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A LIFECYCLE COMPARISON OF PRIMARY ENERGY USE AND CLIMATE IMPACT OF BIOFUEL AND ELECTRIC CARS

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Methodology
Life cycle comparison

- **We compare BEV (Battery Electric Vehicle) and liquid-fuel ICV (Internal Combustion Vehicle)** cars that provide equivalent transport service
- **Analysis includes**:
  - primary energy use of manufacturing the cars and batteries
  - operating primary energy use of the vehicles over their lifespans
  - **full fuel cycle fossil and biogenic CO_2 emissions and resulting Cumulative Radiative Forcing (CRF)**
- **Main analysis**: **medium sized** passenger car going **15,000 km** annually during **15-year** lifespan, **mid range** batteries, **slash** (branches and tops) forest residues including international transport, **emerging technologies**
- **Sensitivity analysis**: car size, car driving distance, car lifespan, battery type, biomass source and transport distance, conventional technologies

Methodology

CO_2 emissions accounting

- We consider **all fossil CO_2 emissions from technological systems**
- We consider **all biogenic CO_2 emissions from technological systems**
- We consider **biogenic CO_2 emissions from slow natural decay of forest residues** if left on the forest floor instead of being used for energy (current default)
- To understand the climate impact of complex patterns of CO_2 emissions and removals, we calculate **cumulative radiative forcing (CRF)**

Methodology
Car operating energy pathways

- **BEVs get electricity from:**
  - stand-alone electricity plants using forest residues
  - stand-alone electricity plants with a mix of 70% wind and 30% forest residues
- **ICVs are powered by:**
  - gasoline from conventional fossil oil refineries
  - biomethanol produced in stand-alone plants using from forest residues
- Each energy pathway is considered **with and without CCS (Carbon Capture and Sequestration)**

Methodology
Energy efficiencies

- Woody biomass >> **electricity**
  - Stand-alone BIGCC plant: 50% conversion efficiency [40%]
- Woody biomass >> **biomethanol**
  - Gasification-synthesis biorefinery: 57% conversion efficiency [48%]
- **CCS energy penalty**
  - 20% [24%] (percent increase in fuel input per unit of delivered product)
- **Fuel cycle** energy (percent of LHV of delivered fuel)
  - Gasoline: 9%
  - Slash: 2.5% [2.1%]
  - Stumps: 4.6% [4.2%]

[Values in brackets are used in sensitivity analysis]

Methodology

CO_2 emission of car and battery manufacture

- CO_2 emissions (**tCO_2/vehicle**) from manufacture of BEV and ICV cars of different sizes
- Vehicle production model includes chassis, drivetrain and battery
- BEV data includes production of 1 base-case battery

	Car size		
	Small	Medium	Large
BEV	8.0	10.0	14.4
ICV	6.0	8.0	10.0

- CO_2 emissions (**tCO_2/battery**) from manufacture of batteries for small, medium and large size BEVs
- Using battery chemistries and processes that result in low, medium and high CO_2 intensities

Car size	Battery intensity		
	Low	Medium	High
Small	1.2	2.4	3.6
Medium	2.0	4.0	6.0
Large	4.0	8.0	12.0

Methodology
Car operation

- **Final operational energy use (MJ/km)** of different size cars
- Electrical energy includes wall-to-vehicle charging losses
- Liquid fuel energy is given as the lower heating value (LHV) of fuels including delivery to fueling stations
- Methanol and gasoline cars of the same size are assumed to have identical energy efficiencies

	Car size		
	Small	Medium	Large
BEV	0.50	0.70	1.0
ICV	1.6	2.1	2.5

Methodology

Scenario analysis of 68.7 billion km of annual passenger car driving

- **Passenger cars in Sweden travelled 68.7 billion km** in 2018
- We allocate **annually 60 TWh of forest residues to operate cars** for each of 8 energy pathways
- If **more energy than 60 TWh** is needed to operate the cars, **gasoline is used instead**
- If **less energy than 60 TWh** is needed to operate the cars, the **surplus biomass produces electricity to replace fossil gas**

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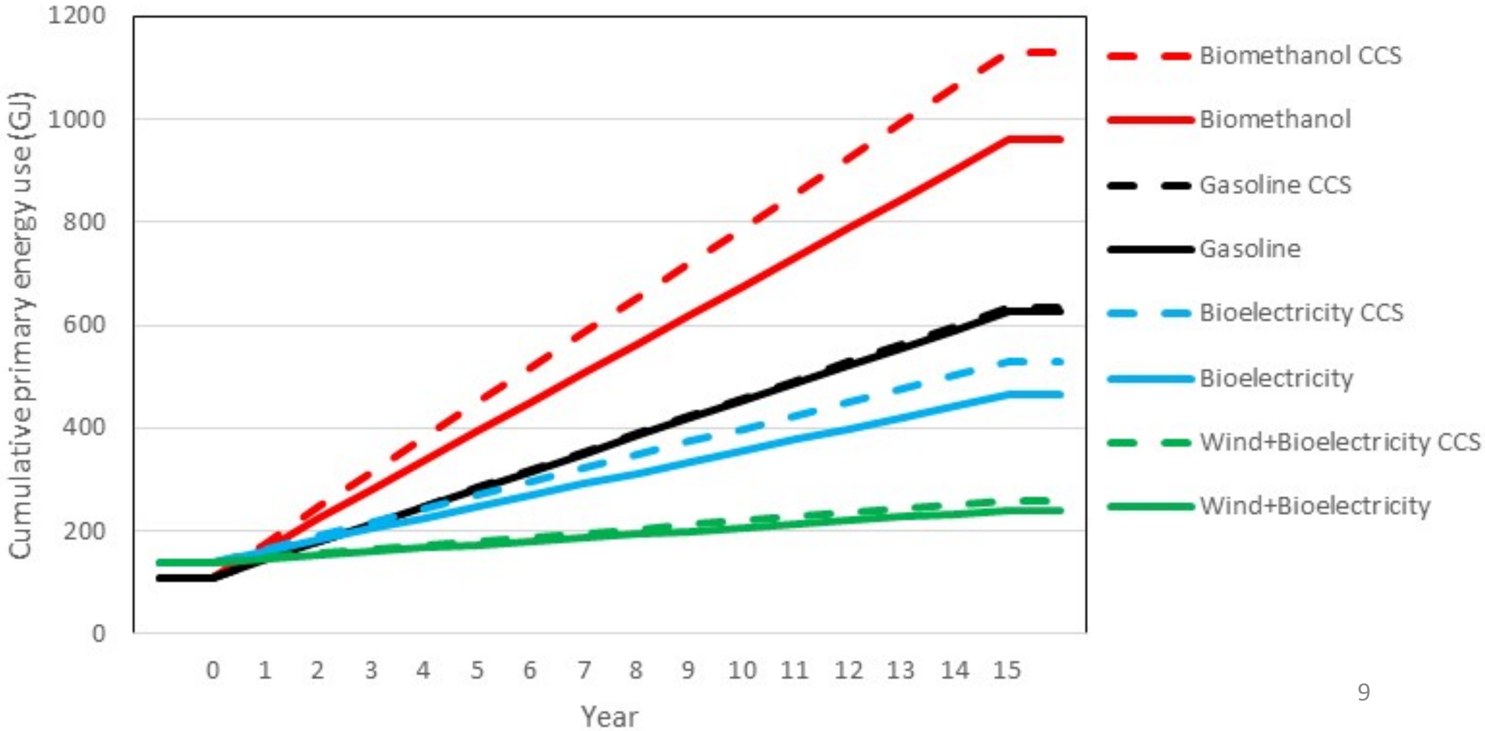
Results

Cumulative primary energy use (GJ)

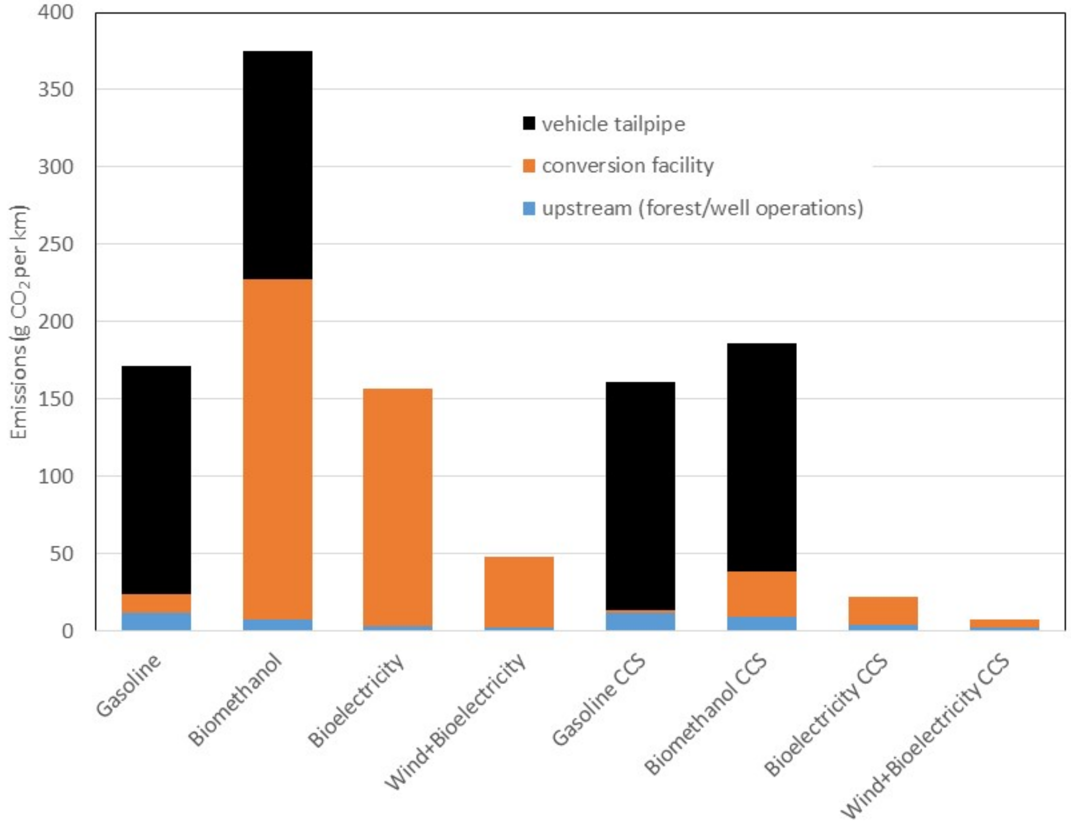
Per medium-size car during
its 15-year life cycle



Results

Vehicle operating emissions (g CO_2/km)

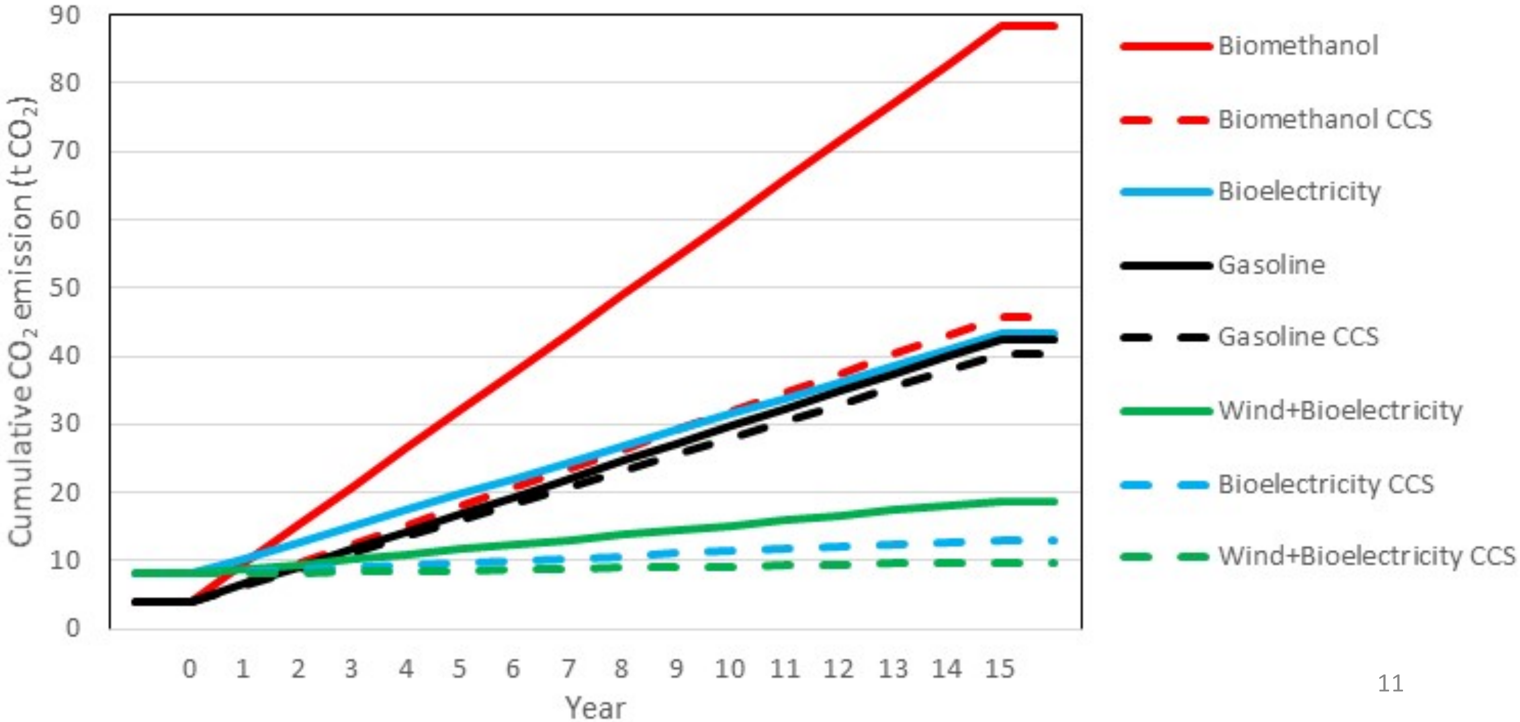
- Full fuel cycle
- Biogenic and fossil CO_2 emissions
- Medium-size cars



Results

Cumulative biogenic and fossil CO_2 emissions (t CO_2)

Per medium-size car during its 15-year life cycle

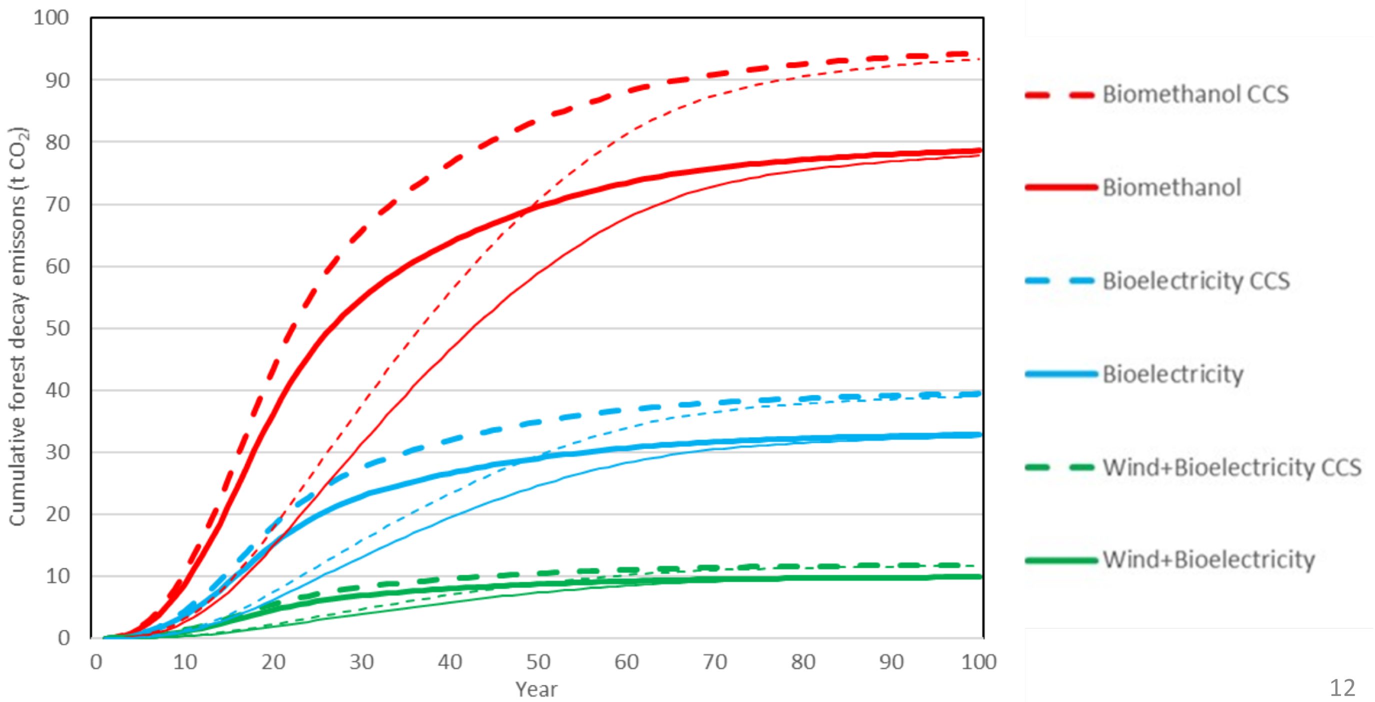


Results

Cumulative avoided forest decay emissions (t CO_2)

Corresponding to harvest residues for medium-size car during its 15-year life span

- thick lines: slash decay
- thin lines: stumps decay

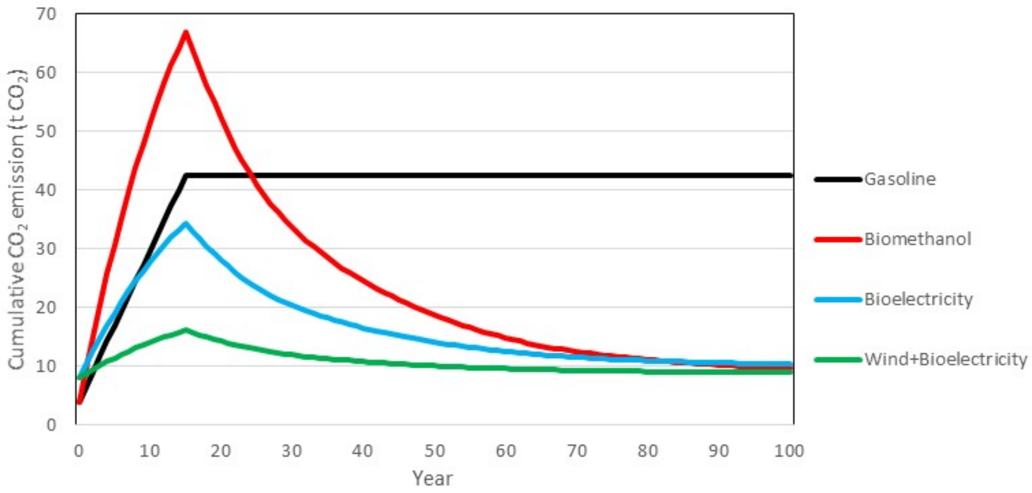


Results

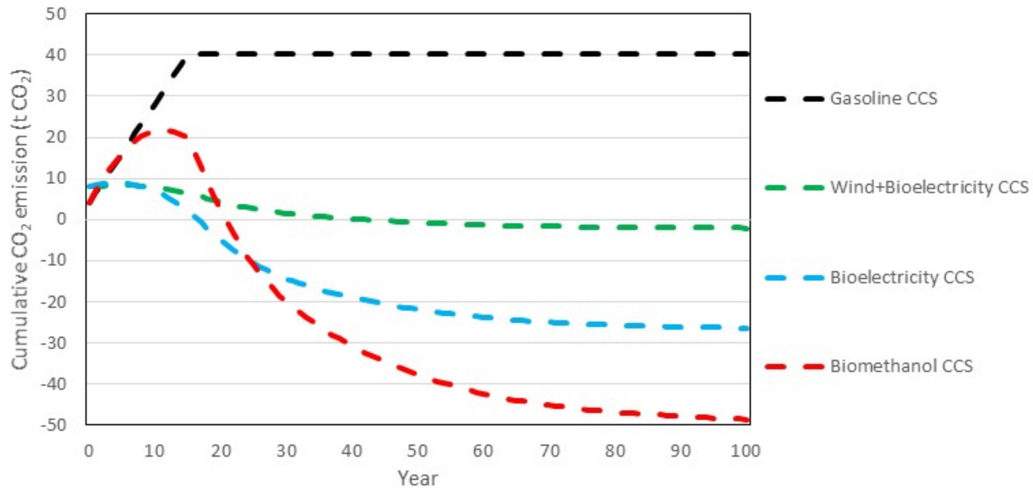
Cumulative net biogenic and fossil CO_2 emissions for each pathway, including avoided forest decay emissions (t CO_2)

Medium-size cars, operated 15 years, using slash

without CCS



with CCS

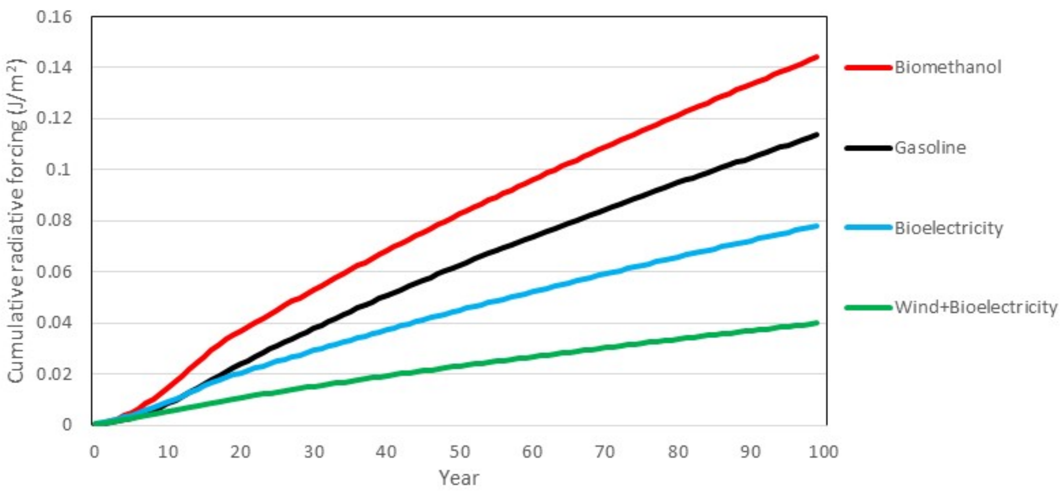


Results

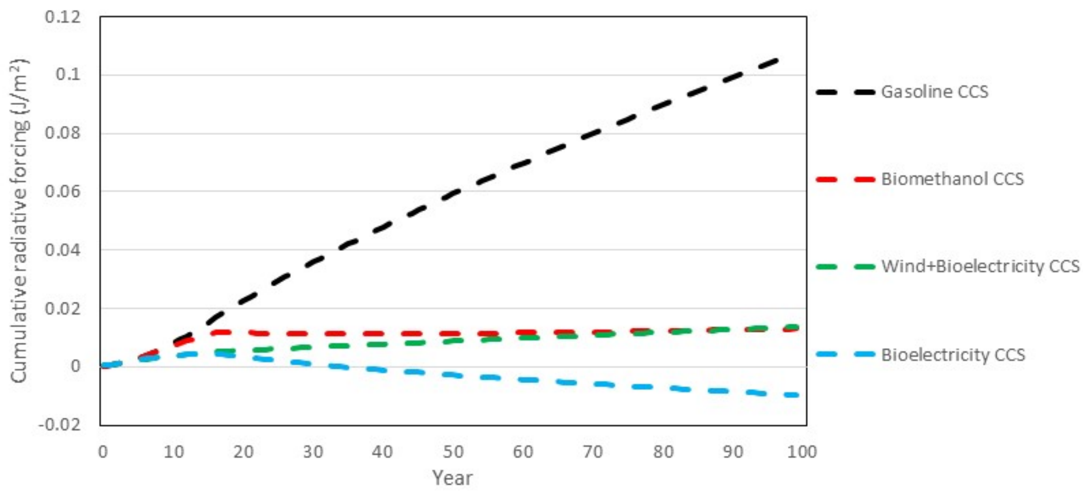
Cumulative radiative forcing of net CO_2 emission including avoided forest decay emissions (J/m^2), corresponding to emissions in the earlier figure

Medium-size cars, operated for 15 years, using slash

without CCS



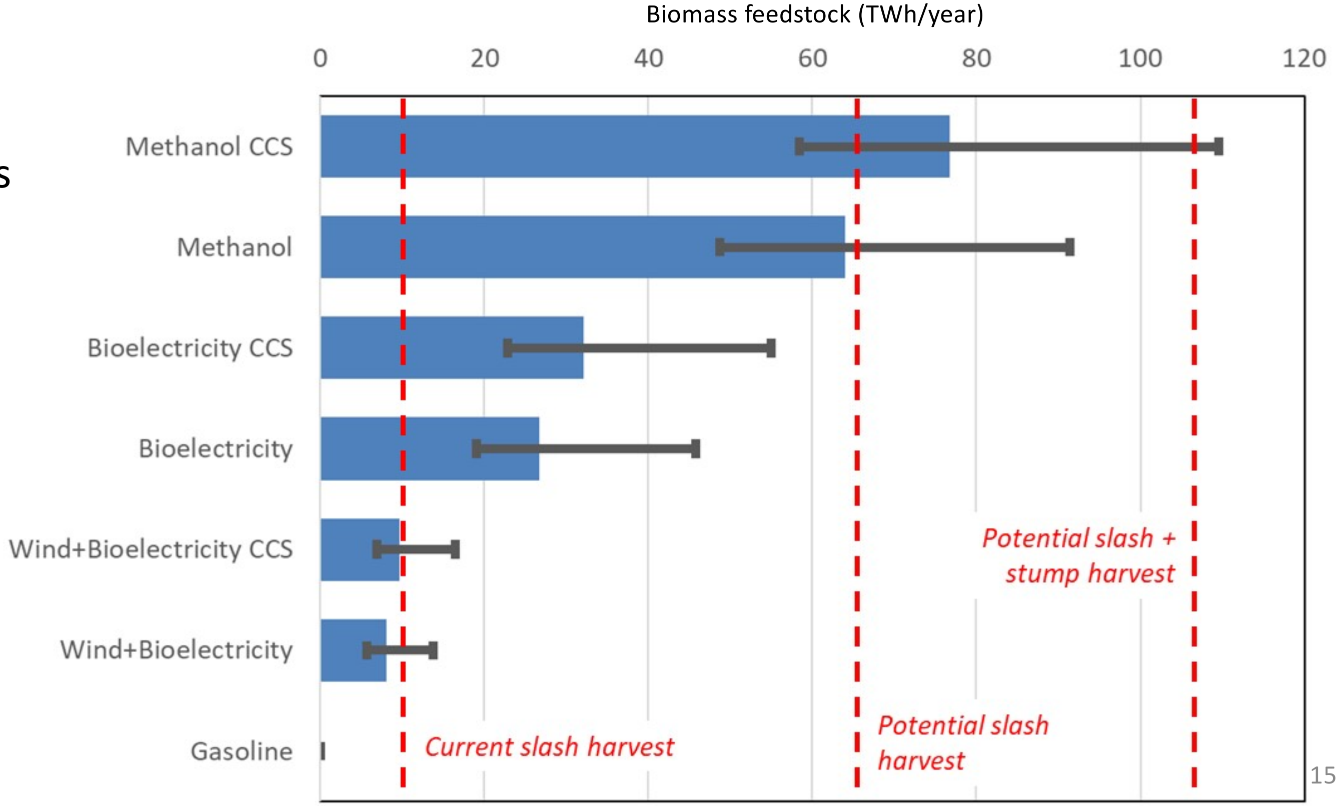
with CCS



Scenario

Required biomass feedstock to drive 68.7 billion km in passenger cars (TWh/year)

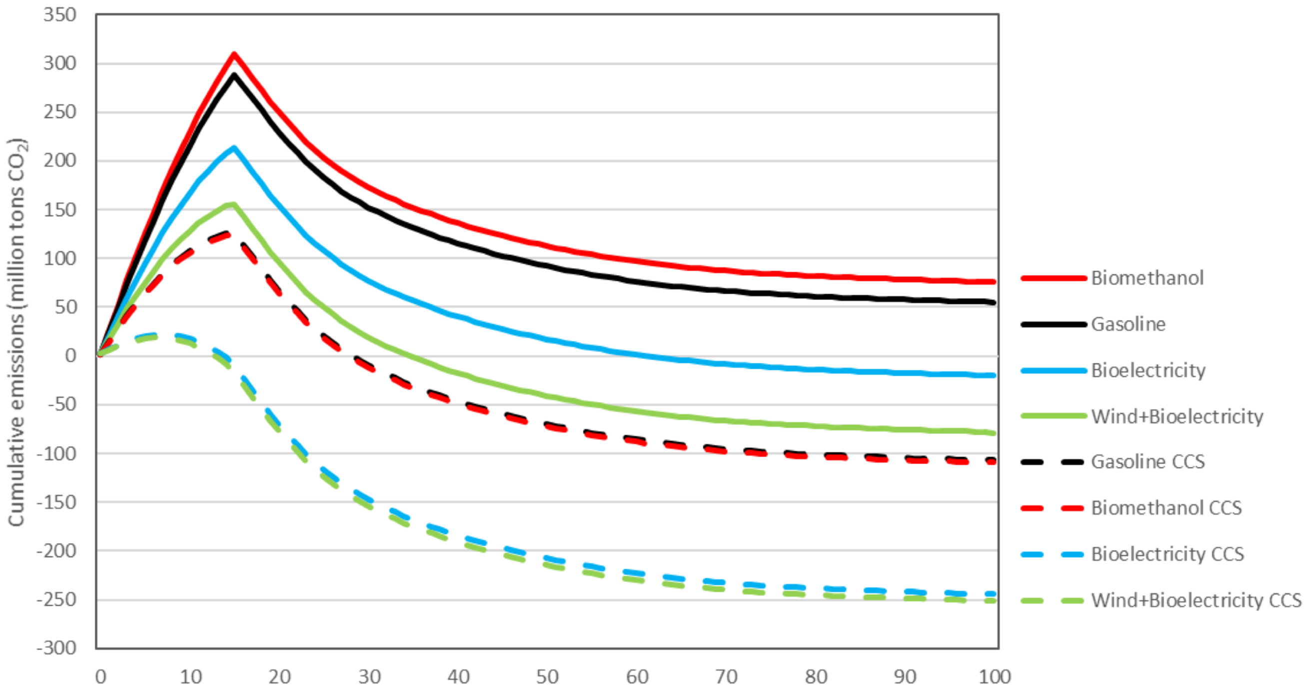
- Blue bars: medium size cars
- Error bars: small and large cars
- Red dashed lines: based on *IRENA, 2019, Bioenergy from boreal forests: Swedish approach to sustainable wood use*



Scenario

Cumulative net biogenic and fossil CO_2 emissions (t CO_2) from 8 energy pathways, including avoided forest decay emissions, to drive 68.7 billion km annually during 15 years

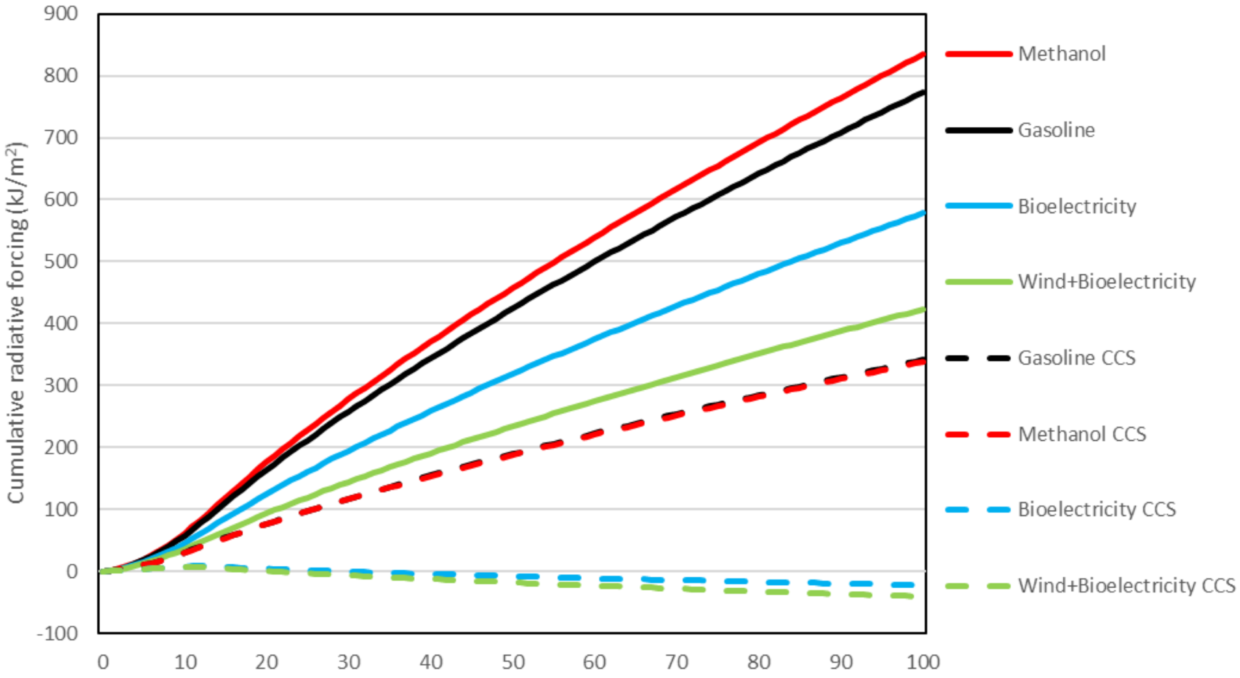
- **60 TWh of forest slash** is allocated annually to power medium-size cars for 15 years
- **If more energy** than 60 TWh is needed for transport, **gasoline is used instead**
- **If less energy** than 60 TWh is needed for transport, the surplus slash makes electricity to **replace fossil gas**



Scenario

Cumulative radiative forcing (J/m²) from net CO_2 emission from 8 energy pathways, including avoided forest decay emissions, to drive 68.7 billion km annually during 15 years

- **60 TWh of forest slash** is allocated annually to power medium-size cars for 15 years
- **If more energy** than 60 TWh is needed for transport, gasoline is used instead
- **If less energy** than 60 TWh is needed for transport, the surplus slash makes electricity to replace fossil gas



Results
Sensitivity analysis

Most important parameters:

- **Car size**
- Lifespan and driving distance

Less important parameters:

- Technology level (conventional vs. emerging)

Least important parameters:

- Battery type and number
- Biomass type and distance

Change in primary energy use caused by variation of parameters

	Gasoline	Biomethanol	Bioelectricity	Wind+Bioel	Gasoline CCS	Biomethanol CCS	Bioelectricity CCS	Wind+Bioel CCS
Base case (GJ)	**625**	**959**	**464**	**240**	**632**	**1129**	**529**	**260**
Small car	-24%	-24%	-26%	-24%	-24%	-24%	-26%	-24%
Large car	20%	20%	38%	34%	20%	20%	39%	34%
10,000 km per year	-27%	-30%	-23%	-14%	-28%	-30%	-25%	-15%
20,000 km per year	27%	30%	23%	14%	28%	30%	25%	15%
10-year service life	-27%	-30%	-23%	-14%	-28%	-30%	-25%	-15%
20-year service life	27%	30%	23%	14%	28%	30%	25%	15%
2 batteries	0.0%	0.0%	6.9%	13%	0.0%	0.0%	6.0%	12%
Low intensity battery	0.0%	0.0%	-3.4%	-6.7%	0.0%	0.0%	-3.0%	-6.2%
High intensity battery	0.0%	0.0%	3.4%	6.7%	0.0%	0.0%	3.0%	6.2%
Stumps biomass	0.0%	1.9%	1.6%	0.9%	0.0%	1.9%	1.7%	1.0%
Local biomass transport	0.0%	-0.4%	-0.3%	-0.2%	0.0%	-0.4%	-0.3%	-0.2%
Conventional technology	0.0%	18%	17%	12%	0.2%	22%	21%	15%

Change in radiative forcing caused by variation of parameters

	Gasoline	Biomethanol	Bioelectricity	Wind+Bioel	Gasoline CCS	Biomethanol CCS	Bioelectricity CCS	Wind+Bioel CCS
Base case (J/m^2)	**0.115**	**0.237**	**0.117**	**0.052**	**0.108**	**0.123**	**0.036**	**0.028**
Small car	-25%	-25%	-31%	-34%	-26%	-25%	-36%	-38%
Large car	27%	23%	54%	68%	28%	27%	79%	90%
10,000 km per year	-30%	-32%	-27%	-19%	-30%	-30%	-12%	-5.7%
20,000 km per year	30%	32%	27%	19%	30%	30%	12%	5.7%
10-year service life	-29%	-30%	-26%	-18%	-29%	-29%	-12%	-5.4%
20-year service life	27%	29%	25%	17%	27%	28%	11%	5.2%
2 batteries	0.0%	0.0%	9.2%	21%	0.0%	0.0%	30%	39%
Low intensity battery	0.0%	0.0%	-4.9%	-11%	0.0%	0.0%	-16%	-21%
High intensity battery	0.0%	0.0%	4.9%	11%	0.0%	0.0%	16%	21%
Stumps biomass	0.0%	1.6%	1.4%	0.9%	0.0%	3.8%	5.3%	2.1%
Local biomass transport	0.0%	-0.3%	-0.3%	-0.2%	0.0%	-0.7%	-1.0%	-0.4%
Conventional technology	0.0%	28%	20%	14%	0.02%	8.7%	11%	5.5%

Conclusions

- BEVs use less primary energy than ICVs
- Biomass usage is 7-9 times higher for biomethanol than for wind+bioelectricity pathways
- BEVs have lower climate impact than ICVs
- Gasoline and biomethanol cars have similar climate impacts
- CCS has limited benefit for ICVs due to tailpipe emissions
- Bioelectricity with CCS and BEVs will give some global cooling effect
- Comprehensive sensitivity analysis shows that our conclusions are robust

Shifting to electric cars, while scaling up renewable electricity generation, is a wise strategy for climate-adapted passenger car transport

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