Climate effects of woody biomass and fossil fuel use in stand-alone and integrated energy systems

Nguyen Le Truong
Linnaeus University
SE-351 95 Växjö
Sweden
nguyen.truong@lnu.se

Leif Gustavsson
Linnaeus University
SE-351 95 Växjö
Sweden
leif.gustavsson@lnu.se

Keywords

bio fuel, vehicles, climate change, electric vehicles, primary energy, integrated energy system, radiative forcing

Abstract

Biomass is a key resource in a society based on renewable energy, but is a limited resource and the use of biomass in one sector will influence its availability for other sectors. The global energy system is heavily dependent on fossil fuels, and the climate impacts of CO_2 occur regardless of the source of emissions. As a result, the climatic effects of biomass use in an energy system depend largely on which biomass feedstock and bioenergy pathway is being used, and what type of fossil fuel pathway is being replaced. In this study, we evaluate the CO_2 emissions and climate effects of woody biomass and fossil fuel use. We analyse the potential production of electricity, heat or transport distance when using one kWh of woody biomass and fossil energy system designed to provide the same service to society as the most energy efficient bioenergy systems. The fuel cycle inputs are included in the analyses and are based on different state-of-the art as well as emerging technologies for energy conversion. We quantify the primary energy use and annual CO_2 emission of different bioenergy and fossil alternatives. We then calculate the cumulative CO_2 emission and climate effects in terms of cumulative radiative forcing for the fossil and bioenergy systems. The results show that primary energy use, CO_2 emission, and cumulative radiative forcing vary strongly between the studied alternatives. The use of biomass should be considered in the context of the overall energy system, and in relation to the development of energy conversion technologies and potential integration between different energy sectors. This may identify pathways that are primary energy efficient and that give climate benefits in both the short and the long term. The use of bioelectricity and electric vehicles instead of biomotor fuel-based vehicles gives about twice the transport distance per unit of consumed woody biomass. Integrated energy systems that supply a package of energy services including electricity, heat and transport distance reduce the primary energy use and increase the climate benefits of woody biomass. The replacement of coal for heat and electricity production by the here studied woody biomass could give climate benefits immediately.

Introduction

Global energy supply depends heavily on fossil fuels. In 2014, fossil coal, oil and gas provided 81% of global primary energy use, and the use of fossil fuels is projected to increase even though the part of renewable energy use may also increase in global energy mix [1] [2]. However, efficient use of energy and switching to energy efficient supply chains based on renewable energy resources are key elements to mitigate climate change and improve energy security [3]. Of the renewable energy resources, biomass is a key resource with large potential for expansion [2] and unlike other renewable resources, biomass can be stored and converted to different energy carriers. The conversion from the existing fossil fuel systems to more sectors integrating renewable-based systems will take a long time and energy services are also likely to be supplied the coming 30-40 years from standalone fossil fuel plants [1].

Electricity, heat, and motor fuels are the major energy carriers to supply different energy services [4]. Woody biomass can be used directly for electricity and heat production. Woody biomass can also be used in conventional fuel-based vehicles (FV) after conversion to suitable motor fuels by using different state-of-the-art and emerging technologies for biomotor fuel production. Furthermore, the recent development of technologies shows that electric vehicles (EV) could be an efficient means for transportation, also helping to integrate the transport sector with heat and electricity production systems [5]. However, biomass is a limited resource and the use of biomass in one sector will influence its availability for other sectors, stressing the importance of using highly energy-efficient bioenergy systems to supply energy services.

In Sweden, biomass is a key resource in the existing national energy system. In 2015, 134 TWh of biomass was used in Sweden and that covered 25.4 % (31.3 % excluding losses in nuclear power plants) of total energy supply [6]. However, a large portion of forest residues such as forest slash (branches, foliage and tops) and stumps are left on the forest floor and decay naturally. The potential production and harvest of biomass in Sweden is large and increasing due to factors such as improved forest management and recovery practices of forest slash [7]. Various studies (e.g. [8], [9]) suggest that biomass production could be doubled, while some recent studies have estimated the potential recovery to be higher due to improved forest management and harvest strategies [10] [11].

Development of energy conversion technologies and sectoral integration of energy systems could improve the primary energy efficiency of energy systems. Heat and electricity can be coproduced from woody biomass and used interchangeably in several end-use applications. Biomotor fuel production may have different coproducts [12] [13] which could be integrated in energy systems in other sectors that may improve their system efficiency.

In this study, we evaluate the climate effects of using forest slash for energy in heat, electricity and transportation sectors. We consider different pathways for using bioenergy to replace fossil fuels to provide an equivalent service to society including district heat, electricity and transport distance based on different state-of-the art and emerging technologies for energy conversion. We quantify the primary energy use and annual CO_2 emissions of different bioenergy and for corresponding fossil fuel alternatives. Thereafter, we calculate the cumulative CO_2 emissions and climate change effects in term of cumulative radiative forcing (CRF) for the bioenergy and corresponding fossil fuel system, per unit of consumed biomass. Finally, we analyse the primary energy savings of some integration of electricity, heat and transport systems and calculate the cumulative CO_2 emissions and CRF for such bioenergy systems and corresponding fossil fuel systems.

Method and Assumptions

We compare bioenergy alternatives with fossil fuel alternatives, to provide the same energy services. The fossil alternatives include electricity and heat production by fossil coal or fossil gas in standalone plants and fossil motor fuels used in light-duty vehicles as well as EV using fossil electricity. Woody biomass is used to produce the corresponding energy services. The potential production of electricity, heat or transport distance when using one kWh of biomass, including the biomass used in the fuel cycle, is analysed for different stand-alone production systems. The use of fossil energy for the different fossil systems is then analysed when the same amount of electricity, heat and transport distance is produced as in the best stand-alone bioenergy system.

The woody biomass considered here is forest slash, which has a large potential expansion in Sweden [14] [15]. The fuel cycle of biomass includes harvest of slash, chipping of slash, transport 100 km by truck to a terminal, then 250 km by train to the coast, and then 1,100 km by ship to an international end-user. Dry matter loss during forwarding, chipping roadside and transport is not considered. The lifecycle fossil CO_2 emission for the different fossil systems is calculated. The fuel-cycle CO_2 emission includes all emission from full lifecycle fuel use for the collection, processing, transportation and delivery of fuel to the conversion plants based on data from [16]. All calculations are based on the lower heating value (LHV) of fuels.

If forest slash is not collected and used for bioenergy it is left and decays on the forest floor and releases biogenic carbon as CO_2 to the atmosphere. These decaying biogenic CO_2 emissions are calculated for a 100-year time period, beginning from year 0 when the energy services are produced. This biogenic CO_2 emission is added to the fossil energy system. For all the bioenergy systems the use of one kWh of slash emits 403 g biogenic CO_2 emission in year 0 when the forest slash is used for energy [17]. The cumulative biogenic and fossil CO_2 emission is then calculated for a 100-year time period for the bioenergy and fossil energy systems. Hence, we consider annual emissions of biogenic and fossil CO_2 over a 100-year time period for the whole energy chains. Based on annual biogenic and fossil CO_2 emissions, we then calculate the CRF.

For the different integrated systems, we assume that the same amount of electricity, heat and transport distance should be produced as in the stand-alone systems. However, we show only results for the most energy efficient integrated systems using woody biomass, coal or fossil gas. We calculate primary energy use, cumulative biogenic and fossil CO_2 emission, as well as CRF over a 100-year time period for these integrated systems.

BIOENERGY AND FOSSIL SYSTEMS

The characteristic of selected energy conversion systems for district heat, electricity and motor fuels based on state-of-the-art and emerging technologies for fossil fuel and biomass-based system are shown in Table 1.

Light-duty vehicles exist with FVs, both diesel and gasoline versions, and as EVs. Different biomotor fuels can replace fossil motor fuels. Dimethyl ether (DME) and methanol (MeOH) is suitable to replace diesel in compression-ignition engines [23] and gasoline in spark-ignition engines [24], respectively. We assume that DME and MeOH replace diesel and gasoline, respectively. Furthermore, we assume that the use of a fossil motor fuel or a corresponding biomotor fuel will not to change the conversion efficiency of the motor. The energy performance of vehicles varies with manufacturers and vehicle models. In this study, we consider the light-duty vehicle model B-class from the European car manufacturer Mercedes-Benz. This vehicle model exists in electric, gasoline and diesel versions (Table 2). In Table 2, the electricity consumption includes wall-to-vehicle charging losses while the motor fuel consumption is dispensed fuel to vehicles.

Table 1. Characteristics of selected conversion technologies. A minus sign indicates net demand instead of production by the plant.

Technology	Production efficiency (%)			Note
	Heat	Electricity	Motor fuel	
Existing technologies				
Heat production				
Coal boiler	89.0			
Fossil gas boiler	105			a
Wood chip boiler	108			a
Electricity production				
BST		45.0		a
CST		46.0		b
FGCC		58.0		b
CHP production				
CHP-BST	75.0	31.0		b
CHP-CST	75.0	31.0		c
CHP-FGCC	43.0	46.0		b
Emerging technologies				
Electricity production				
BIGCC		50.0		d
CHP production				
CHP-BIGCC	48.0	42.0		e
Biomotor fuel production				
DME	-24.5	-5.6	66.0	f
MeOH	-14.0	6.3	46.0	f

[a] [18]; [b] [19]; [c] [20]; [d] [21] technology for 2030; [e] [22]; [f] [12] system with maximum electricity production using condensing steam turbine.

Note: BST: biomass steam turbine; CST: coal-based steam turbine; FGCC: fossil gas combined cycle; BIGCC: biomass integrated gasification combined cycle.

Table 2. Characteristics of selected vehicle versions.

Vehicle type	Fuel type	Vehicle consumption (kWh/km)			Note
		Electricity[a]	Gasoline[b]	Diesel	
EV	Electricity	0.249	–	–	c
FV	Gasoline	–	0.597	–	d
FV	Diesel	–	–	0.510	d

[a] Including wall-to-vehicle charging losses; [b] dispensed fuel to vehicles; [c] [25]; [d] [26].

For the delivered electricity to vehicles, we consider electricity transmission and distribution losses of 7.4 % which is based on the average losses during 2003–2012 in Sweden [27]. The distribution, storage and dispensing from the refineries to the final distribution point of motor fuels are assumed to be 2 % of final used fuel [5] [28].

DECAY OF FOREST SLASH

If the forest slash is left in the forest, it will be decomposed by macro- and micro-organisms and release biogenic carbon as CO_2 to the atmosphere. The decay rate of the slash varies in time because the initial quality changes to lower qualities that decompose more slowly. Here, CO_2 emission from the decay of forest slash is estimated using the process based Q-model [29] with the parameters given in Table 3. The model has been described in several papers, and has proven capability to estimate soil organic carbon changes at stand level and regional and national scales in Sweden [29] [30].

CUMULATIVE RADIATIVE FORCING

Based on the annual CO_2 emissions for each year, we calculate the cumulative radiative forcing as described by Zetterberg [13] using updated parameter values from IPCC [14] [15] [16]. We use Equation 1 to estimate the removal of CO_2 from the atmosphere by natural processes at varying time rates [14] [15] [16]:

$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.224 e^{\frac{-t}{394.4}} + 0.282 e^{\frac{-t}{36.54}} + 0.276 e^{\frac{-t}{4.304}} \right] \qquad (1)$$

where t is the number of years since the emission, $(CO_2)_0$ is the mass of CO_2 initially emitted, and $(CO_2)_t$ is the masses of CO_2 in the atmosphere at year t. We convert atmospheric mass to atmospheric concentration. Marginal changes in instantaneous radiative forcing due to the changed CO_2 concentration are then estimated using Equation 2 [14] [15] [16]:

Table 3. Parameters used in the Q-model to calculate decay of forest slash [10].

Parameter	Description	Value
q_{0n}	Initial quality of needles and fine roots	1.01
q_{0w}	Initial quality of woody litter	1.0
ε_{11}	Parameter determining how rapidly substrate quality decreases as substrate is used by decomposers	0.36
β	Shape parameter determining how steeply decomposer growth rate changes with substrate quality	7
e_0	Microbial decomposer growth efficiency	0.25
u_{00}	Parameter for decomposer growth rate	0.0855
u_{01}	Parameter for decomposer growth rate	0.0157
fC	Carbon concentration in decomposer biomass	0.5
$t_{maxbr+to}$	Time for total invasion of branches and tops	13
$t_{maxro+st}$	Time for total invasion of coarse roots and stumps	60

$$F_{CO_2} = \frac{3.7}{\ln(2)} \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\} \qquad (2)$$

where F_{CO2} is instantaneous radiative forcing in W/m^2, ΔCO_2 is the change in atmospheric concentration of CO_2 in units of ppmv, and CO_{2ref} is the reference CO_2 concentration in the atmosphere which is assumed to be 400 ppmv, based on measured data in 2015 [31]. The accumulation of instantaneous radiative forcing over time is then estimated. We extend the analysis and present results as μJ of heat accumulated within each m^2 of the surface of the earth's troposphere over a 100-year time period.

Results

STAND-ALONE OPTIONS

Figure 1 shows the quantity of electricity, heat and transport distance that could be produced by a kWh of biomass, including fuel cycle energy inputs, when using state-of-the-art and emerging technologies. The use of bioelectricity and EV instead of FV using biomotor fuels gives about twice the transport distance per unit of consumed forest slash.

The maximum final energy services provided by a kWh of forest slash are 0.48 kWh of electricity, 1.04 kWh of heat or 1.80 km of transport distance. These maximum values are used as references for the comparison of systems based on fossil standalone production and of integrated energy systems. The most fuel-efficient bioenergy pathways are using BIGCC for electricity, biomass boiler for heat, and BIGCC and EV for transport.

Figures 2 and 3 show the corresponding quantity of fossil fuels used by standalone conversion facilities and the full fuel-cycle CO_2 emission to provide the same energy services of electricity, heat and transport distance as in the most energy efficient bioenergy pathways. The difference in fuel-cycle fuel use between EV and FV is rather small. The results show that 1 kWh of biomass can replace 0.90 to 1.28 kWh of fossil fuels, depending on energy service and fossil fuel type. The corresponding value for the whole energy service package produced from 3 kWh of forest slash, is 2.88 to 3.61 kWh of fossil fuels.

The quantity of fossil CO_2 emission that could be avoided by biomass varies strongly with the type of replaced fossil fuel. Except for the case of using coal in heat-only plants, fossil-based systems have lower instantaneous CO_2 emission than the biomass-based system for the same energy service. However, the fossil systems emit fossil CO_2 emission while the bioenergy systems emit biogenic CO_2 emission.

Nevertheless, along with the instantaneous fossil CO_2 emission the unused forest slash will decay and cause a gradual CO_2 emission to the atmosphere as shown in Figure 4. During a 100-year time period, the decaying biomass releases 383 g CO_2 emission, while a complete decay releases 403 g CO_2 emission. Taking this decay emission into account, cumulative CO_2 emission of fossil based system increases over time (Figure 5). The coal-based systems have the highest amount of cumulative CO_2 emission follow by diesel and gasoline for transportation and then fossil gas systems. Systems for electricity production and EV have exactly the same cumulative emission pathway for the same type of fossil fuel. For the fossil gas system the cumulative CO_2 emission is lower than for bioenergy systems during 12 years. The corresponding number for diesel and gasoline FV is about eight years. The time before the cumulative CO_2 emission from bioenergy system is lower than from the corresponding fossil system is often referred to as the carbon debt.

Figure 6 shows the CRF of different energy systems when producing the same amount of energy services that could be produced in the most energy-efficient bioenergy systems using of 1 kWh forest slash. The CRF does not differ between the bioenergy systems, as all those systems use the same amount of forest slash and have the same cumulative CO_2 emission pathway. The CRF for the different energy systems follow the same pattern as for the cumulative CO_2 emission.

Figure 7 shows the changes in CRF when 1kWh of biomass is used to replace fossil fuels for different energy services using different standalone conversion units. Negative values give global cooling while positive values give global warming. Replacing coal-based energy systems give the highest global cooling of the studied systems with immediately benefits. However, the use of bioenergy results in global warming during an initial period of about 20–30 years when it replaces low-carbon and high-efficiency fossil gas-based systems for electricity and heat

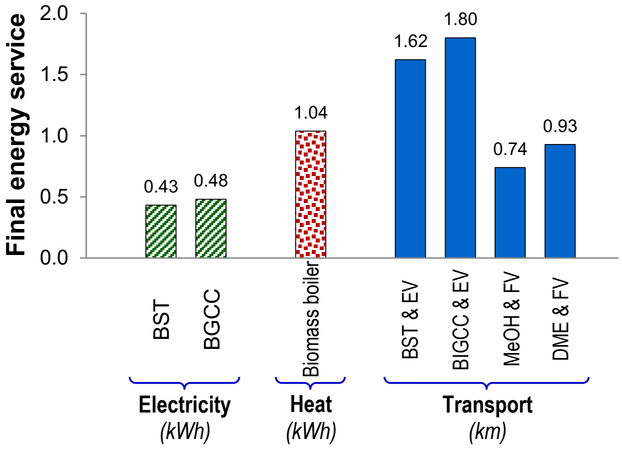

Figure 1. Energy services produced by a kWh of forest slash using different standalone production technologies and pathways.

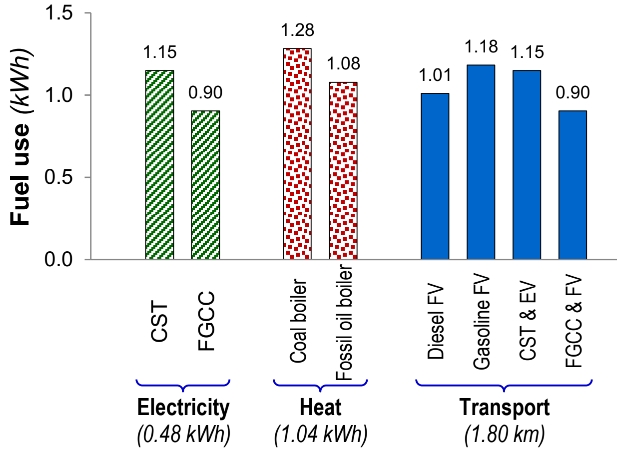

Figure 2. Fuel-cycle fossil fuel use for the production of different energy services using different standalone conversion units and fossil fuels.

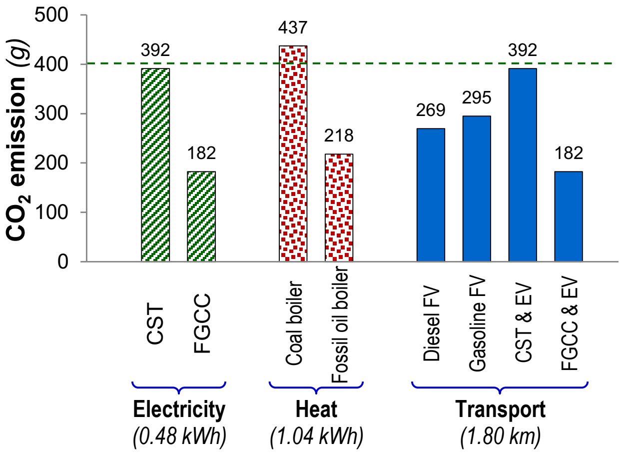

Figure 3. Instantaneous fossil CO_2 emission for the different energy services using different standalone conversion units and fossil fuels. The dash line shows the biogenic CO_2 emission from 1 kWh biomass.

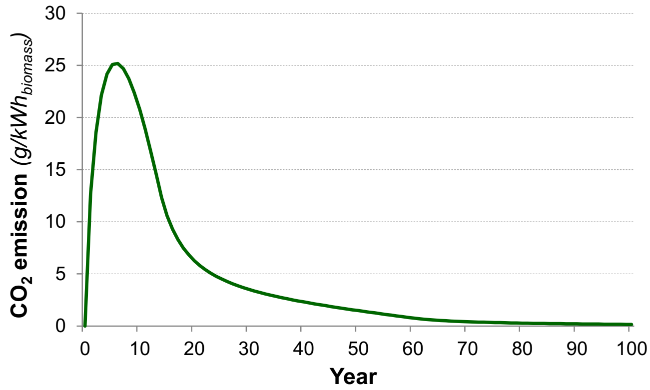

Figure 4. CO_2 emission from the decay of 1kWh of forest slash left on the forest floor in year 0 [10].

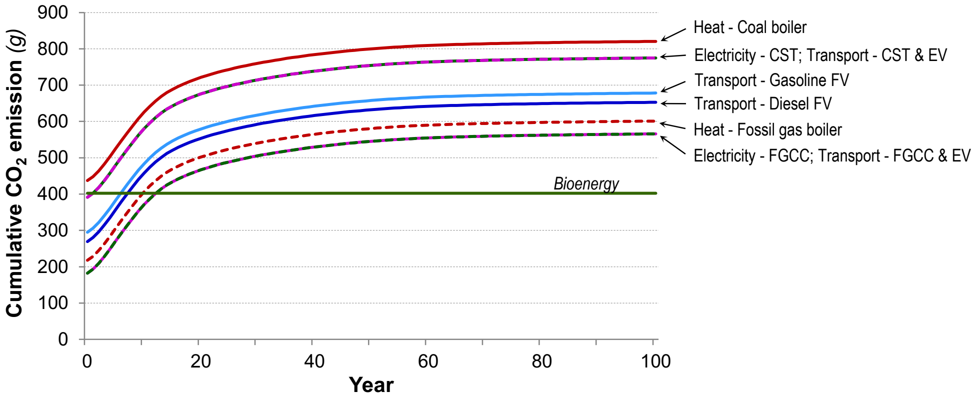

Figure 5. Cumulative CO_2 emission of different energy systems.

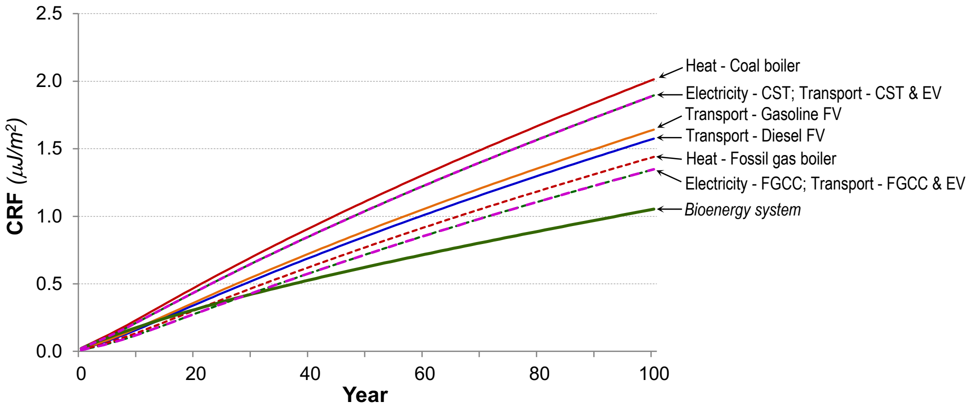

Figure 6. Cumulative radiative forcing of different energy systems.

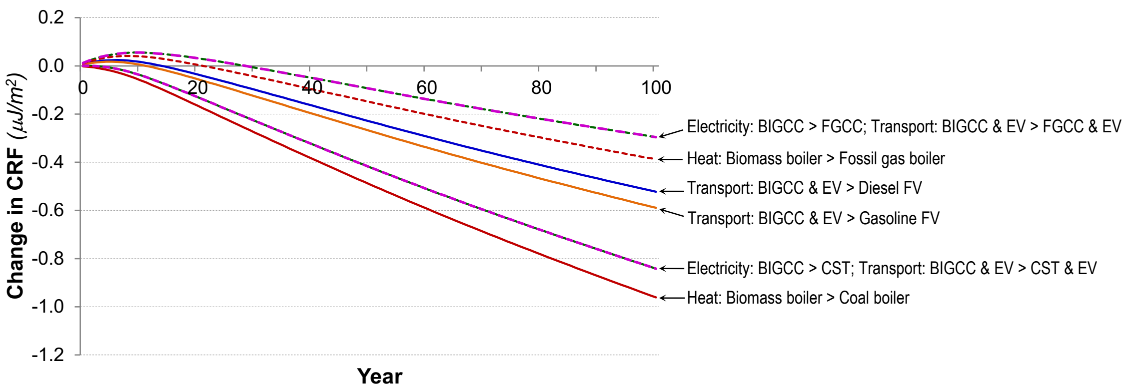

Figure 7. Change in CRF when bioenergy is used instead of fossil fuels.

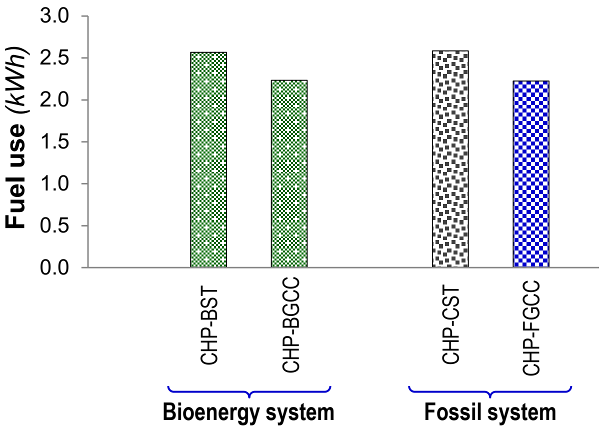

Figure 8. Fuel use of integrated energy systems providing of 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance.

production. Replacing gasoline and diesel vehicles with electric vehicles powered by bioelectricity give climate benefits between fossil gas- and coal-based systems. Hence, CRF benefit of the substitution could begin immediately and have large magnitude in the long term when forest slash is used to replace coal.

INTEGRATED OPTIONS

The transport service based on EV and bioelectricity was shown to be more primary energy efficient than biomotor fuels. Therefore, EV with bioelectricity for transport service is used in further calculations. Integrated production of electricity and heat is considered. Figure 8 shows fuel use of different integrated energy systems for an energy service package of 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance. In these systems, we assumed that the production in combined heat and power (CHP) units is maximized and the deficit of corresponding energy services is fulfilled by standalone production units of the same levels of technologies and fuel types.

Compared to standalone production, the integrated options could reduce the total use of forest slash by 14-26%, depending on technologies being used. The corresponding values for the integrated options using fossil fuels are 10–38 %, depending on fuel types and technologies being used.

Figures 9 and 10 show cumulative CO_2 emission and CRF from different integrated energy systems when 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance is produced in year 0 when using BST or BIGCC as bioenergy reference technology. In fossil-based systems, the corresponding quantity of biomass being decay depends on the bioenergy technology used as a reference. The use of forest slash to replace coal give much higher climate benefits compared to when fossil gas is replaced.

Figure 11 shows the changes in CRF when biomass is used to replace fossil fuels in year 0 in an integrated energy system for an energy service package of 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance. The higher instantaneous CO_2 emission of bioenergy system compared to fossil gas-based system (Figure 9) results in positive CRF during an initial period when bioenergy system is used. As a result, a bioenergy substitution requires 25–30 years to balance the CRF. However, replacing coal with forest slash triple the CRF benefits after 100 years compared to replacing fossil gas and the benefits are immediate.

Discussion and Conclusions

This study shows that forest slash could be used to reduce cumulative CO_2 emission and global warming. The climate effects depend on type of produced energy service, the technology used and the replaced fossil-based system. The maximum energy service provided by a kWh of forest slash in standalone systems is 0.48 kWh of electricity, 1.04 kWh of heat or 1.80 km of transport distance. The most fuel-efficient bioenergy pathways are using BIGCC for electricity, biomass boiler for heat, and BIGCC and EV for transport. The use of bioelectricity and electric vehicles instead of fuel-based biomotor vehicles gives about twice the transport distance per unit of consumed forest slash.

Of the fossil standalone systems studied, coal-based systems have the highest amount of cumulative CO_2 emission follow by diesel and gasoline for transport and then fossil gas systems. Therefore, the replacement of coal for heat and electricity production by forest slash gives the largest climate benefits. For transport, the climate benefits vary with type of vehicle version. If electricity from BIGCC technology replaces that from CST for electric vehicles, climate benefits will be high. However,

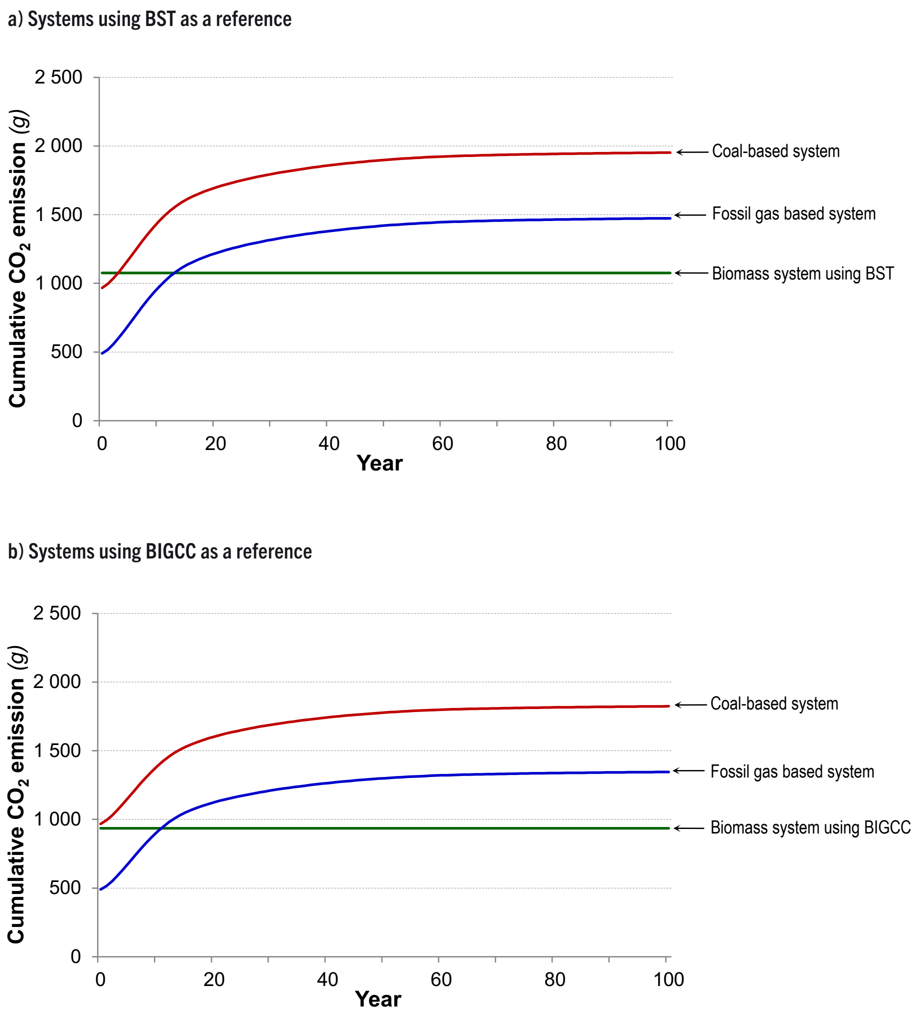

Figure 9. Cumulative CO_2 emission of integrated energy systems providing 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance.

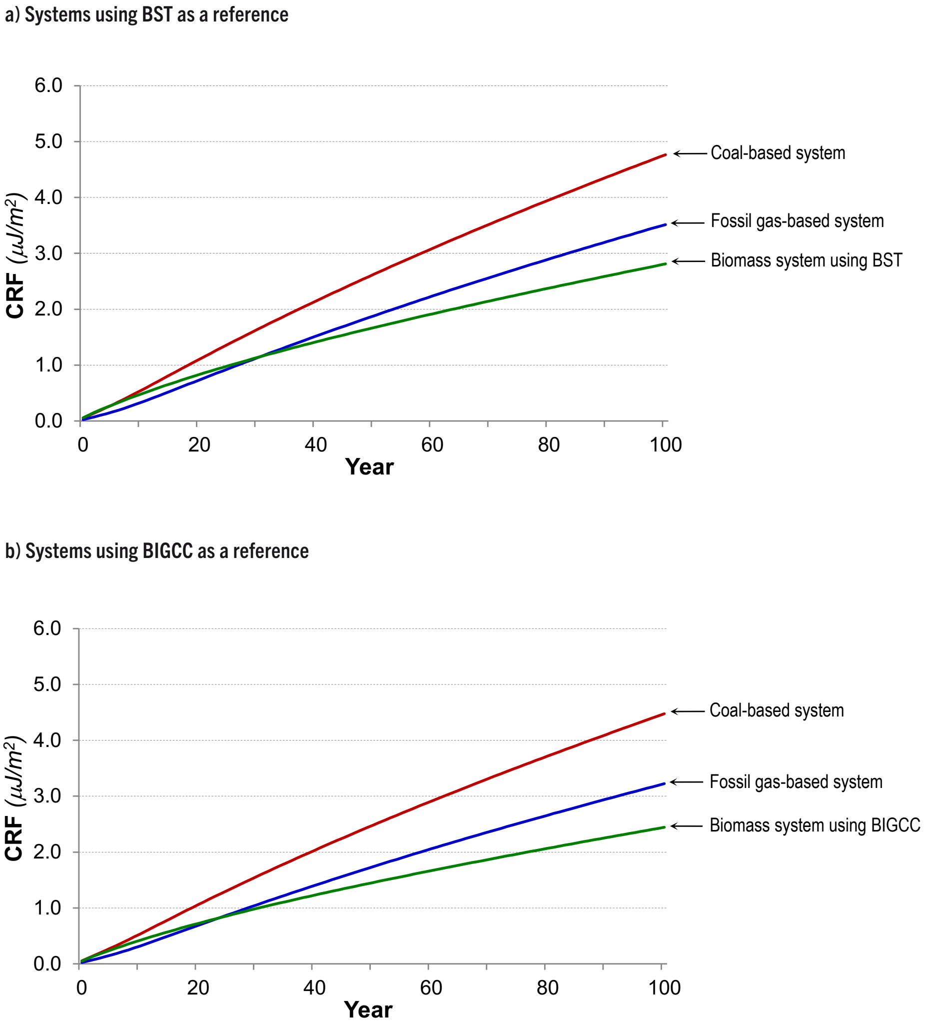

Figure 10. CRF of integrated energy systems providing 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance.

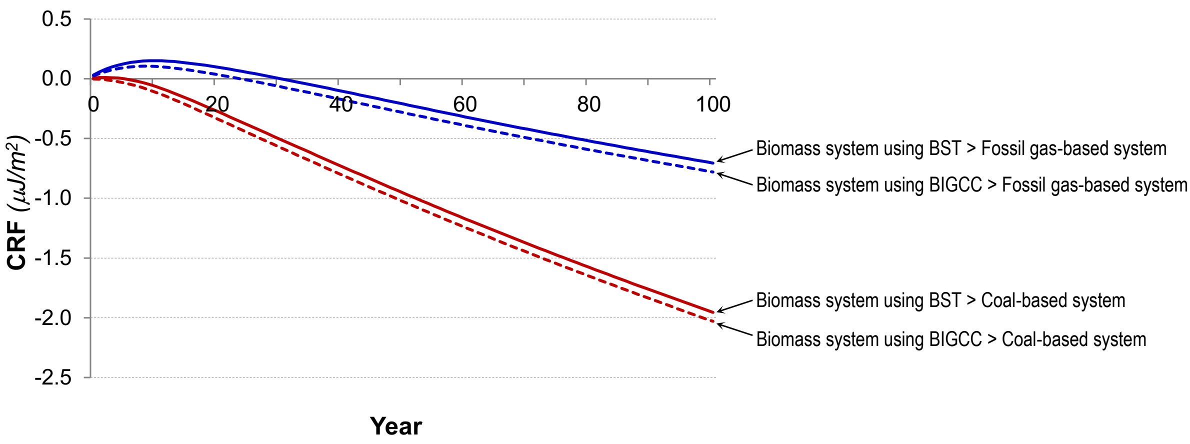

Figure 11. Change in CRF when bioenergy is used instead of fossil fuels in an integrated system providing 0.48 kWh electricity, 1.04 kWh heat and 1.80 km transport distance.

the use of forest slash in less energy efficient pathways could increase the radiative forcing during an initial period and the climate benefits could be rather small for the studied 100-year time period.

Integrated energy systems that supply a package of different energy services including electricity, heat and transport reduce the primary energy use and increase the climate benefits of woody biomass. Compared to standalone production, the integrated options could reduce the total use of forest slash by 14–26 %, depending on the used technologies. The corresponding values for the integrated options using fossil fuels are 10–38 %, depending on fuel types. The climate benefit of forest slash in integrated systems using CHP plants depends mostly on the fossil fuel type replaced. Using forest slash instead of fossil gas increases the CO_2 emission in the first 10–12 years and the climate benefits is further delayed, while replacing coal gives climate benefits immediately and this is about triple compared to replacing fossil gas at end of the studied 100-year time period.

We have assumed that forest slash if not used for energy is left on the forest floor, decaying naturally. If the slash is used for energy instead of fossil fuels, the decay emission is avoided while the biogenic emission occurs immediately when the slash is used for energy. However, the collection and processing of slash, including forwarding, chipping and transport may accelerate the decay process. The amount of emission released by the decay depends on several factors such as the process time of slash in the fuel chain. The decay emission from the fuel chain has here not been distinguished from the emission from natural decay which occurs somewhat later. This may have a minor impact on cumulative CO_2 emission and CRF for the bioenergy systems.

Different state-of-the-art and emerging technologies for energy conversion and integration have been considered. Hence, the analysis reflects investments and performances of new and future energy systems. There are some uncertainties of technology development which may influence our results. Efficient pathways using biomass rely on emerging technologies of integrated gasification combined cycle which is not yet fully commercialized [19] [21]. A better performance of biomass-to-energy conversion units increases the climate benefits, and vice-versa [32]. Nevertheless, to maximize climate benefits it is crucial to use resource-efficient pathways taking into account the whole chain from natural resources to energy services.

This study suggests that the use of woody biomass should be considered in the context of the overall energy system. Woody biomass could be used in efficient ways to replace fossil fuels in standalone plants. However, biomass could be used even more efficiently in integrated energy systems to produce electricity, heat and transport distance, and the development of energy conversion technologies will help to improve the system efficiency of bioenergy systems.

References

1. IEA, *World Energy Outlook 2016*. 2016, International Energy Agency.
2. IEA, *World Energy Outlook 2013*. 2013, International Energy Agency. p. 708.
3. R.E.H. Sims, R.N.S., A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, and C.T. J. Torres-Martínez, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang, *Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. 2007: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
4. Connolly, D., et al., *Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system.* Energy Policy, 2014. 65 (0): p. 475–489.
5. Gustavsson, L. and N.L. Truong, *Bioenergy pathways for cars: Effects on primary energy use, climate change and energy system integration.* Energy, 2016. 115 (3): p. 1779–1789.
6. Swedish Energy Agency, *Energy in Sweden - Facts and figures 2016*. 2016, Energimyndigheten, Box 310, 631 04 Eskilstuna, Sweden. Web-accessed at http://www.energimyndigheten.se.
7. Gustavsson, L., et al., *Using biomass for climate change mitigation and oil use reduction.* Energy Policy, 2007. 35 (11): p. 5671–5691.
8. Börjesson, P., et al., *Future production and utilisation of biomass in Sweden: Potentials and CO_2 mitigation.* Biomass and Bioenergy, 1997. 13 (6): p. 399–412.
9. Commission on Oil Independence, *Making Sweden an Oil-free Society*. 2006, Swedish Government Office of Sweden.
10. Gustavsson, L., et al., *Climate effects of bioenergy from forest residues in comparison to fossil energy.* Applied Energy, 2015. 138: p. 36–50.
11. Gustavsson, L., et al., *Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels.* Renewable and Sustainable Energy Reviews, 2017 (67): p. 612–624
12. Thunman, H., F. Lind, and F. Johnsson, *Inventory of future electricity and heat production technologies - Interim Report Energy combines (in Swedish: Inventering av framtidens el- och värmeproduktionstekniker – Delrapport Energikombinat). Elforsk rapport 08:79*. 2008, ELFORSK. Web accessed at: http://www.elforsk.se/Rapporter/?rid=08_79_.
13. Goldschmidt, B., *Biomass based energy combines with motor fuel production (In Swedish: Biobränslebaserade energikombinat med tillverkning av drivmedel)*. 2005, Varmeforsk Service AB.
14. Skogsstyrelsen, *Rundvirkes- och skogsbränslebalanser för år 2007 (Roundwood- and forest energy balances for 2007). Meddelande 4-2008. (in Swedish)* 2008.
15. Gustavsson, L., et al., *Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels.* Renewable and Sustainable Energy Reviews, 2017. 67: p. 612–624.
16. Gode, J., et al., *Estimated emission factors for fuels, electricity, heat and transport in Sweden*, in *Miljöfaktaboken 2011*. 2011, Värmeforsk, Stockholm, 2011.
17. IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. 2006, Intergovernmental Panel on Climate Change. Web-accessed at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/.
18. Danish Energy Agency, *Technology data for energy plants*. 2010, Danish Energy Agency. p. 155.

19. Nohlgren, I., et al., *Electricity from new and future plants 2014 (in Swedish: El från nya och framtida anläggningar 2014)* 2014, Elforsk AB, Stockholm (SE). Web-accessed at http://www.elforsk.se/Programomraden/El--Varme/Rapporter/?rid=14_40_.
20. Ahlgren, E., et al., *Biokombi Rya – Final report from subprojects (in Swedish: Biokombi Rya – Slutrapporter från ingående delprojekt)*, in *CEC report 2007:3* 2007, Centre for Coordinated Energy Research (Chalmers EnergiCentrum-CEC), Chalmers University of Technology, Göteborg, Sweden. Web-accessed at http://publications.lib.chalmers.se/records/fulltext/65604.pdf.
21. IEAGHG, *Potential for biomass and carbon dioxide capture and storage*. 2011, Report: 2011/06. July 2011. International Energy Agency. Web accessed at: http://ieaghg.org/docs/General_Docs/Reports/2011-06.pdf.
22. Nyström, O., et al., *Electricity from new and future plants 2011 (in Swedish: El från nya och framtida anläggningar 2011)*. 2011, Elforsk AB, Stockholm (SE). Web-accessed at http://www.elforsk.se/Rapporter/?rid=11_26_.
23. Joelsson, J.M. and L. Gustavsson, *Reduction of CO_2 emission and oil dependency with biomass-based polygeneration.* Biomass and Bioenergy, 2010. 34 (7): p. 967–984
24. Liu, S., et al., *Study of spark ignition engine fueled with methanol/gasoline fuel blends.* Applied Thermal Engineering, 2007. 27 (11–12): p. 1904–1910.
25. U. S. EPA, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014*. 2014, United States – Environmental Protection Agency.
26. Green Car Congress. *Facelifted Mercedes-Benz B-Class with diesel, gasoline, natural gas and electric drives debuting at Paris show*. 2014; Web-accessed at: http://www.greencarcongress.com/2014/09/facelifted-mercedes-benz-b-class-with-diesel-gasoline-natural-gas-and-electric-drive-on-sale-in-euro.html].
27. Swedish Energy Agency, *Energy in Sweden - Facts and figures 2014*. 2014, Energimyndigheten, Box 310, 631 04 Eskilstuna, Sweden. Web-accessed at http://www.energimyndigheten.se.
28. Reilly-Roe & Associates Ltd. and (S&T)^2 Consultants Inc., *Life cycle analysis of transportation fuel pathways – prepared for IEA Advanced Motor Fuels Annex 40*. 2012, Web-accessed at http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_40.pdf. p. 197.
29. Ågren, G.I., R. Hyvönen, and T. Nilsson, *Are Swedish forest soils sinks or sources for CO_2 – model analyses based on forest inventory data.* Biogeochemistry, 2007. 82 (3): p. 217–227.
30. Ortiz, C.A., et al., *Soil organic carbon stock changes in Swedish forest soils – A comparison of uncertainties and their sources through a national inventory and two simulation models.* Ecological Modelling, 2013. 251: p. 221–231.
31. Dlugokencky, E. and P. Tans, *Trends in Atmospheric Carbon Dioxide*. 2016, Global Greenhouse Gas Reference Network. Web-accessed at http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global.
32. Sathre, R., L. Gustavsson, and N.L. Truong, *Climate effects of electricity production fuelled by coal, forest slash and municipal solid waste with and without carbon capture.* Energy, 2017. 122: p. 711–723.