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Entropy of energy crops and GHG mitigation

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Abstract. The photosynthesis process generates beside carbon hydrates also complex chemical compounds. The artificial synthesis of such compounds is often impossible or may require high energy input compared to their heat value. In other words, the entropy of energy crops is low compared to fossil fuels. This fact is usually neglected in energy analysis of bio fuels resulting in questionable political decisions concerning renewable energy. The objective of this paper is to demonstrate that the GHG mitigation potential of e.g. fibre crops may be enhanced using them first as raw material for commercial products before processing to fuel at the end of their lifetime. For example, reed canary grass may be used for paper production and after recycling, the used paper can be processed to insulation material in buildings before thermal use. Such a chain of usage trades off both, the low entropy as raw material for pulp and the heat value of the carbon hydrates. A calculation model is used to estimate the reduction of CO_2 equivalents of two options: Alternative A: Production of reed canary grass + processing to fuel for heating. Alternative B: Production of reed canary grass + processing to paper + recycling of paper + processing to insulation material + installation of insulation material in buildings + recycling of insulation material + processing for heating. The results show, that alternative B is outclassing alternative A. However, fossil fuels render a higher energy return of investment and are for the time being more competitive than both options.

Key words: energy analysis, energy crops, GHG mitigation, reed canary grass

INTRODUCTION

Energy crops are still considered as an important renewable energy source even though there are many doubts whether they may replace fossil fuels sustainably. The question whether the ‘cure is worse than the disease’ (Doornbosch & Steenblik, 2007) emerged, when the awareness about environmental impacts of energy crop production especially in the tropics reached public awareness (Fritsche et al., 2006; Mathews, 2007; European Environment Agency, 2007; Fargione, 2008; Searchinger et al. 2009, Young, 2009). A living crop decreases the entropy of matter by the photosynthesis process generating beside carbon hydrates also more complex chemical compounds. Therefore, many crops are used not only for food production but also as raw material for production of commodities (Smeder & Liljedahl, 1996). Energy crops not only compete with food crops and feed crops, but also with fibre crops for industrial products. This fact is often neglected in energy analysis of energy crops. The GHG mitigation potential of fibre crops may be enhanced using them first as raw material for commercial products before processing to fuel at the end of their lifetime. Such a chain of usage trades off both, the low entropy of the fibre and the heat value of the fibre.

MATERIALS AND METHODS

The calculation model to estimate the reduction of CO_2 equivalents of fibre crops uses reed canary grass (RCG) (*phalaris arundinacea)* as an example. Alternative A includes the production and the processing of RCG to fuel for heating. Hadders & Olsson (1997), Mäkinen et al. (2006), and Lötjönen (2009) describe the process of cultivating and processing and the assumptions made.

Alternative B includes the production of RCG, the processing of RCG to paper, recycling of used paper, processing of recycled paper to pulp as insulation material, installation of pulp in buildings, recycling of pulp, and processing the residues to fuel for heating as in alternative A.

The fibre yield is processed to paper with a mean mass efficiency η_y of 65% (Finell, 2003). The process energy of paper production from birch is 38 MJ kg^{-1} and the CO_2 eq. 1.1 kg kg^{-1} (Gromke & Detzel, 2006). The credit of lower process energy of paper production from RCG compared to pulp from wood is neglected. The recycling efficiency η_p of used paper is estimated to 80% and the mass efficiency η_{pr} of processing used paper to pulp is estimated to 90%. The process energy of pulp production is 3.25 MJ kg^{-1} and the CO_2 emissions about 0.2 kg kg^{-1} (Rakennustieto, 2000). The heat value of the mass losses for processing may compensate the energy demand for installation of the pulp as insulation material in buildings, recycling, and transport.

To calculate the saved energy using the pulp in buildings for improvement of heat insulation, the model wall or ceiling construction described in fig. 1 is used. Fig. 1a shows a simple wall element made of two d = 0.022 m thick wood walls filled with pulp insulation. The U-value of the wall insulation declines widening the insulation thickness

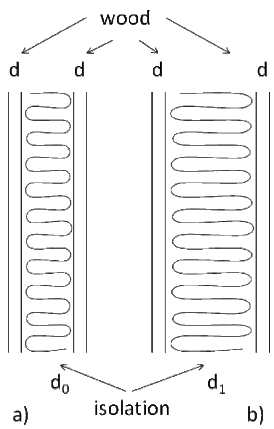

Figure 1. Model wall construction, a) original isolation, b) improved isolation.
d_0 = original thickness, d_1 = thickness of wider insulation, d = thickness of the inner and outer wood wall

increment $\Delta d = d_1 - d_0$ in fig 1b. Therefore, the saved energy depends on both variables, the original insulation, and the improved insulation. The installation density ρ of the pulp is 30 kg m^{-3} and determines together with the thickness of insulation the amount of square meters of the model wall or ceiling to be isolated with the fibre yield of one hectare. The thermal conductivity of wood λ_w is 0.14 and of pulp λ_p 0.041 W K^{-1} m^{-1}. The mean temperature in middle Finland (Jyväskylä) T_m is -0.87°C during the heating period of 273 days from September to May (Finnish Meteorological Institute, 2011). The room temperature T_r is +20°C. The lifetime of the insulation v is estimated to 50 years. The saved energy E_S during the lifetime of the wall is then calculated with following equations:

$$E_S = (U_0 - U_1)\, Y\, \eta_y\, \eta_p\, \eta_{pr}\, (\rho\, \Delta d)^{-1}\, (T_r - T_m)\, d\, v\; 0.0864 \text{ MJ ha}^{-1} \quad (1)$$

$$U_0 = (2\, d_w \lambda_w^{-1} + d_0 \lambda_p^{-1})^{-1} \text{ W K}^{-1}\text{m}^{-2} \quad (2)$$

$$U_1 = (2\, d_w \lambda_w^{-1} + (d_0 + \Delta d)\, \lambda_p^{-1})^{-1} \text{ W K}^{-1}\text{m}^{-2} \quad (3)$$

At the end of the lifetime the pulp can be used as fuel for burning assuming a recycling efficiency of 90%. The heat value of pulp may be similar to that of RCG and burning this waste may additionally improve the energy balance. However, often boron is added to the pulp as flame retardant compound, which decreases the lower heat value.

The energy return on investment (EROI) is calculated from the energy input E_{in} and output E_{out} using the following equation:

$$EROI = (E_{out} - E_{in})\, E_{in}^{-1} \quad (4)$$

The CO_2 equivalent emission mitigation from the saved energy depends mainly on the fuel mix used for processing. Any conversion factor for energy conversion into CO_2 equivalents may be used. It will not change the quality of the results.

RESULTS AND DISCUSSION

The *EROI* for heat production of RCG is 11.8 MJ MJ^{-1} and the CO_2 eq. balance is 0.015 kg MJ^{-1} (Lötjönen et al. 2009 after Mäkinen et al. 2006) assuming a dry matter yield of 6 Mg ha^{-1} corresponding to an energy yield of 102 GJ ha^{-1}. However, this calculation takes into consideration only the energy input of fuels and fertilisers. The proportion of indirect energy input reached in 1999 in Danish agriculture more than 70% (Rydberg & Haden, 2006) of the total energy input. Thus, a realistic value of the *EROI* is about 6 MJ MJ^{-1} assuming that crop production requires ⅓ of the energy input in the agricultural production. The realistic net energy gain is then about 50 GJ ha^{-1}.

The saved energy of alternative B is expressed as a function of the original insulation thickness and the insulation thickness increment Δd as parameter. The original insulation thickness may e.g. range between 0.05 and 0.15 m. Then the area enclosed by the points ABCD in Fig. 2 embraces the energy saving potential widening the insulation thickness from 0.01 to 0.15 m resulting in final insulation thickness of 0.06 to 0.3 m.

Table 1 shows the result of the energy saving calculations. The calculation of CO_2 equivalents savings is given in table 2. Widening the pulp insulation thickness of a well-

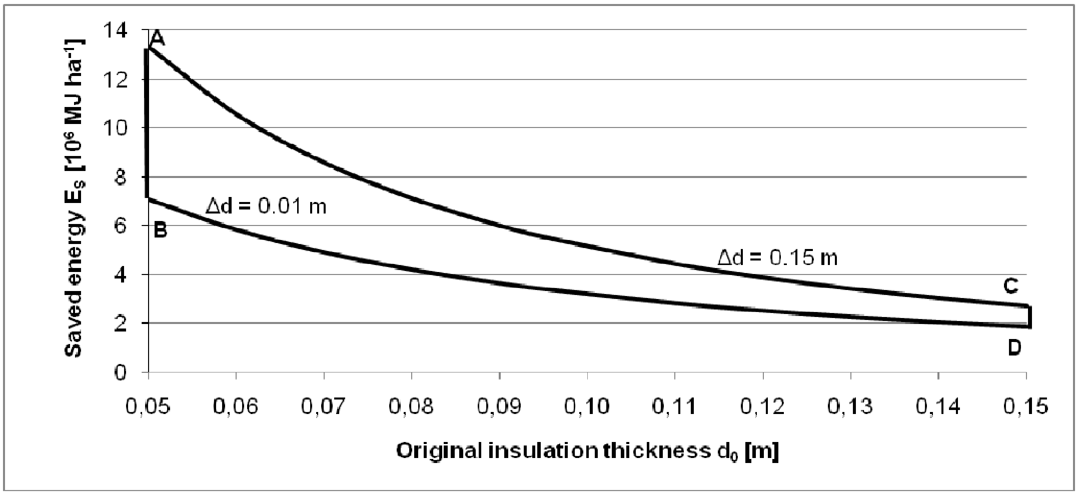

Figure 2. Saved energy of alternative B as a function of the original insulation thickness d_0 and the insulation thickness increment *Δd*.

Table 1. Calculation of the energy saving potential at CD of fig. 1.

Process	Energy	Unit
Energy input of RCG production	7,956	MJ ha^{-1}
Energy input of paper production:	140,244	MJ ha^{-1}
38 MJ kg^{-1} 3,900 kg ha^{-1} - 7,956 MJ ha^{-1} energy input of RCG production		
Energy gain from waste: 6,000 - 3,900 MJ ha^{-1} = 2,100 MJ ha^{-1} 17.6 MJ kg^{-1}	-36,960	MJ ha^{-1}
Energy input of pulp production from recycled paper: 2,808 kg ha^{-1} 3.25 MJ kg^{-1}	9,126	MJ ha^{-1}
Energy gain from waste: 3,900 - 2,808 kg ha^{-1} = 1,092 kg ha^{-1} 17.6 MJ kg^{-1}	-19,219	MJ ha^{-1}
Sum energy input	**101,147**	**MJ ha^{-1}**
Energy gain by saving energy from additional insulation at CD of fig. 1	870,000	MJ ha^{-1}
EROI using RCG as insulation material at CD of fig. 1	7.60	MJ MJ^{-1}

Table 2. Calculation of GHG mitigation potential at CD of fig. 1.

Process and substitution alternatives	kg CO_2eq. ha^{-1}
Emissions from RCG production 0.015 kg CO_2eq. MJ^{-1} 102,000 MJ ha^{-1}	1,530
Emissions from paper production: 1.1 kg CO_2eq. kg^{-1} 3,900 kg ha^{-1}	4,290
Emissions from pulp production of recycled paper 0.2 kg CO_2eq. kg^{-1} 2,808 kg ha^{-1}	562
Sum emissions	**6,382**
Mitigation from saved light fuel oil: 870,000 MJ ha^{-1} 86 g CO_2eq. MJ^{-1}	68,777
Mitigation from saved natural gas: 870,000 MJ ha^{-1} 69 g CO_2eq. MJ^{-1}	53,310
Mitigation from saved district heating: 870,000 MJ ha^{-1} 61 g CO_2eq. MJ^{-1}	46,785
Mitigation from saved electric power: 870,000 MJ ha^{-1} 190 g CO_2eq. MJ^{-1}	158,677

insulated wall or ceiling from 0.15 m (D) to 0.3 m (C) saves 870 GJ ha^{-1}, about eight to sixteen times more energy than the heat potential of alternative A. One may object that this energy saving is accumulated over a period of 50 years. However, during the lifetime of 50 years every year the harvest of RCG can be processed to paper and pulp. If the process of paper production is excluded and the yield of RCG is immediately processed to pulp for insulation purposes, the energy saving increases even more. The EROI in terms of saved energy is 7.6 MJ MJ^{-1}. It is evident that this energy saving is realistic in new construction buildings or under circumstances where the insulation improvement of existing buildings does not require additional demolition and construction work, e.g. improving the insulation thickness of a ceiling.

Another aspect of energy saving and GHG mitigation is the replacement of artificial insulation material by pulp. The energy requirement of rock wool production is about five times higher. Thus, 5,400 kg ha^{-1} pulp saves additionally 77 GJ ha^{-1}.

CONCLUSIONS

The calculation example shows clearly that crops should first be used as food, feed, or fibre before the residues are converted to energy at the end of the lifetime. Producing a table from wood and burning the residues together with this table at the end of its lifetime renders the same energy gain as using this wood for firewood. Because of the second law of thermodynamics, decrease of entropy without energy input is impossible. Only the photosynthesis process, powered by sun energy, guaranties low entropy products for humans and animals. The reason, why energy crops are recently used for energy purposes only, may be explained by subsidy policies and by neglecting external cost of energy crop production. Anyway, the energy return of fossil fuels is still higher (between 10 and 20, Pimentel, 2008) and therefore CO_2 mitigation using renewable energy sources is more expensive for the time being.

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