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Efficient use of arable land for energy: Comparison of cropping natural fibre plants and energy plants

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Abstract. With focus on renewable energy from agriculture governments can either support the growing production of energy crops or it can invest in technology or measures to reduce the energy consumption. But what is more efficient with regard to the use of the limited resource arable land: to insulate a building with fibre material grown on arable land to reduce the heating demand or to use such land for growing energy plants for the sustainable energy supply of a building? To answer this question, a long term balance calculation under consideration of numerous framework parameters is necessary.
Based on traditional fibre plants like hemp, flax, and woody fibre crops (e.g. poplar), these agricultural plants and their processing to insulation material were examined. Based on available data for the typical building structure of detached and semi-detached houses in Germany, models of buildings were developed and the accessible potentials for heating energy savings by using suitable insulation measures with natural fibre materials were determined. As a comparable system for the supply of renewable energy, bio-methane from silage maize was chosen, since it can be used efficiently in conventional gas boilers for heat generation. The different levels of consideration allow the following interpretations of results: in a balance calculation period of 30 years, the required acreage for heating supply with methane can be reduced by approx. 20%, when at the beginning of the use period fibre plants for the insulation of the houses are grown on the arable acreage. Contrariwise, to compensate only the existing loss in heating energy due to inadequate insulation of older detached and semi-detached houses (build prior to 1979) an annual acreage of approx. 3 million ha silage maize for bio-methane would be required in Germany. Therefore, from the land use perspective the production of biogas plants in agriculture for heating should be accompanied by the production of fibre plants for a reasonable improvement of the heat insulation of houses.

Key words: natural fibre plants, fibre, bioenergy, biogas, heat insulation, heating.

INTRODUCTION

Due to an increasing awareness for global warming and a simultaneously increasing worldwide demand of energy, the interest in alternative energy resources from agricultural production is growing continuously. The EU's Renewable energy directive sets a binding target of 20% final energy consumption from renewable sources as an average of all members states by 2020 (Directive 2009/28/EC). To achieve this, EU countries have committed to reaching their own national renewables targets ranging from 10% in Malta to 49% in Sweden. According to the individual national action plans of the EU countries biomass from forestry and agriculture plays an important role for the majority of all member states to reach the targets for renewable energy and reduction of CO_2 emissions (National action plans 2016). Hence, the acreage for cropping energy plants for bioheat, bioelectricity and biofuels has increased in the last years (European Commission, 2016). For example, in Germany the acreage for energy plants has about tripled in the past 10 years (FNR, 2015). With a total of 2.07 million ha, energy plants have covered approx. 12% of the total arable area in Germany in 2014 (Statistisches Bundesamt, 2015). Therefore, the annual increase of the required crop area for silage maize for biogas production and the relation with regard to the competition for acreage of other field crop, the high expense for fertilizers, and the effects on the humus balance are discussed controversially (AEE, 2010; Willms, 2013; Scholz et. al, 2010). An important driver for the increasing share of renewable energy in the German total energy mix is the long term regulation of remuneration for renewable energies (EEG, 2011 and EEG, 2014). Thus, the share of renewable energy in the final energy mix for electric power could be increased to currently approx. 27% (BMWI, 2015) and for the total consumption of end-use energy to approx. 13.7% for the year 2014 in Germany. Although at present an area of 1.27 million ha (approx. 60% of total energy plant area) is required for biogas generation alone, the energy generated from biogas covers only 1.2% of the end energy demand, or respectively 4.9% of the electric power consumption (BMWI, 2015; BMWI, 2016). The acreage for fibre plants in Germany has significantly been decreased in the past 10 years and presently only 500 ha are cultivated with fibre plants (FNR, 2015). Main reason for that is, besides certain process technological problems at the beginning (Pecenka et al., 2009a), the increasing competition to other field crop, not least the competition to energy plants, since in energy production numerous additional subsidies have their effects. Thus, growing of energy plants is substantially more attractive for farmers in Germany (Carus, 2008). From the aspects of sustainable energy supply this is certainly correct; however, it raises the question regarding the efficient use of available acreage and the related costs for the national economy on the whole.

A significant share of energy from renewable sources is used for the supply to households. The total demand of private households in 2013 was at approx. 2,603 PJ and thus represents approx. 28% of the final energy demand in Germany (UBA, 2016). About 69% of the total demand of private households is required for heating alone (year 2012). Besides the use of renewable sources, the reduction of the absolute consumption is a substantial factor for sustainable resource management. Thus various statutory incentive implements are available, particularly for the reduction of demanded heating energy of residential buildings, e.g. by insulation of building substance. However, various studies about age and structure of existing buildings have shown that 70 to 75% of detached and semidetached houses in Germany build prior to 1979 do not feature any heat insulation in addition to the conventional brickwork (Diefenbach et al, 2010a; Diefenbach et al., 2010b; Weiß & Dunkelberg, 2010).

At present the annual progress of insulation activities in old buildings is only about 1%. Considering this level, it can be expected that a period of 65 to 70 years will be required before all buildings feature sufficient insulation. The cultivation of fibre plants and their consecutive processing into insulation material for subsequent insulation of resident buildings could tap this potential of lasting energy savings (Krüger, 2011). Simultaneously, not only substantial emission of CO_2 could be avoided, but also carbon would be bound long term as a substantial compound of natural insulation material. Moreover, natural insulation materials provide significant advantages compared to the mainly synthetic materials applied at present. The production of natural fibre insulation requires up to 20 times less energy (Tscheutschler, 1999; UBA, 2011) and allows for resource-neutral disposal by thermal recycling, simultaneously delivering renewable energy.

To answer the question, what is more efficient with regard to the use of the limited resource arable land: to insulate a house with fibre material grown on arable land to reduce the heating demand or to use this land for growing energy plants for the sustainable supply of heating energy, several sub-questions have to be answered. For a long term balance analysis some of the most important points are:

- What is the typical heating energy demand of common detached and semi-detached houses typical for rural areas?
- What is the share of houses with inadequate heat insulation?
- What is the acreage of agricultural land required to cover the heating energy demand of a common detached or semi-detached house with bioenergy?
- How much insulation material is necessary to improve the heat insulation of older houses to meet current standards?
- What is the acreage of agricultural land required to crop fibre plants for an upgrade of the heat insulation of a house to current standard using natural fibre insulation materials?

All research and balance calculations required to answer these questions were made exemplarily for Germany, since a good data base is available due to up-to-date inquiries. However, the results are also interesting for other European countries in particular for countries with similar climate conditions and a comparable state of the building stock.

MATERIALS AND METHODS

Fig. 1 shows the relation between age and heating energy demand of detached and semi-detached houses according to Weiß & Dunkelberg (2010), which has been used to determine saving potentials for heating. These types of houses represent 59% of the entire inventory of residential buildings in Germany (Destatis, 2011).

Characteristic model houses were designed for this study based the analyses on building inventory as well as on heating requirements of different residential buildings carried out by Weiß & Dunkelberg (2010) and Diefenbach et al. (2010a). To analyse the possible savings of heating energy as well as the required amount of insulation material to realise these savings, the model houses H1 – H5 have been investigated in detail (Table 1). Based on the model houses, the balance could be calculated about the demand and effects of different insulation measures on the exterior walls. Beside the shape of the building, the structural-physical properties of the used building materials have also an important impact. Therefore, the different properties of the basic structure of existing buildings, e.g. different wall structures and their impact on heating energy demand had to be considered in the model calculations (Table 2).

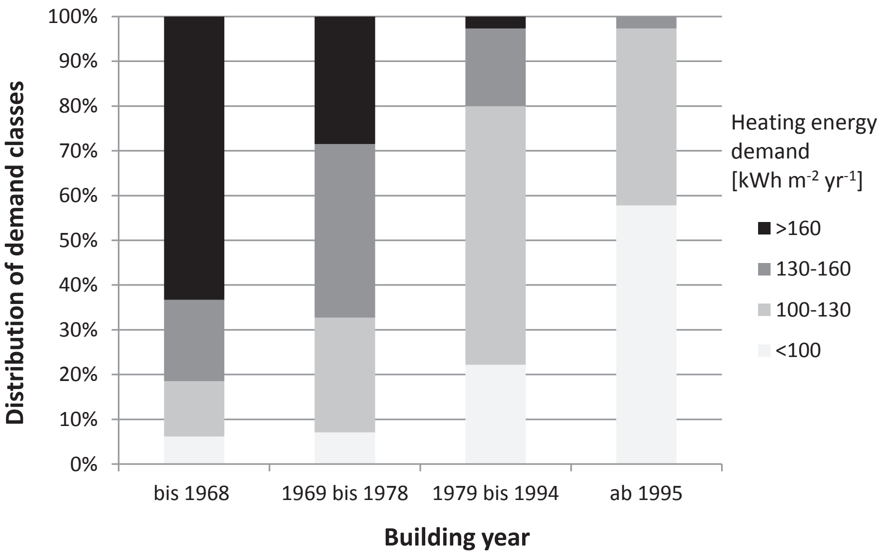
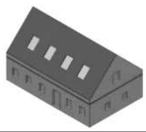
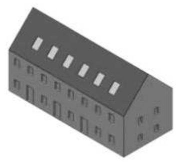


Figure 1. Classes of heating energy demand of detached and semi-detached houses in Germany, dependent on year of construction (Weiß & Dunkelberg, 2010).

Table 1. Building concepts

Model code	Model buildings	Living space [m²]	Exterior wall area [m²]
	Detached houses		
H1 – H3	  	139 to 163	142 to 162
	Semi-detached and three-family houses		
H4 – H5	 	238 to 357	246 to 311

The building-specific insulation properties relevant for the calculation of heating energy demand were implemented in the calculation as U-values. On basis of the heat transmission coefficient (U-value) of an individual bounding surface of a house (roof, exterior wall, window, door and floor plate) the heat flow through this specific surface can be calculated according to Equation 1.

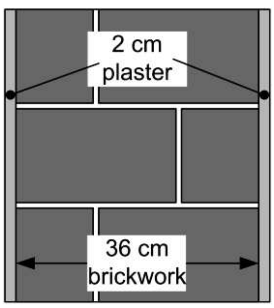
$$\dot{Q} = -U\,A\,\Delta T \qquad (1)$$

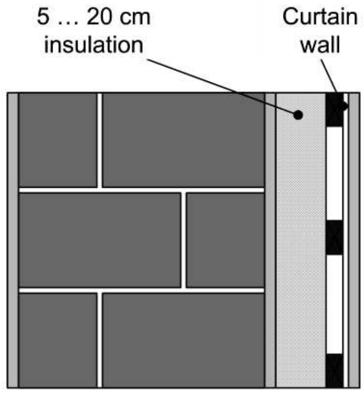
where: $\dot{Q}$ – Heat flow in Wh; U – Coefficient of heat transmission in W m^{-2} K^{-1}; ΔT- Temperature difference between inner and outer wall surface in K.

To calculate the total heating energy demand of a house the complex structure of the whole house has to be considered taking the heat flows through all bounding surfaces into account. For this purpose the software Energieberater 7 (Hottgenroth, 2011) was used to calculate the heating energy demand for all combinations of different model houses (Table 1, H1 – H5), wall types and insulation thicknesses (Table 2) based on the climate conditions of Braunschweig (middle Germany, 52°19'N 10°33'O). For the roof, windows, doors, and floor plate typical values for houses built prior 1979 have been chosen from the database provided by the software Energieberater 7 in accordance with the analysis of Weiß & Dunkelberg, 2010.

Table 2. U-values of various typical wall building materials (Hottgenroth 2011)

Non-insulated wall	Insulated wall





	U-value [W m^{-2} K^{-1}]	insulated 5 to 20 cm	U-value [W m^{-2} K^{-1}]
Poroton (P)	0.41	Poroton	0.27 to 0.14
Perforated brick (PB)	0.77	Perforated brick	0.39 to 0.17
Solid brick (SB)	1.01	Solid bricks	0.45 to 0.18
Heavy solid brick (HSB)	1.28	Heavy solid bricks	0.49 to 0.19

Results from long-term crop measurements on ATB's raw material plantation (Fig. 2) as well as data from the German agriculture statistic (Destatis, 2011) were used for research on supply of energy as well as fibre materials. The harvested fibre crop needs to be mechanically decorticated and processed into insulation mats or insulation boards for its use in building industry. Substantial for the material balance is the achievable fibre yield in this process for the different raw materials. Based on own research in a pilot plant and several production plants (Munder et al., 2004; Pecenka, 2009b; Scholz et al., 2010), crop data and yields shown in Table 3 were used for further calculations. Fast growing poplar was used for the comparison of fibre production from wood on agricultural land.

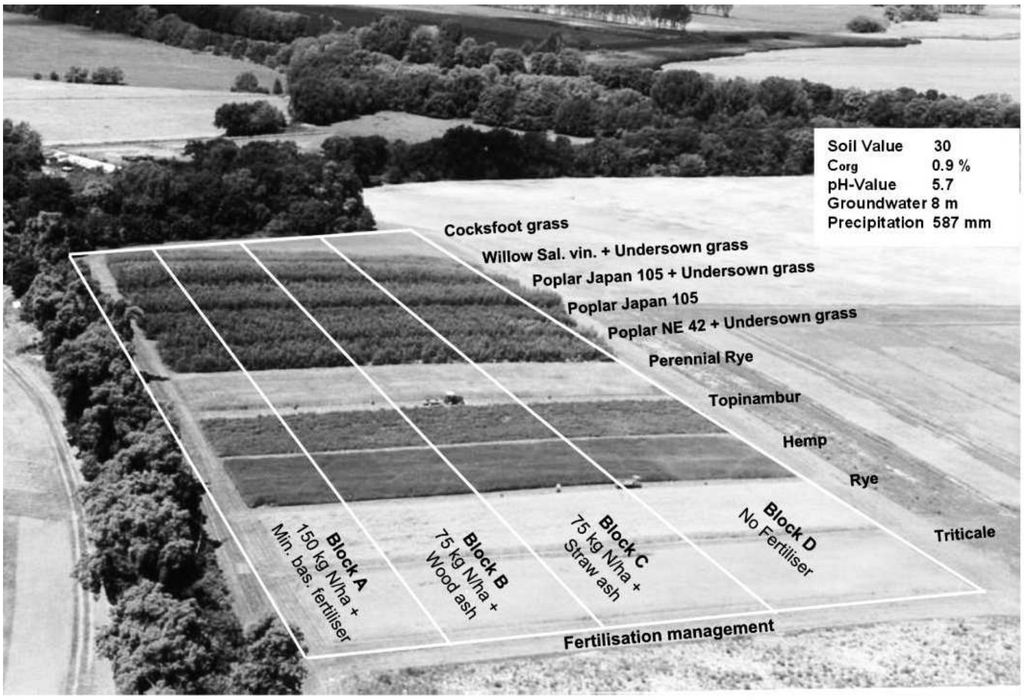


Figure 2. Raw material and energy plantation (ATB).

Table 3. Crop data used for the calculations of yields of energy and insulation materials

Material use				
	biomass yield t_{DM} ha^{-1} yr^{-1}	fibre yield t ha^{-1}	insulation material density kg m^{-3}	yield of insulation material m^3 ha^{-1}
Maize	17.5	-	-	-
Hemp	7	1.75	100	17.5
Flax	5.5	1.4	80	17.2
Poplar	10	7.2	180	40
Energetic use				
	biomass yield t_{DM} ha^{-1} yr^{-1}	methane yield m_N^3 ha^{-1} yr^{-1}	processing loss %	energy yield GJ ha^{-1} yr^{-1}
Maize	17.5	4997	28	116.5
Hemp	7	-	-	136.0
Flax	5.5	-	-	9.89
Poplar	10	-	-	177.1

DM – dry mass, poplar yields data based on 20 years averages from own measurements at the ATB energy plantation (county Brandenburg, Germany), all other yields based on averages for sandy soils under the growing conditions in the county Brandenburg (Germany), (Munder et al., 2004; Pecenka, 2009b; Scholz et al., 2010; Destatis, 2011).

Not considered in the point balance were energy yields for natural fibre insulation materials from their thermal recycling when being disposed of at the end of their life (poplar fibre approx. 120 GJ ha^{-1}, hemp fibre 24 GJ ha^{-1}). Poplar from short rotation plantations were estimated to achieve 72% fibre yield at considered storage loss of 20%

dry matter, and hemp and flax were estimated to achieve fibre yields of 25% (Pecenka et al., 2014; Lenz et al., 2015). The generation of biogas or bio-methane (processed biogas, fit for feed into domestic gas network) from silage maize were used as reference for energy plant production. Silage maize yield of 50 t with 35% dry mass content per hectare and year were considered for the calculation of the bio-methane yield. 12% storage loss and 28% loss due to processing of biogas into bio-methane were taken into account (KTBL 2009; KTBL 2010; Mühlenhoff & Dittrich, 2011).

RESULTS AND DISCUSSION

Contingent saving potential for heating energy demand of detached and semi-detached houses were investigated based on the data for building inventory in Germany (see Fig. 1). The most economically accessible potentials are present in houses build prior to 1979, as shown in Fig. 3.

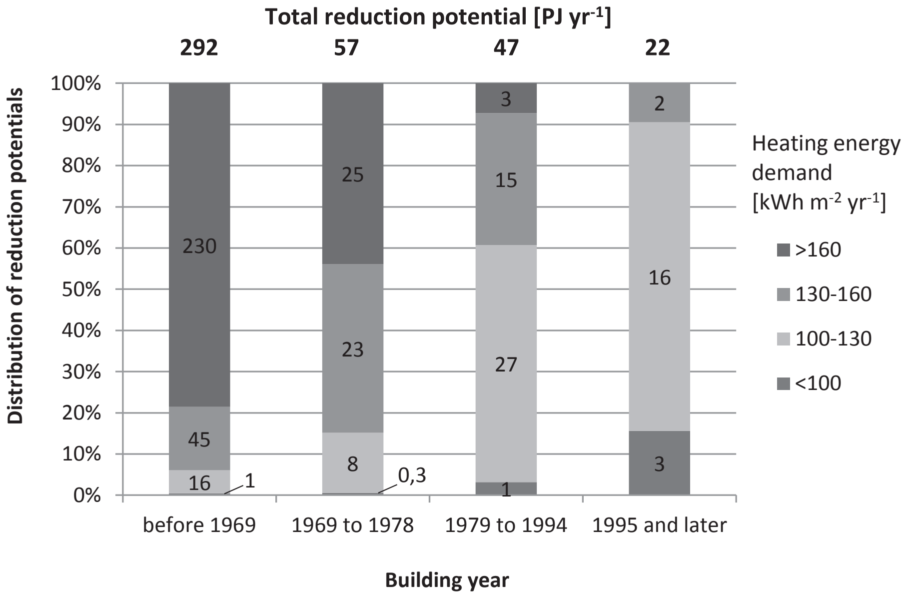
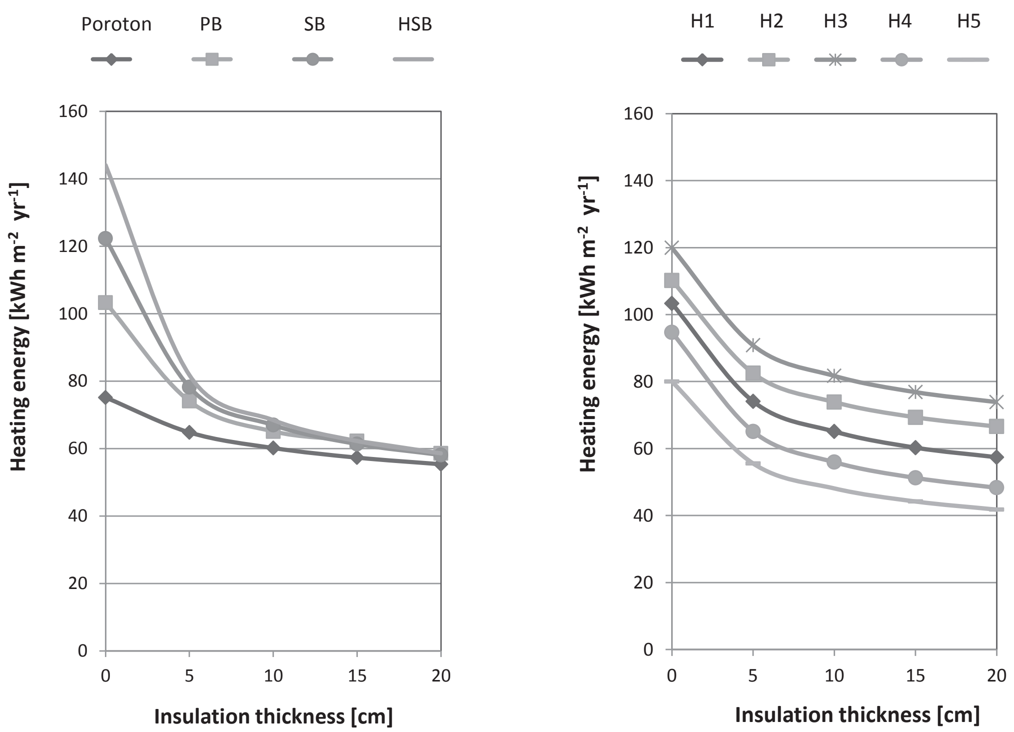


Figure 3. Saving potentials for heating energy for detached and semi-detached houses in Germany (target for specific heating energy demand: 80 kWh m^{-2} yr^{-1}).

Total annual energy savings of approx. 349 PJ could be achieved by implementing suitable insulation measures for houses built prior to 1979, targeting on a reduction of the specific heating energy demand to 80 kWh (m^2 a)$^{-1}$ which represents an average of the current standards for newly build houses in Germany. With regard to the final energy demand of households in Germany in 2013 of approx. 2,603 PJ this equals savings of 13%.

To answer the question how many hectares of fibre plants have to be cultivated to use the calculated saving potential, the specific demand of insulation material has to be investigated for houses built prior 1979. Firstly, the impact of different building concepts on heating energy demand was determined dependent on the type of model house, insulation thickness, and wall material. As shown in Fig. 4a, the choice of wall material for non-insulated walls has a substantial impact on the heating energy demand. Whereas a single house (type H1) with common heavy solid brick (HSB) walls has a specific heating energy demand of 144 kWh m² yr^{-1}, the same house with Poroton (porous clay brick) walls requires 75 kWh m^{-2} yr^{-1} only. These differences are already reduced by applying an insulation thickness of 5 cm to a heating energy demand of 82 resp. 65 kWh m^{-2} yr^{-1} and at 10 cm insulation thickness they are only at 68 resp. 60 kWh m^{-2} yr^{-1}.



a) influence of wall types, house type H1 b) influence of house types, wall type PB

Figure 4. Impact of different model house concepts and insulation material thicknesses on heating energy demand for subsequent exterior wall insulation in old buildings
(Poroton – Porous clay brick, PB – Perforated brick, SB – Solid brick, HSB – Heavy solid brick H1…H5 – model house type 1…5).

Similar results are shown in Fig. 4b for the impact of the chosen type of model house on the heating energy demand. The well-known energetic disadvantages of detached houses (H1 to H3) compared to semi-detached and three family houses (H4 and H5) become clear. In general, a heat insulation of 5 to 10 cm on the exterior walls showed to be already quite efficient to use the most of the available saving potentials. Further common refurbishment measures, e.g. additional insulation of the roof, insulation of the basement ceiling, or heating modernization were not considered at this stage of evaluation.

A large-scale cultivation of fibre plants is required for the utilization of these potentials if natural fibres should be used as heat insulation material. A potential 10 cm exterior building insulation with natural fibre material of all detached and semi-detached houses (built prior to 1979) within 1 year would theoretically require cultivation of 7.5 million ha of hemp or 3.3 million ha of short rotation plantations with poplar (Fig. 5, column A). On the other hand, a lasting coverage of the so far unused potential for savings of 349 PJ yr^{-1} in heating energy by using renewable energies in form of bio-methane would require the cultivation of approx. 3 million ha maize every year.

A substantial reduction of annual required arable land for cultivation of fibre plants is possible when considering more realistic plans for refurbishing houses in a period of 10 to 20 years. If wood fibre (poplar) should be used in the coming 10 years, an annual cultivation area of 329,000 ha will be required (column B). For a balance period of 20 years the required area would decrease to 165,000 ha respectively (column C). Hemp cultivation would require much larger cultivation areas due to a lower fibre yield (factor 2.3). However, when evaluating hemp cultivation the use of hemp shives as by-product is not taken into consideration. Hemp shives are subsequent building insulation as well (Bevan & Woolley, 2008) and represent approx. 60% of the overall mass flow of hemp processing.

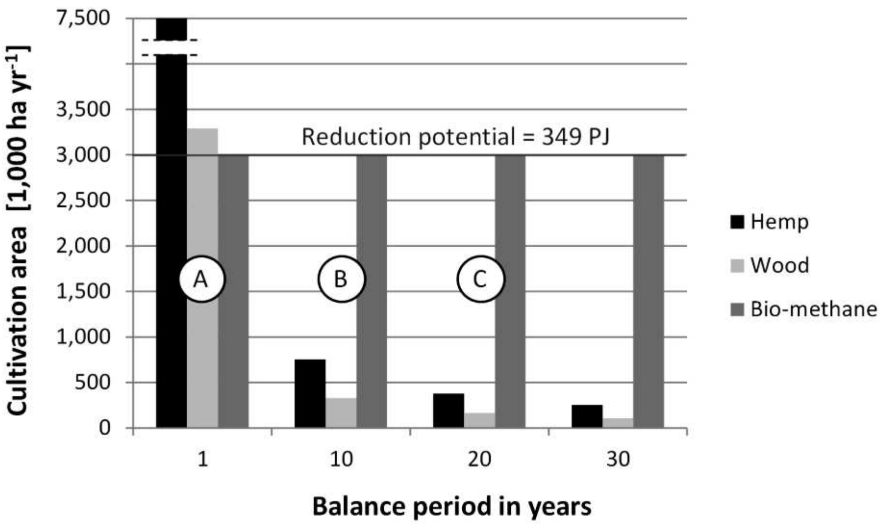


Figure 5. Area requirements for production of insulation material and respectively for generation of bio-methane for heating (required heating energy = saving potential of 349 PJ)
A: Required acreage for fibre plants in order to achieve the energy savings potential of 349 PJ within one year by providing the insulation for the facade.
B/C: Required acreage for fibre plants in order to achieve the energy savings potential of 349 PJ within 10 resp. 20 years through insulation of the house facade.

The amount of saved heating energy increases proportional to the length of the useful life of exterior wall insulation. Considering the potential energy savings over the usual depreciation period for buildings of 50 years, it can be calculated that in the case of model house H1, by making an exterior wall insulation from natural fibre with a thicknesses of 10 to 20 cm it can be saved a total of 950 to 1,150 GJ in heating energy during the evaluated time of 50 years. This is equivalent to the annual energy generated from cultivation of silage maize and the subsequent generation of biomethane from 8 to 10 ha of acreage.

Balancing the achievable energy savings for a house (model H1, wall material: perforated brick – PB), the demand in arable land for agricultural supply of raw material and energy are as shown in Fig. 6. Applying exterior wall insulation from natural fibre at thicknesses of 10 to 20 cm, the demanded acreage for bio-methane production for heating energy supply can be reduced by 19 to 22% over a balance period of 30 years.

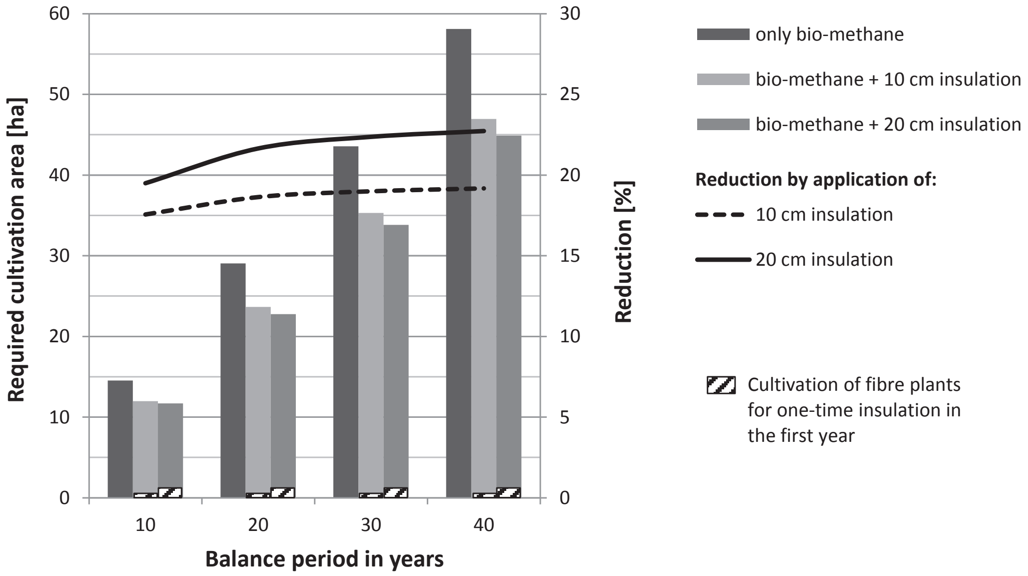


Figure 6. Acreage demand for heating energy supply of a detached house (model H1) with bio-methane (with and without exterior wall insulation).

Further positive environmental effects of using natural fibre insulation materials lie in their potential for long term CO_2 storage and the possibility of thermal utilization when being disposed at the end of their useful life. Furnishing the model house H1 with 10 cm or 20 cm exterior wall insulation respectively requires 1.2 to 4.5 t natural insulation material. Thus, 2.1 to 7.8 t CO_2 equivalent are sequestrated in such wall insulation. Looking at the overall potential of older detached and semi-detached houses (built prior to 1979 – comp. Fig. 5) for CO_2-sequestration, 22 million tons of CO_2 equivalent could be sequestrated long term by using hemp fibre insulation, or 41 million tons of CO_2 equivalent respectively by using wood fibre insulation. Energy yields of thermal utilisation on disposal would be at approx. 200 PJ for hemp fibre insulation, or approx. 360 PJ for wood fibre insulation respectively (KTBL 2006). However, additional CO_2-sequestration potentials of the cultivation of fibre plants were not taken into account in this analysis. According to Scholz et al. (2010) for the cultivation of poplar in short rotation an annual sequestration of carbon in the soil between 880 to 1,600 kg ha^{-1} respectively 3.2 to 5.9 t ha^{-1} CO_2 can be assumed. Whereas for the cultivation of maize for bio-methane a reduction in the soil carbon content between -560 to -800 kg ha^{-1} have to be assumed and compensated by organic fertilisation (Willms, 2013). Furthermore, the required application of mineral fertiliser, which is required for efficient cropping maize, hemp and flax leads to high emissions of nitrous oxide. Cropping poplar for the production of fibres for insulation materials requires no or only minimal fertilisation. Therefore, nitrous oxide emission can be reduced from 2 to 4 kg N ha^{-1} yr^{-1} common for maize and hemp cultivation to approx. 0.5 kg N ha^{-1} yr^{-1} for poplar (Dambreville et al., 2008; Scholz et al., 2010, Willms, 2013,). These additional environmental effects should be taken into account as well if a life cycle assessment is undertaken for a more comprehensive comparison of the discussed different supply scenarios.

CONCLUSIONS

Besides the use of renewable energy sources, the reduction of the absolute consumption is an essential factor for sustainable resource management. Economically relevant energy savings are potentially possible by cultivating fibre plants and processing them into insulation material for subsequent heat insulation of residential buildings. Compared to energy plant cultivation only, the existing acreage can be used much more efficiently. In addition to that, the emission of considerable volume of CO_2 can be avoided, while substantial amounts of carbon as an essential compound of natural fibre insulation could be long term sequestrated.

The biggest savings with respect to the required acreage for renewable raw materials and energy sources can be achieved with the cultivation of poplar on short rotation plantations and its use for insulation materials. Hemp cultivation would require larger cultivation areas due to lower fibre yield. Besides the efficient material use of shives in building materials, the woody shives can be used as energy resource as well.

Due to the high demand for agricultural land to produce bio-energy and natural insulation materials public incentives should focus on the continuous modernisation of detached houses over a longer balance period of 10 or more years, starting with houses built prior 1979 for the German case. Already a natural fibre insulation with a thickness of 10 cm proved to be very efficient to use 90% and more of the calculated energy saving potential. An insulation of 20 cm thickness needs the double of raw material as well as agricultural land for fibre plant production, whereas the additional energy savings are lower than 10% compared to an insulation of 10 cm thickness.

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