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CO_2-reduction potentials and costs of biomass-based alternative energy carriers in Austria

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ABSTRACT

A forced use of renewable energy sources (RES) is necessary to reduce greenhouse gas emissions significantly. Among RES biomass-based resources play a specific role regarding their CO_2-reduction potentials, their energetic potentials and their overall costs for different derived energy carriers. From various categories of biomass resources – forestry, agricultural crops, short rotation coppices or waste products – different alternative energy carriers (AEC) like biofuels 1st or 2nd generation, electricity or hydrogen can be produced. In this paper we analyse possible biomass-based energy chains for different AEC in Austria. We investigate their overall potential by 2050, corresponding CO_2-reduction potentials and resulting CO_2 saving costs. The core results of this analysis are: (i) the overall potential by 2050 is approximately 130 PJ compared to 30 PJ in 2010; and (ii) the corresponding CO_2-reduction potential is about 7 million tons CO_{2equ}. This is roughly two-third reduction compared to the use of conventional fuels.

The major conclusion is that only if a tuned portfolio of actions – CO_2-tax, ecological monitoring system, a focussed R&D programme for second generation biofuels and fuel cells – is implemented the potential of new biomass-based AEC can be exploited up to 2050 in an optimal way for society.

1. Introduction

The current energy supply is mainly relying on fossil fuels. Alternative energy carriers (AEC) – based on renewables, CO_2-poor or CO_2-free sources of energy – are of central importance for the transition towards a sustainable energy system and economy.

Among renewable energy sources, biomass-based resources play a specific role regarding their CO_2-reduction potentials, their energetic potentials and their overall costs for different derived energy carriers, see, e.g. Faaij (2006) [1].

The core objectives of this paper are (i) to show the quantities of non-conventional biomass-based AEC that can be produced in Austria and used in transport until 2050 in a Policy Lead Scenario (one of the various scenarios derived in the project “ALTETRÄ” [2]), (ii) the resulting CO_2 saving potential due to the increasing use of AEC and (iii) corresponding CO_2 saving costs.

From various categories of biomass resources – forestry, agricultural crops, short rotation coppices or waste products – different biomass-based AEC can be produced. The most important ones considered in this paper are (i) 1st generation biofuels; (ii) 2nd generation biofuels; (iii) hydrogen and (iv) electricity from biomass. In this context it is important to note that second generation biofuels currently are expected to offer the largest biofuel quantity potential since the range of raw materials includes all plant components and waste products.

In the next section specific information on Austria is provided. Our research methodology is described in Section 3. In Section 4 we present future long-term prospects of AEC in Austria. Resulting CO_2 emission savings and costs of emission reductions are discussed in Sections 5 and 6, respectively. Conclusions complete the analysis, Section 7.

2. Biomass-based energy in Austria: some background information

Already in 2004 the Directive on the promotion of the use of biofuels or other renewable fuels for transport (Directive 2003/30/EC) – adopted by the European Parliament and the Council in 2003 [3] – was transformed into Austrian national law [4].

According to the EU legislation by 2020 the share of renewable energy in transport sector should be 10% [5,6].

Since 2005 biofuels have been placed on the Austrian market mostly by blending biodiesel with fossil diesel. Two years later also bioethanol blend was available. In 2010, 0.5 million tonnes of

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biodiesel and 0.1 million of bioethanol were placed on the market and the annual substitution target of 5.75% was surpassed by a large margin, at 6.58% [7].

The future production of biomass-based AEC is dependent on implemented policies as well as on land and resources availability. Regarding land, the total land area in Austria is 8.2 million hectares. This total land area can be divided into five groups: arable land (17%), permanent crop (1%), permanent meadows and pastures (22%), forest area (46%) and other land (14%), see Fig. 1.

Up to 2010 the most important biomass-based energy carriers in Austria were fuel wood, wood chips and pellets, see Fig. 2. However, since about 2005 the share of new biomass-based AEC, which can be used in transport sector and electricity generation, on total energy output from biomass-based resources has been increasing faster. In 2010 biofuels as well as electricity and hydrogen from biomass have contributed to about one quarter of the total energy output from biomass.

The maximal potentials for biomass-based AEC that we have used for our scenarios are based on the estimations provided in literature, e.g. Refs. [9–11]. Potentials for area-dependent resources are shown in Table 1.

With respect to future land use we have assumed that maximal 30% of arable land in 2010, 10% of pasture land, 10% of meadows and 3% of wood and forest wood residues could be used for feedstock production for biofuels by 2050. Regarding non-area-dependent resources it is assumed that additional 5% of wood industry residues could be used for biofuel production.

Table 2 provides a survey on maximal potentials for non-area-dependent resources in Austria in 2010 and 2050. The largest quantities available are forest wood residues and wood industry residues.

Table 3 provides an overview on AEC and primary energy resources considered in this paper.

As shown in Table 3 there are different resources which could be used for the production of biomass-based AEC in Austria. For example for biofuel production we can use different feedstocks. Basically the major characteristics of the ideal energy crop are high yield, low inputs, low costs, low composition of contaminants and nutrients and high pest resistance. However, not one crop has all these characteristics and therefore a choice must be made from available crops to select the most optimal crop-mix that can be cultivated in Austria [15].

3. Method of approach

The method of approach applied in this paper consists of the following major steps (see also [16,17]):

- extraction of the most promising energy chains and AEC based on the availability of feedstocks and resources in Austria for a further detailed analysis;
- a dynamic ecological assessment which is based on the Life Cycle Assessment (LCA) up to 2050 is used as a basis for the calculation of the CO_2 savings and costs (see Ref. [2])
- a dynamic economic assessment is conducted for all considered AEC based on technological learning up to 2050; and
- a dynamic modelling of decision-making processes based on the competitiveness of biomass-based AEC (see Section 4).

3.1. Ecological assessment

The calculation of greenhouse gas (GHG) emissions and primary energy demand is based on the method of Life Cycle Assessment. According to EN ISO 14040:2006 the environmental impacts are calculated along the supply chain of a product or service: from extraction of raw materials for its production through its use to its disposal. In the LCA main greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – are considered. All gasses are converted into the equivalent amounts of CO_2 (CO_2eq.) using the IPCC Global Warming Potentials related to a time frame of 100 years, see Table 4.

The LCA was performed with the Global Emission Model of Integrated Systems (GEMIS) model, version 4.5 [20]. In this model CO_2 fixation is considered as negative CO_2 emission during agricultural production. Carbon losses in fuel production processes (e.g. carbon in press cake from rapeseed pressing) are accounted as biogenic CO_2 emissions (see Fig. 2). The corresponding method of approach is described in Bird et al. [16].

In LCA are included all relevant materials, energy inputs and emissions related to the environment and to the primary resource, transportation of the resource to a conversion facility, conversion of the resource into a final energy carrier, distribution of the final energy carrier and its use to provide transport service.

Hence, in the LCA, GHG emissions from all stages of the biomass-based AEC process chain including combustion of AEC in the engine (fuel cycle) as well as the manufacturing of the car (vehicle cycle) are considered and so formed system includes (see Ref. [18]):

- Extraction, production, collection, and transportation of the resource to a conversion facility;
- Production plant and operating materials;
- Process residues used for the cogeneration of by-products and process heat;
- AEC distribution and use in vehicles;
- Construction of the vehicle;
- Use of by-products;
- Disposal or use of wastes.

With respect to the GHG emissions associated with the biomass-based AEC production plant include (i) emissions from construction materials, erection and disposal of the plant, (ii) emissions associated with the manufacture and transport of auxiliary materials, (iii) emissions associated with waste water treatment, (iv) emissions from combustion of residual biomass, and (v) in the concepts where electricity is purchased from the grid the emissions from electricity production. As far as biomass-based AEC plant emissions from fermentation and combustion of residual biomass are concerned CO_2 emissions are not counted as GHG emissions [18].

In the LCA land use change due to expanded biomass production was not considered because actually no land use changes takes place. All area categories change only very slightly up to 2050 (see Table 1). It is important to emphasize that in this analysis we do not consider imports of feedstocks or biofuels.

Since in this paper focus is put on AEC which could be used in transport sector the total energy supply chain – Well to Wheel (WTW) – is divided into Well to Tank (WTT) and Tank to Wheel (TTW) part, see Fig. 3.

The most important conversion chains for Austria are described in Table 5. Because some resources like soybeans or sugar beets turned out to be of less relevance they are not listed in this table.

The calculation of WTT CO_2 emission balances described in detail in Fig. 4 is based on the following equation:

$$WTT = WTT_{minus} + WTT_{plus} \tag{1}$$

Where WTT_{plus} is CO_2 fixation due to biomass planting, and WTT_{minus} are CO_2 emissions during fuel production. Further on WTW emissions are calculated as:

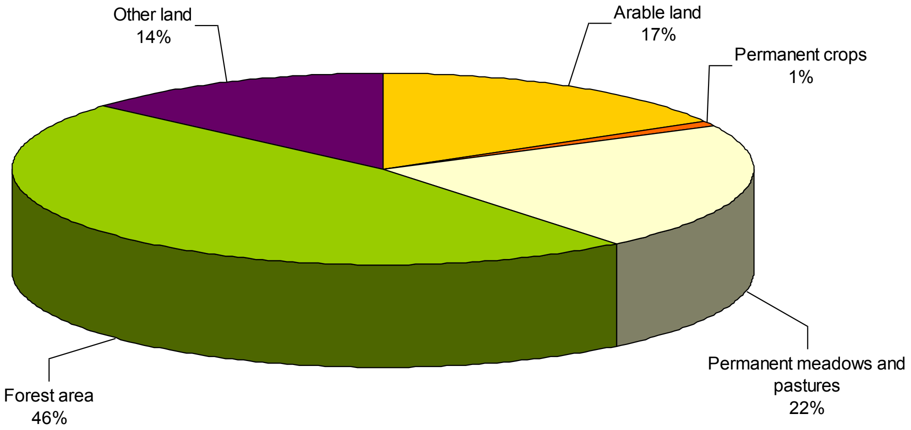

Fig. 1. Land area in Austria 2010 [8].

$$WTW = WTT + TTW \quad (2)$$

The detailed data for the single components in Fig. 4 are presented in Appendix in Fig. A1. The data for the other biomass-based energy chains are documented in Appendix in Table A1.

In a dynamic analysis also the WTW-GHG emissions for 2050 were calculated. They were lower than for 2010 for all AEC-systems. Biomass and biofuel production processes as well as the passenger cars are assumed to be more efficient by 2050. Electricity and process heat as input to the biofuel production processes have a higher share of renewable energy in 2050 (e.g. bioethanol from wheat). In AEC-systems with non-energy co-products substituting conventional products it is assumed that the avoided GHG emissions will be lower in 2050 due to more efficient conventional production processes. In AEC-systems with electricity as co-product the share of electricity will be lower in 2050 due to an increased biofuel-orientated production process (e.g. FT-Diesel from wood). The electricity-mix substituted by the co-product electricity has a higher share of renewable energy in 2050 therefore avoided GHG emissions will be lower in 2050.

3.2. Economic assessment and calculation of CO_2 savings

The prices of AEC (P_{AECt}) are for every year obtained from the costs (C_{AECt}) and the taxes (τ_{AECt}):

$$P_{AEC_t} = C_{AEC_t} + \tau_{AEC_t} \quad (3)$$

The prices of conventional fuels (P_{f_inc}) are:

$$P_{f\_inc_t} = P_{f\_exc_t} + \tau_{f_t} \quad (4)$$

P_{f_exc} is the fuel price exclusive tax; and τ_f is the tax

The total specific production costs of AEC (C_{AEC}) for year t are calculated as follows:

$$C_{AEC} = C_{FS} + C_{CONV} + C_{DR} - Sub_{AEC} \quad [EUR/kWh\ AEC] \quad (5)$$

where C_{FS} is the net feedstock costs; C_{CONV} is the gross conversion costs; C_{DR} is the distribution and retail costs and Sub_{AEC} is the subsidies for biofuels.

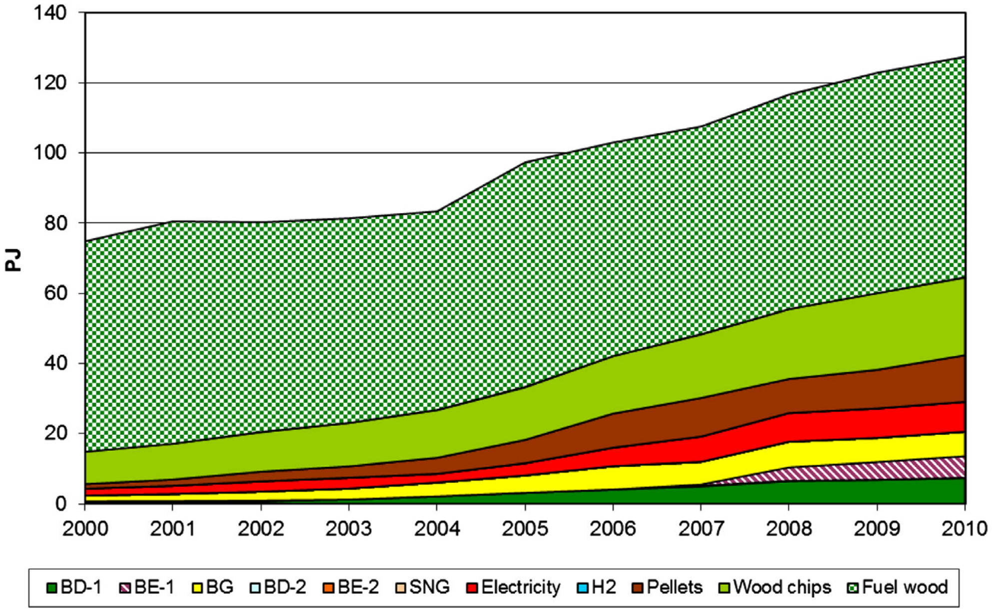

Fig. 2. Biomass-based AEC in Austria, 2000–2010 (data source [2,8]).

Table 1
Survey on maximum potentials for area-dependent resources (data sources [9–11]).

	2010			2050		
	Total area	AEC current		Total area	AEC max	
	(1000 ha)	(1000 ha)	(%)	(1000 ha)	(1000 ha)	(%)
Total crop area	1378	170	12%	1303	390	30%
Crop area oil seeds	276	60	22%	260	260[a]	100%
Other crop area	1102	109	8%	1043	390[a]	30%
Grass land	260	2	1%	260	260	100%
Poplar & pasture	64	1	1%	66	66	100%
Forest wood residues	3865	324	56%	3791	580	100%

[a] Numbers do not add up to total crop area.

The gross conversion costs C_{CONV} for converting feedstock into AEC are calculated as:

$$C_{CONV} = CC + C_{LABOUR} + C_{INP} + C_{OM} - R_{AEC\_by-product} \quad [EUR/kWh\ AEC] \tag{6}$$

where CC is the capital costs per year [EUR/year]; C_{LABOUR} is the labour costs; C_{INP} is the input costs (chemicals, energy, water, etc); C_{OM} is the costs for maintenance and insurance; and $R_{AEC\_by-product}$ is the revenues from by-products from AEC production (e.g. glycerine or DDGS).

Capital costs depend on specific investment costs (IC) and capital recovery factor (CRF). Annual capital costs are calculated as:

$$CC = \frac{IC \cdot CRF}{P \cdot T} \quad [EUR/kWh\ AEC] \tag{7}$$

where IC is the investment costs [EUR]; CRF is the capital recovery factor; P is the capacity [kW]; and T is the full load hours [h/yr].

Future biofuel production costs or at least capital costs could be reduced through technological learning. In this analysis the effects of technological learning play a major role for the dynamic of economics. An in-depth analysis on technological learning is conducted by Ajanovic et al. [2].

In our model we split up specific investment costs $IC_t(x)$ into a part that reflect the costs of conventional mature technology components $IC_{Con\_t}(x)$ and a part for the new technology components $IC_{New\_t}(x)$.

$$IC_t(x) = IC_{Con\_t}(x) + IC_{New\_t}(x) \tag{8}$$

where $IC_{Con\_t}(x)$ is the specific investment cost of conventional mature technology components (EUR/kW).

For $IC_{Con\_t}(x)$ no more learning is expected. For $IC_{New\_t}(x)$ we have to consider a national and an international learning effect:

$$IC_{New\_t}(x) = IC_{New\_t}(x_{nat\_t}) + IC_{New\_t}(x_{int\_t}) \tag{9}$$

$IC_{New\_t}(x_{nat\_t})$, specific national part of $IC_{New\_t}(x)$ of new technology components (EUR/kW); and $IC_{New\_t}(x_{int\_t})$, specific international part of $IC_{New\_t}(x)$ of new technology components (EUR/kW).

For both components of $IC_{New\_t}(x)$ we use the following formula to express an experience curve by using an exponential regression:

$$IC_{New\_t}(x) = a \cdot x_t^{-b} \tag{10}$$

where $IC_{New\_t}(x)$ is the specific investment cost of new technology components, x_t is cumulative capacity up to year t, b is learning index, and a is specific investment cost of the first unit (EUR/kW).

Table 2
Survey on maximal potentials for non-area-dependent resources (data sources [9,12–14]).

	kWh/kg	2010		2050	
		1000 tons	PJ (primary energy)	1000 tons	PJ (primary energy)
Straw (2.3 tons/ha)	4.5	39	0.7	480	7.8
Forest wood residues	4.3	1450	22.4	1450	22.4
Manure	8.33	215	6.4	280	8.4
Waste wood	5.30	300	5.7	600	11.4
Wood industry residues	5.00	830	14.9	2400	43.2
Organic waste/waste fat	7.60	230	6.3	420	11.5
Black liqueur	3.36	200	2.4	240	2.9

Details on the numbers used are described in Section 4.

The possible CO_2 savings (ΔCO_2) due to the increasing use of AEC are calculated as:

$$\Delta CO_2 = CO_{2\_fossil} - CO_{2\_AEC} \tag{11}$$

where CO_{2_fossil} are the corresponding CO_2 emissions of the matching reference fossil energy carrier (e.g. biodiesel is compared with diesel).

Life cycle GHG emissions of reference fossil energy carriers (fossil fuels, electricity and hydrogen from compressed natural gas) are shown in Table 6.

Costs of CO_2 savings ($C_{\Delta CO_2}$) are calculated as:

$$C_{\Delta CO_2} = \frac{\Delta C}{\Delta CO_2} \tag{12}$$

ΔC is the difference in costs between a specific AEC and corresponding reference fossil fuels (e.g. between bioethanol and

Table 3
AEC and primary energy resources relevant for Austria (adapted from Ref. [2]).

Resource	AEC							
	BD-1	BE-1	BG	BD-2	BE-2	SNG	Electricity	H_2
Feedstock								
Rapeseed	x							
Sunflower	x							
Soybeans	x							
Wheat		x						
Corn maize		x						
Sugar beet		x						
Green maize (incl. cover crops)			x					
Short rotation coppice				x		x	x	x
Corn stover				x		x	x	x
Grass			x					
Forest wood								
Residue								
Straw		x		x	x	x	x	x
Forest wood residues				x		x	x	x
Wood industry residues				x	x	x	x	x
Liquid manure			x					
Dry manure			x					
Waste wood							x	
Organic waste (incl. waste fat)	x		x					
Black liquor							x	

Table 4
CO_2-equivalent conversion factors [19].

Gas	CO_2-equivalent
CO_2	1
CH_4	25
N_2O	298

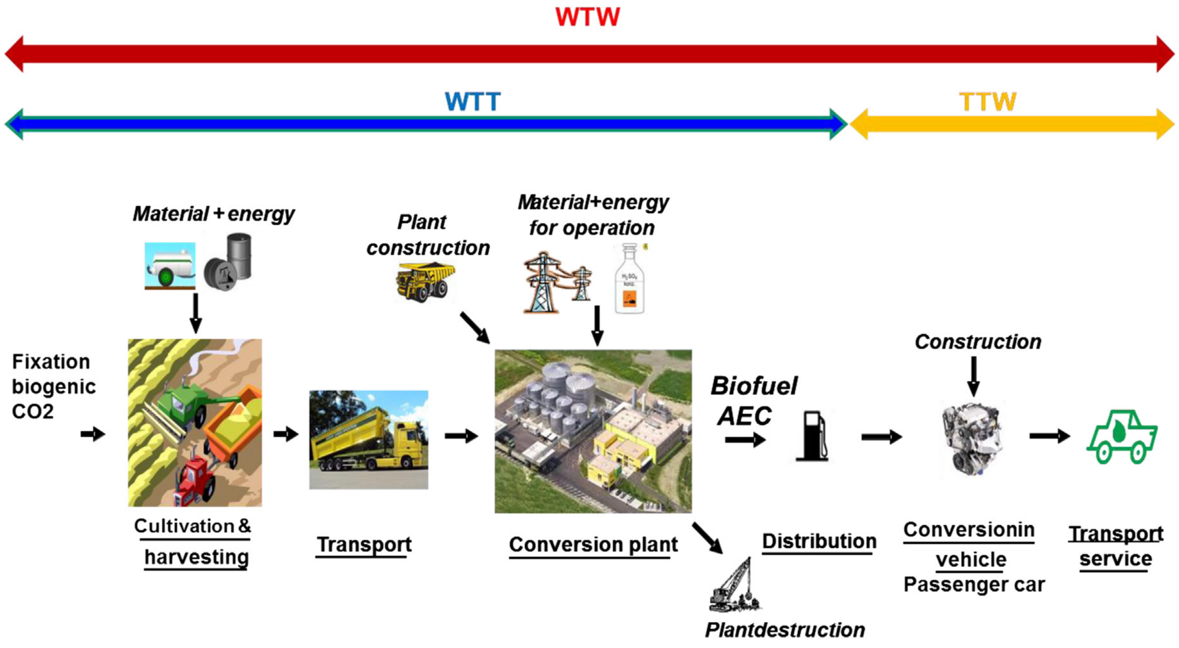

Fig. 3. Example of the WTW biofuel supply chain (adapted from Ref. [2]).

Table 5
Selected most preferable AEC-systems relevant for Austria (adapted from Ref. [2]).

Primary energy	Conversion	AEC	Conversion	Energy transport	Service electricity
Rapeseed	Pressing + biodiesel plant	Biodiesel	ICE vehicles	x	
Wood from forestry	Gasification + FT-synthesis	FT-Diesel + electricity	ICE vehicles	x	x
Wheat, corn	Bioethanol plant	Bioethanol	ICE vehicles	x	
Wood from forestry	Bioethanol plant	Bioethanol + electricity	ICE vehicles	x	x
Straw, corn stover	Bioethanol plant	Bioethanol + electricity	ICE vehicles	x	x
Corn silage, grass, manure	Biogas plant + gas treatment	Biomethane	ICE vehicles	x	
Wood from forestry	Gasification + methanisation	SNG	ICE vehicles	x	
Wood from forestry, waste wood	CHP station	Electricity	Electric vehicles	x	x
Wood from forestry	Gasification + H2-separation	Hydrogen	Fuel cell vehicles	x	
Wood from short rotation crops	Gasification + H_2-separation	Hydrogen	Fuel cell vehicles	x	
Corn silage	Biogas plant + gas treatment + reforming	Hydrogen	Fuel cell vehicles	x	

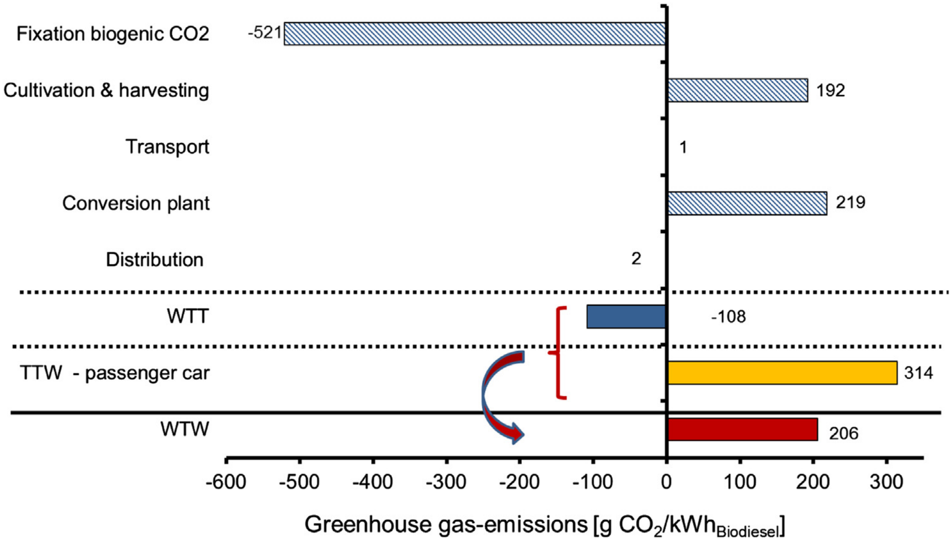

Fig. 4. Balance of biogenic CO_2 emissions for biofuels (example biodiesel from rapeseed) 2010 [2].

gasoline); and ΔCO_2 is the difference in specific CO_2 emissions between AEC and corresponding fossil fuels (e.g. between bioethanol and gasoline).

4. Future prospects of AEC from biomass in Austria up to 2050

In order to provide a sound assessment of the future prospects of alternative energy carriers in Austria up to 2050 the following major influence parameters (drivers) are considered:

- possible developments of prices of fossil fuels, feedstocks and residues;
- global developments regarding technological learning; and
- a taxation of CO_2 emissions.

The results in this paper refer to a “Policy Lead Scenario” which relies on the major assumption that an additional use of arable land up to 30% for AEC is achieved. In addition we base the analysis on the area potentials (see Table 1) and the potentials for non-area-dependent resources (Table 2). Furthermore, this scenario is based on the following assumptions regarding the three major drivers.

Price development: regarding the development of fossil fuel prices it is assumed that increases are based on expected price developments as documented in IEA [21,22] and own analyses for feedstock and wood prices. In our scenario we have used price increases for fossil fuels of 3% per year up to 2050, of 2% per year for feedstocks (oil seeds, cereals) and 1% per year for wood-based resources.

Table 6
Life cycle GHG emissions of reference fossil energy carriers.

Energy carrier	Year	WTT	TTW	WTW
		g CO_2 eq/KWh		
Gasoline (*Reference to bioethanol*)	2010	61	299	360
	2050	53	316	369
Diesel (*reference to biodiesel*)	2010	28	305	333
	2050	26	321	347
CNG CHP (*reference to electricity*)	2010	512	133	645
	2050	462	145	607
CNG reforming (*reference to hydrogen*)	2010	369	104	472
	2050	341	138	479

Technological learning: technological learning used for the dynamic cost analyses in this work is based on the quantities of international deployments of biofuels and hydrogen according to IEA [23,24]. The detailed assumptions regarding technological learning effects used for the scenario analysis are: (i) the development of alternative fuel costs is based on international learning rate of 25% and national learning rate of 15% regarding the investment costs of these technologies; and (ii) international learning corresponds to world-wide quantity developments in the Alternative Policy Scenario in IEA [21] up to 2030.

CO_2-taxes: in this analysis we consider the introduction of a CO_2-based tax for all energy carriers. The design of taxation of CO_2 emissions is as follows: The highest excise tax in 2010 – which was on gasoline – is converted to a CO_2-tax of the same magnitude. For all other fuels including diesel and compressed natural gas (CNG) this tax is set relative to their WTW – CO_2 emissions compared to gasoline. This tax starts in 2013 and is increased by 0.015 EUR/kg CO_2 per year up to 2050. This increase is a compromise between acceptance and price as well as fuel switching effects. It leads to total price increases for fossil fuels which are moderate on a year-by-year base but nonetheless increase the total final price related to gasoline by the factor of three up to 2050. The major effect is of course that AEC with lowest CO_2 balances have lowest tax levels [25].

Fig. 5 depicts the resulting development of prices of various AEC in comparison to conventional fuels including all taxes up to 2050. The fuels with the lowest CO_2-taxes – electricity and hydrogen from biomass, BD-2 and SNG (synthetic natural gas) – are the cheapest ones by 2050. In the presence of this CO_2-tax AEC could become competitive with fossil fuels starting from about 2020.

The major decision-making process in our model is as follows:

- All biomass-based AEC compete based on their full costs with fossil fuels’ market prices (incl. taxes);
- AEC compete among each other regarding use of resources (e.g. areas). However, if an AEC is not competitive in the market an area allowed or an available side-products (non-area-dependent resource) will not be used for producing this AEC;

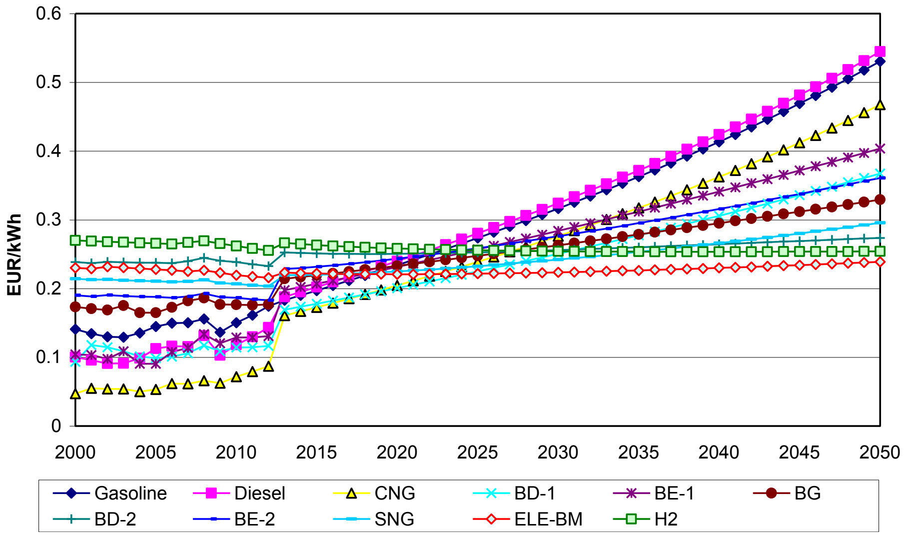

Fig. 5. Development of the costs of various AEC in comparison to conventional fuel prices including taxes up to 2050.

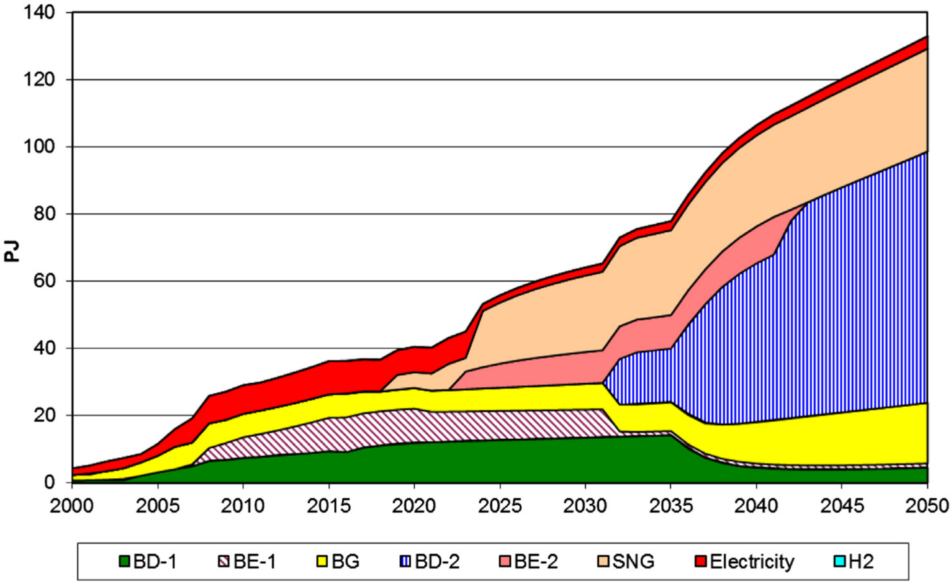

Fig. 6. Energy production (final energy) in the policy lead scenario (with max. 30% arable land in 2010, with CO_2-tax, and with priority for biofuels).

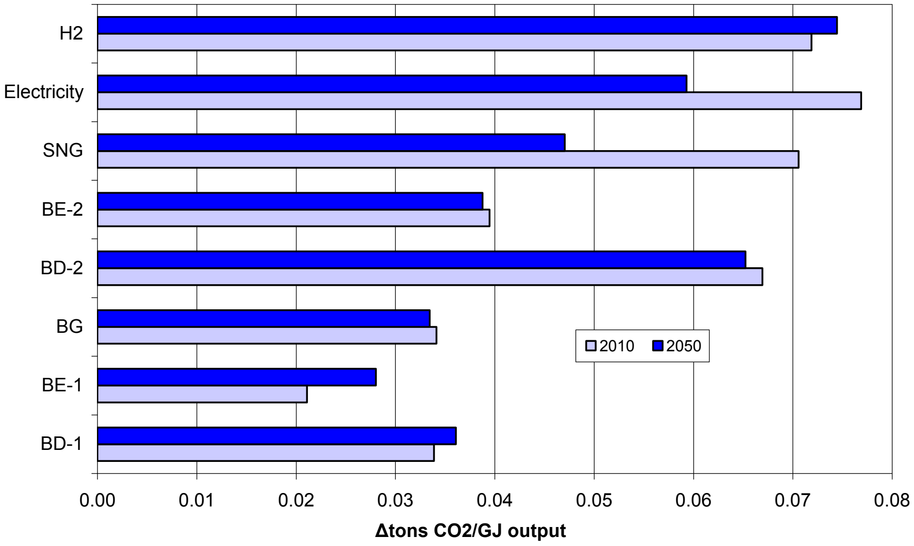

Fig. 7. CO_{2equ} savings per GJ output of AEC, 2010–2050 in Austria.

- In the Policy Lead Scenario priority is given to the production of liquid biofuels over electricity. Priority for biofuels means that if different energy carriers can be produced from same feedstocks – e.g. biofuels and electricity from wood industry residues – biofuel will be produced even if electricity would be cheaper. In this case electricity will be produced only from those feedstocks which are not usable for biofuels production such as waste wood.

The energy production of AEC in the PLS scenario is depicted in Fig. 6.[1] As can be seen in this scenario by 2050 finally more than 130 PJ of AEC will be produced. This is about four times more than in 2010. After about 2023, due to technology maturity, a significant and continuously increasing share of the second generation bioethanol (BE-2) can be noticed. The share of second generation biodiesel (BD-2) is increasing starting from 2032. Finally, most BD-2 are produced from corn stover (whole plant used) from arable land. In this scenario with biofuels priority synthetic natural gas (SNG) provide significant contribution to energy production starting from 2017. Yet, this takes place only if it can be managed that these technologies become mature and if significant learning effects are achieved. Due to the finally better energetic and economic performance of BD-2 it also substitutes BE-2 production after 2040. However, it must be noticed that energetic as well as economic developments of the different categories of BF-2 are of course not known in detail today. Due to these uncertainties other fractions of second generation biofuels could also “win”. What can be stated today is that – given the economic performance of any BF-2 leads to cost-effectiveness under the suggested CO_2-tax policy – there is a significant potential for BF-2 after 2030 regardless which one will succeed.

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[1] Note that we have also conducted a sensitivity analysis with other assumptions like no priority for biofuels. less arable land allowed and no CO_2-tax. The most significant impact is the quantity of arable land to be used for biofuel production. Major effects are: if no additional arable land is used for production of AEC in 2050 drops from 130 PJ to 70 PJ. If no CO_2-tax is implemented the major effect is that the switch to BF-2 is later and smaller. All other impacts are neglectable compared to this parameter.

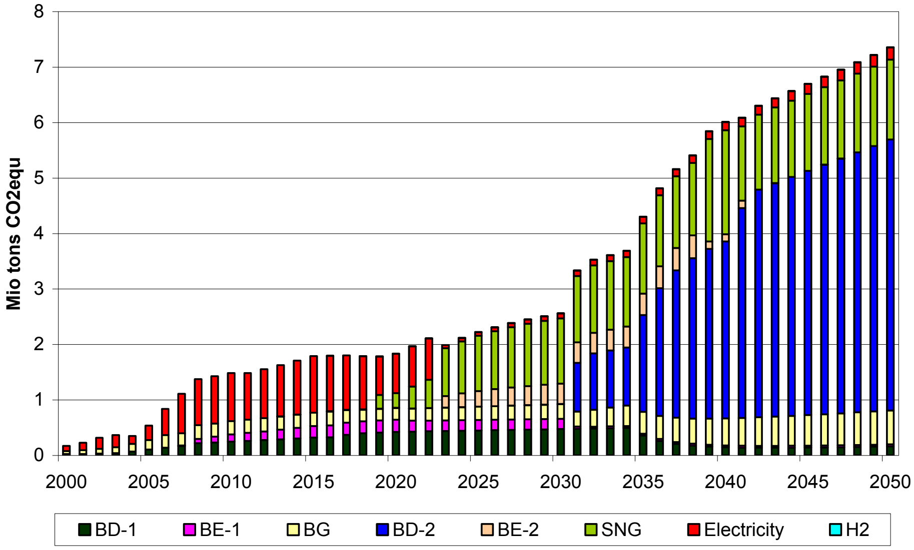

Fig. 8. CO_2 emissions savings due to biomass-based AEC in Austria from 2000 to 2050 in the Policy Lead Scenario.

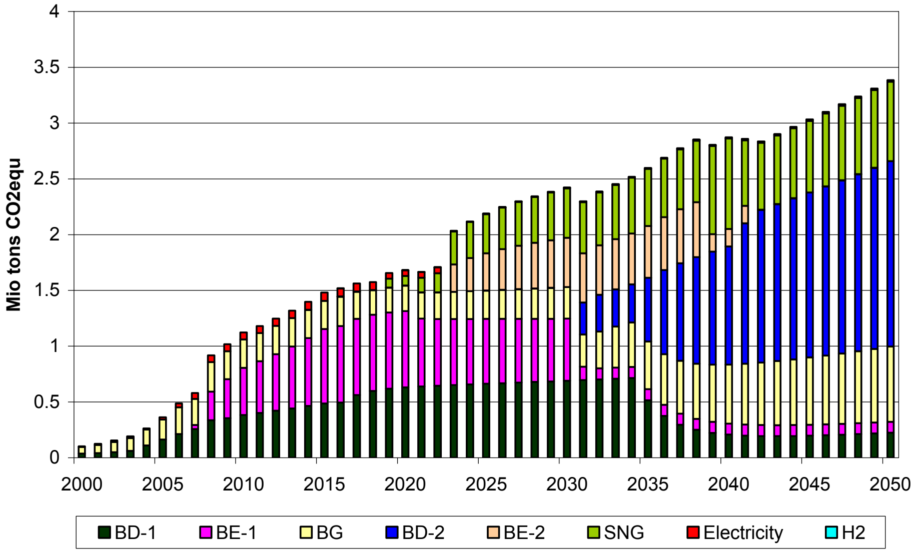

Fig. 9. Remaining CO_2 emissions from biomass-based AEC in Austria from 2000 to 2050 in the Policy Lead Scenario.

A note on biogas: there is a temporarily slight decrease of biogas, because its production from maize silage will phase out. But on the other hand gradually more biogas will be produced from grass and cover crops.

The major reasons why in Fig. 6 BD-2 and SNG reach so high amounts are as follows:

- they have highest energy efficiency and hence lowest feedstock costs; and
- they have lowest CO_2 emissions and hence lowest CO_2-taxes.

5. Potentials of CO_2 emission savings

One of the major reasons for a forced introduction of AEC is that they are expected to reduce GHG emissions significantly. The following figures depict for the Policy Lead Scenario the effects on CO_2 emissions in Austria.

In Fig. 7 the CO_{2equ} savings per GJ output of AEC in 2010 vs. 2050 in Austria are shown. Hydrogen, electricity and BD-2 as well as SNG are from this point the most favourable AEC.

The total CO_2 emission savings compared to fossil fuels are shown in Fig. 8 (bioethanol compared to gasoline, biodiesel compared to diesel, biogas compared to gasoline and electricity and hydrogen compared to conventional production). It can be seen that with increasing shares of BF-2 the CO_2 savings increase. Finally, the largest shares of savings are achieved by the use of BD-2 and SNG. The remaining CO_2 emissions from biomass-based AEC are depicted in Fig. 9. Yet, most interesting is how the difference of savings vs. remaining emissions evolves. This effect is shown in Fig. 10.

Fig. 10 depicts the total CO_2 emissions from AEC in Austria from 2000 to 2050 in the Policy Lead Scenario in comparison to total CO_2 emissions without the use of biomass-based AEC. We can see that by 2050 the CO_2 emissions will be reduced finally by about 7 million tons CO_{2equ}. This is about two-third reduction compared to the use of conventional fuels.

6. Costs of CO_2 emission reduction

In addition to the reduction in CO_2 emissions also the costs of CO_2 savings of biomass-based AEC are relevant. The costs of CO_{2equ} savings

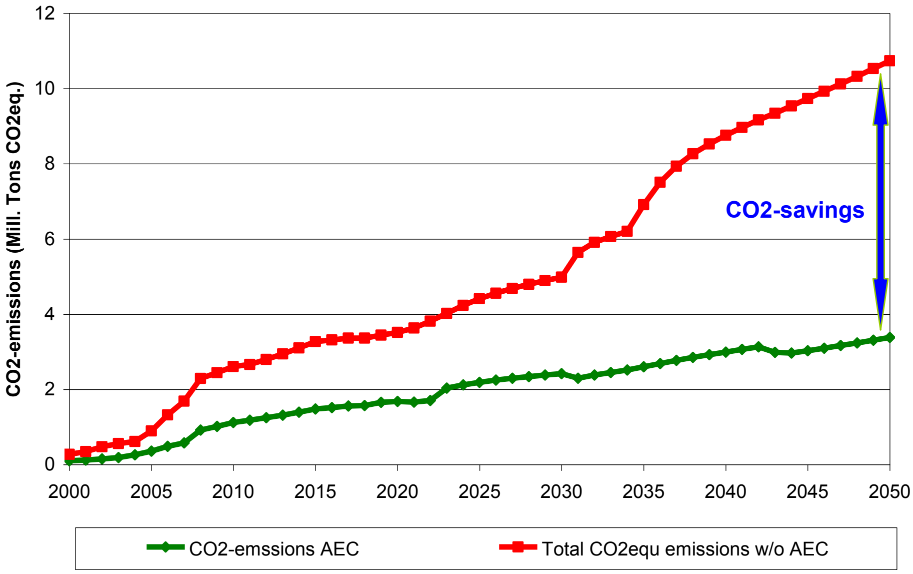

Fig. 10. Total CO_2 emissions from biomass-based AEC in Austria from 2000 to 2050 in the Policy Lead Scenario in comparison to total CO_2 emissions without the use of AEC.

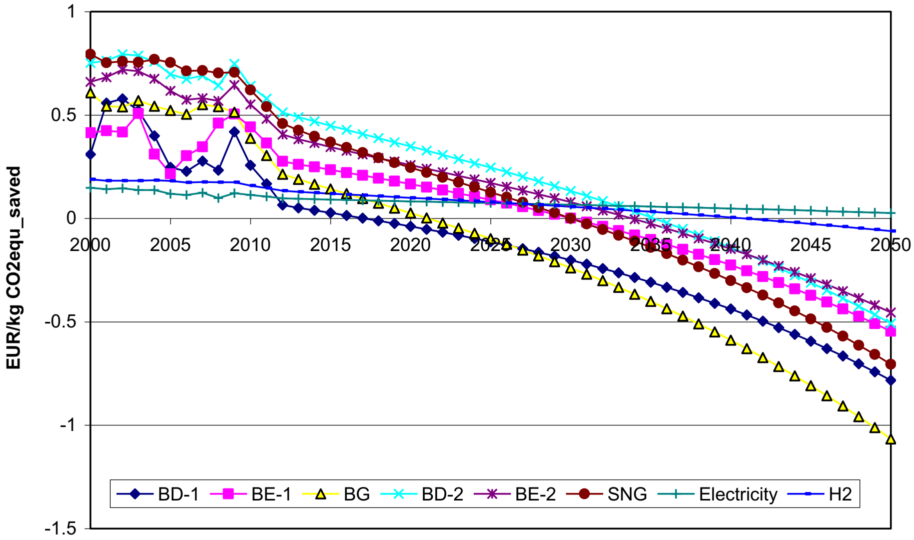

Fig. 11. Costs of CO_{2equ} savings by type of AEC, 2010–2050 in Austria in the Policy Lead Scenario.

by type of AEC are depicted in Fig. 11 over the period 2010–2050 in Austria in the Policy Lead Scenario. This figure shows very impressive that due to the increases in the prices of fossil energy carriers up from about 2020 the CO_{2equ} savings show negative costs. That is to say that after this period of time it is even profitable to use these AEC.

A comparison of the costs saved per kg CO_{2equ} and the overall savings of CO_{2equ} per GJ in 2010 and 2050 is shown in Fig. 12. The major perception is that up to 2050 costs of all AEC investigated will turn into profits. With a CO_2-tax these AEC will earlier become economically competitive.

7. Conclusions

The major steps towards harvesting an optimal portfolio of AEC in Austria up to 2050 are as follows:

1. Introduction of a CO_2-based tax on fuels in transport: This tax ensures that different biomass-based AEC will enter the market depending on their dynamic ecological performance;
2. A rigorous tightening of the standards regarding CO_2 emissions of these biomass-based AEC: It should be ensured that (e.g. by means of a strict and continuous certification and monitoring programme) the ecological balance mainly of BF-1 but also of the emerging new BF-2 is improved gradually;
3. A focussed R&D programme for BF-2 and for fuel cells with an accompanied performance evaluation from energetic and environmental point of view.

The final major conclusion is that only if the portfolio of actions described above – CO_2-tax, ecological monitoring system, and a focussed R&D programme for BF-2 and fuel cells – is implemented in a tuned mix it will be possible to exploit the potential of AEC up to 2050 in Austria in an optimal way for society.

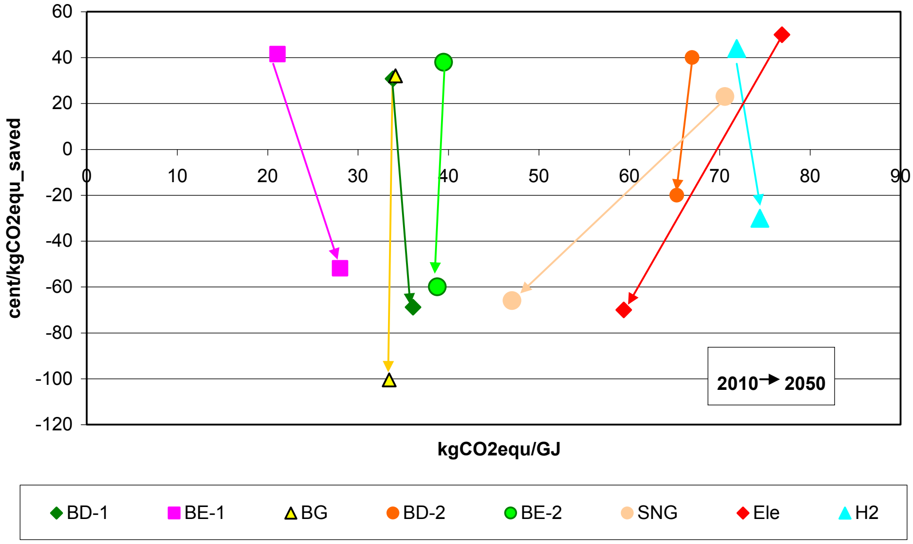

Fig. 12. A comparison of the costs per $kgCO_{2equ}$ saved and the overall savings of CO_{2equ} per GJ in 2050 and 2010.

Acknowledgement

This paper provides a summary of the work conducted in the research project “ALTETRÄ - Perspectives for Alternative Energy Carriers in Austria up to 2050” (see Ref. [2]) conducted for the Austrian Research Promotion Agency (FFG).

Nomenclature

AEC	alternative energy carriers
BD-1	1st generation biodiesel
BE-1	1st generation bioethanol
BG	biogas
BD-2	2nd generation biodiesel
BE-2	2nd generation bioethanol
BF-1	1st generation biofuels
BF-2	2nd generation biofuels
CHP	combined heat and power
CNG	compressed natural gas
ELE-BM	electricity from biomass
FT-Diesel	Fischer–Tropsch diesel
GHG	greenhouse gas
H_2	hydrogen
ICE	internal combustion engine
LCA	life cycle assessment
RES	renewable energy sources
R&D	research and development
SNG	synthetic natural gas
TTW	tank to wheel
WTW	well to wheel
WTT	well to tank

Appendix

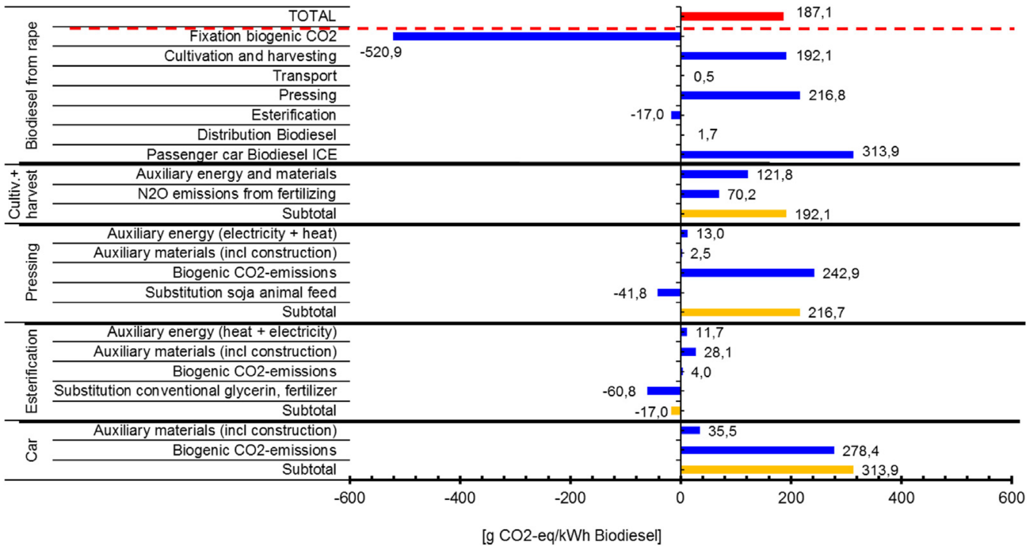

Fig. A1. Balance of biogenic CO_2 emissions for biofuels (example biodiesel from rapeseed) 2010 [2].

Table A1
WTW-GHG emissions of AEC-systems analysed (based on Ref. [2]).

	[g/KWh]	2010			2050		
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Biodiesel from rape	Fixation biogenic CO_2	−520.9	0.00	0.00	−496.3	0.00	0.00
	Cultivation and harvesting	73.7	4.45	113.98	57.0	3.98	108.33
	Transport	0.5	0.00	0.01	0.5	0.00	0.01
	Pressing	245.6	−0.68	−28.08	218.5	−0.70	−25.88
	Esterification	−14.0	−2.67	−0.28	−15.2	−2.76	−0.29
	Distribution biodiesel	1.6	0.01	0.03	1.6	0.01	0.03
	Passenger car biodiesel ICE	307.5	2.92	3.54	322.9	3.87	3.69
	Total	93.9	4.04	89.20	88.9	4.41	85.89
Bioethanol from wheat	Fixation biogenic CO_2	−590.1	0.0	0.0	−536.6	0.0	0.0
	Cultivation and harvesting	55.9	3.1	86.9	25.9	1.5	78.1
	Transport	0.8	0.0	0.0	0.8	0.0	0.0
	Bioethanol plant	455.8	19.0	−13.2	352.0	7.1	−10.8
	Distribution bioethanol	2.2	0.0	0.0	2.2	0.0	0.0
	Passenger car bioethanol ICE	285.3	2.6	0.7	301.7	3.6	0.9
	Total	209.9	24.7	74.5	145.9	12.3	68.3
Biogas from corn silage	Fixation biogenic CO_2	−1130.9	0.0	0.0	−942.7	0.0	0.0
	Cultivation and harvesting	11.1	0.6	20.2	5.7	0.4	21.4
	Transport	0.7	0.0	0.0	0.6	0.0	0.0
	Biogas plant	836.9	0.5	7.5	648.7	0.5	7.5
	Biogas treatment	115.3	26.2	0.0	111.0	25.8	0.1
	Distribution biomethane	9.8	1.0	0.0	6.0	0.7	0.1
	Passenger car biomethane ICE	225.7	3.8	1.6	240.3	4.6	1.7
	Total	68.6	32.0	29.3	69.7	32.0	30.7
Bioethanol from straw	Fixation biogenic CO_2	−920.1	0.0	0.0	−836.7	0.0	0.0
	Collection straw	68.9	5.1	55.7	63.0	4.7	50.6
	Transport	1.4	0.0	0.0	1.3	0.0	0.0
	Bioethanol plant	664.6	0.1	0.0	580.3	0.1	0.0
	Distribution bioethanol	2.2	0.0	0.0	0.0	0.0	0.0
	Passenger car bioethanol ICE	285.7	2.6	0.7	301.7	3.6	0.9
	Total	102.7	7.9	56.4	109.7	8.4	51.5
FT-Diesel from wood	Fixation biogenic CO_2	−1312.7	0.0	0.0	−774.5	0.0	0.0
	Collection wood	20.7	0.2	0.3	12.5	0.1	0.2
	Storage wood	15.4	0.0	0.0	8.9	0.0	0.0
	Transport	2.4	0.0	0.1	1.4	0.0	0.0
	Gasification + FT-synthesis	1030.8	0.0	1.1	498.8	0.0	0.6
	Distribution FT-diesel	1.4	0.0	0.0	1.4	0.0	0.0
	Passenger car FT-diesel ICE	307.4	2.9	3.5	322.9	3.9	3.7
	Total	65.6	3.1	5.0	71.4	4.0	4.5
SNG from wood	Fixation biogenic CO_2	−625.5	0.0	0.0	−568.7	0.0	0.0
	Collection wood	10.0	0.1	0.1	9.1	0.1	0.1
	Storage wood	7.0	0.0	0.0	6.4	0.0	0.0
	Transport	1.2	0.0	0.0	1.1	0.0	0.0
	Gasification + SNG-synthesis	419.1	0.0	1.1	363.2	0.0	1.0
	Distribution SNG	9.8	1.0	0.0	6.0	0.7	0.1
	Passenger car SNG ICE	225.7	3.8	1.6	240.0	4.6	1.7
	Total	47.3	4.9	2.8	57.1	5.4	2.9

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