Implementing bioenergy villages – a promising strategy for decarbonizing rural areas?

Till Jenssen[1*], Andreas König[2], Ludger Eltrop[1]

[1] *Institute of Energy Economics and the Rational Use of Energy (IER), Stuttgart, Germany*
[2] *German Academy of Science and Engineering (acatech), Munich, Germany*
* Corresponding author. Tel: +49 711 68587868, E-mail: till.jenssen@ier.uni-stuttgart.de

Abstract: An increasing number of rural municipalities want to meet their entire energy demand with biomass. This article gives a system analytic view on these "bioenergy villages" by balancing pros (GHG reduction potential) and cons (costs) using the example of a model municipality in Germany. The results indicate that a 100 % energy supply based on biomass potentials within the boundaries of a rural municipality is technically possible but less reasonable with respect to land-use competition and costs of energy supply. Whereas heat and power demand in bioenergy villages can be covered WITH RELATIVELY LITTLE LAND and to relatively low costs, the production of transport fuels based on energy crops (rape seed) leads to significant negative impacts. For a cost-efficient decarbonization of rural areas it can therefore be recommended to particularly expand the utilization of biomass for heat and power production.

Keywords: *rural supply concepts, sustainable energy, life cycle assessment*

1. Concept and status of bioenergy villages

Numerous bioenergy villages have been realized in rural areas of Central Europe over the last decade, for instance in Güssing (Austria), Jühnde (northern Germany) or Mauenheim (southern Germany). In Germany alone, planning and implementation of 55 additional bioenergy villages[1] is in progress or already completed [1]. These villages aim to maximize coverage of energy demand with biomass and to operate the bioenergy infrastructure independently. The German Agency for Renewable Resources (FNR) emphasizes that using fossil technologies for covering peak load demand can be compatible with the concept of bioenergy villages and specifies that – while balancing economic and environmental impacts – at least 50 % of heating demand and 100 % of electricity demand[2] should be met with biomass [2]. To fulfill the requirements of the concept, energy autarky (within the territory of a municipality) can be aimed but is not a mandatory goal [3]. It is rather emphasized that biomass provision should be „regional" or „decentral".

Table 1 highlights some pros and cons of bioenergy villages. Looking at the realized villages, it is interesting to see that they do not restrict themselves to biomass utilization and some even underline the implementation of additional renewable energy such as solar or geothermal energy. Moreover, it is noticeable that despite a relatively low energy demand density all bioenergy villages trust in district heating systems instead of using separate technologies for each building (such as split log boilers). This is because district heating systems offer the opportunity to gain economies of scale, to switch over to renewable energy fast and collectively as well as to keep the added value completely within the region (by using regional energy sources and operating the plant by local stakeholders). Besides, the rollout of district heating systems in rural areas often benefits from the lack of competing grid bound systems (e.g. pipelines distributing natural gas) [4].

[1] Moreover, more than 100 regions in Germany intend to cover 100 % of their future energy demand with renewable energy [11].
[2] the latter with regards to a yearly balance

And in fact, using renewable energy in rural areas seems to have advantages compared to urban areas. They have a good resource base, a case study of Baden-Württemberg for instance points out that in rural areas seven times more biomass (per capita) is available compared to large cities [5]. Moreover, market penetration is much higher, 60 % of Germany's installed bioenergy capacity is located in rural areas [6].

Table 1. Pros and Cons of bioenergy villages

pros	cons
Low fuel costs	High up front costs (Investments)
Stimulation of regional and rural economy	Transport of biomass (Traffic)
Reduction of energy related greenhouse gas emissions	Increase of „local" emissions (particulate emissions)
Shifting away from finite resources	
Reaching (to a large extent) independency from price development of fossil energy carriers	Increase of land use competition
Image building and strengthening of tourism	Acceptance of residents is an important pre-condition for economic feasibility

2. Research design

Against the background of the rapid development of bioenergy villages, this survey investigates the prospects of a range of bioenergy technologies such as fermentation biogas plants, district heating-plants and CHP[3]-plants (combustion and gasification), biodiesel plants and BTL[4] plants. The complete list of technologies is given in Table 2. The typology of bioenergy technologies is deduced from those technologies which are implemented in the cases of Güssing, Jühnde and Mauenheim. Alternative renewable energy sources such as solar and geothermal are not considered.
This article draws on a previous work [7]. It presents updated information, more detailled data on technologies and new evaluations and illustrations.

The analysis is carried out using the example of a rural "model municipality" representing an average German village and provides a system analysis focusing on costs and CO_2-reduction. The methodology is inspired by the pioneer of urban ecology Abel Wolman, who applied a similar approach in the 1960s to analyze the material flows of an US-American City [8]. The demand characteristics of the village result from a comprehensive evaluation of statistics and a literature review [5], [9], [10]. The analyzed model village has 1,050 hectares of agricultural land, 400 hectares of permanent grassland and 900 hectares of forest land. The number of inhabitants accounts for 3,000.

In a first step, a technology analysis is carried out to define the specific CO_2-emissions (g/kWh) and specific energy generation costs (EUR-cent/kWh) of biomass technologies as well as fossil reference technologies for the provision of heat, electricity and transport fuel. The analysis follows the principle of life cycle assessments (LCA) and – as illustrated in Fig. 1 – includes direct and indirect emissions (up- and downstream processes,

[3] CHP = Combined Heat and Power
[4] BTL = Biomass to Liquid

such as transport-diesel, fertilizer or deconstruction of facilities) as well as generating costs [11].

Table 2. Analyzed technologies for the provision of heat, electricity and transport fuel

Technology	Capacity	Fuel	End energy	Abbreviation
Fermentation biogas plant	150 kW_{el}/200 kW_{th}	Manure	heat/power	BG 150 M
	150 kW_{el}/200 kW_{th}	Corn	heat/power	BG 150 C
	600 kW_{el}/700 kW_{th}	Manure	heat/power	BG 600 M
	600 kW_{el}/700 kW_{th}	Corn	heat/power	BG 600 C
District heating plant	2.5 MW_{th}	Wood chips	heat	HP 2.5
	5 MW_{th}	Wood chips	heat	HP 5
	10 MW_{th}	Wood chips	heat	HP 10
	12.5 MW_{th}	Heating oil	heat	HP 12.5 HO
CHP plant (extraction condensing steam turbine)	max. 1.7 MW_{el} max. 3.5 MW_{th}	Wood chips	heat/power	CHP ST
CHP plant (gasification+gas engine)	2.0 MW_{el}/4.5 MW_{th}	Wood chips	heat/power	CHP gas
Biodiesel plant	3.6 MW/2.9 Mio. l/a	Rape seed	Biodiesel	RME
BTL plant	3.6 MW/2.8 Mio. l/a	Wood chips	BIODIESEL AND GASOLINE	BTL

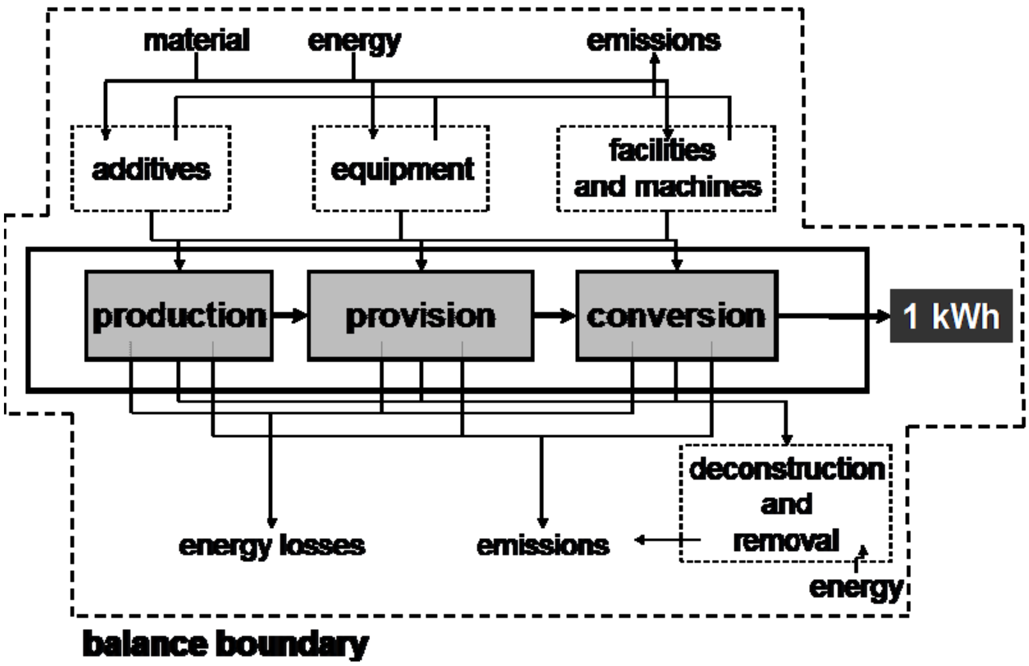

Fig. 1. Balance boundaries and elements of the life cycle assessment (LCA)

In a second step, six different combinations (BF1, BF2, BB1, BB2, BBB1 and BBB2) of the selected technologies are assessed. They are designed to cover the energy demand (heat, electricity, transport fuels) of the model village. The energy demand is considered as the cumulative energy demand during the period of one year. The actual coverage of the fluctuating energy demand during the period of a day or the four seasons is (with the exception of heat supply) not considered. The six technology combinations are shown in table 3 and represent different cases for the substitution of fossil fuels:

- In BF1 and BF2 (Bio + Fossil) more than 100 % of electricity demand is provided by biomass technologies. At the same time, 30 % of heat demand is covered by fossil fuels[5] (peak load). Biofuels are not produced at all.
- In BB1 und BB2 (Bio + Bio) 100 % of heat demand and more than 100 % of electricity demand are covered by biomass-technologies. Biofuels are not regarded.
- In BBB1 and BBB2 (Bio + Bio + Bio fuel) 100 % of heat and fuel demand are covered by biomass technologies and surplus electricty is generated.

For every export and import of electricity (surplus production), an economic and environmental value is credited: The credits for emissions equate the electricity mix in Germany (576 g/kWh). The credits for costs are calculated in two ways: One credit (FIT) is based on the feed-in tariff of the German renewable energy law depending on the kind and capacity of the technology used (8.0 to 14.7 EUR-cent/kWh). The alternative credit (AVEL) is based on the average costs of the German electricity production (5.5 EUR-cent/kWh).

Finally, the results of the biomass utilization options are compared to a fossil reference supply system which is defined as follows: 60 % of heating demand are covered by individual boilers with fuel oil (371 g CO_2/kWh; 10.5 EUR-cent/kWh), 30 % by natural gas condensing boilers (226 g CO_2/kWh; 10.4 EUR-cent/kWh) and 10 % by boilers with split logs (12 g CO_2/kWh; 8.0 EUR-cent/kWh). Moreover, the electricity mix in Germany (576 g CO_2/kWh; 5.5 EUR-cent/kWh) as well as the shares of conventional diesel and gasoline in Germany's fuel mix (210 g CO_2/kWh; 3.7 EUR-cent/kWh) are taken into account for the reference supply system.

Table 3. Analyzed supply systems and technology combinations

Supply system	Abbr.	Combination of technologies	Coverage rate biomass [% of demand]		
			heat	elect.	fuel
Bio + Fossil	BF1	BG 150 M + 3x BG 600 C + HP 5 + HP 12.5 HO	70	133	0
	BF2	BG 150 M + 3x BG 600 C + CHP ST + HP 2.5 + HP 12.5 HO	70	272	0
Bio + Bio	BB1	BG 150 M + 3x BG 600 C + HP 2.5 + HP 5 + HP 10	100	133	0
	BB2	CHP ST + HP 2.5 + HP 5 + HP 10	100	116	0
Bio + Bio +	BBB1	BG 150 M + 3x BG 600 C + HP 2.5+ HP 5 + HP 10 + RME	100	133	100
Bio fuel	BBB2	HP 5 + HP 10+ CHP gas + BTL	100	131	100

3. Performance of technologies and technology combinations

Fig. 2 shows the results of the technology assessment. It contains the bioenergy technologies for heat, electricity and fuels without credits as well as the associated CO_2-emissions. There is quite a huge bandwidth of results, from 10 g/kWh (BG 600 M) to 116 g/kWh (RME) or (looking at costs with credits) 3.2 EUR-cent/kWh (BG 150 M) to 19.4 EUR-cent/kWh (BG 150 C).

[5] In these two cases the oil heating plant covers 63 % of the total capacity demand of 19.5 MW_{th}.

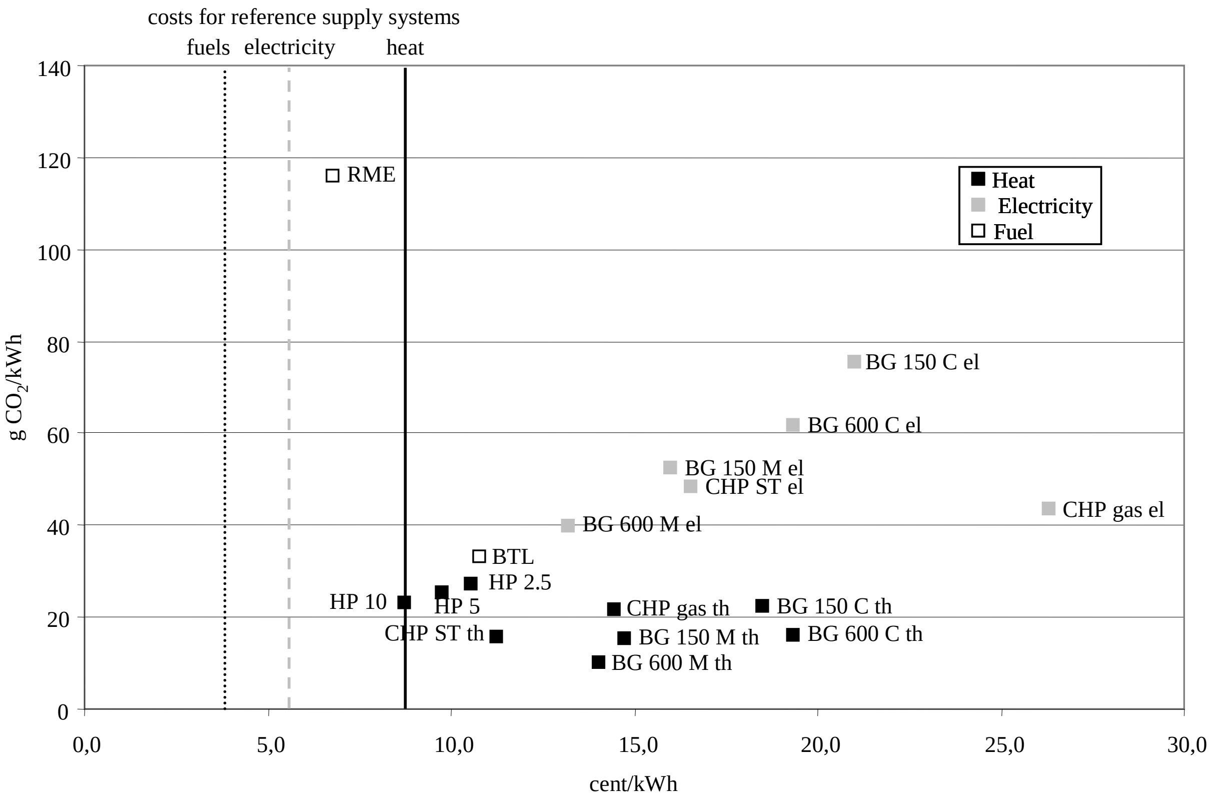

Fig. 2. Costs and CO_2 emissions of 11 bioenergy technologies[6] without credits (exergy allocation[7])

The results clearly indicate that:

- all bioenergy technologies come along with less CO_2 compared to the fossil reference technologies and (without feed-in tariffs) hardly achieve lower costs.
- heat provision is the most economic form of bioenergy and the provision of transport fuels comes along with the highest CO_2 emissions.
- using residues (manure) is much more favorable than energy crops. This is true for both, environmental and economic balances.

When looking at the six technology combinations in Fig. 3, the analysis furthermore proves that massive contributions to decarbonization of the rural energy supply can be achieved by implementing bioenergy villages. Even the least ambitious supply system (BF1) cuts emissions by 56 %, whereas the most ambitious approach (BBB2) reduces CO_2 emissions by even 97 %. Supply systems using biomass for peak load have considerably better results than systems with fossil peak load.

[6] The CO_2 emissions of the fossil reference technologies amount to 292 g/kWh (heating), 576 g/kWh (electricty) and 201 g/kWh (fuels).

[7] Exergy allocation attributes costs and emissions with respect to the share of energy that can be converted into any other from of energy (“available work”). Thus, the weight of useful heat depends on its temperature: the higher the temperature, the higher its weight. Due to thermodynamics, however, heat is always lower than 1. In turn, electricty always equals 1 per definition.

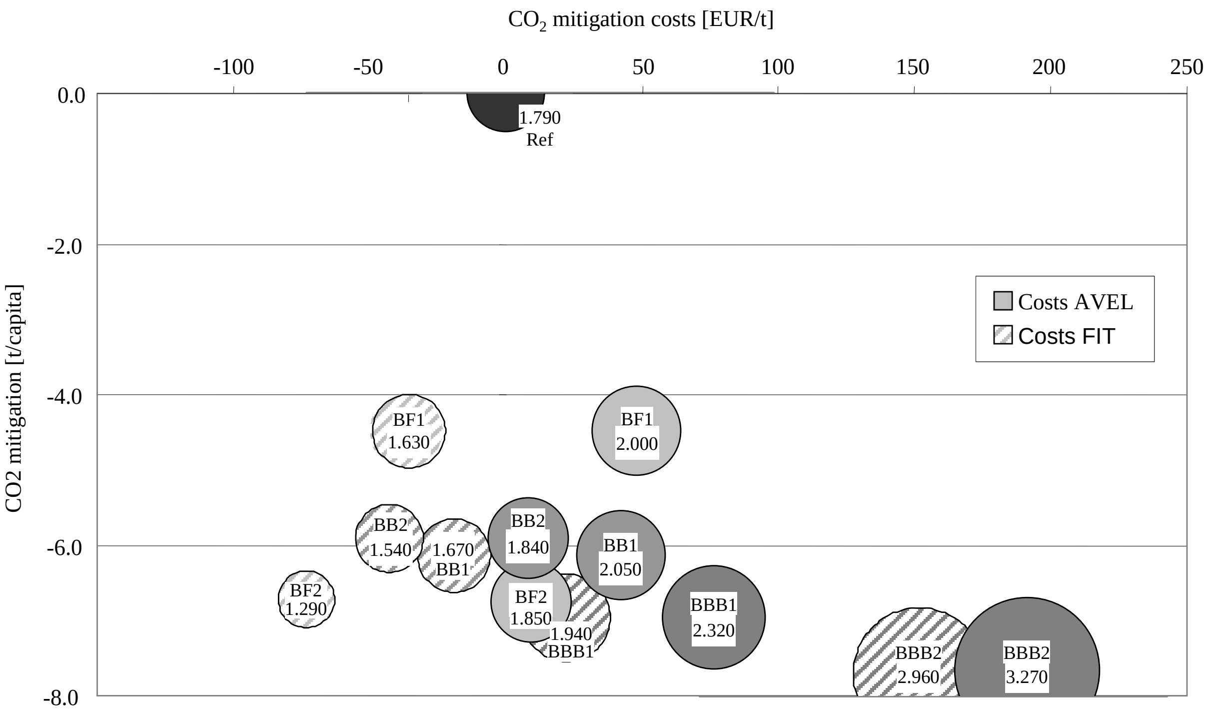

Fig. 3. CO_2 mitigation (compared to the reference supply system[8]), CO_2 mitigation costs and yearly costs per capita (bubble size, EUR/capita/a)

In contrast, under current prices for energy carriers, bioenergy villages hardly reach conventional supply systems without considering feed-in tariffs: the four cases BF1 (1,630 - 2,000 EUR/capita/a), BF2 (1,290 - 1,850 EUR/capita/a), BB1 (1,670 - 2,050 EUR/capita/a) and BB2 (1,540 - 1,840 EUR/capita/a) show higher costs (with regards to AVEL-costs) than the fossil reference system. In turn, costs based on credits for feed-in tariff certainly (FIT) are lower in BF1, BF2, BB1 and BB2 than the reference supply system.

In BB2 for instance costs are considerably lower compared to BB1 due to the utilization of less expensive woody biomass instead of energy crops. Comparing BB1 and BF1, only a small increase of costs (+2.5 %) can be seen. Therefore, it can be concluded that replacing a heating oil plant (peak load) with the wood chip heating plant can achieve moderate CO_2-mitigation costs. In turn, including transport fuels (BBB1 and BBB2) leads to a considerable increase of costs (up to 3,270 EUR/capita/a in BBB2).

Fig. 4 highlights that limits for the mass role out of bioenergy villages can appear with regards to resource base. In rural areas a 100 % supply with biomass – even though it is technically possible – can only be reached with unreasonably high competition to the food, fodder production, goods of the pulp and paper industry, and derived timber products. From this point of view, the combination with other renewable energy carriers ("renewable energy villages") should have good potentials to reducing the problems of spatial limits.

[8] 8.0 t/capita

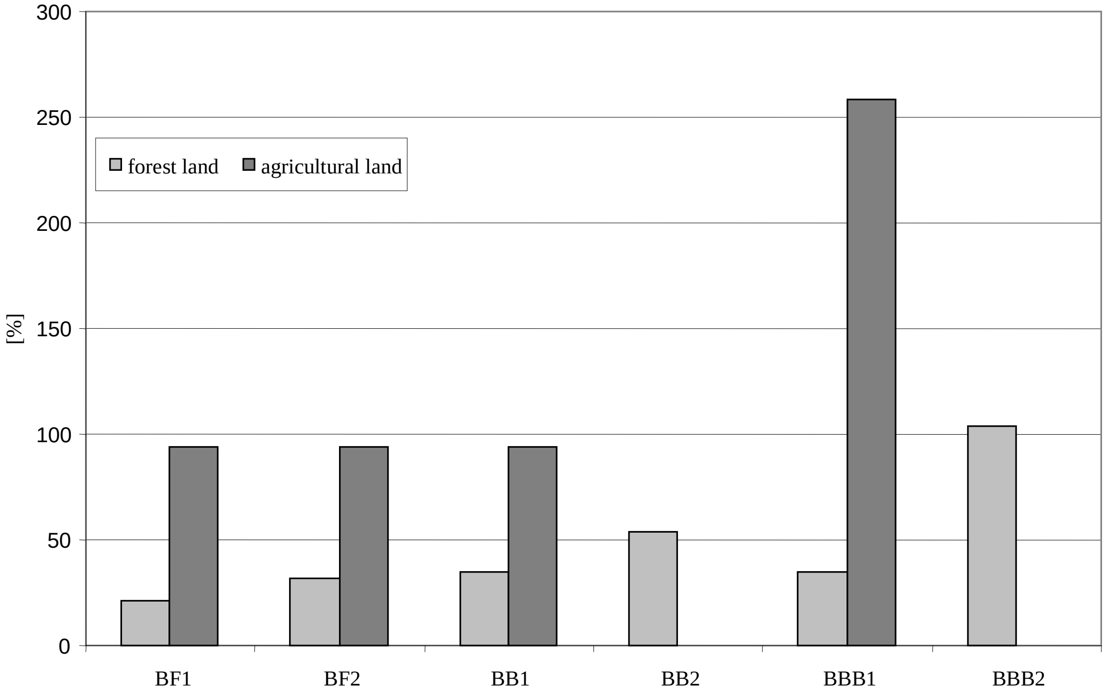

Fig. 4. Consumption of existing resource base (the share of all forest- and agricultural land is shown without considering non-energy use of forestry or agricultural products)[9]

4. Prospects for low carbon rural areas

The survey clearly proves that bioenergy villages offer good opportunities for achieving low carbon rural areas. In addition, most supply concepts – at least under current feed-in tariffs in Germany (FIT) – stood the economic test and (except the ambitious supply system BBB1 and BBB2) show negative CO_2 mitigation costs. Moreover, it demonstrates that a 100 % supply with heat, electricity and mobility is 'technically feasible' within the territory of an average German village. But such status can only be achieved if second generation biofuels are employed, which currently come along with significantly higher costs. Generally, energy autarky can only be reached with high competition to food- and fodder-production (conflict of aims). But it is possible to cover heating and electricity demand without causing significant land competitions.

Especially those municipalities which have large forest areas within their territory offer excellent prospects to become a bioenergy village. This is due to the circumstance that wood combustion technologies are the most developed and low-cost bioenergy technologies (see Fig. 2). In contrast, biogas technologies are competitive only due to the feed-in tariffs even when residues (manure) are used. The most expensive way of CO_2-mitigation is the production of biofuels. Therefore, the current strategy of most bioenergy villages (first providing heat and/or combined heat and power, then electricity and then fuels) is a wise approach.

Whereas a large resource base is given in rural areas, implementation of renewable concepts is facing serious drawbacks as low settlement densities lead to higher specific costs and losses

[9] Values < 100 % indicate that less biomass is used than can be provided within the boundaries of an average German rural municipality. In turn, values > 100 % imply that imports of biomass are mandatory to implement the respective bioenergy concept.

for heat distribution. Therefore, the implementation of individual technologies without heat distribution (e.g. pellet boilers) and the combination with other renewable energy carriers have good potentials to add to the concept of bioenergy villages.

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