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A method for life cycle assessment environmental optimisation of a dynamic process exemplified by an analysis of an energy system with a superheated steam dryer integrated in a local district heat and power plant

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Abstract

In this study a new approach of using life cycle assessment (LCA) in design situations is adopted. The environmental impact of the different sub-processes is simplified and expressed as a cumulative formation rate of environmental impact (expressed as ecopoints or equivalent). The LCA does not change over time but the LCA is dynamic due to its dependence of the chosen design parameters (residence time and temperature). Therefore, it is possible to environmentally optimise different systems such as energy systems.

The method is applied to an energy system where a superheated steam dryer is integrated in a local district heat and power plant. Although some primary environmental data are uncertain in the analysis, it is clear that the externally produced electrical energy, due to the exergy losses of the steam used for drying, effects the environmental optimisation of the system. If it is assumed that any additional electricity that may be required in the total energy system is obtained from old Danish coal plants a lower drying temperature is preferred. The capital goods are not important in the environmental study but it is important in the economic study. Many environmental and economical effects are coupled. A dried biofuel will create lower losses during combustion, due to the flue gas, and will therefore make use of less biofuel, less transports, etc. The effects of organic losses of the biofuel are estimated to be of minor importance due to the optimisation of the system if the organic compounds from the exhaust steam are reduced inside the system. If combined economical and environmental optima are demanded it is possible that Pareto curves can support the decision making.

Keywords: Life cycle assessment; Energy system; Environmental design; Dynamics

1. Introduction

Life cycle assessment (LCA) is a method for analysing and assessing the environmental impact of a material, product or service throughout the entire life cycle. A whole life cycle includes all processes from the cradle to the grave, i.e. raw material, extraction, processing, transportation, manufacturing, distribution, use, reuse, maintenance, recycling and waste treatment. An international standard (ISO 14040–14043 [1–4]) of life cycle assessment was decided in 1997–2000. LCA is mostly used to study systems in a static way, as in the previous study by the authors [5], to compare systems or to identify critical stages in the life cycle.

Recently LCA's utility in dynamic situations, such as process optimisation, has been tested by using multiobjective optimisation techniques. The multiobjective formulation of the process combines economic objectives with the LCA-based environmental objectives. Azapagic and Clift [6] proposed the use of multiobjective optimisation (MO), where the system optimisation is based on a variety of environmental objective functions, defined and quantified through the LCA approach. Brett et al. [7] presented a case study of a nitric acid plant. The approach entails the transfer of mass and energy information from the Hysys© model to the optimisation algorithm. Environmental objectives, based on the Hysys© model, are initially formulated using a life cycle assessment toolbox. The published literature in the area of dynamic use of LCA is, however, still very limited. In the present study a new approach to design situations is proposed.

2. Method

To conclude that one alternative is environmentally superior to another, it is often necessary to have evaluation methods. These methods allow the energy and pollution

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Nomenclature

A	heat transfer area (m^2)
$\dot{B}(t, T)$	biofuel consumption as a function of time and temperature (kg/s)
$\dot{COD}(t, T)$	formation rate of COD as a function of time and temperature (g/s)
E	energy of truck transports (MJ/t km)
h	heat transport coefficient (W/m^2 K)
ΔH_0	decrease in heat value (MJ/kg dry wood)
$H(t, T)$	the heat value as a function of time and temperature (MJ/kg dry wood)
$H_{tot}(t, T)$	the effective heat value as a function of time and temperature (MJ/kg dry wood)
k_1	an environmental constant related to bark combustion (p/MJ)
k_2	an environmental constant related to biofuel combustion (p/MJ)
k_3	an environmental constant related to truck transports (p/MJ)
k_4	an environmental constant related the organics released during drying (p/g)
k_5	an environmental constant related to steel manufacturing (p/kg)
k_6	an environmental constant related to timber-cutting (p/m^3)
k_7	an environmental constant related to external electricity, Danish coal (p/MJ)
k_8	an environmental constant related to external electricity (p/MJ)
$m_{biofuel}$	mass of the dried bark (kg)
Δm	mass of water evaporated (kg water/kg dry wood)
$\dot{m}$	rate of mass transport (kg water/kg dry wood s)
P_{heat}	produced heat to the municipal heating networks (MW)
P_{out}	produced heat in the boiler (MW)
r	the enthalpy of evaporation (kJ/kg)
t	time (s, min)
T	temperature (K)
T_{sa}	the temperature at the chips surface (K)
T_{su}	temperature of the superheated steam (K)
$\dot{TOC}$	release rate of organic compounds (g/min kg dry wood)
X_{ton}	the product of transport distance and mass (t km)

Greek letters

α	the ratio between produced electrical and thermal energy
$\alpha(t, T)$	the ratio between produced electrical and thermal energy as a function of time and temperature

data from an inventory to be totalled as a single number of ecopoints (or equivalent). Several methods have been developed for this purpose. In the proposed design method the environmental impacts of the different sub-processes are simplified and expressed as cumulative formation rates of ecopoints. These cumulative formation rates are expressed as functions of important process parameters such as residence time and temperature. This makes it possible to environmentally optimise processes or different systems such as energy systems due to the chosen process parameters. System effects can thus be included in the environmental optimisation of a specific unit. Of course it is also possible to choose specific environmental effects such as global warming or acidification instead of cumulative environmental effects.

3. Goal

The aim of this study is to develop and evaluate the optimisation method described above. Application of this method to an energy system with a super heated steam dryer integrated to a local district heat and power plant is made. The energy system is described below. The functional unit used is 25 MW heat produced to the municipal heating networks. The residence time and temperature of the dryer are used as optimisation parameters. The data from the evaluation step is expressed as cumulative formation rates of environmental impact (expressed as ecopoints or equivalent), and are functions of drying temperature and drying time. Therefore, it may be possible to optimise the dryer so that the environmental impact of the total system is minimised.

4. Case description

Steam dryers have been integrated to local district heat and power plants, until now, in two places in Sweden, Borås and Skellefteå. The steam dryer in Borås was integrated to an existing heat and power plant. The wet biofuel is dried before combustion in a large pressurised fluid bed steam drier [8]. The heat from the exhaust steam is used in the municipal heating networks. The plant in Skellefteå is entirely new [9,10]. A pneumatic conveying steam dryer is combined with both heat and power generation and wood pellet production. This study is independent of the both existing plants, but some typical experimental data related to the plants are used. There are several existing heat and power plants; needs fuel with a high thermal value. In this study conversion to dried biofuel with in to an imaginary heat and power plant is proposed. Due to the results of an earlier LCA [5] the possibility that coal could be attached to the wet biofuel is excluded. It is also assumed that a pneumatic superheated steam dryer is integrated in the plant.

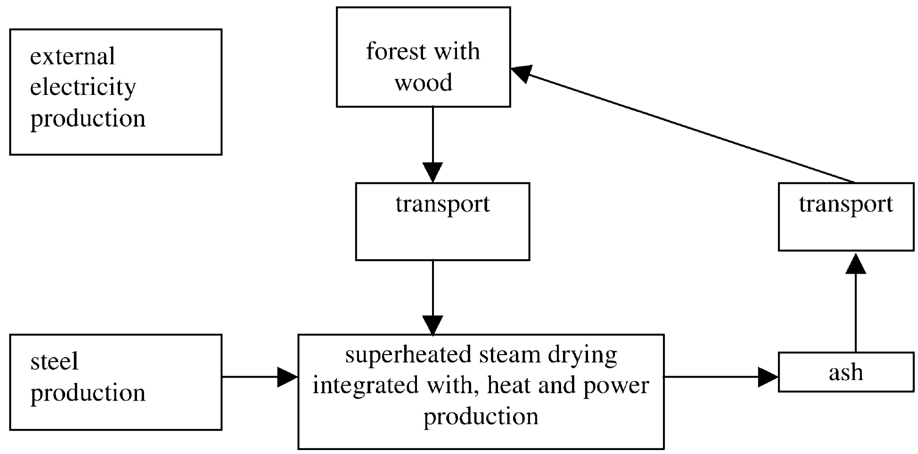

Fig. 1. The material flow of the energy system.

4.1. The energy system

The system boundaries correspond to those of the natural systems. The system boundaries are related to the material flow of wood and the need for electricity produced in external sources (Fig. 1). The output (heat and power) is held constant. In this study the wood used is residues such as grot (tops and branches from the wood) or bark. There is an excess of wood residues today in Sweden, therefore it is reasonable to assume that the biofuel not used in the plant will remain in the forest. It will degrade without any impact on the environment. The level of heavy metals in the ash from the steam generator needs to be very low. Therefore, it is possible to recirculate the ash to the forest. Recycling of the ash is assumed to occur in a closed loop. The ash, in this case, replaces synthetic fertiliser. The environmental impact of the capital goods in the dryer is assessed in this study. The drying rate influences the residence time in the dryer, and therefore the volume and weight of the capital goods. A given value of heat (25 MW) is produced to the municipal heating network. A modern plant with a pressure of 8000 kPa and 500 °C is assumed. The backpressure in the plant is 200 kPa. The capacity of the steam generator is 35 MW. The efficiency of the turbine is 0.75. The steam used in the drying process is bled from the steam turbine. The exergy losses depend on the temperature of the bled steam. These exergy losses of the steam during the drying process reduce the α-value (the ratio between produced electrical and thermal energy) and less electricity is produced. The electricity produced in the system has to be constant. Therefore, the decrease in electricity has to be produced by another source. In this study it is assumed that any additional electricity that may be required in the total energy system is obtained from Danish coal. (The north-European countries have integrated electricity systems.) As a comparison, electricity from a Swedish average is also analysed. Electrical energy is also used for the fans in the dryer. The total amount of electricity used by the fans is about 2% of the incoming wet fuel, estimated from a mass and energy balance over a steam dryer published by Jensen [8]. The temperature in the steam dryer is 15 K less than the temperature of the bled steam.

The dried biofuel is used in the combustion process. An energy balance over the total system gives fuel consumption as a function of temperature and time in the dryer.

During the drying process all of the incoming wet biofuel has to be heated up to the evaporation temperature. The water in the material evaporates and becomes superheated. The steam that is produced and which leaves the dryer is used in the municipal heating networks. This steam is condensed and cooled to 55 °C. The temperature of wet incoming biofuel is assumed to have a temperature of 20 °C. An energy balance of the dryer and the energy system gives that the net consumption is $\dot{m} \times 247$ kJ/kg dry wood.

It is assumed that the boiler has a relative humidity of 50% together with an excess of air of 30% and a fixed flue gas temperature of 150 °C. The flow of air and flue gases depends on the moisture content of the biofuel, and hence also of the drying time and drying temperature. The enthalpy losses from the flue gases can be calculated from the amounts of these gases, their enthalpy and the amount of air and its enthalpy. The temperature of the incoming air is assumed to be 20 °C.

The amount of flue gases in the boiler decreases with the drying time of the biofuel due to the decrease in water content of the biofuel. The enthalpy of the flue gases is dependent on the water content, and is thus also dependent on the drying time of the biofuel.

The enthalpy due to the net consumption of the drying process and the losses due to the flue gases are included in the effective heat value $H_{tot}(t, T)$ when calculating the biofuel consumption.

4.2. Drying kinetics

When a wet material is exposed to a flowing stream of superheated steam, heat is transferred convectively to the wet solid matrix [11,12]. Depending on the temperature of the material, the steam may first condense on the product, thereby increasing the moisture content of the material. However, as the temperature of the material rises, evaporation occurs at a steady surface temperature with a constant rate (under steady drying conditions) as long as the surface of the material is kept wet from the inside. The outer mass transfer resistance is negligible. During this period an increase of steam velocity or temperature increases the drying rate significantly. The heat transfer coefficient, the amount of area exposed and the thermal driving force determine the evaporation rate. The largest amount of moisture evaporates during the constant rate period. When the internal transport of liquid ceases to keep the surface of the material moistened, the falling rate period starts and the so called critical moisture content (m_c) of the wet material is reached. During this period, the mass transport processes within the material are rate limiting and the temperature rises. The pressure increases in the material. The pressure gradient is an important mechanism in the transport of moisture and gas during this period [12]. Finally, when the falling rate period ends, the equilibrium moisture content is reached. To summarise, the drying process can be divided into three main periods: the heat-up period (a), the constant rate period (b) and the falling rate period (c). These periods are shown in Fig. 2.

Even when the intent of dried biofuel is high in industrial applications, it is not common to dry to a moisture content less than 0.15 kg/kg [13]. This is significantly above the falling rate period. The equilibrium moisture content is much lower, at least 0.06 kg/kg at the actual activities [14]. It is thus natural to assume that drying takes place in the constant rate period. In this period the convective heat transfer is rate determining. Therefore, the calculation of mass transport can be simplified as

$$\dot{m} = \frac{hA}{r}(T_{su} - T_{sa}) \quad (1)$$

In this equation $\dot{m}$ is the rate of mass transport from the chips surface, r the enthalpy of evaporation, h the heat transport coefficient, A the heat transfer area, T_{su} the temperature of the superheated steam and T_{sa} is the temperature at the chips surface, which must be equal to the saturated temperature during the constant rate period.

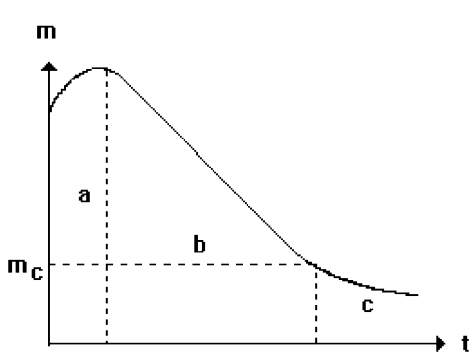

Fig. 2. Moisture content as a function of time during steam drying.

In a study by Fyhr and Rasmuson [15] heat transfer coefficients in a small-scale pilot dryer were measured. The measured heat transfer coefficients were of the order of 300 W/m^2 K and about 10 times larger than in earlier bark experiments performed by Björk and Rasmuson [16]. This may be due to the fact that the slip velocity in the pilot dryer was at least 10 times higher than the gas velocity in the bark experiments. In industrial scale dryers these higher heat transfer coefficients are more realistic and are used in the subsequent calculations. From these bark experiments the area exposed is $A = 0.0265\,m^2$ and the mass of the dried bark is $m_{biofuel} = 0.01575$ kg. $T_{sa} = 393$ K corresponds to the boiling point of superheated steam at 2 bar. Eq. (1) can be integrated to give the total amount of water evaporated in time t (min) related to 1 kg dried wood (kg water/kg dry wood).

$$\Delta m = \int_0^t 2.174 \times 10^{-4}(T - 393) \times 60\,dt \quad (2)$$

4.3. Release of organic compounds into the exhaust steam of the drying process

Björk and Rasmuson [16] have previously studied the release of organic compounds from bark chips (both fresh and stored). The chips were dried at 140 and 160 °C with a constant steam activity of approximately 0.58. The exhaust steam was analysed for the important environmental parameters: total organic carbon (TOC), biological oxygen demand (BOD_7) and the chemical oxygen demand (COD). The total amount for drying of fresh bark, after 62 min at 140 °C was 14.9 g/kg dry biofuel. The results show that the amount of organic compounds depends on the drying time, the age of the bark chips and the drying temperature. This is illustrated in Fig. 3. The organic compounds are released at a constant rate after a short time, but with very strong temperature dependence. Results from industrial dryers show that the level of the organic compounds from the condensed steam also differ substantially. In an industrial study by Münter et al. [13] the amounts of COD were measured in the condensed

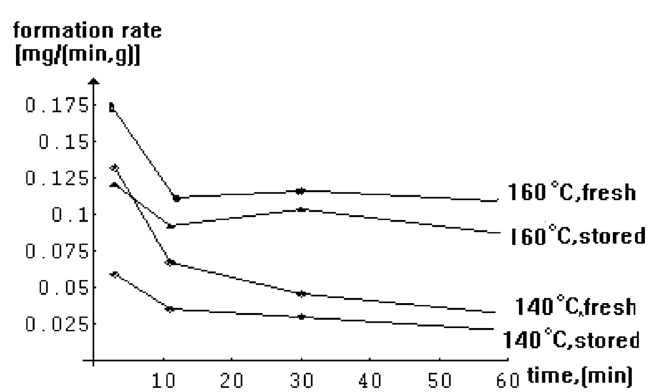

Fig. 3. TOC formation rate in the exhaust steam as a function of (bark drying) time [16].

steam and found to be in the range 1.5–2.0 g/kg dry biofuel. For softwood the values were 0.63 g/kg dry biofuel and for bark it is 14.7 g/kg dry biofuel. The residence time in the industrial dryer was between 60 s for the smaller fractions, up to 6 min for the larger fractions. The COD level in the condensed steam for bark is about 7–10 times larger than the COD levels for grot. The release of α-pinene from a wood chip is studied by Johansson and Rasmuson [17]. In their study different models to the release of α-pinene were analysed and discussed, but the results are not readily applicable to complex industrial systems. It is, however, noteworthy that the temperature and time dependence of the release of α-pinene of a wood chip is similar to that of organic compounds of bark chips.

In the present study a correlation to data depicted in Fig. 3 [16] is made. The expression is correlated to laboratory experiments with the same mass and area exposed as in the Eq. (2). Although the data are uncertain they give information of the importance of release of organics in a total energy system, but it is of course difficult to transform it to an industrial scale without a model. The amounts of COD in the condensed steam for dried bark in the laboratory experiments and for dried bark in the industrial scale are comparable although the drying times were very different. Since the drying rate during the constant period is proportional to the heat transfer coefficient, it must be of great importance for the release of organic compounds. Hence, it is assumed that the release of organic compounds is proportional to the heat transfer coefficient when scaling up the experiments. The release rate used in the system study is therefore 10 times larger than the correlation of the bark experiments. With these assumptions the correlation used is

$$\dot{\mathrm{TOC}} = -11.675 - 8.76 \times 10^{-2} t + 3.0625 \times 10^{-2} T \quad (3)$$

where $\dot{\mathrm{TOC}}$ is in g/min kg dry wood. The organic release can also be expressed as a loss in heat value. The organics consists mainly of substances with C_5H_8 structure. Some organic compounds include oxygen. From these structures a heat value of 0.0452 MJ/g is estimated. Therefore, the decrease in heat value related to 1 kg dry wood (MJ/kg dry wood) is expressed as

$$\Delta H_0 = \int_0^t 0.0452 \times \dot{\mathrm{TOC}}\, \mathrm{d}t \quad (4)$$

The loss of organic compounds also includes those leaving the drier with the evaporated water. This water leaves the system and has an environmental effect on the surroundings. The level of COD is four times the level of TOC. It is possible to express the TOC formation rate as a rate of ecopoints or equivalent. Thus, the formation rate of COD (g/s) in the studied case is

$$\dot{\mathrm{COD}} = 4\dot{B} \int_0^t \dot{\mathrm{TOC}}\, \mathrm{d}t \quad (5)$$

4.4. The combustion process

A totally dried biofuel has a heat value of 19.2 MJ/kg dry wood [18]. The biofuel is assumed to have an average moisture content of 50%. The heat value in this case is 16.8 MJ/kg dry wood. Accounting for the drying rate and the losses of organic material the heat value (MJ/kg dry wood) can be expressed as

$$\begin{aligned} H(t,T) &= H(50\%) + 60\Delta m\, r - \Delta H_0 \\ &= 16.8 + \int_0^t (60 \times 5.218 \times 10^{-4}(T - 393))\,\mathrm{d}t \\ &\quad -\Delta H_0\,\mathrm{d}t \end{aligned} \quad (6)$$

4.5. Generation of electrical energy

In our analysis it is assumed that it is necessary to provide a given value of heat (25 MW) to the municipal heating networks. In addition to this heat, electricity is produced. The electrical power depends on the pressure difference and efficiency of the turbine. Also the bled steam necessary for the heat exchangers in the drier affects the electricity produced. The hot water from the heat exchangers in the drier is assumed to be recirculated back to the boiler. Any eventual losses in this part are assumed to be constant and are therefore neglected. The ratio between produced electrical and thermal energy is defined as α. The produced effect in the boiler (P_{out}) depends on the output of electricity and can be described as

$$P_{out} = (1+\alpha)P_{heat} \quad (7)$$

Due to the assumed pressure difference and the efficiency of the turbine it is calculated that $\alpha_{max} = 0.286$. If a higher drying temperature is used, a higher temperature (pressure) of the bled steam is required. If steam is being bled the α-value will be reduced due to the reduced pressure difference. A drier product increases the flow of the bled steam. The effective α-value is dependent on the temperature of the bled steam and the ratio between the flow of the bled steam and the total steam flow. The temperature dependence of α can be calculated from steam tables by Alvarez [18]. An energy balance makes correlation to the flow ratios. The effective α-value is therefore dependent on the residence time and temperature in the dryer. This dependence is shown in Fig. 4. A temperature difference of 15 K is assumed in the heat exchangers.

The biofuel consumption can now be expressed as

$$\dot{B}(t,T) = \frac{P_{heat}(1+\alpha(t,T))}{H_{tot}(t,T)} \quad (8)$$

The biofuel consumption as a function of time and temperature is shown in Fig. 5.

When compensating for a lower production of electricity, the additional electrical energy for the system provided by external sources can be calculated as

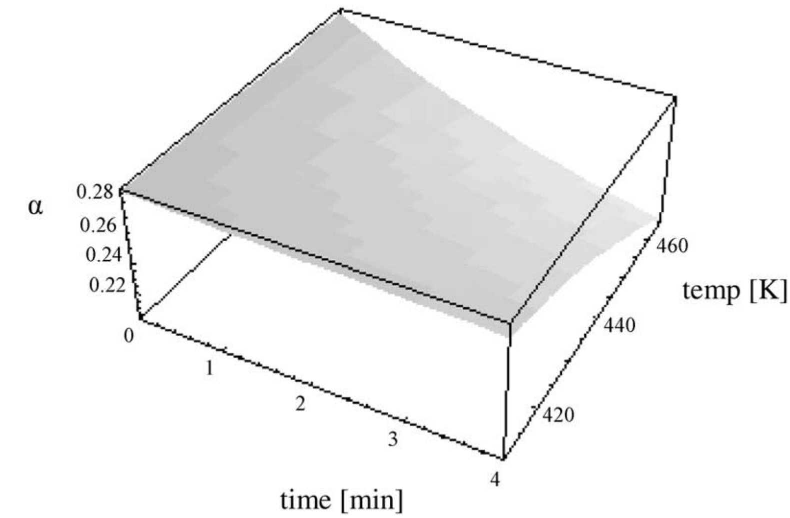

Fig. 4. The effective α-value as function of time and temperature.

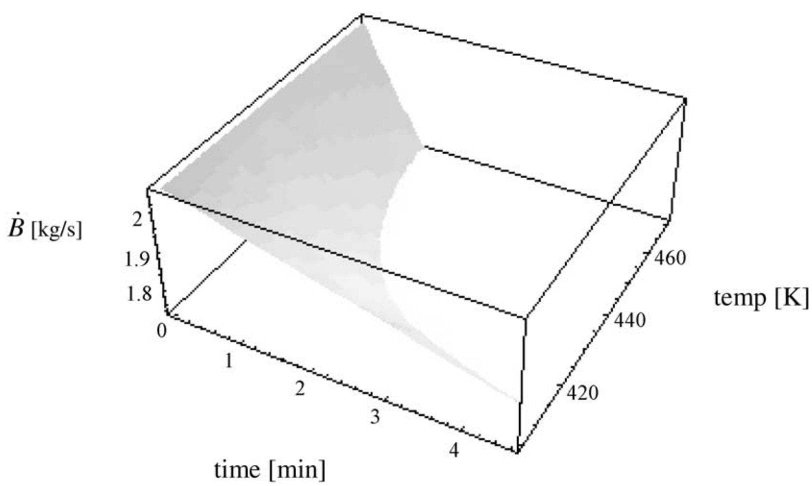

Fig. 5. The biofuel consumption of the system as a function of time and temperature.

$$P_{\text{ext}} = P_{\text{heat}}(\alpha_{\max} - \alpha(t, T)) \quad (9)$$

This energy will be produced in other electrical power generation plants. In this study it is assumed that any additional electricity that may be required in the total energy system is obtained from Danish coal. The emission coefficients during coal burning are presented in Table 1. The emission factors are related to 25,000 kWh (electricity). It is assumed that any additional electricity that may be required in the total energy system is obtained from old Danish coal plants [19]. Since the electric cable to Poland was restored electricity produced from brown coal has also been used. Sometimes it is assumed that an average of electricity production is used. The emissions from the average of electricity are much lower; therefore an alternative analysis with these emissions is made for comparison. These average emissions of Swedish electricity production are showed in Table 1. They are taken from the database in LCAiT 3.0© [20].

4.6. The dryer

The dryer is assumed to be a steam dryer manufactured from 10 steel pipes and two big heat exchangers. The dryer is assumed to be manufactured from steel. The length of the

Table 1
Emission coefficients during coal burning when producing electricity [19] and emissions during production of electricity, Swedish average [20]

Emission	Electricity (Swedish average) (g/MJ_{el})	Electricity from coal (kg per year)
CO_2	11.9	18000
NO_x	1.88×10^{-2}	30
SO_2	1.24×10^{-2}	36
CO	3.31×10^{-3}	1.5[a]
HC	3.73×10^{-3}	0.5
Particulate	2.7×10^{-3}	4

[a] [24].

Table 2
Emissions during steel production [21]

Emission	Value (kg/kg steel)
CO_2	1.97
NO_x	0.00464
SO_2	0.0111
CO	0.000430
HC	0.00023
COD	0.00014

dryer is dependent of the consumption of biofuel, its capacity and the drying time. It is assumed that the capacity of the dryer is 0.5 kg dry biofuel/m. The first part of the dryer is used to heat up the material. Condensation of water on the material is not taken into account in this study. The aim is to test the model and not to find out the exact optima.

The density of the dried bark is 400 kg/m^3. It is assumed that the steel pipes have a diameter of 200 mm with a thickness of 3 mm. The density of the steel is 7800 kg/m^3. The heat exchangers and other pipes in the system are assumed to use an equal amount of steel. Therefore, it is possible to express the steel consumption as $304\dot{B}t$. It is assumed that the lifetime of the capital goods is 15 years. The emissions during steel production are taken from Ryding [21] and are shown in Table 2.

4.7. Transports

The energy consumption (MJ/t km) during the truck transports can be calculated from the general equation [22]

$$E = \left(\frac{10.15}{32}\right)X_{\text{ton}} + \left(\frac{3.15}{32}\right)X_{\text{ton}} \qquad (10)$$

The emission coefficients during transport with diesel driven trucks [22,23] are presented in Table 3. In addition to these emissions there are also emissions and energy requirements when the fuel is produced, i.e. during the extraction of crude oil, transportation by tanker of the crude oil and refining. Emissions arising from fuel extraction and production are summarised in a precombustion increment which is added to the ordinary emissions for burning [24].

The amounts of wet biofuels that are transported are dependent on the fuel consumption. It is assumed that the average transport distance of the wet biofuel is 80 km. The wet biofuel weight is twice the weight of absolute dried biofuel. The level of ash related to the dry substance is 2.2%. The ash is assumed to be recirculated to the forest. Therefore, the energy consumption from the transport will increase by 2.2%. All ash is assumed to be transported back to the environment by the same distance. Therefore, using Eq. (10) the total energy consumption from the transports is 6.8E-02.

Table 3
Emissions during transport [22–24]

Emission	Truck transport (g/MJ)	Precombustion (g/MJ)
CO_2	75	4
NO_x	1.00	0.0041
SO_2	0.024	0.014
CO	0.127	0.00013
HC	0.037	0.0084
Particulates	0.020	0.00048

Table 4
Emissions during timber-cutting [25]

Emission	Silvicultural measure (g/m^3 wood)	Timber-cutting (kg/m^3 wood)
CO_2	212	4.70
NO_x	2.2	0.09
SO_2	–	–
CO	21.3	0.06
HC	2.2	0.01
Particulate	–	–

4.8. Cutting of trees

Berg [25] presented the total emissions to air from fossil fuels during forestry works in Sweden, as a part of a life cycle inventory. The study includes all emissions from the cutting operation, including transports between different locations and the daily travels of the workers. The emissions in the southwest part of Sweden are presented in Table 4. Although there are allocation problems in this study it is assessed that all emissions are related to the wood residues. The density of the bark is about 400 kg dry wood/m^3. To evaluate the environmental load of tree cutting the fuel consumption $\dot{B}$ has to be expressed in m^3/s.

4.9. Emissions during the combustion process

The biofuel consumption depends of the drying time and drying temperature. The emissions depend sensitively on the combustion and the cleaning of the flue gases. In Sweden the environmental legislation is firm and therefore values from new technology are chosen. The emission coefficients during combustion of biofuel [19] are presented in Table 5. These data are obtained at an output of 25,000 kWh. The required biofuel consumption ($\dot{B}$) is described as a consumption of completely dried biofuel. Since the emission coefficients are

Table 5
Emission coefficients during combustion of biofuel [19]

Emission	Combustion	
	Bark (g/MJ)	Biofuel (kg per year)
CO_2	0	0
NO_x	0.140	6
SO_2	0.015	4
CO	0.563	90[a]
HC		3
Particulate	0.116	1
Ash, landfilling	3.6	

[a] [24].

given as a function of energy, it is necessary to express the biofuel consumption as a consumption of energy. The relationship from Eq. (9) must therefore be multiplied by the energy value. The emission coefficients from bark are taken from the database in LCAiT 3.0© [20].

4.10. Limits of heat and drying times

It is assumed that the maximum heat value of the dried wood is 19.0 MJ/kg dried wood due to an approximate end of the constant drying period (the critical moisture content (m_c)). This heat value can be reached by different drying temperatures and drying times. The limits can be solved from Eq. (6) and are given by the heat value.

5. Evaluation

5.1. Environmental

Although the inventory sometimes has enough information to conclude that one alternative is environmentally superior to another it is often necessary to have evaluation methods that allow the energy and pollution data from an inventory to be totalled as a single number. Several methods have been developed for this purpose. In Sweden, the following three methods are used [26]:

- The ecoscarcity method (ES) (developed in Switzerland) relates the emissions to an ecological critical load.
- The weighted environmental theme method (ET): This method was first developed in The Netherlands. The method builds on the classification and characterisation steps and includes analysis in which the environmental impacts are evaluated. In Sweden the evaluation step is related to political targets. Weighting factors are published for both short- and long-term political targets.
- The EPS method, developed by Volvo and IVL (Sweden) is based on the definition of five safeguard subjects and the willingness to pay for protecting them.

The weighting factors are listed in Table 6. They are taken from Nordic Guidelines [26].

Table 6
Valuation weighting factors of three common methods [26]

Emission	EPS (ELU/kg)	ES (Ep/g)	ET short goal (p/g)	ET long goal (p/g)
CO_2	0.0636	0.0159	0.011	0.036
NO_x	0.3948	4.74	3.95	3.66
SO_2	0.0545	5.74	2.42	3.33
CO	0.1912	–	0.333	0.824
HC	–	10.5	3.14	7.54
CH_4	0.978		0.233	0.766
Particulate	0.0071	–	0.036	0.042
Ash, landfilling	–	–	0.036	0.045
BOD	0.002	1.28	0.04	0.032
COD	0.0016	0.4	0.04	0.032

All processes in the total energy system have an effect on the environment. The effects, which are studied, are as follows:

1. The emissions from the biofuel combustion.
2. The emissions from external electrical energy.
3. Organic compounds from the exhaust steam.
4. The emissions from the truck transports.
5. The emissions from timber-cutting.
6. The emissions from steel production.

The environmental impact of the different sub-processes is expressed as a single number (ecopoints/MJ, etc.) in Table 7.

The biofuel consumption, the formation rate of COD, the effective heat value, and the ratio between produced electrical and thermal energy are expressed as functions of residence time and temperature. These expressions, together with the constants from the different sub-processes in Table 7, constitute Eq. (11) which expresses the rate of the environmental impact, $\dot{\mathrm{EI}}(t,T)$, for the whole energy system. Therefore, it is possible to environmentally optimise the dryer including its effect on the complete energy system:

$$\begin{aligned}\dot{\mathrm{EI}}(t,T) = {} & \dot{\mathrm{COD}}(t,T)k_4 + P_{\mathrm{heat}}(\alpha_{\max} - \alpha(t,T))k_7 \\ & +304\dot{B}(t,T)tk_5 + \frac{68}{10^3}\dot{B}(t,T)k_3 \\ & +\dot{B}(t,T)\frac{1}{400}k_6 + \dot{B}(t,T)H(t,T)k_1 \qquad (11)\end{aligned}$$

5.2. Economical

The same equations can be used in a study of the expenses required in the energy system. As a comparison a very brief economic study is done. The purpose of the economic study is just to obtain a reasonable result for the comparison studies of economic and environment. The price for free delivered biofuel is about 0.55 SKr/kg dry substance [27]. (This price includes biofuel, transports and timber-cutting.) The price of electricity from Danish coal is about 0.135 SKr/kWh [28]. The dryer is assumed to be a steam dryer manufactured from 10 steel pipes and two big heat exchangers. The price for the 10 steel pipes is about 7020 SKr/m [29]. The price for the heat exchanger is assumed to be similar. With a Lang factor of 3 the costing is assumed to be 42,120 SKr/m. The cost of the steam generator and the other equipment is not included in the analysis. The cost of the dryer will be returned within 15 years. Electricity production is free from taxes. Biofuels are also free from taxes. The only actual "tax" is the so-called NO_x charge that will be refunded to the different producers. The amount refunded depends on the level of NO_x pollution. No taxes are included in this study, however.

6. Results and discussion

The rate of the environmental impact, $\dot{\mathrm{EI}}(t,T)$ (Eq. (11)), for the whole energy system is analysed with Mathematica© for each of the four evaluation systems. The equation is de-

Table 7
Summaries of the environmental impact expressed in ecopoints (or equivalent) of the different sub-processes

	Bark combustion, k_1 (p/MJ)	Biofuel combustion, k_2 (p/MJ)	Truck transport, k_3 (p/MJ)	Drying organic release, k_4 (p/g)	Steel manufacturing, k_5 (p/kg)	Timber-cutting, k_6 (p/m^3)	Electricity (Danish coal), k_7 (p/MJ)	Electricity (average), k_8 (p/MJ)
EPS	0.000184	4.586E−05	0.00728	0.0016E−3	0.1774	0.4372	1.79E−02	1.064E−3
Ecoscaric	1.215	0.932	6.731	0.4	119.5	93.34	7.157	0.393
ET short	1.162	0.5583	5.175	0.04	67.94	61.95	4.516	0.250
ET long	1.282	0.726	7.093	0.032	127.0	188.9	9.808	0.569

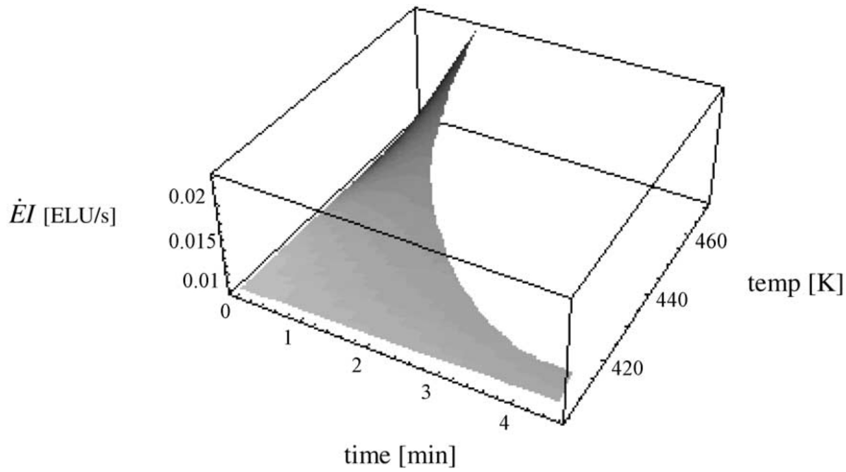

Fig. 6. The environmental impact of the energy system as a function of drying time and temperature evaluated with the EPS system.

pendent on time and temperature in the dryer and it is therefore possible to optimise these two factors for the whole energy system. It is, of course, questionable to express all pollution in a single subjective number but it is a way to include and weight together different environmental impacts. A way to draw attention to the subjectivity of the evaluation methods is to use several of them in the same analysis. This is done in the present study. It is also possible to study specific and more objective environmental effects such as global warming or acidification instead of cumulative environmental effects but this was not done in this study.

The results from the study using the EPS system are shown in Fig. 6. This study shows that drying at a low temperature until the limit of the constant rate drying period will create a low environmental impact. A small increase of the environmental impact is noted but this is acceptable since a high thermal value is demanded. The COD formation does not influence the result of evaluation.

The ecoscarcity system estimates that the COD production, when using bark as biofuel, has a big influence on the optimisation of the environmental impact on the total system. Drying of the bark worsen the environmental impact of the energy system. The results from the study using the ecoscarcity system are shown in Fig. 7. If the COD level is reduced by about 95%, in a wastewater purifying plant the ecoscarcity system yields the same result as the EPS method. (The wastewater purifying plant is assumed to be inside the system boundaries.)

The ET short method shows the same result as the ecoscarcity system, but a lower reduction of the COD is needed also, the increase of environmental impact virtually disappears at lower temperatures. The results from the study using the ET short method, with 95% reduction of COD, are shown in Fig. 8.

The ET long method shows a similar result as the ET short method but a larger reduction of the COD is needed. If a single plant converts to a dried biofuel it is natural to evaluate the effects of the last units of electricity that are produced, i.e. the marginal effects of electricity production. Sometimes it is assumed that electricity from a Swedish average is to be

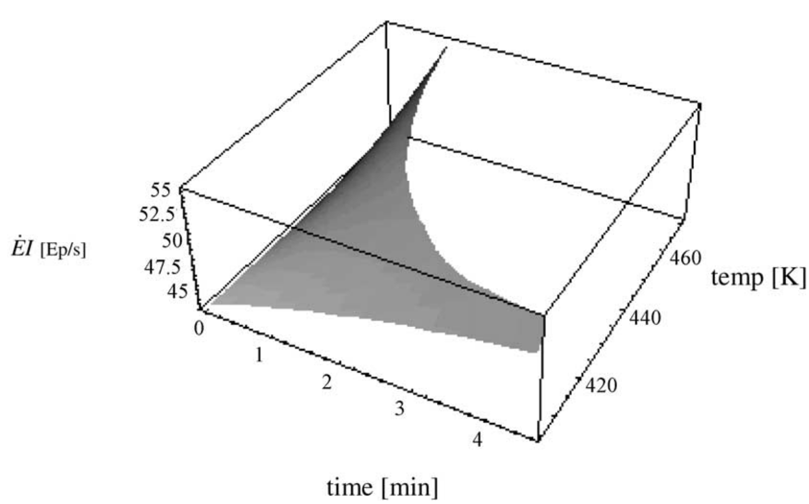

Fig. 7. The environmental impact of the energy system as a function of drying time and temperature evaluated with the ecoscarcity system.

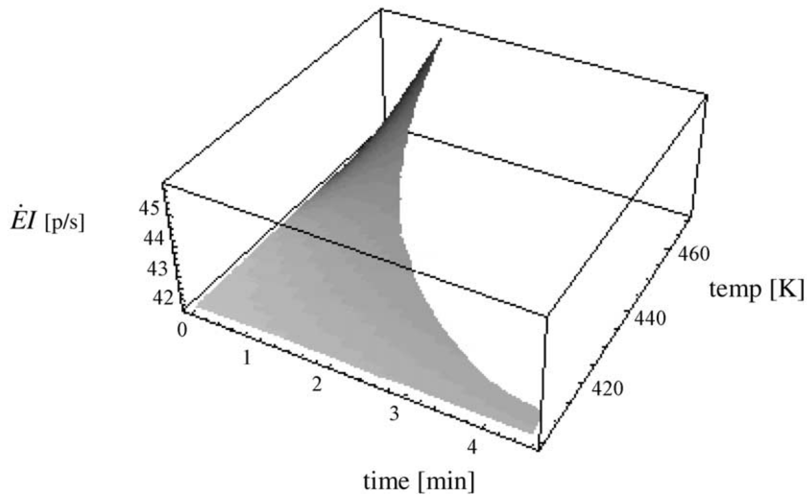

Fig. 8. The environmental impact of the energy system as a function of drying time and temperature evaluated with the ET short method (after reduction of 95% of COD).

used in the evaluation. This proposal neglects these marginal effects but the result is enlightening. The EPS system shows that drying at low temperature decrease the environmental impact. The results are shown in Fig. 9.

The other evaluation systems show that the impact of the temperature level is opposite to the case when Danish coal power is assumed being used. In this cases drying until the limit at a high temperature is preferable. Also the environmental impact follows the lower consumption of biofuel. The environmental impact of the energy system as a function of drying time and temperature evaluated with the ET long method system and electricity from a Swedish average is presented in Fig. 10.

If the effects of the external need for electricity, due to the exergy losses, is neglected the environmental effects for all evaluation systems are equal and similar to the result of the ET long method. Drying at a high temperature until the limit is preferred.

A dried biofuel is environmentally superior since the losses of flue gases, etc. decrease, and thus less biofuel needs to be used. This will of course create less emissions due to the combustion, transports, less timber-cutting, etc. To summarise the results of the environmental optimisation it is noteworthy that the environmental effects of the combustion process dominates overall, and that the environmental effects of truck transports and timber-cutting are small compared with the combustion process. It is also easier to control the environmental effects of the combustion process with a dried fuel. This is not taken into account in this study. The environmental effects of timber-cutting and truck transports are, of course, coupled with the biofuel consumption. A higher drying temperature generates both

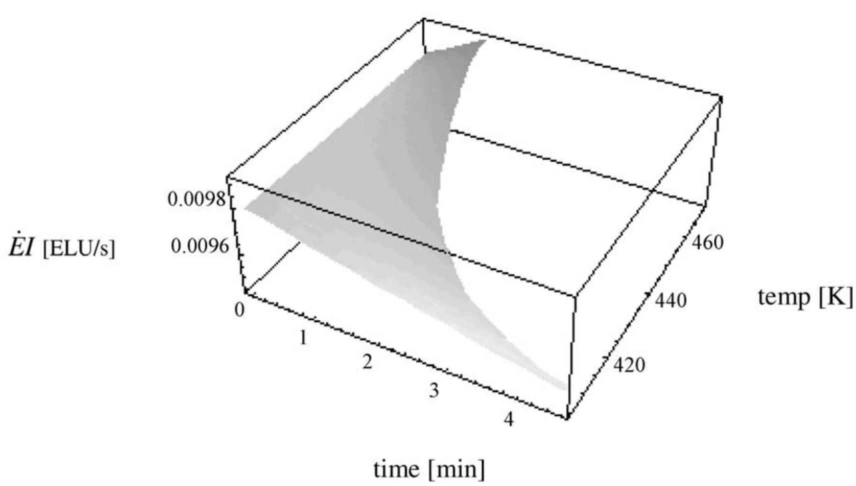

Fig. 9. The environmental impact of the energy system as a function of drying time and temperature evaluated with the EPS system and electricity from a Swedish average.

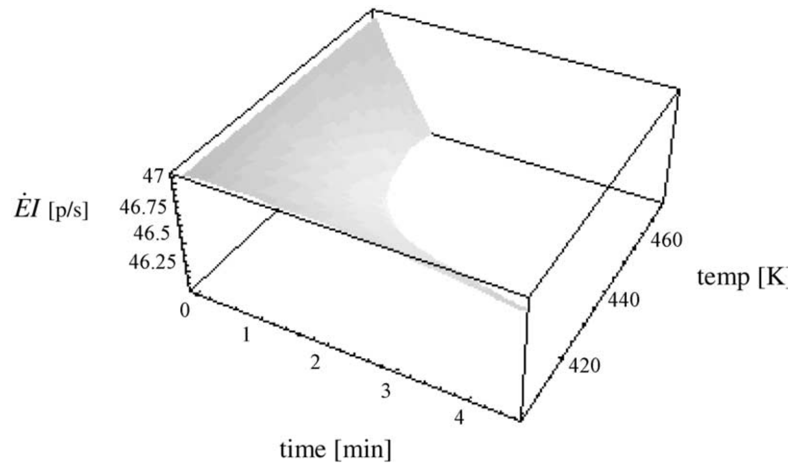

Fig. 10. The environmental impact of the energy system as a function of drying time and temperature evaluated with the ET long method system and electricity from a Swedish average.

exergy losses and a shorter dryer. The environmental effects of the need for external electricity effects the optimisation of the system. The level of this impact is estimated to be of a relatively high importance in all evaluation systems especially in the EPS system due to the fact that this system gives a high priority to the green house effect. The environmental effects of the size of the dryer are estimated to be small. Therefore, drying at a lower temperature is preferred. Drying of biofuels increases the release of organic compounds. The water evaporation and organic release are in some way coupled. A strong temperature dependence of the organic release has been shown in many studies. A higher temperature will also increase the driving force of the drying process if the pressure in the dryer is kept constant. In this study the organic losses at a high temperature and a lower drying time seems to be comparable with the losses at a low temperature and a longer drying time. These organic compounds are estimated to be fairly significant in the ecoscarcity system. In this evaluation system drying of bark would worsen the environment if the organics not were reduced inside the system borders. If grot or softwood is used as biofuel the release rate of organic compounds is much lower than if bark is used. The organic compounds (especially the terpenes) from the condensed water can cause problems if they are directly released to the natural system. The terpenes and phenols will also reduce the expected reduction of nitrate in wastewater purifying plants, and therefore they must be removed before the purification treatment. The formation (release) data used in the study are uncertain, but the total level seems to be relevant compared to other studies. How does the uncertainty of the organic release effect the optimisation? Probably not at all if the drying is managed in the constant period and if the temperature is "normal". Although it is not possible to exclude the temperature dependence of the organic release

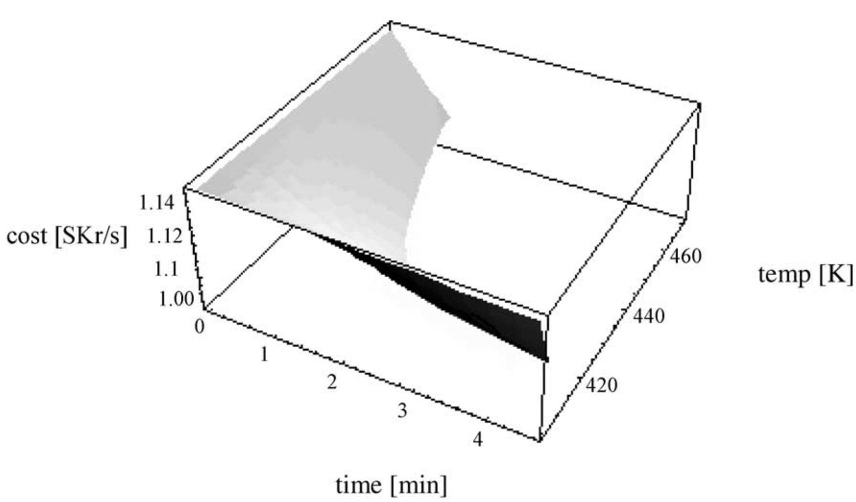

Fig. 11. The production cost of the energy system as a function of time and temperature.

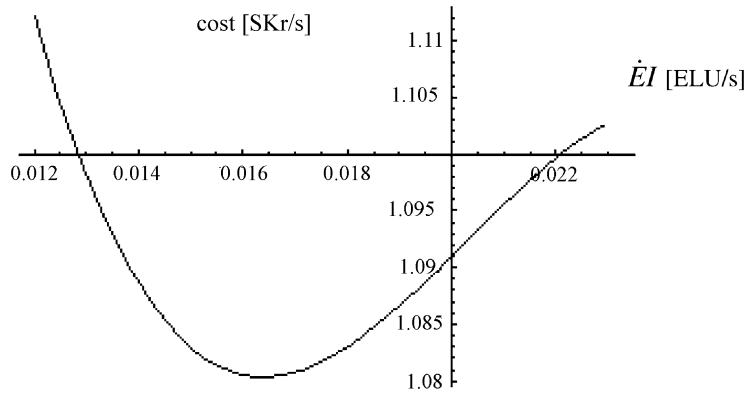

Fig. 12. The production cost as a function of the rate of environmental impact (EPS system).

on the optimisation. If the temperature is important then a lower temperature is preferred. The effects of the falling water content are normally more important than the effects of the organic release. Continued drying to the falling rate period might induce other optima due to fact that the organic release will continue even after the product is dried.

In the economic study the production cost of the delivered heat and power (including the eventual external need of electricity) was analysed. The results are shown in Fig. 11. This study shows that drying until the time limit gives the best result. The analyses of the studies show that there are minima in the production cost of heat and power in the temperature interval. In this simplified study it seems that drying 2 min at 430 K yields the best economic result. A drier product gives a better economic result due to fewer losses, less transport, etc. Drying at a high temperature requires steam at a high temperature. Therefore, less electricity is produced. This electricity has to be produced externally. Drying at a low temperature will require a huge dryer; therefore the cost of the dryer will increase. Therefore, this optimum seems reasonable. The optimum of course depends on the cost of the externally produced electricity. A complete economic study is, however, beyond the scope of this paper.

Is it possible to make combined economic and environmental optimisation? One proposed solution is the EPS system, which is partly an economic study. The EPS environmental minima are economic minima due to the willingness to pay not compared with the actual producing cost. In this study many environmental effects are coupled with economic effects. Therefore, the environmental and economic minima are closely correlated. If combined optima are required so called Pareto curves are sometimes constructed [30]. The lowest production costs are obtained for the temperature–time combinations that are at the edge of the surface shown in Fig. 10, i.e. at the limiting conditions studied in this work. If it is assumed, as done here, that the biofuel has to be dried, then the environmental results are also chosen at the edge of the surface (see Fig. 5). It is also shown that if the environmental effect of the external electricity is neglected, the environmental impact is minimised when using temperature–time combinations that are at the extremes of the range studied. The results on the edges of the surfaces shown in these two figures are related to the end of the constant drying rate section at equal time and temperature.

Therefore, it is possible to combine and construct a Pareto curve from the extremes of the range studied. In the economic study a minimum between the temperature limits were found, but in the environmental study the minima were found on the surface edge at the lower temperature limit. Consequently the environmental minima and economic minima are different. At the high temperature limit (short residence time) a high environmental impact is related to a higher need for external electricity (Danish coal). This will also increase the cost. At the lower temperature limit (high residence time) the need for external electricity is minimised, but the producing cost due to the bigger size of the dryer has caused a local maximum at the lower temperature limit. The combined results from the surface edges are at locus in Fig. 12. As can been seen in Fig. 11 an economic minimum exist at 1.081 SKr/s. A compromise between the goal to minimise production costs and to obtain the lowest environmental impact has to been made. If, for example, the production cost increases by 1.3% from the lowest production cost (1.081 SKr/s) the environmental impact will decrease with 18.5%.

Continued drying might induce other environmental and economic optima, which are not related to the limiting conditions studied. If so the optimum will be in the falling rate section, although drying to this length of time is uncommon.

7. Conclusions

LCA has been shown to be a valuable tool for environmental optimising of energy systems. In this study a new approach to design situations is adopted where the environmental impact is expressed as cumulative formation of ecopoints (or equivalent).

Many primary environmental data are uncertain in the analysis but it is obvious that the externally produced electrical energy, due to the exergy losses of the steam used for drying, effects the environmental optimisation of the system. If the last unit of electricity produced is Danish electricity (old coal power plant) a longer drying time at a lower temperature is preferred. The capital goods (the dryers) are not so important in the environmental study but are important in the economic study. Many environmental and economic effects are coupled. A dry product creates fewer losses during combustion and thus requires less biofuel, less transport, etc. Therefore, drying until the limit is preferable (until the constant drying rate is ended). The effects of organic losses of the biofuel are estimated to be of minor importance due to the optimisation of the system if the organic compounds from the exhaust steam are reduced inside the system. If combined economic and environmental optima are required it is possible that Pareto curves can support the decision making process.

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