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# Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies

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**Abstract**

Policy objectives to increase biomass' contribution to the energy supply in industrialised countries are quite ambitious, but biomass resources are rather limited and expensive in many situations. Therefore, an optimal utilisation of resources producing a maximum of energy at minimal costs is desirable. A wide variety of biomass conversion options with different performance characteristics exists. Also, the economic and energetic performance depends on many variables, such as costs of logistics, scaling effects and degree of heat utilisation to name a few. Therefore, system analysis is needed to identify optimal systems. In this study, different biomass energy systems are analysed regarding their energetic and economic performance related to fossil primary energy savings. The systems studied contain residual woody biomass, logistics, heat distribution and combustion or gasification units producing heat, power or CHP. The performance of systems is expressed as a function of scale. This is done by applying generic functions to describe plants' efficiencies and specific investment costs and by expressing costs and energy use of logistic and heat distribution as a function of conversion unit capacities. Scale effects within biomass energy systems are significant. Up-scaling increases the relative primary energy savings of the studied systems within the scale range of 0–300 $MW_{th\text{-}input}$ regarded, while costs per unit of primary energy savings decrease or have an optimum at medium scales. The relative primary energy savings lay between 0.53 and 1.13 $GJ_{fossil\text{-}saved}\,GJ^{-1}_{biomass}$. With costs of 4–20€ $GJ^{-1}_{fossil\text{-}saved}$ systems are not profitable under Dutch conditions with residual wood prices of 3.8€ $GJ^{-1}_{LHV}$ while firing waste wood with zero costs at the plant gate renders profitable operation possible. Favourable in both economic and energy terms are BIG/CC plants. 

*Keywords:* Biomass; System analysis; Economies of scale; Gasification; Combustion; Logistics; Heat distribution; CHP

## 1. Introduction

At present, in many countries key problems regarding the use of available biomass residues for energy production are their often limited availability and high costs compared to fossil fuels. This is particularly true in a densely populated and industrialised country like the Netherlands. Therefore, an optimal utilisation of biomass resources that means a maximum of energy production at minimal costs is desired. But a wide variety of bio-energy chains is possible. The large number of possible combinations of various

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biomass streams, conversion options, scale ranges, logistics and energy carriers produced, makes it difficult to identify optimal systems. This study presents a comprehensive analysis of those factors and provides an approach to identify optimal bioenergy systems from either a cost or energy point of view.

Several studies compare biomass energy systems using different conversion technologies and fuels, e.g. [1–3]. But, the potential competition between small scale conversion (with allegedly low biomass transport costs and potentially easier heat utilisation) and large scale conversion (in general, with higher efficiency but also higher transport costs) deserves a comprehensive analysis as well. Former analyses discussing optimal biomass energy systems in relation to scale have been carried out as well, e.g. [4–6]. However, these do not include important options of biomass energy systems, namely (combined) generation of heat and systems at very small scales. Besides that, the number of conversion technologies considered is rather limited.

This analysis focuses on a variety of thermal conversion systems including different combustion and gasification options in the 0.1–300 $MW_{th\text{-}input}$ range. They differ with regard to applicable scale ranges, possible biomass fuels, energetic efficiencies, investment and operational costs and energy carriers produced, namely heat, combined heat and power, or power only. Special attention is paid to scale effects that influence energetic efficiencies and investment costs. Other important parameters considered are scale dependent effects on biomass logistics and heat distribution, as well as the conditions of energy markets in the form of heat and power prices. Different residual biomass streams ('clean' wood and waste wood) are exemplary considered in this study.

This system analysis evaluates and compares many bio-energy chains for a wide scale range with respect to energy production and costs. Extensive sensitivity analyses are carried out to investigate uncertainties and the influence of site-specific conditions and parameters. The analysis presented here is carried out for Dutch conditions, but the approach can easily be applied to other regions and countries.

## 2. Methodology

The methodology applied contains three main steps: (1) The target parameters that will serve for the comparison of the biomass energy systems are defined and the way they are calculated is presented. (2) The way to include scale effects of logistic and heat distribution into the chain analysis is described. (3) The mode of composing generic 'trendlines' to represent scale effects of the plants' efficiencies and investment costs is discussed.

### 2.1. Target parameters

The biomass energy systems considered produce different energy carriers, namely heat and/or power. Therefore, *fossil primary energy savings* are chosen as the functional unit to which costs and energy efficiencies of the bio-energy systems are related. In the following, they are simply referred to as *primary energy savings*.

Assuming that bio-energy systems will replace fossil capacities, the primary energy savings are calculated by using the average efficiency of current fossil Dutch heat and power plants. From these primary energy savings, the primary energy use of logistics and losses of heat distribution of the biomass energy system are subtracted. The result gives the overall primary energy savings (see formula (1)):

$$PES = \eta_h P h_h / \eta_{h,nl} + \eta_e P h_e / \eta_{e,nl} - PE_t - PE_d, \quad (1)$$

where $PES$ is the total primary energy savings (MJ yr$^{-1}$), $\eta_h$ the thermal efficiency of plant (dimensionless), $P$ the capacity of the plant ($MW_{th}$), $h_h$ the full-load operation time—heat production (s yr$^{-1}$), $\eta_{h,nl}$ the average thermal efficiency of fossil Dutch heating plants (dimensionless), $\eta_e$ the electrical efficiency of plant (dimensionless), $\eta_{e,nl}$ the average electrical efficiency of fossil Dutch power plants (dimensionless), $h_e$ the full-load operation time—electricity generation (s yr$^{-1}$), $PE_t$ the primary energy use of transport (MJ yr$^{-1}$), and $PE_d$ the primary energy use of heat distribution (MJ yr$^{-1}$).

With respect to the energetic efficiency of entire bio-energy chains, the relative primary energy savings are calculated to enable the comparison of primary energy savings over different plant scales. *The relative primary energy savings* are defined as the system's primary energy savings divided by the energy content of the biomass used (see formula (2)):

$$PES_{\text{relative}} = PES/PE_{\text{b}}, \tag{2}$$

where $PES_{\text{relative}}$ is the relative primary energy savings (dimensionless), and $PE_{\text{b}}$ the energy content of biomass input (MJ yr$^{-1}$).

The parameter used to compare bio-energy systems in terms of costs is the *total costs per unit of primary energy saved*. The total costs are calculated from the plant, fuel, transportation and heat distribution costs and the revenues from energy sales and capacity reimbursements. The plant's costs consist of (1) the capital costs that result from the investment costs and the annuity and (2) the operation and maintenance costs, which are determined by using a percentage of investment costs. Thus, the total costs represent the operator's remaining costs or profits, respectively, under current conditions of the Dutch energy market (see formula (3)):

$$Cost/PES = [r/(1-[1+r]^{-n})IP + O + B + T + H_{\text{d}} - H_{\text{sale}} - E_{\text{sale}} - E_{\text{re}}]/PES, \tag{3}$$

where *Cost* is the total plant's costs (€ MJ$^{-1}$yr$^{-1}$), $r$ the interest rate (dimensionless), $n$ the lifetime (yr), $I$ the spec. investment costs (€ MW$_{\text{th}}^{-1}$), $O$ the operating and maintenance cost (€ yr$^{-1}$), $B$ the costs of biomass fuel (€ yr$^{-1}$), $T$ the transport costs (€ yr$^{-1}$), $H_{\text{d}}$ the costs of heat distribution (€ yr$^{-1}$), $E_{\text{re}}$ the installed capacity reimbursement (€ yr$^{-1}$), $E_{\text{sale}}$ the revenue from electricity sales (€ yr$^{-1}$), and $H_{\text{sale}}$ the revenue from heat sales (€ yr$^{-1}$).

### 2.2. Scaling of transportation and heat distribution

#### 2.2.1. Transport

To determine the energy use and costs of transportation, transport requirements are related to the spatial distribution of biomass. Here, it is assumed that the distribution of biomass over an area is constant, expressed as biomass distribution density. Moreover, it is stated that the biomass is transported over a marginal transport distance that is the radius of a circle in which the biomass is spread with the given distribution density. Consequently, the total amount of ton km to transport a unit of biomass is the integral of the marginal distance over mass (see formula (4)):

$$sm' = \tfrac{2}{3} m^{1.5} (D_{\text{b}}\pi)^{-0.5}, \tag{4}$$

where $sm'$ is the average ton km for transport (ton km yr$^{-1}$), $m$ the biomass fuel (ton yr$^{-1}$), and $D_{\text{b}}$ the biomass distribution density (ton km$^{-2}$ yr$^{-1}$).

#### 2.2.2. Heat

Scale effects of heat distribution are considered in a similar way as those of transportation. In this case the heat utilised and distance of distribution are determined. In order to do so, a constant heat demand density describing the capacity demand in an area is specified. It is assumed that the capacity demand is required during a certain number of operation hours during which heat produced is utilised (see formula (5)):

$$s_{\text{d}}Q' = \tfrac{2}{3} Q^{1.5} (D_{\text{h}} h_{\text{h}} \pi)^{-0.5}, \tag{5}$$

where $s_{\text{d}}Q'$ is the average amount of heat and distance for distribution (MJ km yr$^{-1}$), $Q$ the amount of heat for distribution (MJ yr$^{-1}$), and $D_{\text{h}}$ the density of heat demand (MW km$^{-2}$).

### 2.3. Scale effects of the installation's economic and energetic performance

Crucial values determining the performance of biomass energy systems are the energy efficiencies as well as the specific investment costs of the conversion technologies [4]. These values are dependent on scale, in a way that efficiencies increase and specific investment costs decrease with up-scaling. Efficiencies and cost values do not increase, respectively, decrease to an unlimited extent, but approach a maximum or minimum at large scale, while for smaller capacities, the scale effects are more pronounced. Those scale effects can be described by generic curves or 'trendlines'.

The economies of scale, thus the decreasing specific investment costs while up-scaling a certain technologies can generally be described as a power function e.g. [7,8]. While Jenkins [9] qualifies that this relation might not be applicable at larger scales of about 100–1400 MW$_{\text{e}}$, e.g. Faaij et al. [7] show, that for most major components of BIG/CC in the capacity range of 30–200 MW$_{\text{e}}$ this relation is valid. In this study specific investment costs are thus regarded as a power function in the scale range of 0–300 MW$_{\text{th-input}}$.

Table 1
Heat and power plant categories[a]

| Abbreviation | Technology | Energy carrier | Power cycle | Scales ($MW_{th\text{-}input}$) |
|---|---|---|---|---|
| UPB/H | Underfed pile burner | Heat | — | 0.03–5 |
| GF/H | Grate firing | Heat | — | 1–20 |
| UG/H | Updraft-gasification | Heat | — | 0.1–10 |
| FBC/ST | Fluidised bed combustion | CHP, Power | Steam cycle | 10–200 |
| GF/ST | Grate firing | CHP, Power | Steam cycle | 10–200 |
| DG/GE | Downdraft-gasification | CHP, Power | Gas engine | 0.01–3 |
| FBG/GE | Fluidised bed gasification—atmospheric | CHP, Power | Gas engine | 3–30 |
| BIG/CCa | Fluidised bed gasification—atmospheric | CHP, Power | Combined cycle | 10–300 |
| BIG/CCp | Fluidised bed gasification—pressurised | CHP, Power | Combined cycle | 20–300 |

[a]Data on energetic and economic performances are taken from [6,15,17–33]. Besides the technologies are selected according to [34–40].

Electrical and thermal efficiency are also described as a power or logarithmic relation to account for the decreasing scale effect at larger capacities [4,10].

In this study, trendlines of efficiencies and investment costs are composed by regression technique, wherever possible. In case the data are insufficient to do so, an estimate based on the trendlines of 'comparable' technologies is made. The trendlines are based on efficiencies and investment costs of plants as observed in practice. Most data used here represent real plants or estimates about average values and ranges. Other data are taken from projections, which in turn are derived from model calculations.

## 3. Biomass energy systems

The parts of bio-energy systems (conversion units, biomass fuels, logistics and heat distribution) and the economic parameters used in the analysis are discussed below.

### 3.1. Heat and power plants

A broad variety of combustion and gasification technologies producing heat, CHP or power at different scale ranges is considered. Throughout this study, *scales of conversion systems are given in thermal capacity of biomass input* to facilitate comparisons of technologies and systems.

For heat generation only, three technologies are considered: underfed pile burners at small scales below $5\,MW_{th\text{-}input}$, grate-firing with capacities from 1 up to $20\,MW_{th\text{-}input}$ and updraft gasifiers supplying a capacity range from 0.03 up to $10\,MW_{th\text{-}input}$.

For power generation, both CHP and power production variants are assessed within every technology. Six different technologies are included. At scales of 10 up to $200\,MW_{th\text{-}input}$, fluidised bed combustion and grate firing with steam cycles are analysed. Downdraft gasifiers up to $3\,MW_{th\text{-}input}$, and atmospheric fluidised bed gasification up to $30\,MW_{th\text{-}input}$ are linked with gas engines. Atmospheric and pressurised fluidised bed gasification in combination with combined cycles are employed on large scales up to $300\,MW_{th\text{-}input}$. Table 1 summarises the heat and power plant categories studied.

The 'trendlines' describing efficiencies and investment costs of heat and power plants are presented in Figs. 1–4. Fine lines denote estimates, because available data are not sufficient for regression. In the case of underfed pile burners and downdraft gasifiers a constant efficiency is assumed, because only a small scale range is covered. The gradient of the specific investment costs of fluidised bed combustion is based on the investment costs of grate firing and the one of updraft gasification on downdraft gasification which are more or less comparable technologies.

Fig. 1 represents thermal efficiencies of installation solely for heat generation. Fig. 2 contains the electrical efficiencies for power generation technologies. Figs. 3 and 4 show specific investment costs in €$_{1999}$ of the systems. Investment costs are considered to represent facilities making use of 'clean' wood. A complete list of data and references on which the trendlines are based can be found in [11].

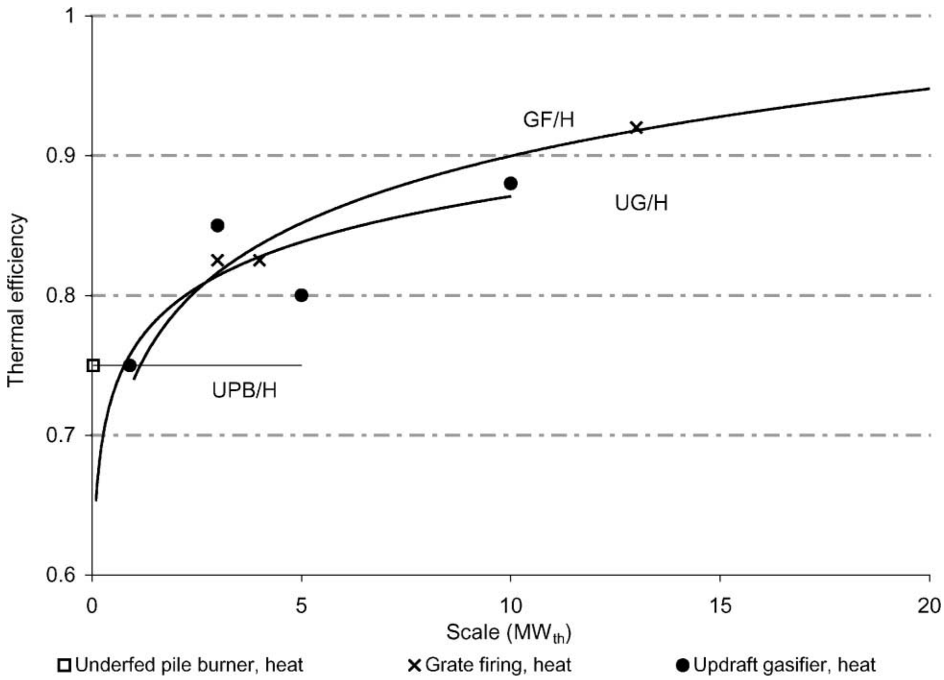


Fig. 1. Thermal efficiencies of heating plants.

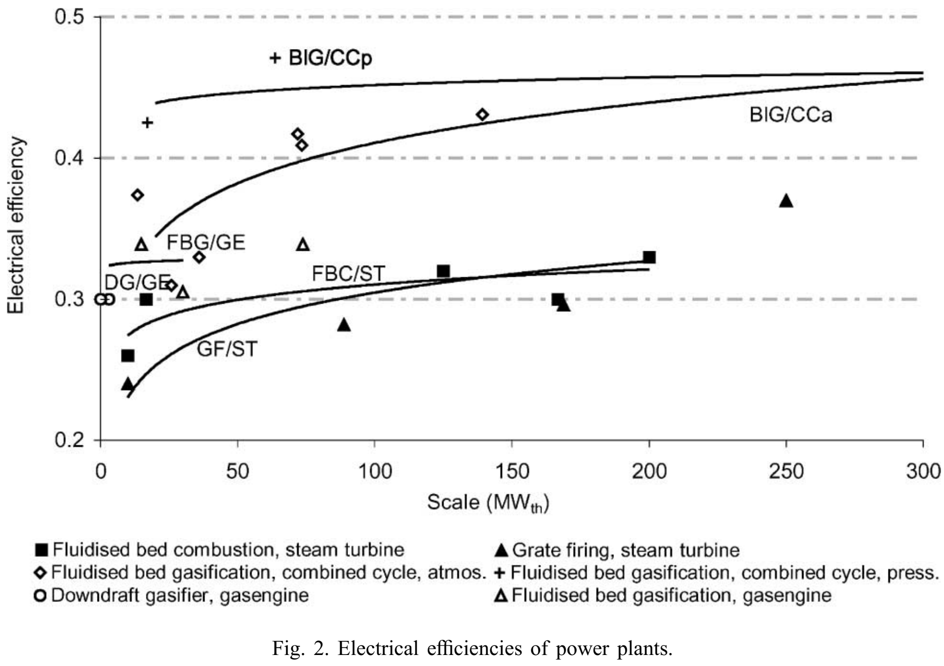


Fig. 2. Electrical efficiencies of power plants.

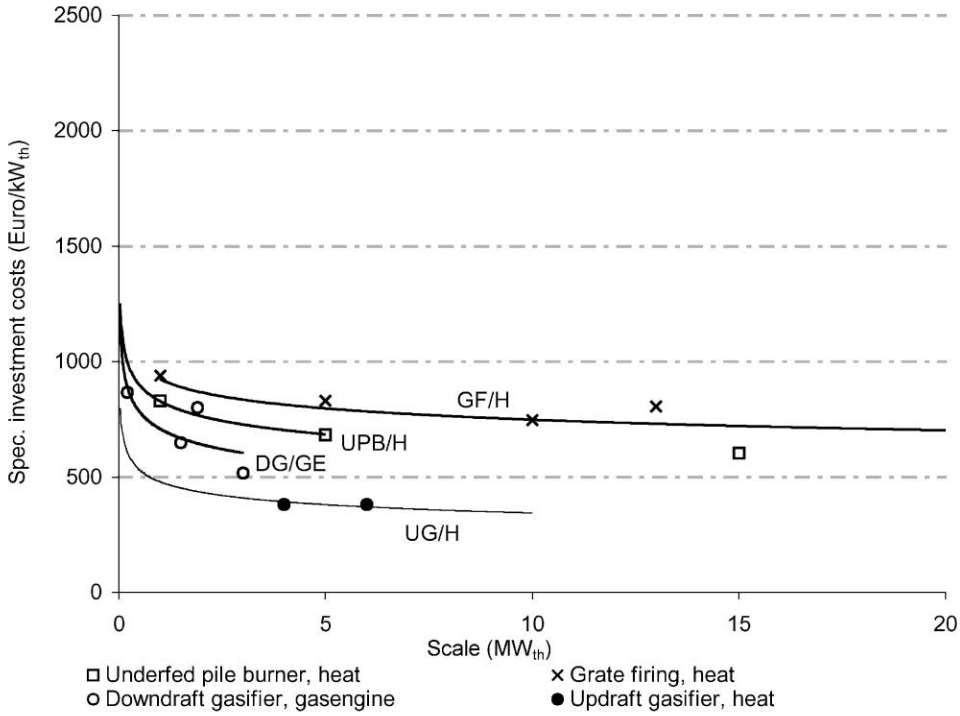


Fig. 3. Investment costs of installations at small scales.

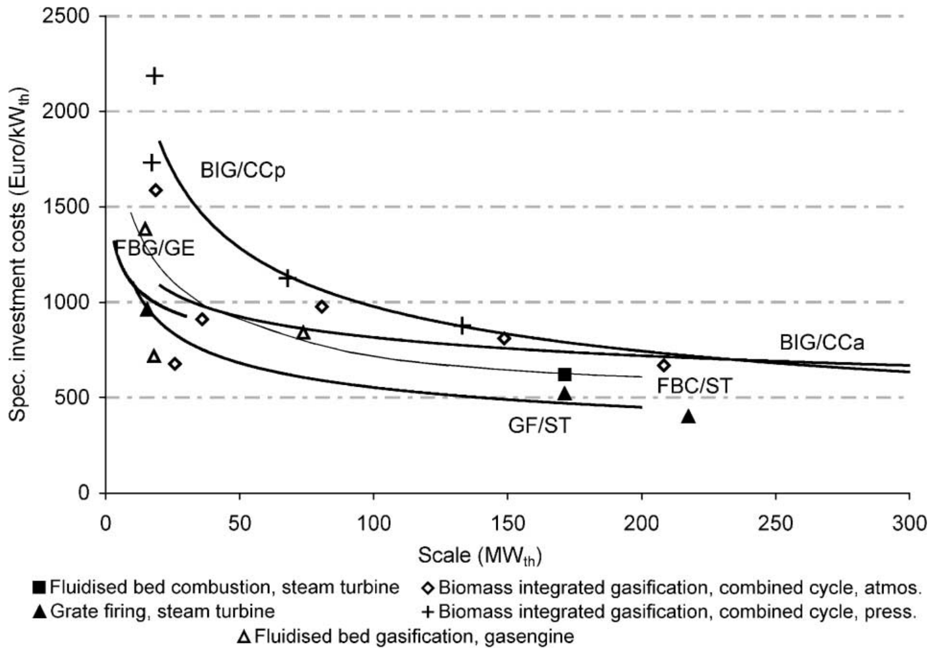


Fig. 4. Investment costs of installations at large scales.

### 3.2. Biomass fuels

The biomass energy systems are studied with 'clean' wood (forestry residues) as biomass fuel. Because it can be used in all installations described in Table 1, it is the basis for the systems comparison. To study the influence of fuel on the total costs also the utilisation of waste wood (industrial waste wood, demolition wood and wood products) is considered. The use of waste wood often necessitates additional gas cleaning. This usually results in higher investment and operation costs which are generally economically more feasible in larger systems. The use of waste wood is also more problematic in hot gas 'clean'-up processes employed in pressurised fluidised bed gasification with combined cycles. Therefore, waste wood is considered as fuel only for larger grate firing systems, fluidised bed combustion and atmospheric fluidised bed gasification with combined cycles.

The prices of biomass are quite variable and market price development cannot be forecasted with certainty at the moment. 0–15.8€ $GJ_{LHV}^{-1}$ for residual wood are estimated in the European context [12], while Faaij et al. [13] estimates for wood from thinning in the Netherlands 3.5–4.1€ $GJ_{LHV}^{-1}$. A price of 3.8€ $GJ_{LHV}^{-1}$ for 'clean' wood is used here. For waste wood in shorter term planning, and thus, in this study zero costs are often assumed at the plant gate.

### 3.3. Logistics

Concerning logistics road transport is assumed in all cases. Furthermore, on average two transfer operations are assumed to take place [4]. Energy farming, waste production and collection are not considered here; we focus on presently available residual streams.

The specific costs of transportation depend on the distance of transport, while the specific energy use depends on truck load capacities. Here it is assumed that fuel supply is transported by multiple loads of 28 ton. This might not fully describe the situation for plants smaller than 0.1 $MW_{th\text{-}input}$, but, however, the resulting error is not significant.

### 3.4. Heat distribution

In this study heat distribution is limited to district-heating networks to supply space heating demands below 100°C, because this seems least dependent on site-specific conditions and the results are applicable more generally. Delivery of high temperature process heat is not considered in this study.

The heat demand as well as the distribution costs depend on the area to where the heat is distributed. Here a medium demand and costs representative for a residential area with mainly single family houses and some apartment buildings are used. According to Ossebaard et al. [14] the heat demand density of such areas amounts on average 2.2 MW $km^{-2}$. This is equivalent to the largest plants considered in this study with 300 $MW_{th\text{-}input}$ distributing their heat within a radius of about 11 km. The specific energy losses of heat distribution depend on plants' capacities as well. Heat losses range from 0.5 to 45% $km^{-1}$ for current heat distribution networks in the considered capacity range of 0.03–300 $MW_{th\text{-}input}$ [14].

### 3.5. Economics

Heat and power plants are considered for two different modes of operation. Power generation is calculated with a full-load operation time of 7000 h $a^{-1}$ [4]. Heat is used during 2500 h $a^{-1}$ full-load. This estimation is made according to [15]. Operating costs including maintenance, insurance and personnel vary for different technologies and annual costs range from 3 to 6% of total investment costs [7]. A value of 4% is used in this study.

The rate of real interest supposed is 4% and the average lifetime span is 25 years [4]. Heat prices usually include the costs of heat distribution. Because here distribution is accounted for separately, the upper limit of heat prices (3.6€ $GJ^{-1}$) is calculated with. The revenues from power sales are determined by means of current Dutch electricity prices (6.5€ $GJ^{-1}$). A reimbursement for installed power generating capacity (95.3€ $kW_e^{-1}$) paid by the Dutch government is taken into account, too. The electricity price and the reimbursement all in all with the assumed operation time result in an electricity revenue of about 10.34€ $GJ^{-1}$ or 0.037€ $kWh^{-1}$.

The main data relevant to describe biomass fuels, logistics, heat distribution, and overall economic parameters used in system's performance calculations are summarised in Table 2.

Table 2
Input data related to biomass energy systems

| Parameter | Value | |
|---|---|---|
| Biomass fuels | 'Clean' wood | Waste wood |
| Biomass distribution density (ton $km^{-2}$)[a] | 46 | 24 |
| Lower heating value (GJ $ton^{-1}$)[b] | 8 | 14.5 |
| Costs (€ $GJ_{LHV}^{-1}$)[c] | 3.8 | 0 |
| Logistics | | |
| Specific transport costs (€ $km^{-1}$ $ton^{-1}$)[d] | 5.8× (average transport distance (km))$^{-0.6}$ | |
| Specific energy use of transport ($km^{-1}$ $ton^{-1}$)[e] | 0.8 | |
| Mininimum distances transfer (km) | 1st: 20; 2nd: 100 | |
| Costs of transfer (€ $ton^{-1}$)[f] | 0.28 | |
| Energy use of transfer (MJ $ton^{-1}$)[a] | 0.47 | |
| Heat distribution[g] | | |
| Specific costs of heat distribution (€ $kW^{-1}$ $km^{-1}$) | 64.8 | |
| Percentual energy loss of heat distribution ($km^{-1}$) | 0.08× (capacity of plant ($MW_{th\text{-}input}$))$^{-0.5}$ | |
| Heat demand density (MW $km^{-2}$) | 2.2 | |
| Economic parameters[f] | | |
| Load factor (h $yr^{-1}$)—Power: | 7000 | |
| Load factor (h $yr^{-1}$)—Heat: | 2500 | |
| Part operation costs from investment costs (%) | 4 | |
| Lifetime (yr) | 25 | |
| Rent (%) | 4 | |
| Heat price (€ $GJ^{-1}$) | 3.6 | |
| Electricity price (€ $GJ^{-1}$) | 6.5 | |
| Installed capacity reimbursement (€ $kW_e^{-1}$) | 95.3 | |
| Dutch heat and power plants | | |
| Electrical efficiency (%)[h] | 43 | |
| Thermal efficiency (%)[i] | 90 | |

[a] Made up from prognosis of total amounts in the Netherlands 1,930,000 ton $yr^{-1}$ (thinnings and prunings) and 1,050,000 ton $yr^{-1}$ (industrial waste wood, demolition wood and wood products) respectively [13].
[b] Average values derived from [13,41–44].
[c] Average values derived from [12,13].
[d] Trendline derived from [12], based on a load factor of 100% and empty return; the transport costs of waste wood are defined to be zero.
[e] Ref. [45].
[f] Besides load factors all data on economic parameters according to [4].
[g] Source of all data on heat distribution [14].
[h] Ref. [46], efficiency based on LHV.
[i] Ref. [47], efficiency based on LHV.

## 4. Results: energetic and economic performances

In this section results of the analysis are described (for abbreviations see Table 1). The main results are related to 'clean' wood firing.

### 4.1. Relative primary energy savings

The relative primary energy savings for the entire biomass energy systems, i.e. the primary energy savings per unit of biomass energy used of all single heat and power generation technologies and two selected CHP cases are presented in Fig. 5. Generally, relative primary energy savings increase with scale. The largest possible scale of a conversion system provides the highest net energy returns. Thus in all cases and at the scales considered the scale effects of increasing efficiencies outweigh the larger energy use of logistics as well as losses of heat distribution.

The highest relative primary energy savings are obtained with atmospheric and pressurised BIG/CC plants. Power generation with fluidised bed

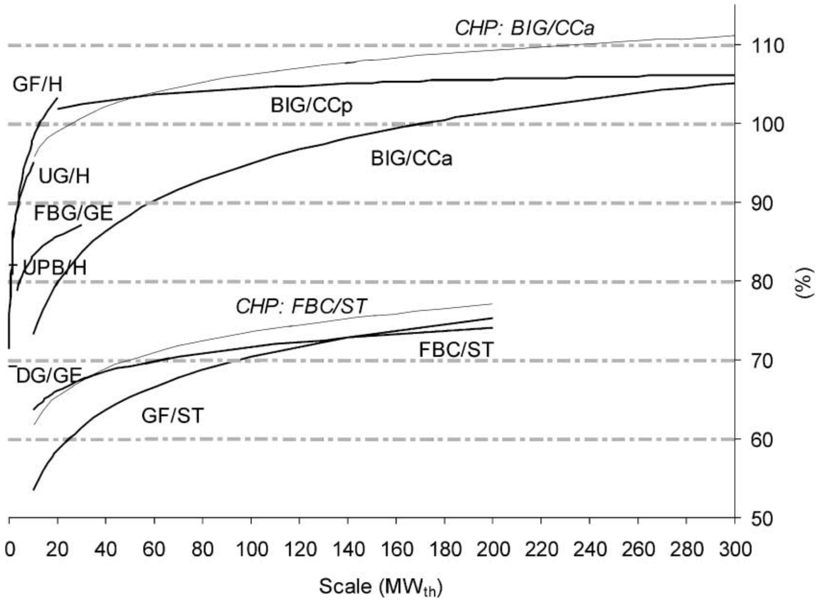


Fig. 5. Relative primary energy savings with 'clean' wood firing.

combustion and grate firings achieves the lowest relative primary energy savings. At small scales, the relative primary energy savings of heat production with grate firings and updraft gasifiers can nearly compete with BIG/CC systems.

Comparing CHP generation of a certain technology with the respective power generation case, reveals that not surprisingly, CHP generation generally provides higher relative primary energy savings than the respective power production cases.

Fossil primary energy savings are defined by using average current efficiencies for Dutch heat and power plants. Relative primary energy savings above 100% can be explained by the fact that certain biomass conversion technologies have higher efficiencies than the Dutch reference energy systems. Between the biomass technologies relative primary energy savings show a wide range between 53% and 113%. Therefore, it can be concluded that the selection of a conversion technology has a substantial influence on the relative primary energy savings of biomass energy systems and therefore on the effective use of (available) biomass resources in energy terms.

### 4.2. Costs per primary energy savings

The total costs per unit of primary energy saved including all heat and power revenues in relation to scale are shown in Fig. 6. The economic performance of power production improves with increasing scales. With the assumptions made and within the regarded scale range, it can be stated that scale effects of decreasing specific investment costs and higher revenues from power sales due to increasing efficiencies, prevail over the increasing costs for logistics and heat distribution. But, in contrast, the costs per unit of primary energy savings of heat generation in general and CHP-production with fluidised bed combustion fall to a minimum and then rise again. This can be explained by the fact that the costs for logistics and especially heat distribution costs increase more strongly from above a certain scale than the cost benefits obtained by economies of scale and the higher efficiencies of the conversion options. This behaviour of having a cost optimal scale could be observed for other technologies at scales above 300 $MW_{th\text{-}input}$ as well.

The lowest costs per unit of primary energy saved are observed for BIG/CC. These are therefore favourable with regard to both economic and energetic

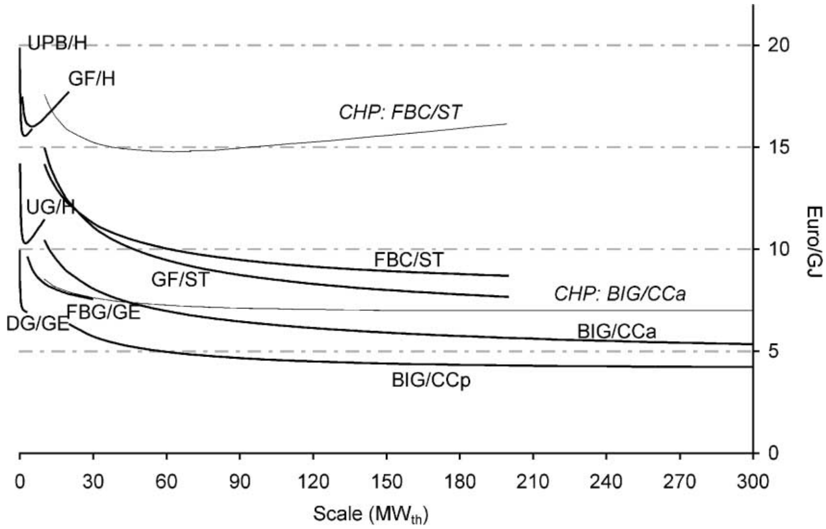


Fig. 6. Costs per unit of primary energy saved with 'clean' wood firing.

performances. With regard to small scale biomass energy systems, power generation with downdraft gasifiers results in the lowest costs per unit of primary energy saved.

In most cases, power generation only is more favourable to CHP generation with regard to costs per primary energy savings. This can be explained by the fact that the reduced income, caused by reduced electrical efficiencies in CHP-mode, outweighs the income generated from heat supply. Because the price for heat is only 3.6€ $GJ^{-1}$, the load factor of heat production is 2500 $h\,a^{-1}$ and moreover costs of heat distribution are quite high with 65€ $kW^{-1}\,km^{-1}$, the income from heat supply is low or even negative. At scales of 10–30 $MW_{th\text{-}input}$ costs per unit of primary energy saved of fluidised bed gasification with gas engines or BIG/CC are in the same range.

Looking at the overall results, the costs per unit of primary energy saved can vary from 4 to 20€ $GJ^{-1}$. The figures of total costs are positive, which means that under energy market and all assumptions made, none of the investigated technologies can compete with current heat and power production in the Netherlands.

The heat and electricity production costs of the non-CHP systems are between 14–25€ $GJ_{heat}^{-1}$ and 0.06–0.15€ $kWh^{-1}$, while those of the CHP-systems are even higher. These costs are in the range, that other studies indicate for biomass energy systems, e.g. [1,6].

### 4.3. Other biomass fuels

Firing waste wood does not change the relative primary energy savings remarkably. Compared with firing of 'clean' wood differences in the relative primary energy savings are less than 1%. This is due to the fact that changes of biomass distribution density and lower heating value are considered, but no changes of the efficiency of the conversion itself.

In contrast to the relative primary energy savings, the economic performance improves notably using waste wood. The reason for this is that fuel as well as transportation costs are zero as they are assumed to be off-set by tipping fees. The costs per primary energy savings are presented in Fig. 7 for the technologies capable to fire waste wood. Compared to 'clean' wood utilisation, the major difference is that (1) combustion technologies are competitive with atmospheric BIG/CC and (2) total costs reach negative values so that competitive biomass energy production is possible above scales of about 50–80 $MW_{th\text{-}input}$. The costs per unit of primary energy savings are in the range of −2–8€ $GJ^{-1}$. The according electricity production costs are 0.001–0.012€ $kWh^{-1}$.

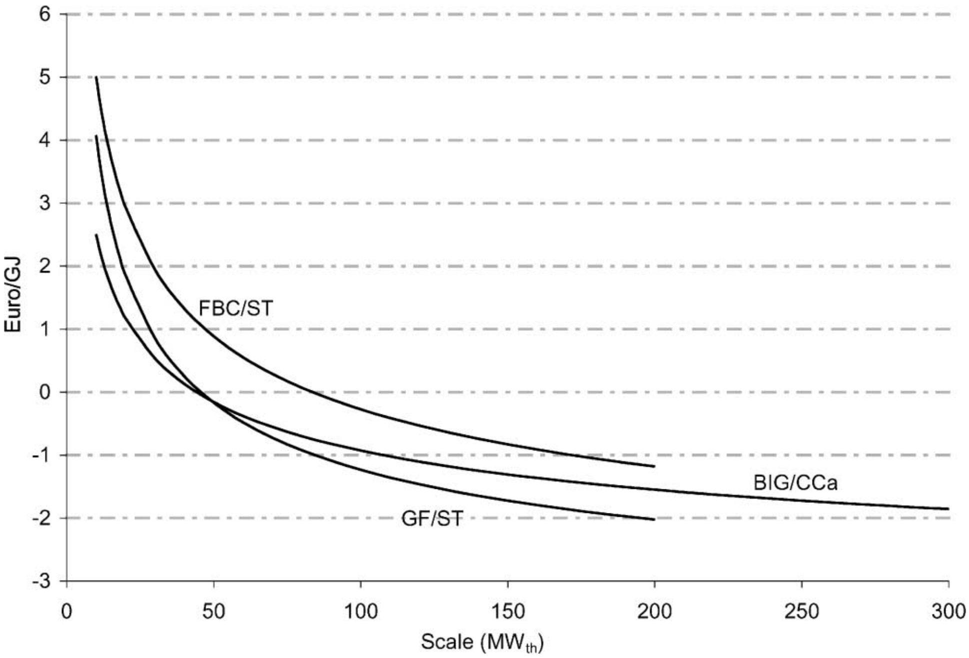


Fig. 7. Costs per unit of primary energy saved with waste wood firing.

Lowest costs per unit of primary energy saved are achieved by grate firings with steam cycles at largest possible scales. However differences between the technologies in comparison with 'clean' wood fuelling are relatively small. Clearly, conversion systems with lower specific capital costs and lower electrical efficiencies are more advantageous with very cheap or negative cost fuels. It should be noted, however, that zero fuel costs for waste wood are unlikely on longer term.

## 5. Sensitivity analysis

### 5.1. Sensitivities

To determine how and to what extent the results are influenced by the input data an extensive sensitivity analysis is carried out. For a first screening, potential maximum and minimum values of input parameters are estimated. Subsequently, the percent changes of costs per unit of primary energy saved and of relative primary energy savings are calculated. 'Clean' wood fuelled CHP generation with downdraft gasifiers and atmospheric fluidised bed gasification with combined cycle serve as reference cases. These are selected, because they cover a wide capacity range and heat as well as power generation are included. The maximal percent changes relative to the results of the base case are presented in Table 3.

This exercise reveals that costs per unit of primary energy saved are strongly influenced by a number of specific input parameters, while they are not by other parameters. The most important parameters with respect to sensitivity of costs are: biomass costs, annuity (rent and lifetime), investment costs, lower heating values, plants' efficiencies, transport costs, load factors of heat and power production, electricity prices and heat distribution costs.

With CHP generation with atmospheric BIG/CC technology as reference, scale specific analysis shows that the sensitivity of the costs for most parameters listed above does not strongly depend on the scale of the conversion unit. But, some sensitivities are very scale specific. Lowering the operation time of power production, increasing the investment costs or increasing the annuity leads to much stronger increases of costs per unit of primary energy saved at small scales.

Table 3
Maximal changes of costs per unit of primary energy saved and relative primary energy savings varying input data[a]

| Parameter | Variation (%) | Change of costs/*PES* (%) | Change of $PES_{relative}$ (%) |
|---|---|---|---|
| Biomass fuels | | | |
| Biomass distribution density | 50–200 | 95–106 | ≈100 |
| Lower heating value | 50–200 | 75–157 | ≈100 |
| Costs | 0–400 | 36–292 | 100 |
| Logistics | | | |
| Specific transport costs | 50–200 | 56–143 | 100 |
| Specific energy use of transport | 50–200 | ≈100 | ≈100 |
| Minimum distances transfer | 50–200 | ≈100 | ≈100 |
| Costs of transfer | 50–200 | ≈100 | 100 |
| Energy use of transfer | 50–200 | ≈100 | ≈100 |
| Heat distribution[a] | | | |
| Specific costs of heat distribution | 50–200 | 87–113 | 0 |
| Percentual energy loss of heat distribution | 50–200 | ≈100 | ≈100 |
| Heat demand density | 50–200 | 99–104 | ≈100 |
| Economic parameters | | | |
| Load factor—Power: | 75–114 | 97–120 | 99–107 |
| Load factor—Heat: | 50–200 | 66–135 | 87–122 |
| Part operation costs from investment costs | 75–150 | 93–113 | 100 |
| Lifetime | 40–100 | 100–142 | 100 |
| Rent | 100–300 | 100–139 | 100 |
| Heat price | 0–100 | 100–112 | 100 |
| Electricity price | 50–200 | 62–138 | 100 |
| Conversion units | | | |
| Specific investment costs | 50–200 | 65–169 | 100 |
| Efficiencies (heat + power) | 75–125 | 72–144 | y75–125 |

[a]Note: 100% is equal to no variation.

For illustration, the effect of varying annuity is presented in Fig. 8.

Striking is the influence on costs caused by heat distribution. With high operation times of heat production, i.e. high amounts of heat, the smallest scale is favourable with regard to costs per unit of primary energy savings. This is due to the rise of the heat distribution costs. With low operation times of heat production the correlation between scales and costs is reversed (see Fig. 9). A similar, but less pronounced, effect can be observed within the variation of heat distribution costs.

Contrary to the costs, variations in many parameters (biomass distribution density, lower heating value, specific energy use of transport, minimum distances of transfer, specific energy use of transfer, percent energy loss of heat distribution and heat demand density) only have a minor effect on the relative primary energy savings (see Table 3). Only the load factor of heat production and the plant efficiencies influence the relative primary energy savings remarkably. However, further investigation reveals that their sensitivities are not really scale dependent. The Dutch reference plant efficiencies will only change the overall levels of primary energy savings but does not effect the relative differences between the biomass conversion options.

### 5.2. Breakdown of components

To gain additional information about the structure of results the costs and the energy balance of atmospheric BIG/CC with CHP production are split up between (a) investment, operation and maintenance, fuel, transport, heat distribution costs and reimbursements from energy sales and (b) energy uses of logistics and heat distribution and produced energy, respectively.

The breakdown of costs is presented in Fig. 10. The biomass costs are the most important part and their share nearly stays constant at varying scales. The

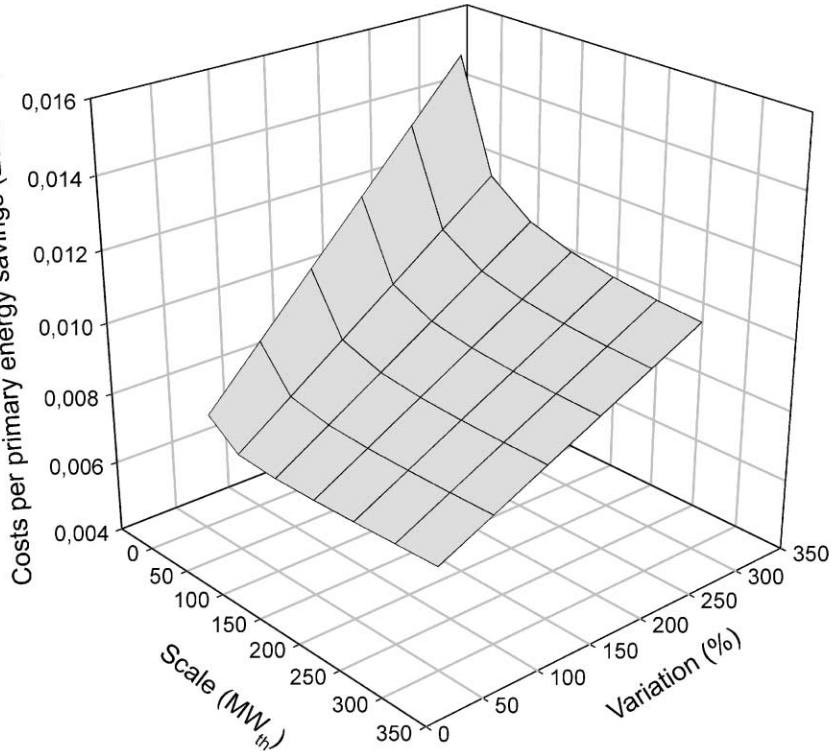


Fig. 8. Variation of annuity in relation to costs per unit of primary energy saved.

shares of the costs of heat distribution as well as of logistics increase with scale, while the shares of capital as well as operation and maintenance costs decrease. Revenues from heat sales are even outweighed by the heat distribution costs at larger scales.

From a breakdown of the energy balance it can be concluded, that the energy use of logistics and losses of heat distribution are very small. They amount to less than 1% of the primary energy saved by heat and power generation.

## 6. Discussion

### 6.1. Methodology

The focus on gasification and combustion in this study leaves out other conversion options that may also be promising for energy production from biomass. These are, e.g. digestion that is more suitable for the conversion of very wet streams than gasification and combustion are, and co-combustion in fossil fired plants that can make the utilisation of biomass possible at low costs.

With respect to the comparison of 'clean' and waste wood, some important aspects are not taken into account that affect the performance of conversion systems using contaminated fuels: (1) increased capital and operation costs related to gas cleaning and the disposal of contaminated solids are not accounted for and (2) conversion efficiencies are generally lower, if plants operate with waste fuels [16]. These aspects deserve further research.

### 6.2. Data quality

Compared to the average biomass costs of 'clean' wood used in this study (3.8€ $GJ_{LHV}^{-1}$ excluding transportation) figures stated in references vary from about 0–16€ $GJ^{-1}$. The level of total costs is very

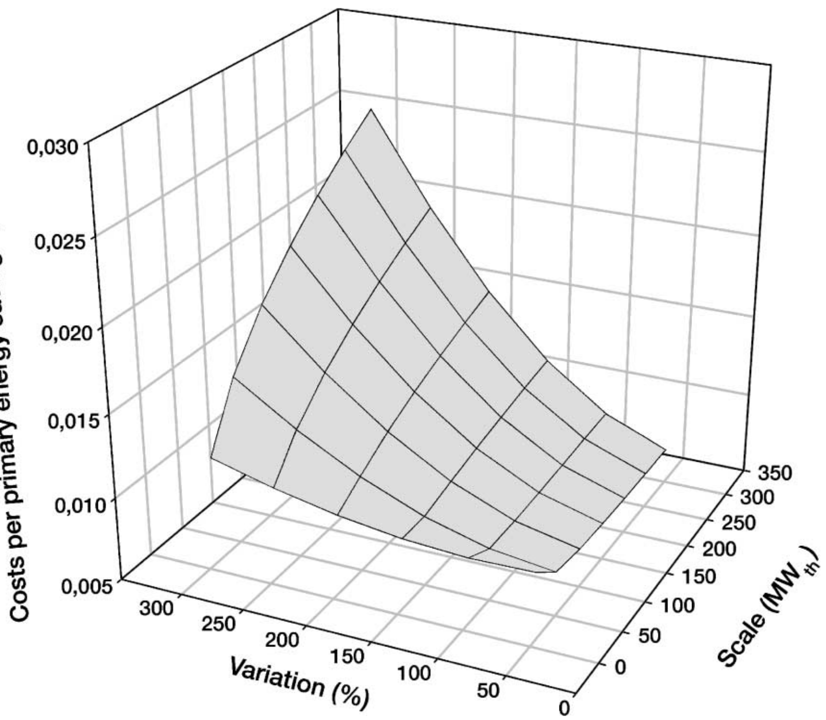


Fig. 9. Variation of load factor of heat generation in relation to costs per unit of primary energy saved.

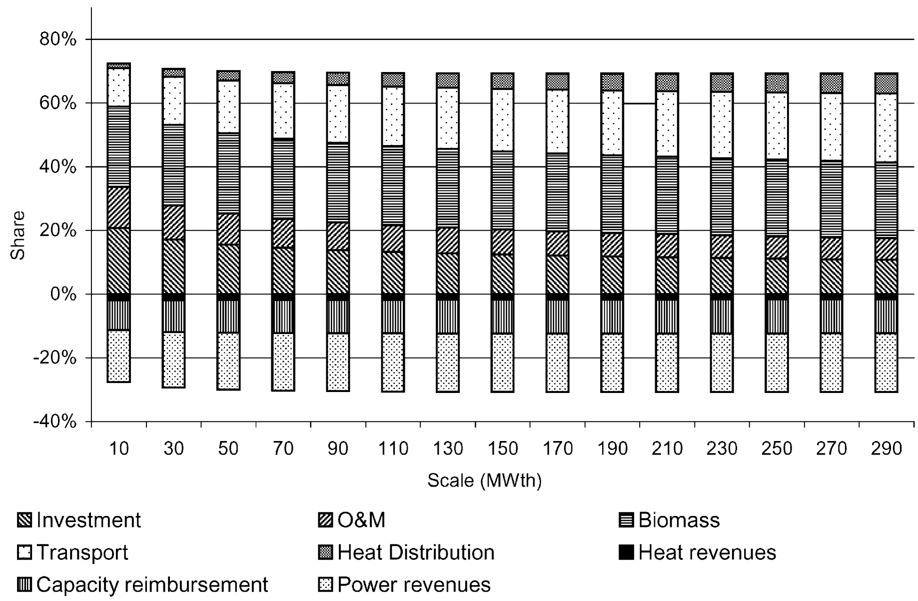


Fig. 10. Breakdown of costs of atmospheric BIG/CC, CHP generation.

sensitive to the biomass costs. (From biomass costs of about 2€ $GJ^{-1}_{LHV}$ at the plant gate profitable power production in large scale BIG/CC is possible with electricity prices of 0.0037€ $kWh^{-1}$.) Moreover, these uncertainties can affect the ranking between different technologies. So, in other regions with other biomass resources, preferences for technologies can change.

The heat prices, electricity prices and capacity reimbursements used in the calculations represent the current situation in the Netherlands which is comparable to other industrialised countries. But, the development of energy prices in the medium term is quite uncertain due to the liberalisation of energy markets and their dependence on subsidies, which in turn depend on political decisions. This is a factor to consider, because the economic performance of biomass energy systems depends strongly on the revenues from energy sales and reimbursements. With higher profits from electricity generation biomass energy systems can become competitive; e.g. by using ‘green electricity’ tariffs.

Capital costs and efficiencies of installations also depend on future developments. Particularly, BIG/CC is still in the demonstration stage and its performance is likely to improve more strongly compared to commercially applied technologies because of learning effects over time. On the other hand, it is not certain, if BIG/CC plants will realise the projected performances.

The trendlines of capital costs and efficiencies of the different heat and power plants are very important for the ranking of the different technologies with respect to primary energy savings and costs. However, the information on which the trendlines are based includes uncertainties.

First, the amount of data is limited for several technologies. For some technologies trendlines are based on estimations. The constant thermal efficiency of 75% of underfed pile burners is estimated while the thermal efficiencies of grate firing and updraft gasifiers range between 70% and 85% in the comparable scale range. It is likely that the real efficiencies of pile burners are scale dependent as well. However, no better quality data were available in literature. Also the electrical efficiencies of downdraft gasifiers are assumed to be constant in the scale range of 0.01–3 $MW_{th\text{-}input}$, because the references cite a narrow interval of efficiencies (30–31% and 28–32%, respectively), that is not related to scale [12,17]. However the capacity range is small, so the resulting error should not be really significant in this case. The trendlines of specific investment costs of fluidised bed combustion and updraft gasification is formed using the gradients from the trendline of grate firing and downdraft gasification. This seems reasonable, however, since they are in the same range as the gradients of other plants. Nevertheless, it should be noted that the specific investment costs of updraft gasfiers are much lower than those of comparable technologies in that range and, thus, the economic results should be considered with care.

Second, some trendlines show a quite large increase or decrease respectively at small scales and the application of a power or logarithmic trendline is questionable for smaller scales. Examples are the thermal efficiency with updraft gasifiers and the capital costs of downdraft gasifiers. In these cases, the energetic or economic performance, respectively, is likely to be better at smaller scales than it appears from the results.

## 7. Conclusions

### *7.1. General*

- Scale effects within biomass energy systems are very significant for both their energetic and economic performance. At the scale ranges considered (0.1–300 $MW_{th\text{-}input}$) the relative primary energy savings, i.e. the primary energy saved per unit of biomass energy input generally improve with increasing scales and the total costs per unit of primary energy saved mostly decrease with increasing scale. In some heat generation and CHP cases curves of total costs per unit of primary energy saved show a minimum at a medium scale applicable to the technology.
- The relative primary energy savings of the ‘clean’ wood fired systems considered are between 53% and 113%. Thus, depending on the system, relative primary energy savings can be doubled or cut in half.
- The costs per unit of primary energy saved of the respective ‘clean’ wood-fired systems are between 4 and 20€ $GJ^{-1}$. None of the technologies can, therefore, compete on the market, with the assumed ‘clean’ wood price of 3.8€ $GJ^{-1}_{LHV}$. This would be

possible with fuel costs of about $2€\,GJ_{LHV}^{-1}$ at the plant gate.

- Of all heat generation systems updraft gasification has the lowest costs per unit of primary energy saved ($8€\,GJ^{-1}$) and the highest relative primary energy savings (103%) are achieved by grate firing systems.
- Assuming the projected performances of SOTA systems, the pressurised BIG/CC has the best relative primary energy savings and costs per unit of primary energy saved on large scales. The highest relative primary energy savings are 113% of the system in CHP mode and the lowest costs per unit of primary energy saving are $4€\,GJ^{-1}$ of the system generating power only. These are the best performance levels of all systems considered.
- Considering CHP and power generation combustion technologies can neither compete with respect to economical nor with respect to energetic performance with all studied gasification technologies in the scale range of 10–200 $MW_{th\text{-}input}$.
- With respect to relative primary energy savings heat generation is favourable to most power and CHP generation systems at the applicable small scales of 0.03–20 $MW_{th\text{-}input}$. At scales of 10–20 $MW_{th\text{-}input}$ relative primary energy savings of heat generation are comparable to those of BIG/CC. Related to costs per unit of primary energy saved heat generation is more expensive than most other systems.
- Firing waste wood with an assumed price of $0€\,GJ^{-1}$ at the plant gate results in costs per unit of primary energy saved between $-2$ and $7€\,GJ^{-1}$. Power plants larger than about 50–80 $MW_{th\text{-}input}$ can be profitable firing waste wood.
- The costs per unit of primary energy saved depend strongly on (in descending order): biomass costs, annuity (rent and lifetime), investment costs, lower heating values, plants' efficiencies, transport costs, load factors of heat and power production, electricity prices and heat distribution costs.
- The net relative primary energy savings are especially sensitive to the load factor of heat generation and the plants' efficiencies.
- On scales up to 300 $MW_{th\text{-}input}$ energy use of logistics and heat distribution losses influence the relative primary energy savings only marginally; energy inputs and losses are limited to less than 1% of the relative primary energy savings. The influences of logistics and heat distribution on the total costs increase with the plant's scales. The share of the costs of logistics and heat distribution (for atmospheric BIG/CC) are about 35% of the total costs at scales of 300 $MW_{th\text{-}input}$.

### 7.2. Further research

- Efficiencies, investment and operation costs with regard to fuel properties and emission standards need to be studied further to determine performances using waste biomasses more clearly.
- To compare and evaluate more currently promising conversion systems including other technologies (e.g. digestion, co-combustion, fuel cells) would be desirable.

The approach presented here can be used to optimise the installation of new biomass energy systems on a regional level, determining kind, scale and location of installations dependent on site specific conditions.

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