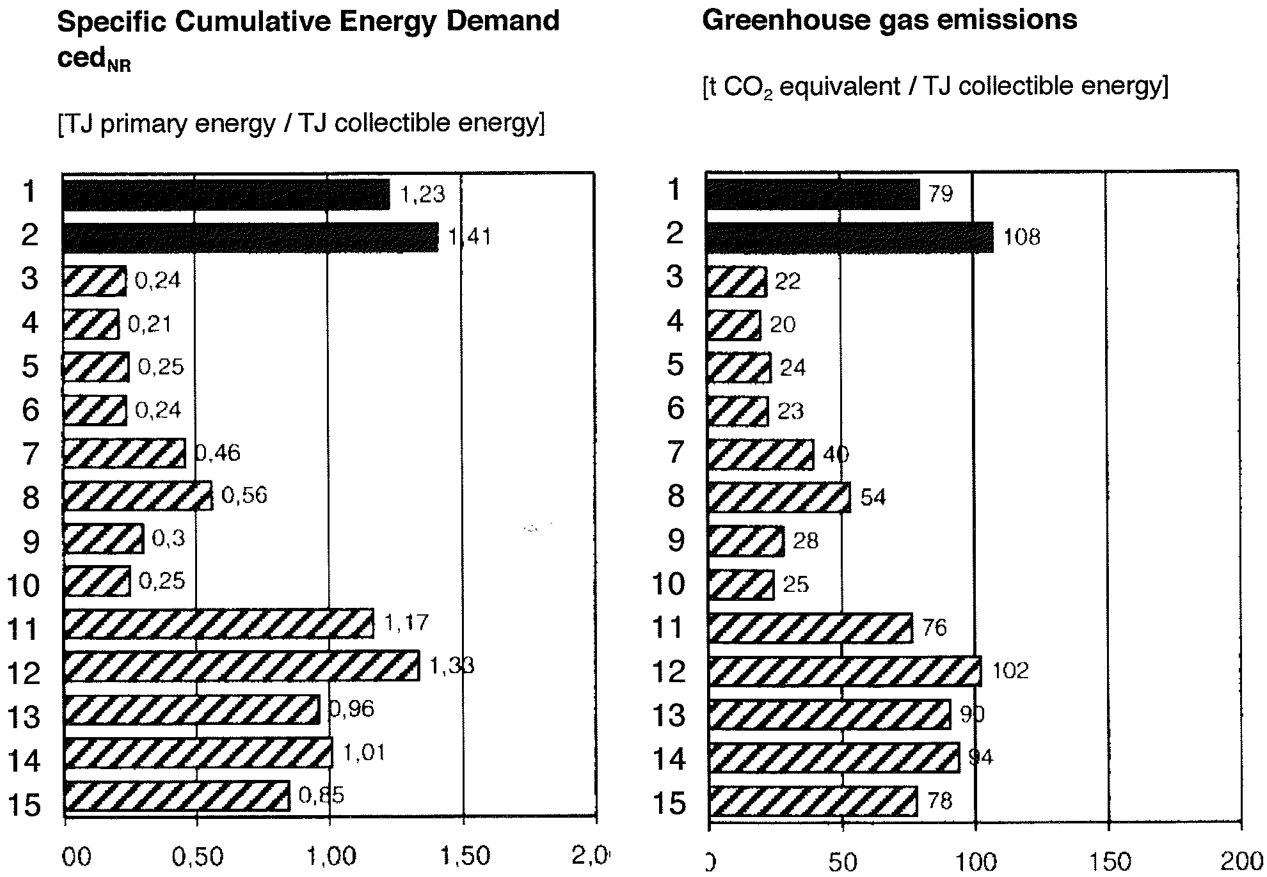

Figure 3.1 Comparison of different systems for heating and hot water supply of a one family house with 18 kW heat demand [Hartmann and Kaltschmitt 2002]. Left: Specific Cumulative Energy Demand with validation of non-renewable fuels during plant operation, defined as ced_{NR} in the present study. Right: Specific greenhouse gas emissions. Legend:

1 Natural gas boiler with flue gas condensation
2 Light fuel oil boiler
3 Log wood boiler
4 Wood chip boiler
5 Small district heating system with wood
6 Large district heating system with wood
7 as 6 but with oil boiler for peak load
8 as 7 but with straw instead of wood
9 Pellet boiler with additional solar energy collector
10 Biomass district heating with additional solar energy collector
11 Gas boiler with additional solar energy collector
12 Oil boiler with additional solar energy collector
13 Heat pump with collector in the soil
14 Heat pump with probe in the soil
15 Geothermal and natural gas with large district heating system

Biomass will become more and more important as a renewable and CO_2 neutral energy source, if its potential is used within the limits of a sustainable forestry management. However, biomass combustion is related to relevant pollutant emissions, especially NO_X and particles, but also heavy metals, polycyclic aromatic hydrocarbons (PAH), polychlorinated dibenzo-*p*-dioxins and polychlorinated furans (PCDD/F).

A life cycle assessment by the eco indicator method or the ecological scarcity method enables a comparison of energy chains with respect to both, CO_2 as the dominant factor for climate change, and environmental pollution for air, water, and soil. The results of an aggregated LCA are valuable for a generic evaluation of different technologies. However, an aggregated LCA is only of limited value for technology decisions, since e.g. the influences on the greenhouse effect and the impact on health are summarized. As a consequence, a comprehensive variation of one specific parameter, e.g. the plant efficiency or the transport distance, is most often not directly available from LCA studies. Furthermore, the conclusions of an LCA on energy systems are strongly influenced by a weighing of the different environmental impacts, especially the greenhouse effect. This is illustrated with a comparison between residential heating with wood fuels, light fuel oil, and natural gas (Figure 3.2 [Kessler et al. 2000] and [Nussbaumer 2002]). The difference between high and low valuation of the greenhouse effect is related to the CO_2 emissions from fossil fuels. Due to the need of a weighing of different ecological impacts, an aggregated LCA is not well suited for technology decisions. Furthermore, the valuation of the greenhouse effect or a weighing to enable a comparison of non-renewable fuels with renewable fuels is highly subjective.

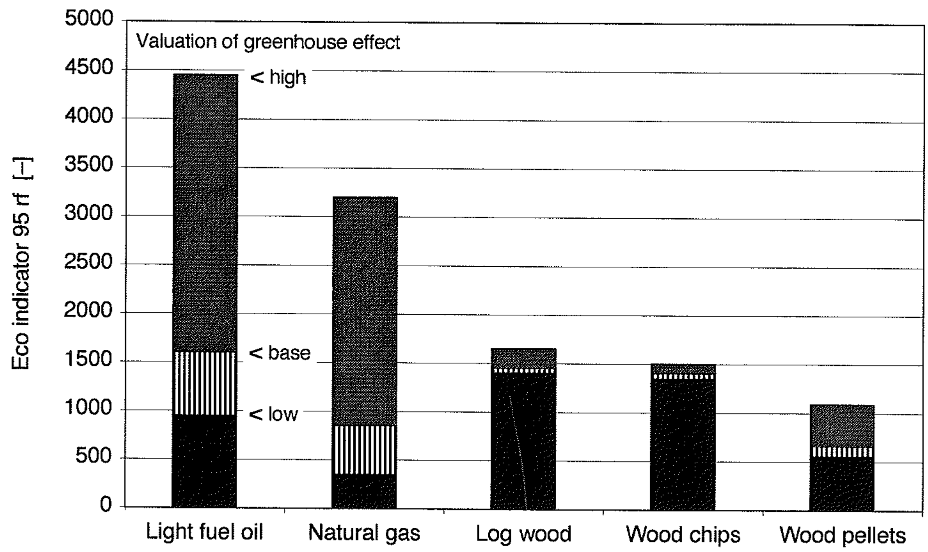

Figure 3.2 Eco indicator for heating with light fuel oil, natural gas, and wood for different valuations of the greenhouse effect (after Data from [Kessler et al 2000] except data for wood pellets by [Nussbaumer 2002]).

4 Aim

The aim of the present study is to introduce a decision tool for an assessment of the primary energy efficiency of energy systems based on biomass combustion. The method shall enable a comprehensive assessment of different supply chains and conversion technologies by a sensitivity analysis of the most relevant parameters. The following technologies shall be evaluated:

- residential heating with log wood,
- heating and district heating with wood chips in automatic biomass combustion plants,
- heating and district heating with wood pellets (including pellet production),
- power production based on biomass combustion and steam cycles (dedicated biomass combustion or co-firing) and utilisation of the electricity for decentralised heat production with heat pumps.

The most relevant parameters shall be identified and conclusions for the future implementation of biomass based energy systems shall be presented. In long term, the identification of the most efficient energy chains will improve both, economy and ecology of biomass combustion systems and hence strengthen the role of bioenergy in the future.

5 Methodology and Definitions

5.1 Scenarios for heat production

In the present study, heat production for housing and hot water is assumed as reference scenario.
The collectible energy is defined as useful heat delivered to the consumer in case of district heating systems or at the outlet of the heat production system in case of decentralised heat production (log wood boiler, pellet boiler without district heating).
The primary energy content of biomass and fossil fuels is respected with the lower heating value. (For a thermodynamic evaluation, the upper heating value or the reaction enthalpy should be regarded. However, the lower heating value is used as standard in literature and norms (e.g. the German norm [VDI 4600]) and therefore also used as reference in this study.)
To determine integrated coefficients during the whole operation period, an assumption of the lifetime is needed and the following terms for **time** are introduced:

t = time in [a]

t_ω = lifetime of the plant in [a]

t_ω = 20 a is assumed for the lifetime of technical equipment such as boilers and heat pumps, while a lifetime of 60 a is assumed for the building. However, all graphs and formula are described for an identical lifetime of 20 years for the whole plant, although 60 years are respected in the calculations for the buildings .

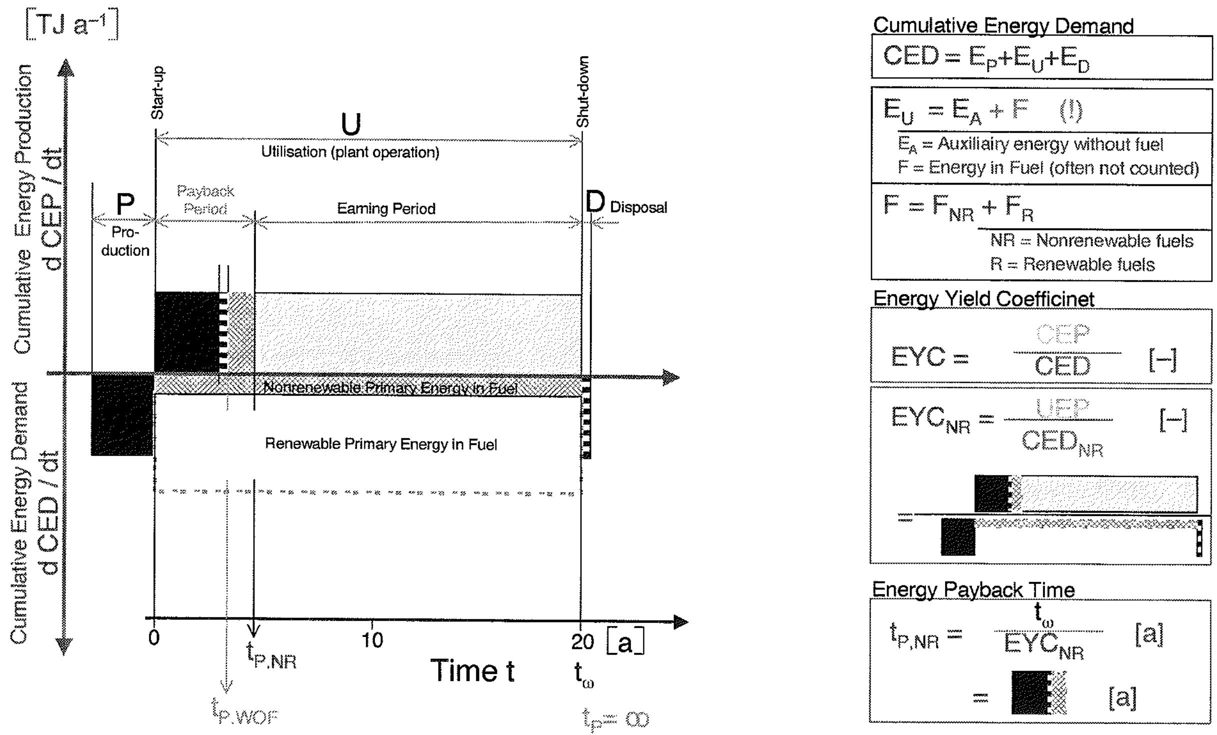

Figure 5.1 Definitions of Cumulative Energy Demand (CED), Energy Yield Coefficient (EYC), and Energy Payback Time (t_P) (following e.g. [Bansal et al. 1998, Wagner et al. 1999]).

5.2 Scenarios for power production and co-firing

As an alternative to heat production, power production from biomass is respected. As reference scenario for the calculations, **dedicated power production** is assumed for small to medium scale combustion plants with steam turbines or steam engines. However, the presented data are also valid for co-firing. To enable a comparison with heat production plants, the utilisation of the electricity in decentralised **heat pumps** is assumed. For this scenario, the most relevant parameters which influence the energy yield are:

- The **net efficiency of power production**. For this parameter, an assumption of 25% and 50% is calculated. For efficiencies between these values, an interpolation of the results is possible with reasonable accuracy.
- The **exergetic valuation of electricity**. For this parameter, a variation of 2.5 and 5 is calculated. Again, other values can be estimated by interpolation of the results.

Furthermore, the transport distance can have a significant influence, if long distance road transport of the fuel is regarded. However, a typical transport distance of 50 km (equivalent to a driving distance of 100 km) is assumed for the fuel transport in case of power production, while the influence of the transport distance is demonstrated in a separate sensitivity analysis for heat production systems. This comparison reveals, that the influence of the transport distance is of secondary importance for distances up to approximately 100 km.

For **co-firing**, several differences are possible in comparison to dedicated power production:

- The main advantage of co-firing is the potentially higher electric efficiency thanks to the strong scale effect of steam cycle plants. This difference is respected in the parameter variation of the efficiency.
- The specific embodied energy can be different and a longer lifetime is expected for large scale plants. However, the calculations show for all investigated scenarios, that the embodied energy has no significant influence on the energetic assessment, if a lifetime of 20 years or longer is regarded. Hence differences in embodied energy and longer lifetime are not relevant for the calculations presented here.
- For co-firing in pulverised combustion, additional fuel pre-treatment can be needed, which leads to a higher energy demand. However, the fuel pre-treatment is respected in the assessment, since the assumed efficiency of the power production plant (25% or 50%) is calculated as *net* plant efficiency including fuel pre-treatment.

As a consequence, the results for power production are **valid for both, dedicated power production and co-firing**. For practical considerations of the results on power production, typical net electric efficiencies as follows are expected with nowadays technologies:

- For dedicated power production: 10% for 0.5 MW_e, 20% for 5 MW_e, 30% for 25 MW_e
- For co-firing in coal fired power stations: 40% for 500 MW_e.

5.3 Cumulative Energy Demand (CED)

According to Figure 5.1, the **Cumulative Energy Demand** is defined as follows:

CED	= Cumulative Energy Demand in $[TJ_{prim}]$
	$= E_P + E_U + E_D$

E_P = Primary energy demand for Production of the plant in $[TJ_{prim}]$

E_U = Primary energy demand for Utilisation of the plant in $[TJ_{prim}]$

E_D = Primary energy demand for Disposal of equipment in $[TJ_{prim}]$

E_P and E_D are assumed as time-independent and are summarized as:

$E_0 = E_P + E_D$

E_U is a function of time:

$$E_U(t) = \int_0^t \dot{E}_U(t)\ dt\ [TJ_{prim}]$$

Hence the primary energy demand for the plant utilisation during its lifetime is:

$$E_U = \int_0^{t_\omega} \dot{E}_U(t)\ dt\ [TJ_{prim}]$$

And the **Cumulative Energy Demand** is also a **function of time**:

$$CED(t) = E_0 + \int_0^t \dot{E}_U(t)\ dt\ [TJ_{prim}]$$

The **integrated Cumulative Energy Demand** during the lifetime is determined as:

$$CED = E_0 + \int_0^{t_\omega} \dot{E}_U(t)\ dt\ [TJ_{prim}]$$

The **primary energy consumption during plant utilisation** can be distinguished as follows:

$E_U = E_A + F$

E_A = Primary energy demand for Auxiliary energy during plant utilisation in $[TJ_{prim}]$

F = Primary energy demand of the Fuel consumption during plant utilisation in $[TJ_{prim}]$

The **primary energy demand of the fuel** is related to the following contributions:

$F = F_H + F_P + F_T$

F_H = Heating value of the fuel in $[TJ_{prim}]$

F_P = Primary energy demand for fuel Pre-treatment (e.g. chipping, drying, palletizing) in $[TJ_{prim}]$

F_T = Primary energy demand for fuel Transport $[TJ_{prim}]$

The contribution of **non-renewable (NR) and renewable (R) fuels is distinguished** as follows:

$$F = F_{NR} + F_R$$

E_0, E_A, F_T are assumed to be 100% non-renewable ($E_{0,R} = E_{A,R} = F_{T,R} = 0$)

F_H is assumed as 100% renewable in the case of biomass

F_P is assumed to be 100% non-renewable for the production of log wood and wood chips, while two cases are distinguished for pellet production: Conventional pellet production is assumed with fossil fuels for drying and non-renewable electricity for pellet production, hence 100% non-renewable. For eco-pellets, the drying process is performed with biomass, while the electricity is assumed to be non-renewable.

In the case of wood, the **primary energy** is defined as the heating value contained in the **mass of wood suited for fuel production**. Hence the mass of thin branches, needles, and leaves which are left in the forest are not counted as primary energy. In some investigations, the whole tree as available in the forest is counted as primary energy. For this purpose [Kessler et al. 2000] assume that 1.1 kg wood mass from the living tree results in 1 kg wood mass as wood chips, while 1.2 kg wood mass from the living tree are needed to produce 1 kg of log wood. This assumptions leads to smaller energy yield coefficients in comparison to the definition used in the present study. Further, wood chips achieve a higher ranking thanks to the assumption of a higher exhaust of the biomass potential than in the case of log wood.

The following **three definitions of CED** can be distinguished:

1)	CED_{WOF}	$= E_0 + E_A$
2)	**CED**	$= E_0 + E_A + F$
3)	CED_{NR}	$= E_0 + E_A + F_{NR}$

The choice of the definition leads to completely different results and conclusions. Hence the choice of the definition is related to a subjective valuation, which is often not clearly indicated, as only one definition is introduced and used (usually without indices). If sustainability is regarded as a target, definition 3 has to be used, since the difference between non-renewable and renewable fuels is not respected in the definitions 1 and 2.

In definition 1, the fuel consumption during the plant operation – which is the dominant primary energy demand – is not considered in the calculation of CED. Hence definition 1 is not suited for a comparison of non-renewable and renewable fuels. Further, the plant efficiency is not adequately validated by this definition, as a high efficiency does not reduce the CED according to definition 1. Although definition 1 is often found in literature, it is not regarded in the present study. As a consequence, the use of definitions 2 *and* 3 is proposed as a method to enable a comparison of energy systems based on non-renewable and/or renewable energies:

Definition 2 enables an assessment of the overall energy chain efficiency without considering a difference between non-renewable and renewable fuels, while definition 3 enables a comparison of energy systems based on renewable and non-renewable fuels. For a comparison of two different energy systems, e.g. of log wood and wood pellets, it is proposed to evaluate the CED according to definition 2 *and* 3. The interpretation of the results can be demonstrated with two examples:

a) If one of the two systems is favourable according to both definitions, it can be assessed as definitively favourable without the need of a subjective valuation. If e.g. wood pellets are favourable according to definition 3 (thanks to higher conversion efficiency) while log wood is favourable according to definition 2 (thanks to lower fossil fuel consumption needed for fuel pre-treatment), the final decision is not clear without a subjective valuation of non-renewable and renewable fuels.

b) An evaluation by definition 2 and 3 enables an assessment of an increased plant efficiency for a large biomass based power plant which demands for an increased transport distance with Diesel trucks, thus leading to two different results. Although the final decision cannot be made without a subjective valuation, the results allow the interpretation, that the optimum plant size is definitively between the two results. This conclusion can be drawn without the need of a subjective valuation.

5.4 Cumulative Energy Production (CEP)

The **Cumulative Energy Production** is defined as follows:

CEP	= Cumulative Energy Production in $[TJ_{sec}]$ or $[TJ_{coll}]$
$\dot{E}_{sec}$	= Annual Energy Production as plant output in $[TJ_{sec}\ a^{-1}]$
$\dot{E}_{coll}$	= Annual Energy Production as consumer input in $[TJ_{coll}\ a^{-1}]$

The Cumulative Energy Production during plant operation is a function of time:

$$CEP(t) = \int_0^t \dot{E}_{sec}(t)\ dt \quad [TJ_{sec}]$$

$$CEP(t) = \int_0^t \dot{E}_{coll}(t)\ dt \quad [TJ_{coll}]$$

In this study, collectible energy production is regarded and hence the **Cumulative Energy Production** as function of time is:

$$CEP(t) = \int_0^t \dot{E}_{coll}(t)\ dt \quad [TJ_{coll}]$$

The **integrated Cumulative Energy Demand** during the lifetime is determined as:

$$CEP = \int_0^{t_\omega} \dot{E}_{coll}(t)\ dt \quad [TJ_{prim}]$$

5.5 Specific Cumulative Energy Demand (ced)

CED is usually normalized with respect to the benefit of the regarded process. In a manufacturing process, the benefit is defined by the mass or number of the product and the specific CED is given e.g. as [TJ per kg product]. For energy systems, the product is secondary or collectible energy. Hence the **specific CED** is defined as a dimensionless factor denoted as **ced** in [–] to distinguish from CED in [TJ].

$$ced = \frac{CED}{CEP} \qquad \frac{[TJ_{prim}]}{[TJ_{coll}]} = [-]$$

5.6 CED* and CEP* as time equivalents

CED and CEP are energies related to a dimension in [TJ]. To enable a visualisation of different energy systems, CED and CEP can be replaced by a lifetime equivalent in [a] with the following auxiliary terms:

$$E^* = \frac{E}{\dot{E}_{coll}} \quad [a]$$

$$CED^* = \frac{CED}{\dot{E}_{coll}} \quad [a]$$

$$CEP^* = \frac{CEP}{\dot{E}_{coll}} \quad [a]$$

The visualisation of CED*(t) and CEP*(t) in a diagram of E* as function of time enables a fast and comprehensive determination of the relevant coefficients. Further, the specific Cumulative Energy Demand can be determined as ratio of the lifetime equivalents as follows:

$$ced = \frac{CED^*}{CEP^*} \qquad \frac{[a]}{[a]} = [-]$$

5.7 Energy Yield Coefficient (EYC)

The specific Cumulative Energy Yield (cey) is denoted as **Energy Yield Coefficient (EYC)**, (EYC is used instead of cey which would correspond to the notation introduced for CED and ced).
EYC is defined as the ratio between the Cumulative Energy Production and the Cumulative Energy Demand and corresponds to the reciprocal value of ced:

$$EYC = \frac{CEP}{CED} = ced^{-1} \qquad \text{in } \frac{[TJ_{sec}]}{[TJ_{prim}]} \text{ or } \frac{[TJ_{coll}]}{[TJ_{prim}]} = [-]$$

$$EYC_{NR} = \frac{CEP}{CED_{NR}} = ced_{NR}^{-1} \qquad [-]$$

For the determination of EYC, the lifetime equivalents can be used:

$$EYC = \frac{CEP^*}{CED^*} \quad \text{in } \frac{[a]}{[a]} = [-]$$

$$EYC_{NR} = \frac{CEP^*}{CED_{NR}^*} = ced_{NR}^{-1} \quad [-]$$

Since the primary energy of the fuel consumption during plant operation is respected in definitions 2 and 3 of CED, the following conditions are valid:

$EYC < 1$

$EYC_{NR} < 1$ for non-renewable fuels

$EYC_{NR} > 1$ is possible (but not guaranteed) for renewable fuels.

The Energy Yield Coefficient describes the efficiency of the whole energy supply chain. Hence the determination of both, **EYC** *and* **EYC_{NR}** is regarded as most useful for an assessment of energy systems. EYC can also be described as „energy supply chain efficiency“ or „energy system efficiency“. For example in [Kessler et al. 2000], EYC_{NR} is denoted as „system efficiency“ („Systemwirkungsgrad S“).

5.8 Energy Payback Time (t_P)

The **Energy Payback Time t_P** describes the time period from the start-up of the plant until the condition CEP(t)=CED(t) is met. This condition can be easily calculated or determined in the diagram E* as function of time. As for EYC, different cases are distinguished according to the definition of CED:

t_P	= **Energy Payback Time**, according to the condition **CEP(t) = CED(t)**
$t_{P,NR}$	= (Non-renewable) **Energy Payback Time**, according to **CEP(t) = CED_{NR}(t)**

With the following conditions:

t_P $= \infty$

$t_{P,NR}$ $= \infty$ for non-renewable fuels

$t_{P,NR}$ $< \infty$ is possible (but not guaranteed) for renewable fuels.

5.9 Visualisation as function of time

Figure 5.2 shows E, CED and CEP as function of time and illustrates the determination of EYC and t_P. Figure 5.3 shows the same graphs. However, the data on the y-axis are normalised to the annual energy production and hence given as a time equivalents in [a]. The transformation to time equivalents is explained in Figure 5.4.

Since absolute values of E, CED, and CEP are not relevant, the visualisation of time equivalents is more favourable and performed for the results in the present study.

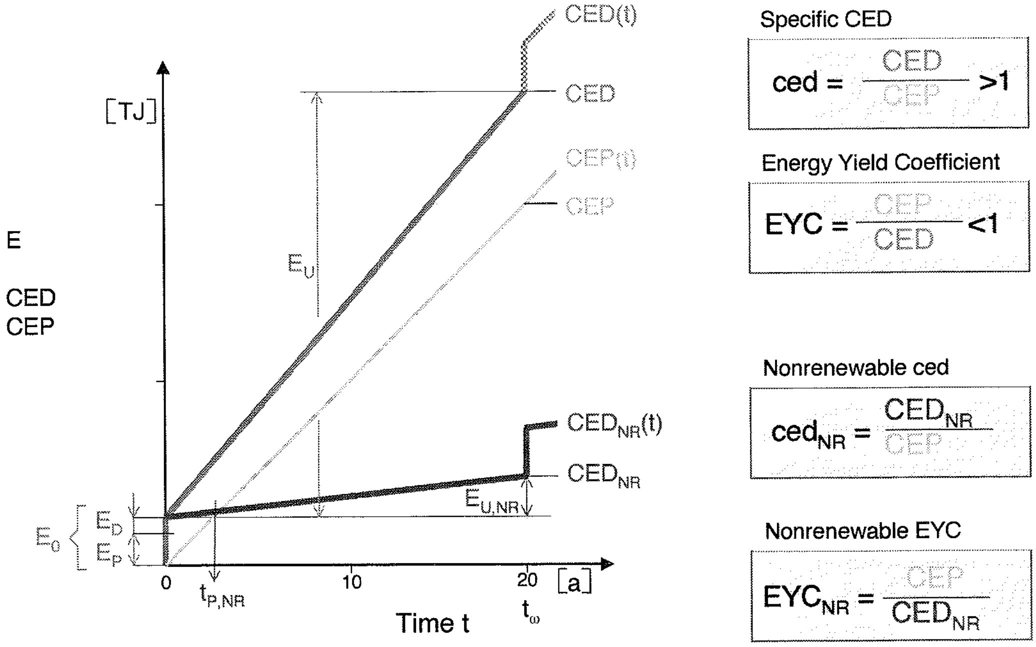

Figure 5.2 Cumulative Energy Demand CED(t) and Collectible Energy Production CEP(t) in [TJ] as function of time in [a]. At t=0 the plant is erected with the primary energy demand E_P for Production and E_D for disposal of the plant. In reality, E_D has to be covered at the end of the lifetime but it is calculated at the start. After t_ω = 20 a, the plant has reached the end of its lifetime and the cycle restarts. With the integrated CEP and CED, the Energy Yield Coefficient can be determined. The energy payback time $t_{P,NR}$ is found, when CEP(t) = $CED(t)_{NR}$.

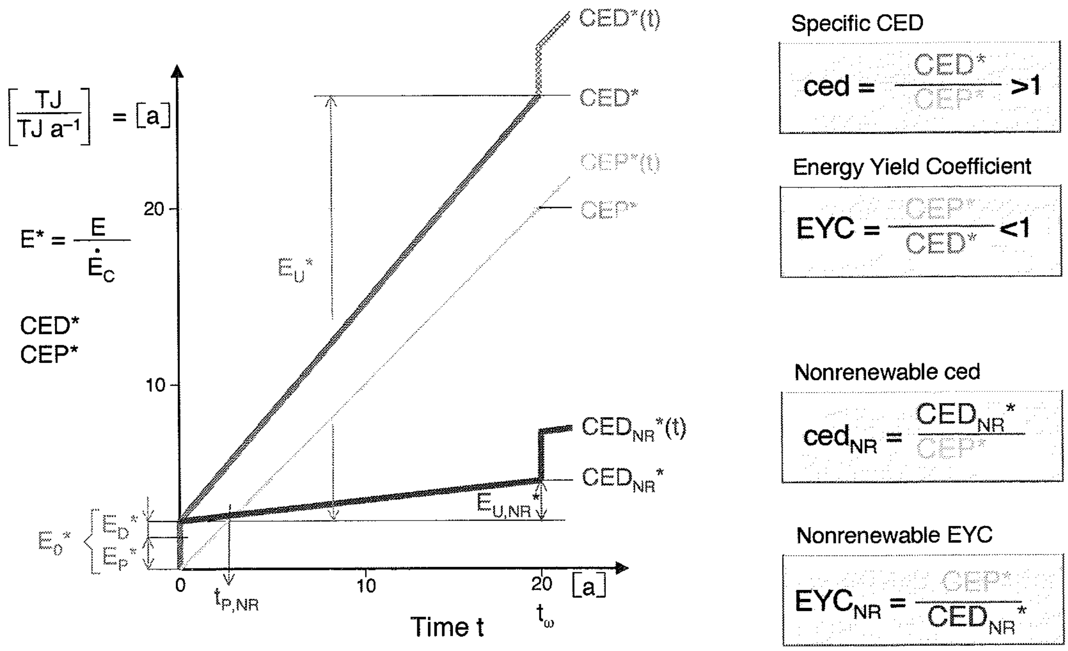

Figure 5.3 Cumulative Energy Demand CED(t) and Collectible Energy Production CEP(t) given as equivalent lifetime E*(t) in [a] as function of time in [a]. This figure is a mathematical conversion of the preceding figure and it is introduced to enable a normalized visualisation of the data. This type of figure is used to present the results in the present study. The values for ced and EYC are given to illustrate the example in the graph.

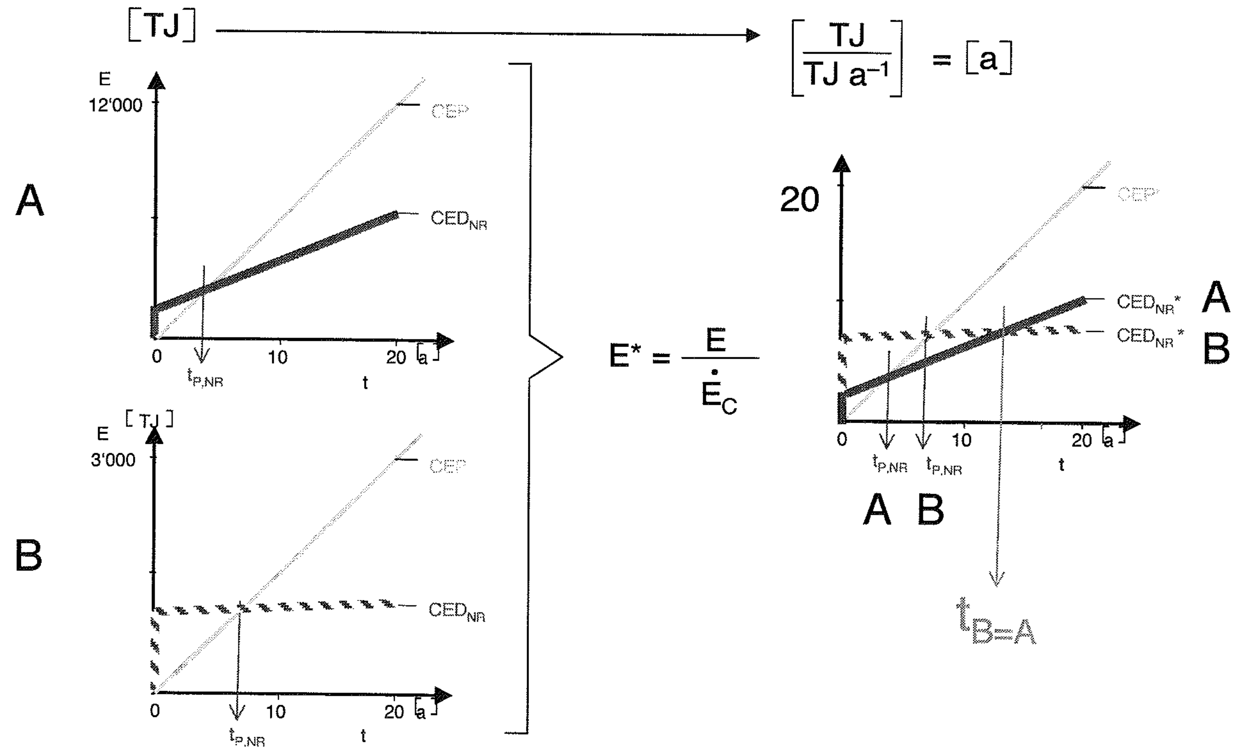

Figure 5.4 Explanation of the transformation from CED in [TJ] to CED* in [a]. Example A is related to low embodied energy but high induced non-renewable energy consumption during operation, while the opposite is assumed for example B. A describes as example a heating system with wood pellets which is related to fossil fuel consumption for fuel pre-treatment. B describes an energy system with biomass fired power plant and local heat pumps. During operation, almost no fossil fuels are used, while the embodied energy is higher. Although A has a shorter non-renewable payback time, B becomes favourable after the time $t_{B=A}$.

5.10 Additional Definitions and Assumptions

The basic assumptions are described in the definitions above. To describe the characteristics of the conversion processes, the following additional definitions are used:

Heating plants

η_a = **Annual plant efficiency** for heat production (excluding heat distribution for district heat, including heat storage for log wood boiler with heat storage tank) in [%]

= $[TJ_{end}/TJ_{coll}]$ with TJ_{end} as lower heating value of the fuel and TJ_{coll} as heat at plant outlet.

η_a = **80%** is assumed as reference case

η_a = 50% – 100% is assumed for the parameter variation.

Power production (including co-firing) and heat pumps

ε_{ex} = **Exergetic valuation of electricity** in $[TJ_{prim}/TJ_{sec}]$ where secondary energy is electricity

COP = **Coefficient Of Performance** of a heat pump here used for the annual COP [–]

= collectible heat per electricity consumption $[TJ_{coll}/TJ_{end}]$

For the reference case $\boldsymbol{\varepsilon_{ex}}$ **= COP = 2.5** is assumed

For the parameter variation η_{ex} = COP = 1 and η_{ex} = COP = 5 are assumed.

Transport

Road transport by Diesel trucks is assumed with a fuel consumption of 35 l Diesel per 100 km.
The primary energy demand for Diesel is calculated with

$\mathbf{ced_{Diesel}}$ = Weighing factor for Diesel = **1.25 $[TJ_{prim}/TJ_{sec}]$** [Kasser et al. 2001]

For wood chips, a cargo capacity of **34 m³** is assumed for a cubical volume (container), while **23 m³** is assumed for pellets transported in cylindrical pellet tanks for pneumatic delivery. With respect to typical fuel characteristics [Nussbaumer et al. 2001], an energy density of **3200 kWh/m³** is assumed for wood pellets and **850 kWh/m³** for wood chips with an average water content of approximately 30%. Hence for long distance transport, higher capacity could be assumed. However, transport distances far greater than 100 km are not proposed and hence the comparison for long distance transport is theoretical.

5.11 Scenarios

Table 5.1 gives a description of the investigated scenarios with the assumptions varied in each scenario. The scenarios 4, 6, 8, 10, 11, 13, and 16 describe the most relevant cases. These scenarios are given in **bold** in all tables and they are visualised with a line in the diagrams indicated with an underlined legend. The following assumptions are introduced for the different scenarios:

TD = Transport Distance of the fuel in [km]. Driving distance = 2 TD due to empty return.

dh = district heat with energy density of the heat net in [MWh $a^{-1}m^{-1}$]

$\dot{Q}_{in}$ = Energy input to the plant based on the heating value of the fuel in [kW] (= $\dot{F}_H$ according to the definition introduced above)
This figure is an additional information which indicates the typical plant size. However, the plant size has no relevant influence on the results, as the embodied energy related to the plant production is of minor importance, while the efficiency, which can be scale-dependent, is investigated in a parameter variation.

Table 5.1 Definition of the scenarios with main assumptions.

	No	Scenario	$\dot{Q}_{in}$ [kW]	TD [km]	dh [MWh $a^{-1}m^{-1}$]
Heat Production	1	Pellets with district heat (dh)	1'000	50	1.5
	2	Pellets w/o dh	15	5000	–
	3	Pellets w/o dh	15	500	–
	4	**Pellets w/o dh**	**15**	**50**	**–**
	5	Pellets w/o dh	15	15	–
	6	**Eco-pellets w/o dh**	**15**	**50**	**–**
	7	Wood chips with dh „worst case“	1'000	15	0.6
	8	**Wood chips with dh „reference“**	**1'000**	**15**	**1.5**
	9	Wood chips with dh „best case“	1'000	15	3.0
	10	**Wood chips w/o dh**	**1'000**	**15**	**–**
	11	**Log wood w/o dh, heat storage tank**	**30**	**5**	**–**
	12	Log wood w/o dh, w/o heat storage tank	30	5	–
Power	**13**	**Power plant, 25%el, hp: COP=2.5**	**25'000**	**50**	**–**
	14	Power plant, 50%el, hp: COP=2.5	25'000	50	–
	15	Power plant, 25%el, hp: COP=5	25'000	50	–
	16	**Power plant, 50%el, hp: COP=5**	**25'000**	**50**	**–**

Additional assumptions are given in Table 5.2. The majority of the data are based on extensive life cycle assessment studies carried out for energy systems [Frischknecht et al. 1994, Jungbluth et al. 2002, Hartmann und Kaltschmitt 2002] and other up-dated results from LCA studies. This is valid e.g. for the embodied energy E_P for plant production. The results indicate, that the embodied energy for plant production does not contribute significantly to the CED. Since the embodied energy for plant disposal is far smaller than the embodied energy for the plant production in the case of biomass heating systems, $E_D = 0$ is assumed in the present study.

In cases, where data from literature were not adequate to the present application, own calculations are used for specific cases. This is true e.g. for the consumption for fuel transport, where energy density and transport type play an important role. Data on energy consumption from pellet production are derived from an investigation from [Hasler et al. 2001]. General physical characteristics are derived e.g. from [Recknagel et al. 1995].

Table 5.2 Basic assumptions for the different scenarios.

Field	Parameter	Value	Source
General	Type of plant	Monovalent	
	Hot-water processing	Without	
	Primary energy / end energy of electricity	2.5 or specifically noted	Kasser et al. 1999, page 110; Frischknecht et al. 1994
	Primary energy / end energy of Diesel/oil	1.25	Kasser et al. 1999, page 110; Frischknecht et al. 1994
Silo	Daily volume demand of wood chips / nominal output	0.03 m3/kW	Nussbaumer et al. 2001, p. 138: 8.4 m3 / 300 kW
	Volume demand of wood chips /vol. demand of pellets	4	
	Needed wood volume in the silo	5x daily volume demand +40 m3	Nussbaumer et al. 2001, p. 138
	Possible filling ratio of the silo	75 %	Nussbaumer et al. 2001, p. 138: Rated value > 70%
	Wall thickness of the silo	0.3 m	
	Inside length of the silo b	5.5 m	
	Inside length of the silo c	8 m	
	Density of normal concrete	2.2 t/m3	Recknagel et al. 1995
	Energy demand of concrete	0.00004 TJ/t	Frischknecht et al. 1994
	Considered materials	Concrete	
	Lifetime of the silo	50 years	
Transporting equipment	Production energy demand / transporting length	2.232 MJ/m	Frischknecht et al. 1994
	Transporting length (wood chips furnace)	20 m	
	Transporting length (pellet furnace)	10 m	
	Transporting length (wood-burning power plant)	150 m	
	Transporting length (log wood furnace)	0 m	
Furnace	Production energy damand (function of boiler output bo)	(0.00001769xbo[kW]+0.00360273)TJ	Frischknecht et al. 1994, interpolated
	Boiler output of the wood chips furnace	1000 kW	
	Boiler output of the log wood furnace	30 kW	
	Boiler output of the pellet furnace	15 kW	
	Boiler output of the pellet furnace with district heating	1000 kW	Like the boiler output of the wood chips furnace
	Auxilliary energy / output energy	1.5 %	Nussbaumer et al. 2001, p. 137: Range of rated value: 1-1.5%
	Annual full working time number	2100 h/years	Frischknecht et al. 1994
	Lifetime of the furnace	20 years	
Heat storage tank	Energy demand of steel	0.372 MJ/kg	Frischknecht et al. 1994
	Energy demand of PUR	42.055 MJ/kg	Frischknecht et al. 1994
	Considered materials	PUR, steel	
	Needed mass of steel (function of tank volume tv)	(tv[l]/7.5+90)kg	Frischknecht et al. 1994, interpolated
	Needed mass of PUR (function of tank volume tv)	(tv[l]x0.0096+19.25)kg	Frischknecht et al. 1994, interpolated
	Tank volume (wood chips furnace)	8000 l	
	Tank volume (pellet furnace)	0 l	
	Tank volume (log wood furnace)	1800 l	
Control system	Production energy demand / mass of control system equipment	0.372 MJ/kg	Frischknecht et al. 1994
	Mass of control system equipment (wood chips/pellets)	60 kg	
	Mass of control system equipment (wood-burning power plant)	600 kg	
	Mass of control system equipment (log wood)	0 kg	
Chimney	Production energy demand / height of chimney	(0.00000017778xbo[kW]+0.000007060222)TJ/m	Frischknecht et al. 1994, interpolated
	Height of chimney (wood chips / pellets)	15 m	
	Height of chimney (log wood)	8 m	
	Height of chimney (wood)	30 m	
	Lifetime chimney	50 years	Like the lifetime of the silo according to Frischknecht et al. 1994
Pelleting machine	Production energy demand of the pelleting machine	8.9 GJ	Assumption: like a 300 kW-furnace
	Annual rate of utilization of the pelleting machine	20 %	Present situation in Switzerland
	Lifetime pelleting machine	10 years	
	Calorific value of the pellets	calorific value of the wood (see below)	Hasler et al. 2001: 18.3 MJ/tatro
Power plant	Output of wood-burning power plant	25 MWe	For example: wood-burning power plant in Kujik
	Specific energy demand of the power plant building materials	1.78 GJ / MWth	Jungbluth et al. 2002, inclusive the whole infrastructure (5MWth)
	Specific energy demand of the power plant building supply	16792 tkm / MWth	Jungbluth et al. 2002, Diesel+vehicle (5MWth)
	Energy demand for the material transport / tkm	2.1729 MJ/tkm	Frischknecht et al. 1994 (lorry: 28t, Diesel+vehicle)
	Lifetime of the power plant building	50 years	Like lifetime of the silo, according to Frischknecht et al. 1994
Heat pump	Heat output	10 kW / heat pump	Frischknecht et al. 1994, appendix D page 1
	Production electricity demand of the heat pump	5.6 GJ / heat pump	Frischknecht et al. 1994, appendix D page 2
	Energy demand of the supply chain of the heat pump	4.7 MJ / heat pump	Frischknecht et al. 1994, appendix D page 4
	Lifetime heat pump	20 years	
Electric network	Loss of the electric network	5 %	
District heating net	Excavation volume per net length (dp: pipe diameter [mm])	(0.045xdp^2+3.5xdp)m3/km	Frischknecht et al. 1994, interpolated
	Energy demand of the excavation / moved earth	6.085 MJ/m3	Frischknecht et al. 1994
	Energy demand for the excavation material transport / tkm	2.1729 MJ/tkm	Frischknecht et al. 1994 (lorry: 28t, Diesel+vehicle)
	Energy demand of steel	0.000372 TJ/t	Frischknecht et al. 1994
	Energy demand of PUR	0.042055 TJ/t	Frischknecht et al. 1994
	Energy demand of PE	0.0087 TJ/t	Frischknecht et al. 1994
	steel demand / net length	0.002xdp^2 t/km	Frischknecht et al. 1994, interpolated
	PUR demand / net length	0.02xdp-1/6 t/km	Frischknecht et al. 1994, interpolated
	PE demand / net length	0.00005xdp^2+0.065xdp t/km	Frischknecht et al. 1994, interpolated
	loss / input	(0.0016*Tnet+0.012)/(0.0016*Tnet+0.012+dcon) TJ/TJin	Nussbaumer et al. 2001
	Densitiy of the excavation material	3 t/m3	
	Transport distance of the excavation material	20 km	
	Mean pipe diameter (dp)	60 mm	
	Connection density (dcon)	1.5 MWh/year*m (or specifically noted)	
	Temperature level of the district heating network (Tnet)	80 °C	
	Auxilliary energy / output energy	1 %	Nussbaumer et al. 2001, p. 116: Range of rated value: 0.5-1%
	Lifetime district heating network	30 years	Frischknecht et al. 1994
Wood	Calorific value of hard wood of deciduous trees	4900 kWh/tatro	Nussbaumer et al. 2001, page 11, averaged
	Calorific value of other wood	5300 kWh/tatro	Nussbaumer et al. 2001, page 11, averaged
	Mass share of hard wood of deciduous trees	0.5	
Supply chain of wood	Energy demand of forest upkeep / mass of hard wood	0.00006 TJ/t	Frischknecht et al. 1994
	Energy demand of forest upkeep / mass of other wood	0.0001 TJ/t	Frischknecht et al. 1994
	Share of forest upkeep ascribing to energy wood	0 %	Assumption: Forest upkeep is also needed without use of energy wood
	Energy demand of cut down / mass of hard wood	0.00006 TJ/tatro	Frischknecht et al. 1994
	Energy demand of cut down / mass of other wood	0.000084 TJ/tatro	Frischknecht et al. 1994
	Energy demand of chop / mass of hard wood	0.00025 TJ/tatro	Frischknecht et al. 1994
	Energy demand of chop / mass of other wood	0.00035 TJ/tatro	Frischknecht et al. 1994
	Energy demand of split / wood mass	88 MJ/tatro	Frischknecht et al. 1994
	Energy loss because of decomposition of wood chips	3 %	
	Energy loss because of decomposition of log wood	0 %	Assuming that the storage is suitable
	Energy loss because of decomposition of pellets	0 %	Assuming that the storage is suitable
	Energy demand because of splitting by the consumer/wood mass	20.12 MJ/tatro	Frischknecht et al. 1994
	Energy demand for the transport to the consumer/tkm	22 MJ/tkm	Frischknecht et al. 1994, part 9 page 33
	Energy demand for pellet transport to the consumer/tkm	1.8 MJ/tkm	Assumption: Lorry is empty during the return passage (Diesel, oil, tyre)
	Energy demand for wood chips transport to the consumer/tkm	4.9 MJ/tkm	Assumption: Lorry is empty during the return passage (Diesel, oil, tyre)
	Production energy demand for the means of transport / tkm	0.17333 MJ/tkm	Frischknecht et al. 1994
	Transport distance to the consumer (wood chips)	15 km	Frischknecht et al. 1994
	Transport distance to the consumer (log wood)	5 km	Frischknecht et al. 1994
	Transport distance to the consumer (pellets)	50 km (or specifically noted)	
	Transport distance to the wood-burning power plant	50 km	

6 Results for Reference Case $\eta_{ex} = 2.5$

6.1 Influence of plant efficiency on ced

The following tables and diagrams show the results for ced and ced_{NR} as function of the annual plant efficiency. The Energy Yield Coefficients EYC and EYC_{NR} ca be derived as reciprocal values.

Table 6.1 Specific Cumulative Energy Demand Coefficient **ced** [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 2.5$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref 80%	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	2.72	2.27	1.96	1.72	1.54	1.39
2	Pellets w/o dh	5000	3.79	3.17	2.72	2.39	2.13	1.92
3	Pellets w/o dh	500	2.58	2.16	1.86	1.63	1.45	1.31
4	**Pellets w/o dh**	50	**2.46**	**2.06**	**1.77**	**1.56**	**1.39**	**1.25**
5	Pellets w/o dh	15	2.45	2.05	1.76	1.55	1.38	1.25
6	**Eco-pellets w/o dh**	50	**2.45**	**2.05**	**1.76**	**1.55**	**1.38**	**1.25**
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	2.70	2.26	1.95	1.71	1.53	1.39
8	**Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$**	15	**2.39**	**2.00**	**1.73**	**1.52**	**1.36**	**1.23**
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	2.29	1.92	1.65	1.46	1.30	1.18
10	**Wood chips w/o dh**	15	**2.16**	**1.81**	**1.56**	**1.37**	**1.22**	**1.10**
11	**Log wood w/o dh, heat storage**	5	**2.09**	**1.75**	**1.51**	**1.32**	**1.18**	**1.07**
12	Log wood w/o dh, w/o heat storage	5	2.09	1.75	1.50	1.32	1.18	1.07

Table 6.2 Specific Cumulative Energy Demand of non-renewable fuels $\mathbf{ced_{NR}}$ [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 2.5$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref 80%	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	0.53	0.45	0.40	0.36	0.32	0.30
2	Pellets w/o dh	5000	1.79	1.50	1.29	1.14	1.01	0.92
3	Pellets w/o dh	500	0.58	0.49	0.43	0.38	0.34	0.31
4	**Pellets w/o dh**	50	**0.46**	**0.39**	**0.34**	**0.31**	**0.28**	**0.25**
5	Pellets w/o dh	15	0.45	0.39	0.34	0.30	0.27	0.25
6	**Eco-pellets w/o dh**	50	**0.17**	**0.15**	**0.13**	**0.12**	**0.11**	**0.10**
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	0.15	0.14	0.13	0.12	0.12	0.11
8	**Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$**	15	**0.14**	**0.12**	**0.12**	**0.11**	**0.11**	**0.10**
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	0.13	0.12	0.11	0.11	0.10	0.10
10	**Wood chips w/o dh**	15	**0.10**	**0.09**	**0.08**	**0.08**	**0.07**	**0.07**
11	**Log wood w/o dh, heat storage**	5	**0.09**	**0.08**	**0.08**	**0.07**	**0.07**	**0.07**
12	Log wood w/o dh, w/o heat storage	5	0.09	0.08	0.08	0.07	0.07	0.07

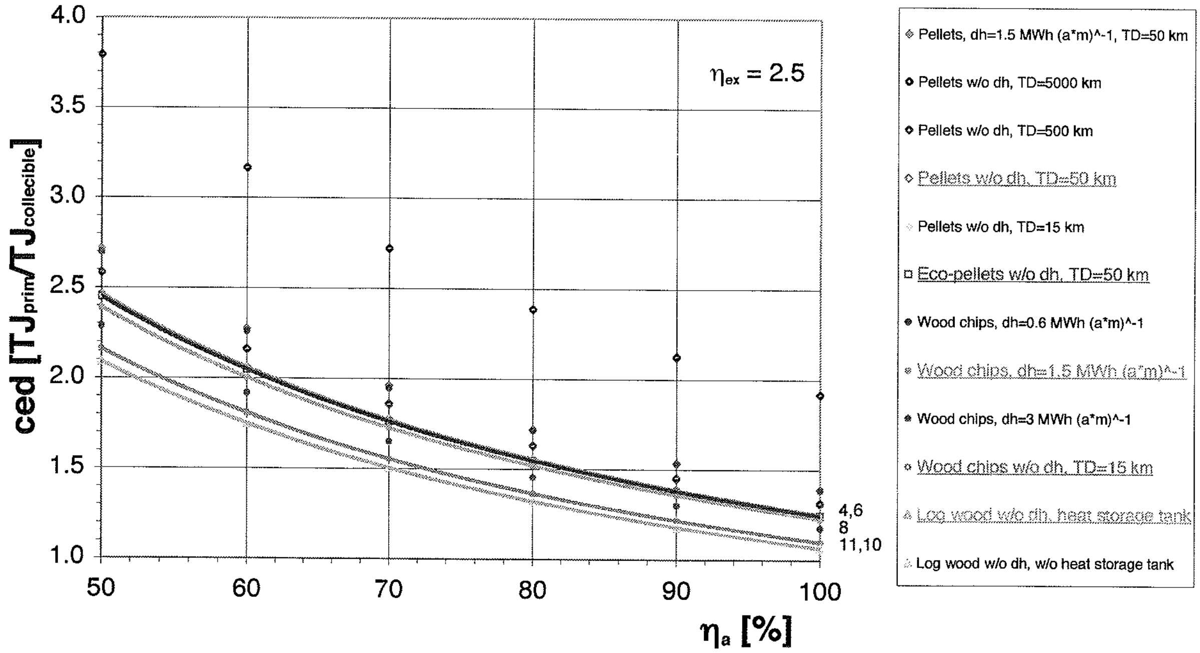

Figure 6.1 Specific Cumulative Energy Demand ced [–] for direct heating applications as function of the annual plant efficiency η_a according to Table 6.1. Electricity is rated with η_{ex} = 2.5.

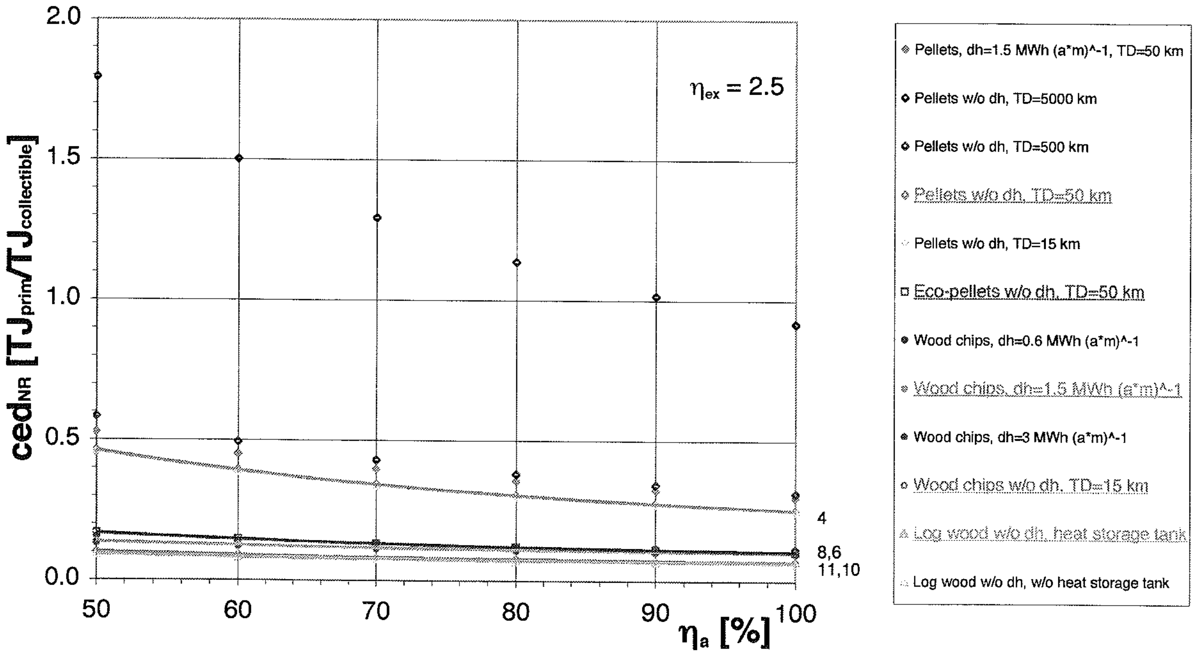

Figure6.2 Specific Cumulative Energy Demand of non-renewable fuels **ced**$_{NR}$ [–] for direct heating applications as function of the annual plant efficiency η_a according to Table 6.2. Electricity is rated with η_{ex} = 2.5.

6.2 Comparison of different energy systems by ced, EYC, and t_P

Table 6.3 gives a summary of the most relevant results for all scenarios with the assumption of an annual plant efficiency of 80% for heat production. In addition, a parameter variation of the transport distance TD is performed for wood pellets, wood chips, and power production. The main results are shown as function of time in Figure 6.3 and Figure 6.4.

Table 6.3 Specific Cumulative Energy Demand, Energy Yield Coefficient, and Energy Payback Time for an annual plant efficiency of the heat production of η_a=80%. Electricity is rated with η_{ex} =2.5. The reference scenarios 4, 6, 8, 10, 11, 13, and 16 are given in bold. They correspond to the scenarios in the diagrams which are underlined in the legend and drawn in the diagram with a line. In addition, the Transport Distance TD is varied.

	No	Scenario	TD [km]	ced [-]	EYC = ced^{-1} [-]	t_P [a]	ced_{NR} [-]	EYC_{NR} = ced_{NR}^{-1} [-]	$t_{P,NR}$ [a]
Heat Production	1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	1.72	0.580	∞	0.356	2.81	0.091
	2	Pellets w/o dh	5000	2.39	0.419	∞	1.137	0.88	∞
	3	Pellets w/o dh	500	1.63	0.613	∞	0.381	2.63	0.158
	4	**Pellets w/o dh**	**50**	**1.56**	**0.643**	**∞**	**0.305**	**3.27**	**0.141**
	5	Pellets w/o dh	15	1.55	0.645	∞	0.300	3.34	0.140
	6	**Eco-pellets w/o dh**	**50**	**1.55**	**0.647**	**∞**	**0.120**	**8.30**	**0.112**
	7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	1.72	0.583	∞	0.127	7.89	0.170
	8	**Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$**	**15**	**1.52**	**0.658**	**∞**	**0.112**	**8.96**	**0.067**
	9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	1.46	0.687	∞	0.107	9.37	0.038
	10	**Wood chips w/o dh**	**15**	**1.37**	**0.732**	**∞**	**0.077**	**13.0**	**0.011**
	11	**Log wood w/o dh, heat storage**	**5**	**1.32**	**0.756**	**∞**	**0.072**	**13.8**	**0.069**
	12	Log wood w/o dh, w/o heat storage	5	1.32	0.757	∞	0.072	14.0	0.050
Power	**13**	**Power plant, 25%el, hp: COP=2.5**	**50**	**1.83**	**0.545**	**∞**	**0.099**	**10.1**	**0.217**
	14	Power plant, 50%el, hp: COP=2.5	50	0.93	1.076	2.46	0.062	16.0	0.209
	15	Power plant, 25%el, hp: COP=5	50	0.92	1.085	2.24	0.054	18.4	0.206
	16	**Power plant, 50%el, hp: COP=5**	**50**	**0.47**	**2.129**	**0.364**	**0.036**	**27.7**	**0.202**
Variation of TD	4'	Pellets w/o dh	2000	1.88	0.531	∞	0.633	1.580	0.265
	10'	Wood chips w/o dh	2000	2.25	0.445	∞	0.959	1.043	0.233
	8'	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	2000	2.48	0.403	∞	1.075	0.930	∞
	13'	Power plant, 25%el, hp: COP=2.5	2000	3.00	0.333	∞	1.266	0.790	∞
	14'	Power plant, 50%el, hp: COP=2.5	2000	1.51	0.661	∞	0.646	1.548	0.544
	4"	Pellets w/o dh	4186	2.25	0.444	∞	1	1	19.9
	10"	Wood chips w/o dh	2093	2.29	0.437	∞	1	1	16.5
	8"	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	1845	2.41	0.415	∞	1	1	21.7
	13"	Power plant, 25%el, hp: COP=2.5	1555	2.74	0.366	∞	1	1	19.6
	14"	Power plant, 50%el, hp: COP=2.5	3183	1.87	0.536	∞	1	1	19.7

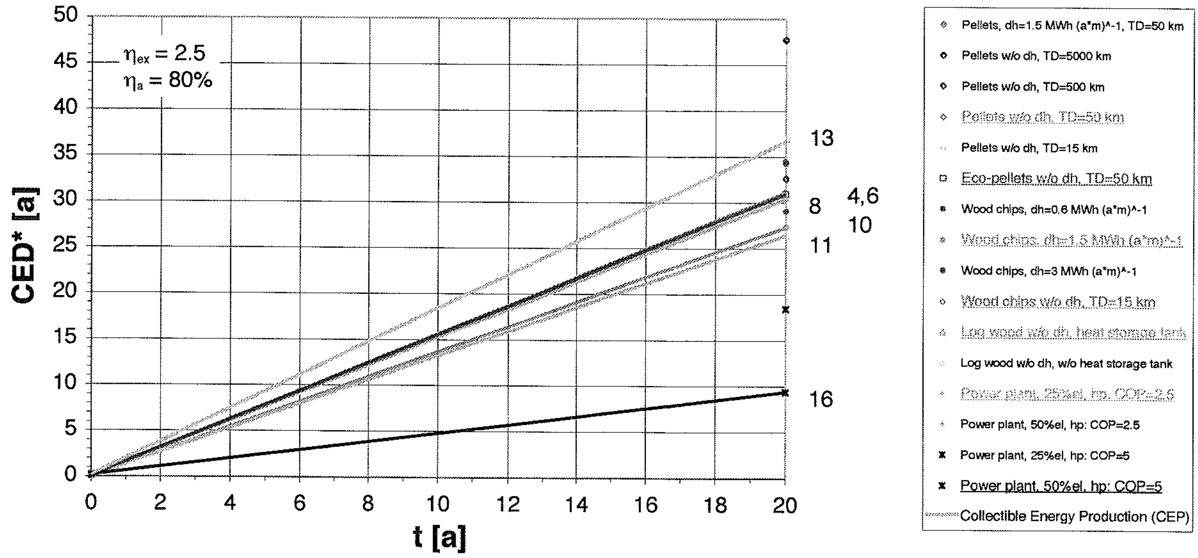

Figure 6.3 Time equivalent CED* in [a] as function of time for the different scenarios.

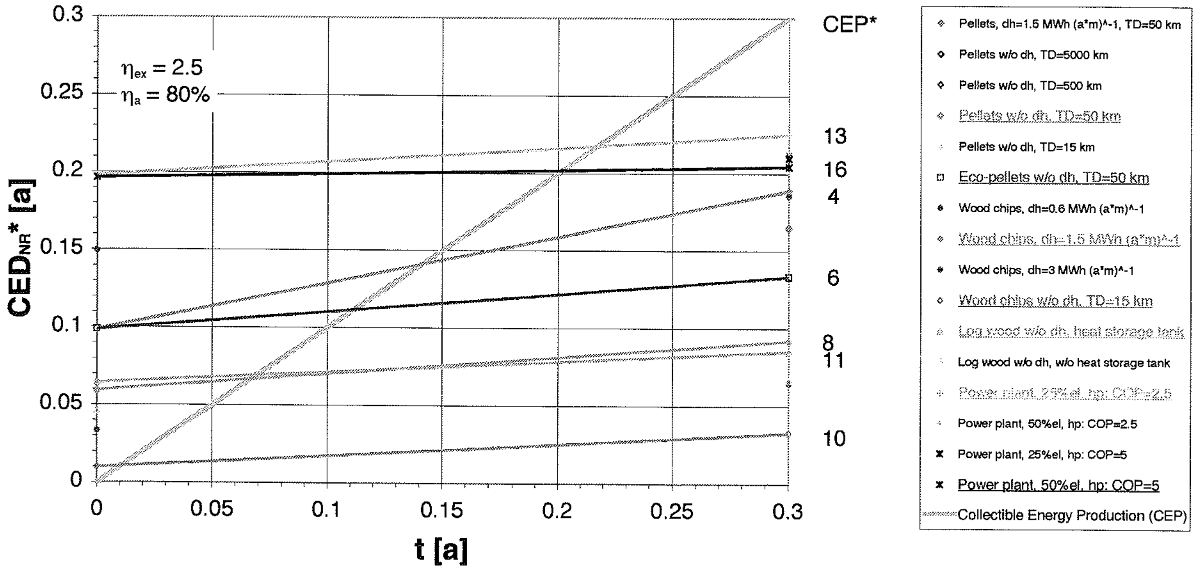

Figure 6.4 CED* for the first 0.3 years as shown in Figure 6.3. In this graph, the payback time $t_{P,NR}$ is determined for the condition $CED_{NR}^* = CEP^*$.

6.3 Influence of the transport distance

Figure 6.5 shows the influence of the transport distance on the scenarios which can potentially be related to long distance transport.

If necessary, the scenario for log wood can be estimated, as the embodied energy is smaller than for wood chips and the slope of the curve is between wood chips and wood pellets due to cargo capacity and energy density in between. However, log wood is not regarded in the diagram, since local supply is assumed for log wood.

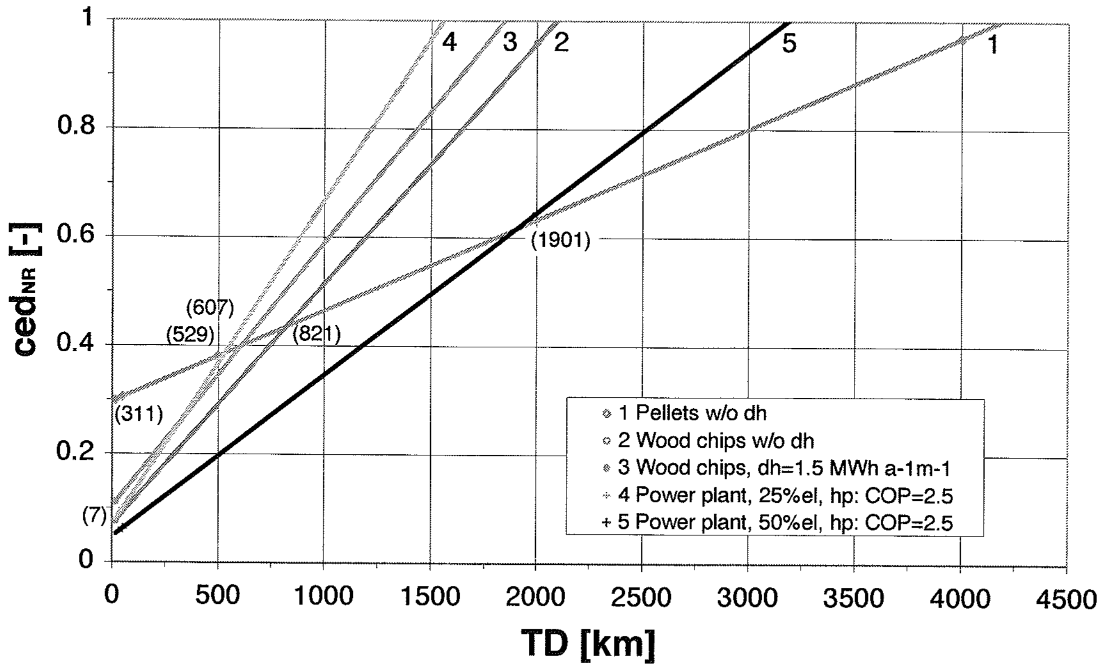

Figure 6.5 Specific Cumulative Energy Demand of non-renewable fuels ced_{NR} as function of transport distance TD for heating applications with pellets, wood chips, and heat pumps driven by power from biomass. The numbers in brackets indicate the crossing point of two different scenarios in km. Road transport with Diesel trucks is assumed with truck capacities of $34 m^3$ for wood chips in a container. For wood pellets, a cylindrical pellet tank is assumed thus leading to a reduced capacity of $23 m^3$. This transport is applied for direct delivery to the consumers. For Diesel, ced=1.25 is assumed, for the heating plants, an annual plant efficiency of 80% is assumed.

6.4 Comparison with literature data

Table 6.4 gives a summary of data from studies on heating applications with light fuel oil, natural gas, wood, and solar panels. Further, data on the energy yield of rape plantation and conversion to bio Diesel are shown. Since end energy instead of collectible energy is regarded for bio Diesel, an additional conversion efficiency < 1 has to be respected and hence a direct comparison of EYC_{NR} with other data is not permitted. For all other data has to be respected, that different assumptions, definitions and boundaries are used. Hence different investigations cannot be compared directly. Further, the definition of EYC_{NR} is not introduced in all studies, although figures which correspond to EYC_{NR} can be derived.

Even with respect to these limitations, different studies from literature confirm the ranking of energy systems as found in the present investigation. [Kessler et al. 2000] confirm the high energy yields of wood energy chains with EYC_{NR}= 10.1 for log wood and 11.0 for wood chips if the whole tree is assumed as primary energy. If the useful mass of wood is assumed as primary energy – as defined in the present study – a value of 12.1 results for both fuel types. In comparison to wood, light fuel oil and natural gas achieve an EYC_{NR} of 0.7 to 0.74, thus leading to the conclusion, that local wood boilers without district heating enable a saving of non-renewable primary energy by a **factor of 14 to 17** compared to heating with oil or gas.

[Sterkele 2001] shows a factor of approximately 10 between wood heating and fossil fuel heating, while [Hartmann & Kaltschmitt 2002] display lower energy yields of biomass than found in the present study and the other cited investigations. However, differences in assumptions on transport distance, plant efficiency, plant lifetime, etc. can result in a difference of the overall results of up to a factor of 2.
Nevertheless, the ranking of different energy systems, which is most relevant for decisions, is similar in all investigations. Further it has to be noted, that the sensitivity analysis presented in this study is valid also if assumptions such as the lifetime or the plant efficiency are varied, but assumed to be identical for all scenarios. Although an improved accordance of different investigations should be aimed at in future, the presented results are regarded as a valuable basis for decisions on the implementation of biomass combustion system.

Table 6.4 Energy Yield Coefficient EYC_{NR} (which respects non-renewable fuels only) for different scenarios from other studies.

Lit	No	Scenario	EYC $= ced^{-1}$ [–]	EYC_{NR} $= ced_{NR}^{-1}$ [–]
[Kessler et al. 2000]		Light fuel oil boiler with flue gas condensation	0.68–0.71	0.70–0.72
		Natural gas boiler with flue gas condensation	0.73	0.74
		Log wood boiler (η_a=65%, *E_{prim}= tree, **E_{prim}=useful wood)	0.46	10.1*/12.1**
		Wood chip boiler (η_a=65%,*E_{prim}= tree,**E_{prim}=useful wood)	0.51	11.0*/12.1**
[Kasser et al. 1999]		Light fuel oil boiler		0.67–0.72
		Light fuel oil boiler with flue gas condensation		0.76
		Natural gas boiler		0.70–0.74
		Natural gas boiler with flue gas condensation		0.81
		Log wood boiler(η_a=65%)	0.51	8.3
		Wood chip boiler(η_a=75%)	0.91	10.0
[Sterkele 2001]		Light fuel oil heating		0.66
		Natural gas heating		0.73
		Wood heating		7.1
		Solar heating		4.0
[Hartmann & Kaltschmitt 2002]	1	Natural gas boiler with flue gas condensation		0.81
(No. as shown in Figure 3.1)	2	Light fuel oil boiler		0.71
	3	Log wood boiler		4.2
	4	Wood chip boiler		4.8
	5	Small district heating system with wood		4.0
	6	Large district heating system with wood		4.2
	7	as 6 but with oil boiler for peak load		2.2
	8	as 7 but with straw instead of wood		1.8
	9	Pellet boiler with additional solar energy collector		3.3
	10	Biomass district heating with solar energy collector		4.0
	11	Gas boiler with additional solar energy collector		0.85
	12	Oil boiler with additional solar energy collector		0.75
	13	Heat pump with collector in the soil		1.04
	14	Heat pump with probe in the soil		0.99
	15	Geothermal and natural gas with large district heat		1.18
	–	Bio Diesel (RME) & by-products		2.4
	–	Ethanol from sugar beets in Europe		2.1
[Studer & Wolfensberger 1991]		Bio Diesel (Rape Methyl Ester RME)		1.50
		Bio Diesel (RME) & by-products (coarse rape meal)		2.43
[Wörgetter et al. 1999]		Bio Diesel (Rape Methyl Ester RME)		≈ 2 – 3
[Jumgmeier & Hausberger 2003]		Bio Diesel (Rape Methyl Ester RME)		≈ 2 – 4

7 Results for $\eta_{ex} = 1$

The following tables show the results as discussed above but with other weighing of the electricity.

7.1 CED as function of efficiency

Table 7.1 Specific Cumulative Energy Demand Coefficient **ced** [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 1$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref **80%**	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	2.62	2.19	1.88	1.65	1.47	1.33
2	Pellets w/o dh	5000	2.51	2.10	1.80	1.58	1.40	1.26
3	Pellets w/o dh	500	2.42	2.02	1.73	1.52	1.35	1.22
4	Pellets w/o dh	50	2.39	2.00	1.71	1.50	1.34	1.20
5	Pellets w/o dh	15	2.38	1.99	1.71	1.50	1.33	1.20
6	Eco-pellets w/o dh	50	2.38	1.98	1.70	1.49	1.33	1.20
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	2.65	2.21	1.90	1.67	1.49	1.34
8	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	15	2.35	1.96	1.69	1.48	1.32	1.19
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	2.25	1.88	1.61	1.42	1.26	1.14
10	Wood chips w/o dh	15	2.14	1.79	1.53	1.34	1.20	1.08
11	Log wood w/o dh, heat storage	5	2.06	1.72	1.48	1.30	1.15	1.04
12	Log wood w/o dh, w/o heat storage	5	2.06	1.72	1.48	1.30	1.15	1.04

Table 7.2 Specific Cumulative Energy Demand of non-renewable fuels **ced**$_{NR}$ [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 1$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref **80%**	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	0.437	0.369	0.320	0.283	0.255	0.232
2	Pellets w/o dh	5000	0.512	0.430	0.371	0.327	0.292	0.265
3	Pellets w/o dh	500	0.418	0.351	0.304	0.268	0.240	0.218
4	Pellets w/o dh	50	0.391	0.329	0.284	0.251	0.225	0.204
5	Pellets w/o dh	15	0.382	0.321	0.278	0.245	0.220	0.199
6	Eco-pellets w/o dh	50	0.096	0.082	0.073	0.066	0.061	0.056
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	0.108	0.095	0.086	0.079	0.074	0.070
8	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	15	0.096	0.084	0.076	0.070	0.065	0.062
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	0.092	0.081	0.073	0.067	0.063	0.059
10	Wood chips w/o dh	15	0.078	0.067	0.060	0.054	0.050	0.046
11	Log wood w/o dh, heat storage	5	0.064	0.056	0.050	0.046	0.043	0.040
12	Log wood w/o dh, w/o heat storage	5	0.063	0.055	0.050	0.046	0.042	0.040

7.2 ced, EYC, and t_P

Table 7.3 Specific Cumulative Energy Demand, Energy Yield Coefficient, and Energy Payback Time for an annual plant efficiency of the heat production of η_a=80%. Electricity is rated with η_{ex} = 1. The reference scenarios 4, 6, 8, 10, 11, 13, and 16 are given in bold. They correspond to the scenarios in the diagrams which are underlined in the legend and drawn in the diagram with a line.

	No	Scenario	TD [km]	ced [–]	EYC $= ced^{-1}$ [–]	t_P [a]	ced_{NR} [–]	EYC_{NR} $= ced_{NR}^{-1}$ [–]	$t_{P,NR}$ [a]
Heat Production	1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	1.651	0.606	∞	0.284	3.52	0.044
	2	Pellets w/o dh	5000	2.332	0.429	∞	1.082	0.924	∞
	3	Pellets w/o dh	500	1.577	0.634	∞	0.327	3.06	0.058
	4	**Pellets w/o dh**	**50**	**1.501**	**0.666**	**∞**	**0.251**	**3.98**	**0.053**
	5	Pellets w/o dh	15	1.495	0.669	∞	0.245	4.08	0.052
	6	**Eco-pellets w/o dh**	**50**	**1.492**	**0.670**	**∞**	**0.066**	**15.12**	**0.042**
	7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	1.670	0.599	∞	0.081	12.40	0.088
	8	**Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$**	**15**	**1.479**	**0.676**	**∞**	**0.071**	**14.17**	**0.034**
	9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	1.416	0.706	∞	0.067	14.85	0.018
	10	**Wood chips w/o dh**	**15**	**1.343**	**0.745**	**∞**	**0.054**	**18.47**	**0.004**
	11	**Log wood w/o dh, heat storage**	**5**	**1.296**	**0.772**	**∞**	**0.046**	**21.78**	**0.027**
	12	Log wood w/o dh, w/o heat storage	5	1.296	0.772	∞	0.046	21.95	0.019
Power	**13**	**Power plant, 25%el, hp: COP=2.5**	**50**	**1.825**	**0.548**	**∞**	**0.090**	**11.10**	**0.225**
	14	Power plant, 50%el, hp: COP=2.5	50	0.920	1.086	2.306	0.053	18.73	0.217
	15	Power plant, 25%el, hp: COP=5	50	0.918	1.090	2.174	0.050	20.03	0.209
	16	**Power plant, 50%el, hp: COP=5**	**50**	**0.465**	**2.150**	**0.369**	**0.032**	**31.67**	**0.206**

8 Results for $\eta_{ex} = 5$

The following tables show the results as discussed above but with other weighing of the electricity.

8.1 CED as function of efficiency

Table 8.1 Specific Cumulative Energy Demand Coefficient **ced** [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 5$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref **80%**	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	2.87	2.41	2.09	1.84	1.65	1.50
2	Pellets w/o dh	5000	2.70	2.27	1.95	1.72	1.54	1.39
3	Pellets w/o dh	500	2.61	2.19	1.89	1.66	1.49	1.35
4	Pellets w/o dh	50	2.58	2.17	1.87	1.65	1.47	1.33
5	Pellets w/o dh	15	2.57	2.16	1.86	1.64	1.47	1.33
6	Eco-pellets w/o dh	50	2.57	2.15	1.86	1.64	1.46	1.33
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	2.77	2.33	2.02	1.79	1.61	1.46
8	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	15	2.46	2.07	1.79	1.59	1.43	1.30
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	2.35	1.98	1.72	1.52	1.37	1.24
10	Wood chips w/o dh	15	2.20	1.85	1.59	1.40	1.26	1.14
11	Log wood w/o dh, heat storage	5	2.14	1.80	1.55	1.37	1.22	1.11
12	Log wood w/o dh, w/o heat storage	5	2.14	1.79	1.55	1.36	1.22	1.11

Table 8.2 Specific Cumulative Energy Demand of non-renewable fuels **ced_{NR}** [TJ_{prim}/TJ_{coll}] for direct heating applications as function of the annual plant efficiency η_a. Electricity is rated with $\eta_{ex} = 5$.

No	Scenario	TD [km]	Annual Plant Efficiency η_a 50%	60%	70%	Ref **80%**	90%	100%
1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	0.681	0.590	0.525	0.476	0.438	0.408
2	Pellets w/o dh	5000	0.703	0.600	0.526	0.471	0.428	0.394
3	Pellets w/o dh	500	0.609	0.522	0.459	0.412	0.376	0.347
4	Pellets w/o dh	50	0.582	0.499	0.440	0.396	0.361	0.333
5	Pellets w/o dh	15	0.573	0.492	0.433	0.390	0.356	0.329
6	Eco-pellets w/o dh	50	0.287	0.253	0.229	0.211	0.197	0.185
7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	0.228	0.216	0.206	0.200	0.194	0.190
8	Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$	15	0.204	0.193	0.184	0.178	0.174	0.170
9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	0.196	0.185	0.177	0.172	0.167	0.163
10	Wood chips w/o dh	15	0.138	0.128	0.120	0.115	0.111	0.107
11	Log wood w/o dh, heat storage	5	0.138	0.129	0.122	0.117	0.113	0.110
12	Log wood w/o dh, w/o heat storage	5	0.136	0.127	0.120	0.115	0.111	0.108

8.2 ced, EYC, and t_P

Table 8.3 Specific Cumulative Energy Demand, Energy Yield Coefficient, and Energy Payback Time for an annual plant efficiency of the heat production of η_a=80%. Electricity is rated with η_{ex} = 5. The reference scenarios 4, 6, 8, 10, 11, 13, and 16 are given in bold. They correspond to the scenarios in the diagrams which are underlined in the legend and drawn in the diagram with a line.

	No	Scenario	TD [km]	ced [–]	EYC $= ced^{-1}$ [–]	t_P [a]	ced_{NR} [–]	EYC_{NR} $= ced_{NR}^{-1}$ [–]	$t_{P,NR}$ [a]
Heat Production	1	Pellets, dh=1.5 MWh $a^{-1}m^{-1}$	50	1.84	0.542	∞	0.477	2.09	0.199
	2	Pellets w/o dh	5000	2.48	0.404	∞	1.227	0.81	∞
	3	Pellets w/o dh	500	1.72	0.581	∞	0.472	2.12	0.367
	4	**Pellets w/o dh**	**50**	**1.65**	**0.608**	**∞**	**0.396**	**2.53**	**0.321**
	5	Pellets w/o dh	15	1.64	0.610	∞	0.390	2.56	0.318
	6	**Eco-pellets w/o dh**	**50**	**1.64**	**0.611**	**∞**	**0.211**	**4.74**	**0.247**
	7	Wood chips, dh=0.6 MWh $a^{-1}m^{-1}$	15	1.79	0.558	∞	0.204	4.91	0.325
	8	**Wood chips, dh=1.5 MWh $a^{-1}m^{-1}$**	**15**	**1.59**	**0.629**	**∞**	**0.180**	**5.56**	**0.129**
	9	Wood chips, dh=3 MWh $a^{-1}m^{-1}$	15	1.52	0.657	∞	0.172	5.80	0.073
	10	**Wood chips w/o dh**	**15**	**1.40**	**0.712**	**∞**	**0.115**	**8.70**	**0.022**
	11	**Log wood w/o dh, heat storage**	**5**	**1.37**	**0.732**	**∞**	**0.117**	**8.56**	**0.145**
	12	Log wood w/o dh, w/o heat storage	5	1.36	0.733	∞	0.115	8.70	0.104
Power	**13**	**Power plant, 25%el, hp: COP=2.5**	**50**	**1.85**	**0.540**	**∞**	**0.118**	**8.5**	**0.286**
	14	Power plant, 50%el, hp: COP=2.5	50	0.95	1.06	3.97	0.081	12.3	0.275
	15	Power plant, 25%el, hp: COP=5	50	0.93	1.07	2.83	0.064	15.7	0.238
	16	**Power plant, 50%el, hp: COP=5**	**50**	**0.48**	**2.09**	**0.424**	**0.045**	**22.0**	**0.234**

9 Outlook

The study presents a comprehensive method for an assessment of different energy systems. The method is applied to the most common technologies of biomass combustion, i.e., direct heating with wood fuels and power production from wood for electricity used for heat pumps. The investigated scenario for power production is valid for both, dedicated power production based on biomass only and co-firing of biomass. The influence of the most relevant parameters such as plant efficiency, fuel pre-treatment, and fuel transport is demonstrated. However, there is a large potential to apply the presented method for **other scenarios**:

1. For other technologies of **biomass utilisation by combustion**.
   a) As an example from district heating plants, there is a potential to optimise the plant operation with respect to summer operation. Plant operators have to decide between two technical solutions: One solution is to maintain the hot water supply with district heating during summer, which results in a relatively low efficiency due to high specific losses. Another solution is a decentralised hot water supply with non-renewable fuels such as electricity from the grid.
   b) In the case of power production, combined heat and power (CHP) can be regarded as an additional option of interest.
   Among many others, the described examples a) and b) can be optimised with respect to minimum fossil CO_2 emissions by application of the presented method.

2. For **biomass utilisation by other conversion technologies than combustion**.
   Alternative technologies such as gasification, pyrolysis, and – for non woody bio fuels with high water content – digestion are of interest for future applications.
   The presented method enables e.g. a comparison of different scenarios with respect to one specific fuel which is suited for the utilisation in conversion technologies, e.g. wood for combustion, gasification, or pyrolysis.
   On the other hand, the method can also be applied to compare different scenarios of biomass plantation and utilisation, e.g. wood production and utilisation in combustion plants versus production of herbaceous plants to be utilised for digestion or rape plantation for the production of bio Diesel.

10 List of Symbols

Symbols

E	Energy
F	Fuel
D	Demand
P	Production
t	time

Abbreviations and Definitions

CED	Cumulative Energy Demand
ced	Specific Cumulative Energy Demand
CED*	Time equivalent Cumulative Energy Demand
CEP	Cumulative Energy Production
CEP*	Time equivalent Cumulative Energy Production
EYC	Energy Yield Coefficient
COP	Coefficient of Performance
t_P	Energy Payback Time
η	Efficiency
η_a	Annual plant efficiency
η_{ex}	Exergetic valuation of electricity
dh	district heating with heat distribution density described by [$MWh\ a^{-1}m^{-1}$] (MWh distributed collectible energy per year and meter of district heating system length)
w/o dh	without district heating
TD	transport distance of the fuel (pellets) to the consumer in [km]
$\dot{Q}_{in} = \dot{F}_H$	Energy input based on the heating value of the fuel
hp	heat pump

Indices

prim	primary energy
sec	secondary energy
end	end energy
coll	collectible energy
a	annual
ex	exergetic
A	Auxiliary energy demand
P	Production (of plant)
U	Utilisation (of plant)
D	Disposal (of plant)
R	Renewable
NR	Non-renewable
WOF	Without Fuel

11 Literature

Bansal, N.; Gürzenich, D.; Mathur, J.; Wagner, H.-J.: Material and Energy Demand for selected renewable energy technologies, Project INI-305-96 by DLR and BMBF, Indian Institute of Technology New Delhi (India), and University of Essen (Germany), 1998

Frischknecht, R.; Hofstetter, P.; Knoepfel, I.; Dones, R.; Zollinger, E.: *Environmental Life-Cycle Inventories of Energy Systems*. Swiss Federal Institute of Technology (ETH), Zürich, Paul Scherrer Institute (PSI) Villigen, Swiss Federal Office of Energy, Berne, Zürich and Villigen 1994

Hartmann, H.; Kaltschmitt, M. (Eds.): *Biomasse als erneuerbarer Energieträger*, Schriftenreihe Nachwachsende Rohstoffe Band 3, Landwirtschafts-Verlag Münster (D), 2002

Hasler, Ph.; Nussbaumer, Th.; Bürli, J.: *Herstellung von Holzpellets*. Bundesamt für Energie, Bern 2001

Jungbluth, N., Frischknecht, R., Faist, M.: *Ökobilanz für die Stromerzeugung aus Holzbrennstoffen und Altholz*. Bundesamt für Energie, Bern/Uster, 2002

Jungmeier, G.; Hausberger, S.: *Treibhausgas-Emissionen von Transportsystemen. Vergleich von biogenen und fossilen Treibstoffen*, Joanneum Research Graz, BMLFUW, BMVIT, Land Steiermark, Graz 2003

Kasser, U.; Pöll, M.; Graffe, K.: *Ökologische Bewertung mit Hilfe der grauen Energie*. Schriftenreihe Umwelt Nr. 315, Bundesamt für Umwelt, Wald und Landschaft, Bern 2001

Kessler, F.; Knechtle, N.; Frischknecht, R.: *Heizenergie aus Heizöl, Erdgas oder Holz*, Schriftenreihe Umwelt Nr. 315, Bundesamt für Umwelt, Wald und Landschaft, Bern 2000

Nussbaumer, T.: Combustion and Co-Combustion of Biomass, *12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection*, 17–21 June 2002, Amsterdam, Volume I, ISBN 88-900442-5-X, ISBN 3-936338-10-8, 31–37

Nussbaumer, Th.; Good, J.; Jenni, A.; Bühler, R.; Gabathuler, H.R.: *QS Holzheizung: Automatische Holzheizungen: Planung und Ausführung*. Bundesamt für Energie, Bern 2001

Recknagel, H.; Sprenger, E.; Schramek, E.R.: *Taschenbuch für Heizung und Klimatechnik*. 67. Auflage, ISBN 3-486-26213-0, Oldenburg, 1995

Sterkele, U.: Alternativenergie im Kosten- und Ökovergleich, *Spektrum der Gebäudetechnik*, 5 2001, 42–45

Studer, R.; Wolfensberger, U.: *Energie- und CO_2-Bilanzen über den Alternativ-Treibstoff Biodiesel*, Landwirtschaft Schweiz, Band 4 (12), 1991, 637–640

VDI 4600: Verein Deutscher Ingenieure: *Kumulierter Energieaufwand – Begriffe, Definitionen, Berechnungsmethoden – Cumulative Energy Demand, Terms, Definitions, Methods of Calculations*, VDI-Richtlinie 4600, Düsseldorf (D), 1997

Wagner, H.-J.; Gürzenich, D.; Pick, E.: Cumulative Energy Demand of Wind Energy and Solar Water Heating Systems, International Renewable Energy Magazine, 1999

Wörgetter, M. et al.: Ökobilanz Biodiesel, Bericht des Bundesministeriums für Land- und Forstwirtschaft, Wien 1999