Lifecycle Analysis of Greenhouse-Gas and Air-Pollutant Emissions from New Fuels and Vehicles

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Outline

- Main messages.
- Overview of lifecycle analysis (LCA).
  - Conventional LCA vs. ideal LCA.
- Why “upstream” emissions matter.
- Air pollutants and greenhouse gases (GHGs).
- Results of recent LCAs of GHG and air-pollutant emissions.
- Lifecycle GHG and air-pollutant emissions from the perspective of social cost.
- LCA of air pollution and GHGs: what do we know relatively well?
- What do we know less well?
- Conventional vs. ideal LCA revisited.
- Summary

Main message #1

- Not surprisingly, the broader, more complex, more multi-faceted, more dynamic, and less well tested the system being analyzed, the less well we know the impacts on air quality and climate.

Main message #2

- Conventional LCA of energy use and emissions can reasonably well represent differences in air-pollutant and (to a lesser extent) GHG emissions between near-term alternatives that are similar to current fuels, but generally needs considerable further development to adequately represent differences between future transport modes or dissimilar fuel production pathways (such as biofuels vs. fossil fuels).

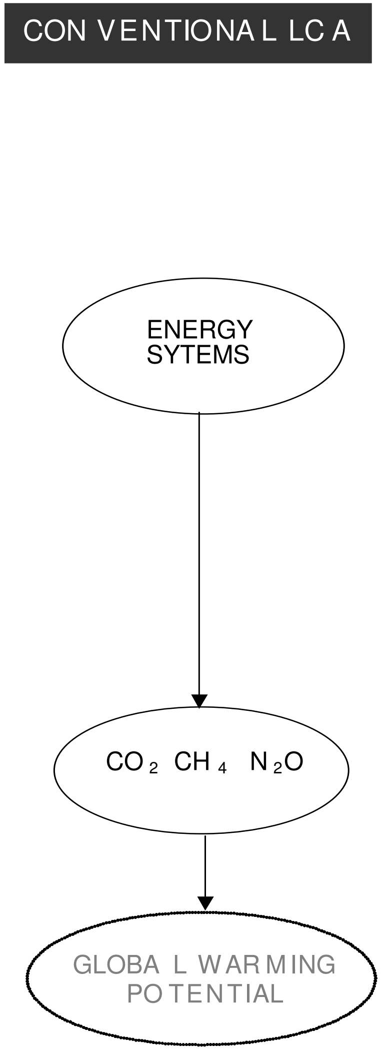
Main message #3

- To make significant further progress in LCA of air-pollutant and GHG emissions, we need to combine engineering, environmental, and economic models to estimate the costs and benefits of energy and environmental policies, considering all important impact pathways of all pollutants.

So, what is the purpose of LCA?

- Ideally, the purpose of LCA is (or ought to be) to *systematically* determine the difference in some environmental measure between a status quo world and the world given some proposed action (usually a policy action). In principle, this requires a careful specification of the action and then an analysis of how the relevant systems change as a result of the action.
- In practice, however, most conventional LCAs fall short of the ideal.

Conceptual structure of conventional LCA of GHGs



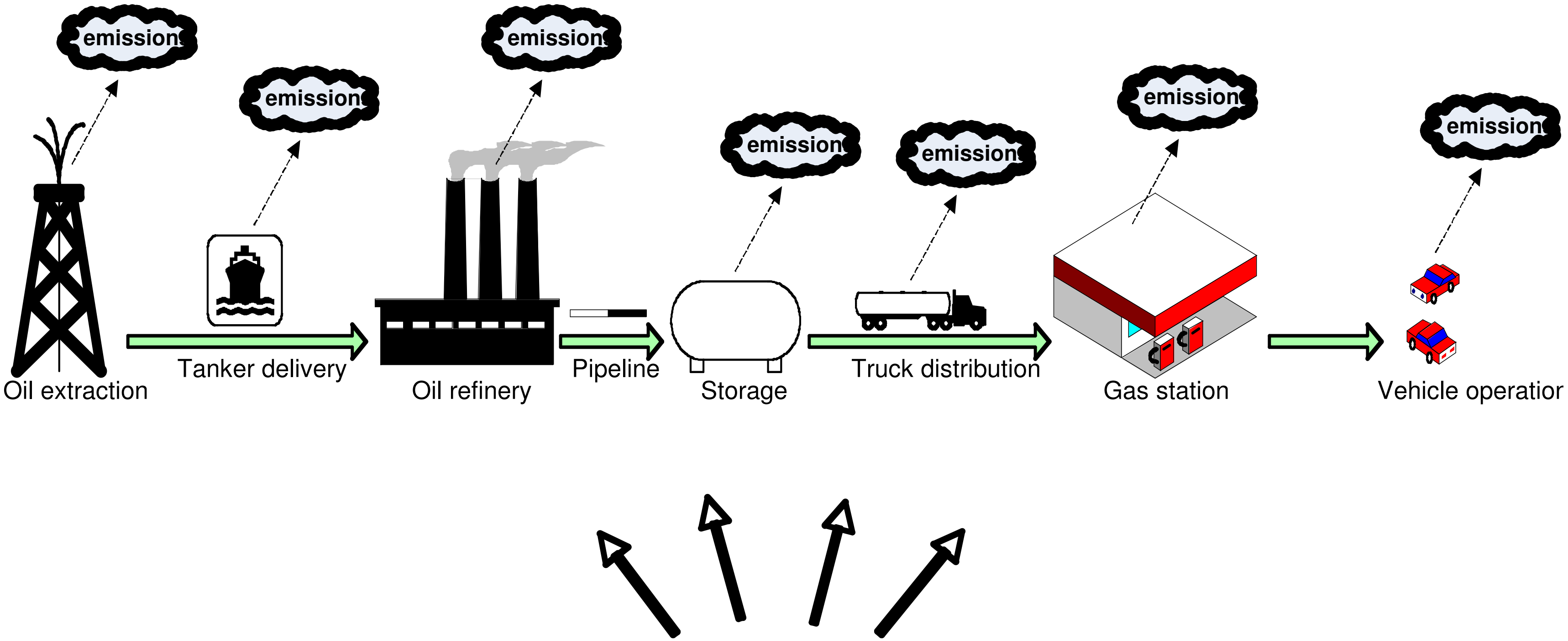
CONVENTIONAL LCA

ENERGY
SYTEMS

CO_2 CH_4 N_2O

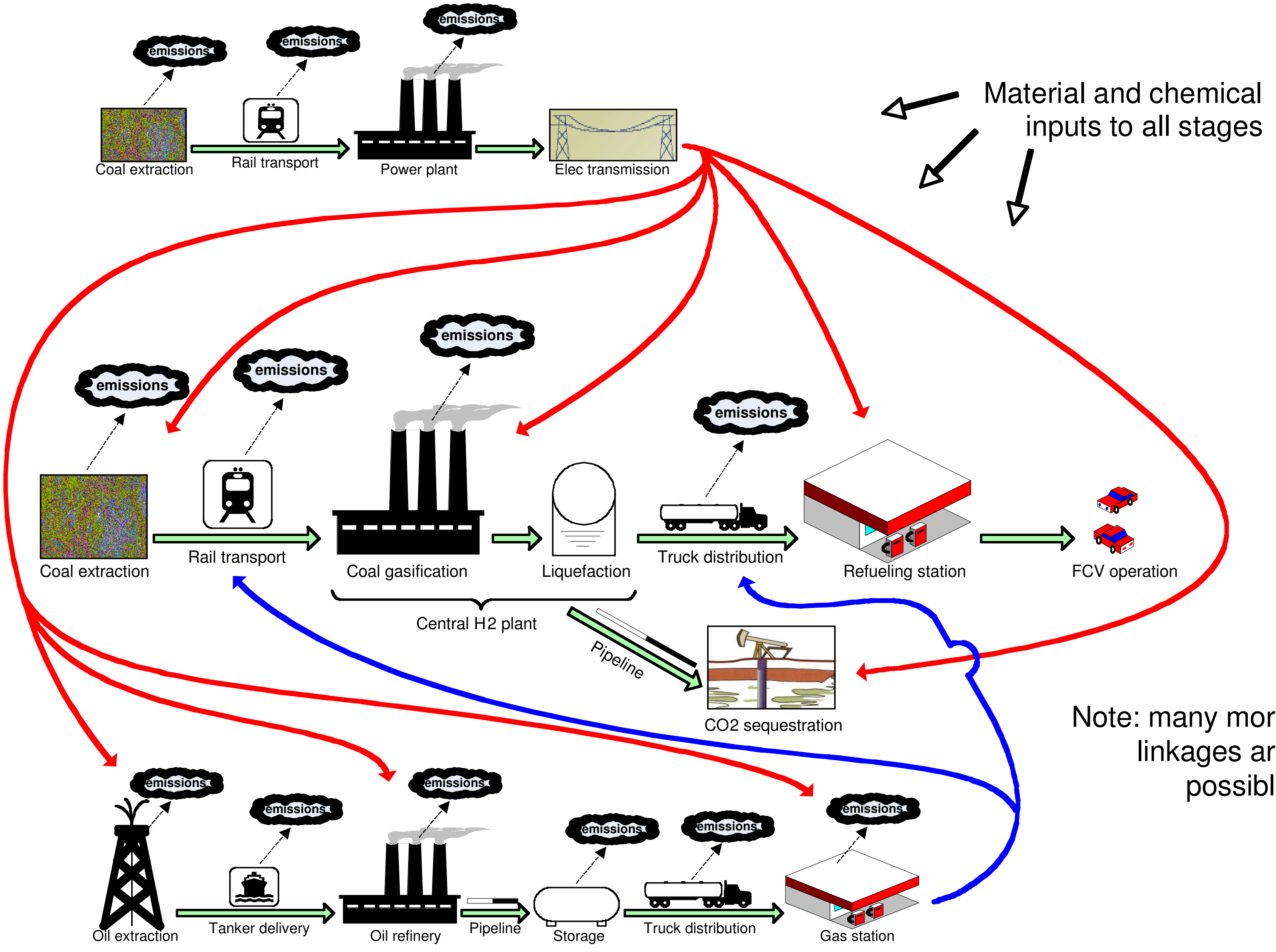
GLOBAL WARMING
POTENTIAL

Illustration of energy system in conventional LCA: petroleum lifecycle



Material and chemical
inputs to all stages

Conventional LCA: coal to H2 with petrol, electricity input



Material and chemical inputs to all stages

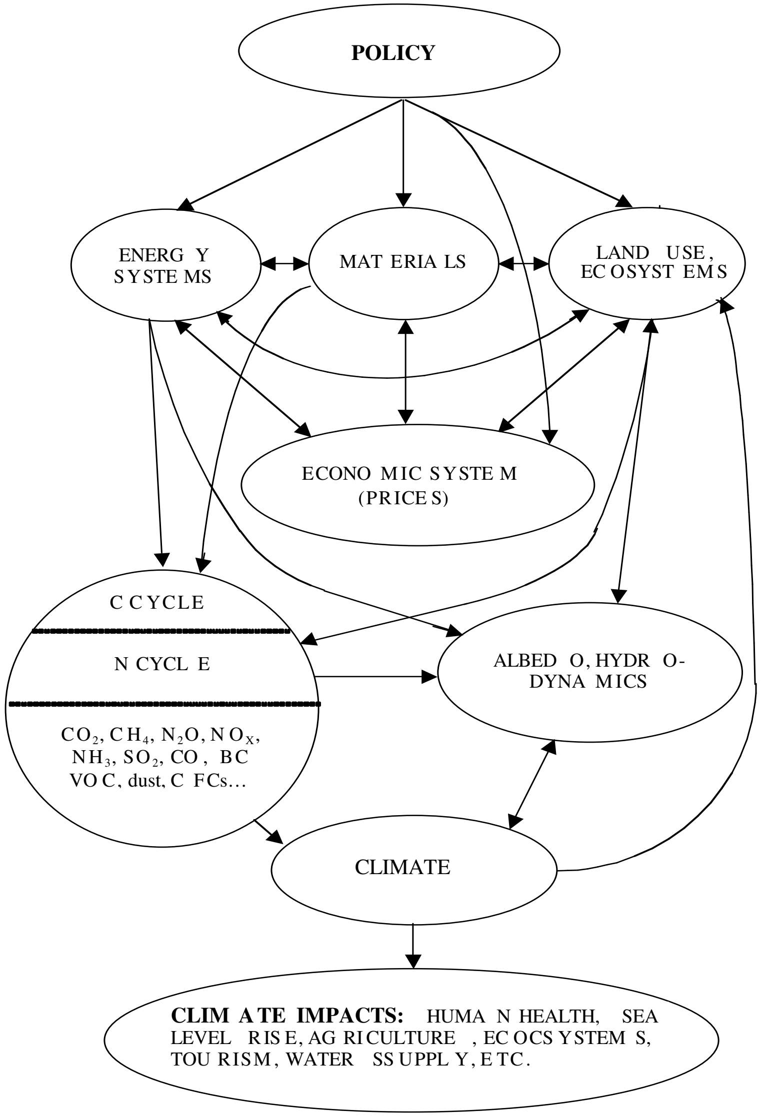
Note: many more linkages are possible

But conventional LCA falls short of “ideal” LCA

	Ideal approach	**Conventional approach**
The aim of the analysis	Evaluate impacts (worldwide if necessary) of one realistic action compared with another	Evaluate impacts of replacing one limited set of “engineering” activities with another
Scope of the analysis	All major production and consumption activities globally, if appropriate	Narrowly defined chain of material production and use activities
Method of analysis	Input/output representation of technology with dynamic price linkages between all sectors of the economy	Simplified static energy-and-materials-in/emissions-out representation of technology
What is evaluated	Ideally, physical and economic impacts of direct interest to society (e.g., damages from climate change)	Emissions aggregated by some relatively simple weighting factors (e.g., “Global Warming Potentials,” ozone-forming potential

Comparison of structure of conventional LCA with ideal LCA

REALITY (IDEAL)



POLICY

ENERGY SYSTEMS

MATERIALS

LAND USE, ECOSYSTEMS

ECONOMIC SYSTEM (PRICES)

C CYCLE

N CYCLE

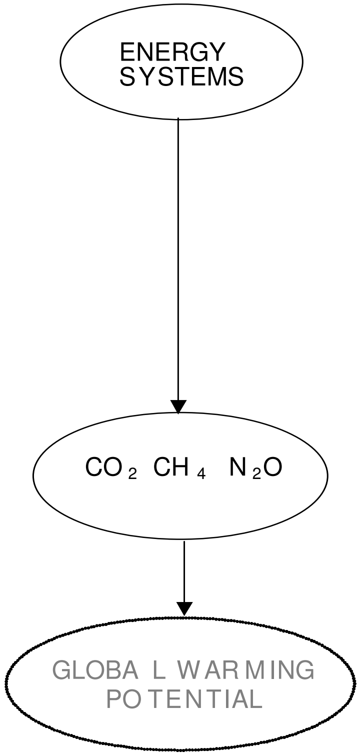
CO_2, CH_4, N_2O, NO_X, NH_3, SO_2, CO, BC VOC, dust, CFCs…

ALBEDO, HYDRO-DYNAMICS

CLIMATE

CLIMATE IMPACTS: HUMAN HEALTH, SEA LEVEL RISE, AGRICULTURE, ECOCSYSTEMS, TOURISM, WATER SSUPPLY, ETC.

CONVENTIONAL LCA



ENERGY SYSTEMS

CO_2 CH_4 N_2O

GLOBAL WARMING POTENTIAL

More on this later…

Why did we get interested in LCA of GHGs?

A few of decades ago analysts recognized that considering only end-use emissions of CO_2 gives an incomplete picture:

Compare CO_2 emissions from end use vs. from the whole fuelcycle, for motor vehicles (as a % of fossil-fuel CO_2):

	End use	**Whole fuel-cycle**
U. S.	22%	30%
OECD-Europe	18%	24%
World	14%	19%

It turns out that there are significant “upstream” emissions of all air pollutants and GHGs for a wide range of transport fuels. Shown here are upstream emissions as a percentage of end-use emissions:

	RFG *oil*	**diesel** *oil*	**LPG** *oil,NG*	**CNG** *NG*	**EtOH** *corn*	**EtOH** *cellul.*	**BD** *soy*	**FTD** *NG*	**CH2** *water*	**CH2** *NG*	**MeOH** *NG*
CO_2	31	22	14	21	101	-14	65	34	1674	7834	42
NMOC	33	22	39	56	225	31	589	19	10	99	30
CH_4	2356	5050	1537	247	1295	491	15562	5378	3059	8727	3856
CO	5	8	4	4	20	19	248	14	3	21	5
N_2O	2	28	1	2	169	64	7736	34	n.a.	n.a.	3
NO_x	57	9	33	41	252	154	-38	11	24	80	75
SO_x	716	898	572	503	1346	108	677	175	592	904	317
PM	311	55	565	315	4444	1708	317	13	364	736	192
CO2eq	32	28	16	29	117	3	164	39	852	3801	40

Source: my runs of the Lifecycle Emissions Model (LEM). Based on 26 mpg LDGV, 6 mpg HDDV, near-term parameters. RFG = reformulated gasoline, LPG = liquefied petroleum gas, NG = natural gas, EtOH ethanol, BD = biodiesel, cellul. = wood & grass, FTD = Fischer-Tropsch diesel, CH2 = compressed hydrogen, MeOH = methanol; CO2e = CO_2equivalent.

Even air-pollutant and GHG emissions from the lifecycle of vehicles (including vehicle assembly, transport, and disposal, and vehicle materials) can be significant compared with end-use emissions:

Pollutant	**Emissions (g/lb)**		**Emissions (g/mi)**		**Emissions (% of end use)**	
	LDGVs	*HDDVs*	*LDGV*	*HDDV*	*LDGVs*	*HDDVs*
CO_2	2,694	2,548	59.7	95.3	18%	5.5%
NMOCs	1.80	1.79	0.04	0.07	4.6%	4.1%
CH_4	5.98	5.49	0.13	0.21	292%	196%
CO	7.29	8.22	0.16	0.31	2.2%	1.7%
N_2O	0.08	0.08	0.00	0.00	1.3%	4.1%
NO_x	6.53	6.40	0.14	0.24	18%	1.1%
SO_x	6.42	6.78	0.14	0.25	147%	164%
PM	3.74	3.95	0.08	0.15	293%	18%
CO2eq	2,970	2,926	65.7	105.4	16%	5.5%

Source: my runs of LEM. Based on 26 mpg LDGV, 6 mpg HDDV, near-term parameters.

Air pollutants and GHGs

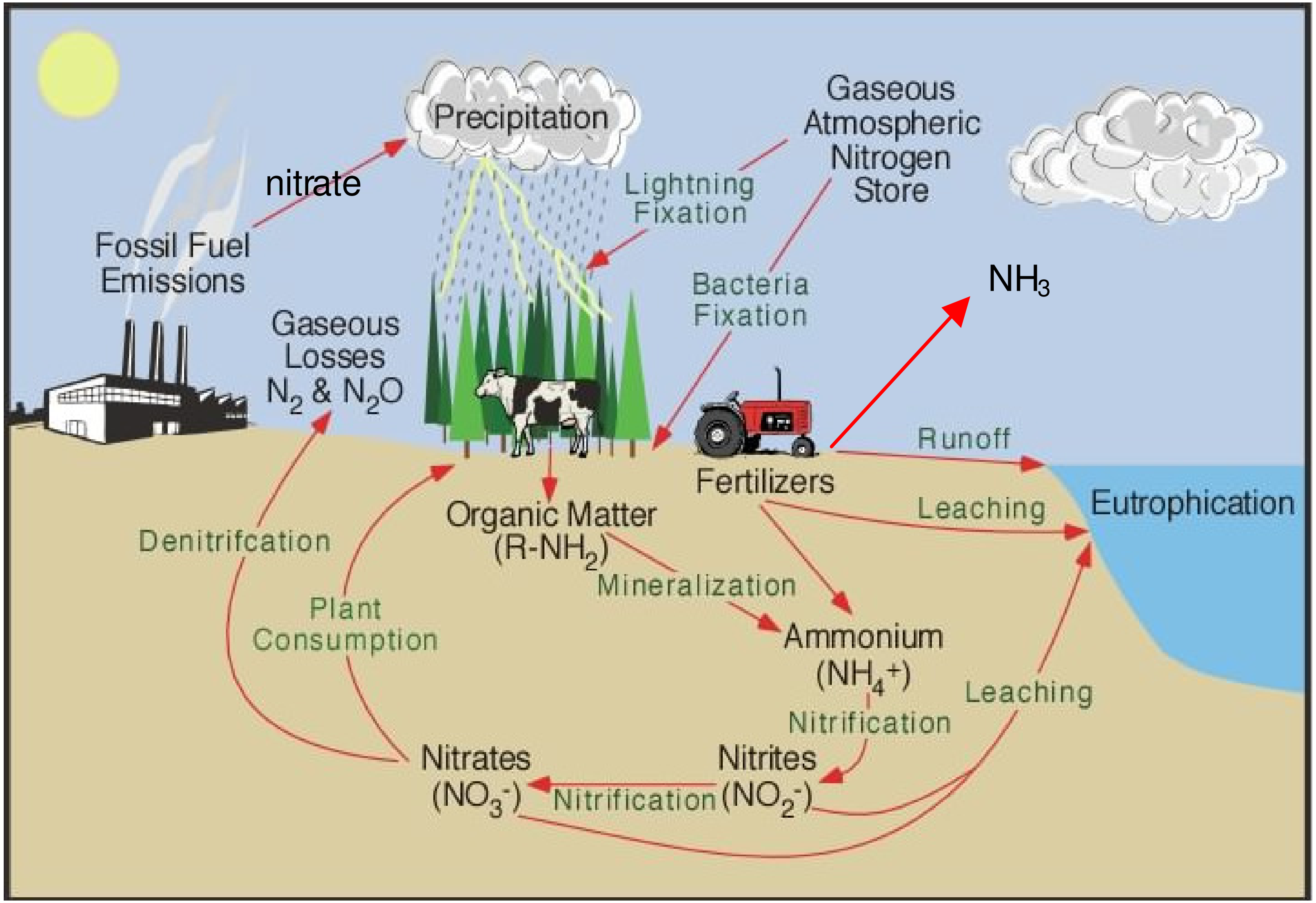
- All pollutants that affect local air quality also affect climate -- this includes, for example, road dust and toxic air pollutants (e.g., benzene).
- We care about air pollution for the same reasons we care about climate change -- because of the impacts on human health, natural ecosystems, economic activity, and so on.
- The data and methods used to estimate lifecycle GHG emissions also produce estimates of lifecycle air pollutant emissions.

All air pollutants affect climate. This shows the treatment of the climate effects of pollutants in the LEM

Pollutant --> effects related to global climate	**CEF (U.S. 2050)**	**CEF (U.S. 1990)**	**IPCC 100yr GWP**
CO_2 → +R	1	1	1
CH_4 → +R, -OH, +O_3 (t), +CH_4, +H_2O (s), +CO_2, +CO, +SO_4	17	19	23
N_2O → +R	230	260	296
O_3 → +R, -soil C, -plant C; see CO, H_2, CH_4, NMOCs, NO_2	4	4	n.e.
PM (black carbon) → +R, clouds, more	1,300	1,400	n.e.
PM (organic matter) → -R, clouds, more	-150	-163	n.e.
PM (sulfate [SO_4]) → -R, clouds, more	-78	-85	n.e.
PM (nitrate [NO_3]) → -R, clouds, more	-97	-106	n.e.
PM (organic aerosol) → -R, clouds, more	-65	-70	n.e.
PM (generic dust) → -R, clouds, more	-3	-3	n.e.
CO → -OH, +O_3 (t), +CH_4, +CO_2, +SO_4	3	3	1.6
H_2 → -OH, +O_3 (t), +CH_4	5	5	n.e.
NMOCs → -OH, ±O_3 (t), +CH_4, +CO_2, +SO_4	6 + C	3 + C	n.e.
NO_2 → -CO_2, +N_2O, ±OH, +O_3 (t), -CH_4, +PM, +SO_4	-12	-16	n.e.
NH_3 → -CO_2, +N_2O, + NO_3, +SO_4	n.e.	n.e.	n.e.
SO_2 → +PM	- 48	- 53	n.e.
H_2O → +R (s), +OH, -CH_4, clouds, more	n.e.	n.e.	n.e.
CFC-12 → +R, -O_3 (s)	12,500	11,400	8,600
HFC-134a → +R	1,300	1,200	1,300
SF_6 → +R	130,000	120,000	22,200

CEF = CO_2-equivalency factor, GWP = Global Warming Potential, IPCC = Intergovernmental Panel on Climate Change.

Complex but often overlooked climate and air quality impacts: the nitrogen cycle



The climate and air pollution effects of NO_X emissions

i) NO_X participates in a series of atmospheric chemical reactions involving CO, NMOCs, H_2O, OH^-, O_2, and other species that affect the production of tropospheric ozone. The production of ozone, in turn, has two kinds of climate effects (as well as direct health effects as an air pollutant):

   i-a) a direct radiative-forcing effect;
   i-b) an indirect effect on carbon sequestration in plants and soil.

ii) In the atmospheric chemistry mentioned in *i)*, NO_X affects the production of the hydroxyl radical, OH, which oxidizes methane and thereby affects the lifetime of methane.

iii) In the atmospheric chemistry mentioned in *i)*, NO_X affects the production of sulfate aerosols, which have a net *negative* radiative forcing (and thereby a beneficial effect on climate) but also directly adversely affect human health as air pollutants..

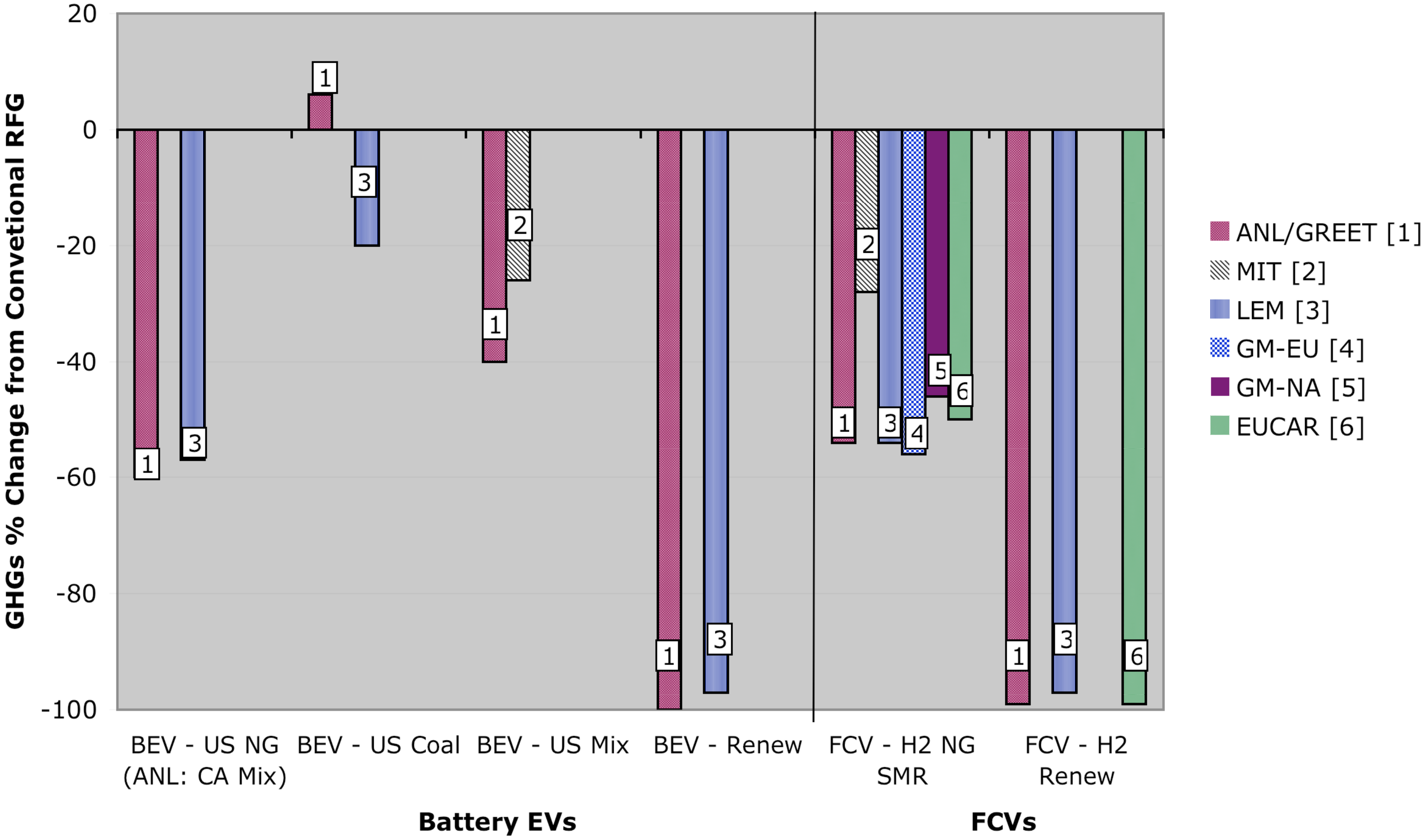
iv) NO_X converts to nitrate which deposits onto soils and oceans and then denitrifies or nitrifies into N_2O (a strong, long-lived direct climate-change gas) and NO (which oxidizes back to the indirect GHG NO_2 that was the source of the deposited N in the first place). Nitrate deposition also affects soil emissions of CH_4.

v) Nitrate from NO_X fertilizes terrestrial and marine ecosystems and thereby stimulates plant growth and carbon sequestration in nitrogen-limited ecosystems.

vi) NO_X forms particulate nitrates, which as aerosols have a net *negative* radiative forcing (and thereby a beneficial effect on climate) but also directly adversely affect human health as air pollutants.

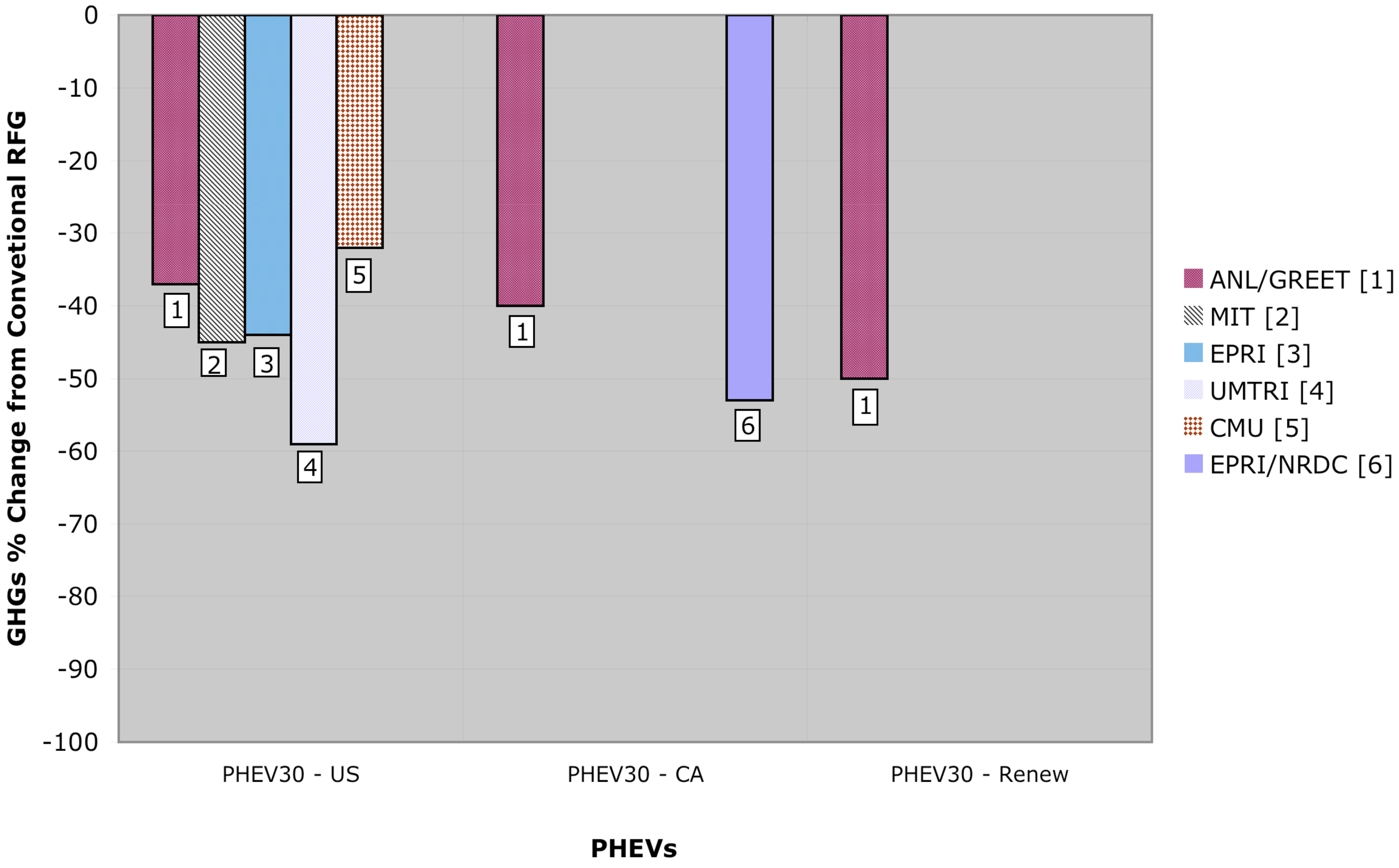
vii) As deposited nitrate, N from NO_X can increase acidity and harm plants and thereby reduce CO_2 sequestration.

Results of LCAs of GHG emissions: battery EVs and fuel-cell EVs



Source: T. E. Lipman and M. A. Delucchi, “Expected Greenhouse Gas Reductions by Battery, Fuel Cell, and Plug-In Hybrid Electric Vehicles,” in *Electric and Hybrid Vehicles: Power Sources, Models, Sustainability, Infrastructure and the Market*, ed. by G. Pistoia, Elsevier B. V., in press (2010).

Results of LCAs of GHG emissions: plug-in hybrid electric vehicles (PHEVs)



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Results of LCAs of GHG emissions: crop and cellulosic biofuels

(% change versus gasoline)

Source	**Ethanol from corn**	**Ethanol from cellulose (grass)**	**Biodiesel from soy**
GREET (see various papers by Wang and GM et al.) GHGenius (see web site), Kim and Dale, De Oliveira, LBST (GM et al. 2002a), CONCAWE et al., Spatari et al. (2005), Farrell et al. (2006) and others	- 50% to 0%	-100% to -40%	- 80% to -40%
LEM estimates	-30% to + 20%	-75% to -40%	-20% to + 50%

Contribution of key factors to total lifecycle emissions (% of fuel+vehicle lifecycle CO_2-equivalent emissions

Factor	**Ethanol/corn**	**Ethanol/grass**	**Biodiesel/soy**	**Source**
NO_2	++	+	+++	LEM.
NH_3	++	+	+++	LEM
N_2O emissions	++	+	+++	LEM.
CH_4 from plants	~ 0 ?	~ 0 ?	~ 0 ?	Literature.
ag., soil dust	?	?	?	
LUC: CO_2	++	- +	+++	LEM.
LUC: albedo, water cycle	similar to LUC CO_2?	similar to LUC CO_2?	similar to LUC CO_2?	Literature.
Co-products	- -	- -	- - -	LEM.
Price changes	+ ?	+ ?	+ ?	My judgment.

LUC = land-use change.

Results of LCAs of GHG emissions: comparison of different transport modes in the US

		g/pass-mile (gasoline FHV) % ch. vs. gasoline FHV	
Mode	**Mode technology**	**Fuel cycle**	**Fuel+ material**
LDV	*gasoline vehicle, 28 city mpg*	*442 g/mi*	*532 g/mi*
LDV	diesel (low-S) vehicle version of gasoline	+ 13%	+ 10%
LDV	hydrogen (NG) fuel cell version of gasoline	-61%	-52%
bus	diesel-fuel (low-S) bus: 10, 20 passengers	+ 2%, -49%	-2%, -51%
HRT	heavy-rail train: 20%, 40% capacity	-60%, -80%	-60%, -80%
LRT	light-rail train: 20%, 40% capacity	-62%, -81%	-65%, -83%
mini-car	gasoline car, 57 mpg city driving	-55%	-56%
min-car	electric car, 7 mi./kWh, U. S. ave. power	-80%	-76%
scooter	4-stroke gasoline scooter	-82%	-82%
scooter	electric scooter, U. S. ave. power	-87%	-84%
	bicycling	-99%	-96%
	walking	-100%	-100%

Source: My runs of LEM. “Fuel cycle” includes fuel and electricity lifecycle, maintenance and repair, and (for transit) station energy. “Fuel+material” includes vehicle and materials lifecycle, refrigerant lifecycle, road dust, brake wear and tire wear, infrastructure construction. LDV = light-duty vehicle; HRT = heavy-rail transit; LRT = light-rail transit.

Results of LCAs of GHG emissions: comparison of different transport modes in several countries (*g/mi*, % ch. vs. gasoline)

Mode	Fuel (feedstock)	U.S.	Mexico	Chile	China	India	S. Africa
LDV	*gasoline (crude oil)*	*453*	*421*	*317*	*229*	*202*	*589*
LDV	diesel (crude oil)	-20%	-20%	-21%	-20%	-18%	-17%
LDV	ethanol (wood & grass)	-56%	-58%	-55%	-49%	-51%	-60%
LDV	electricity (national mix)	-17%	-39%	-58%	-31%	-12%	-23%
LDV	comp. H2 (NG)	-43%	-48%	-54%	-46%	-43%	-49%
bus	diesel (crude oil)	-27%	-73%	-64%	-48%	-59%	-86%
bus	F-T diesel (NG)	-25%	-73%	-62%	-47%	-59%	-86%
bus	CNG (NG)	-30%	-75%	-66%	-48%	-60%	-87%
bus	biodiesel (soy)	-23%	-64%	-49%	-17%	-25%	-83%
rail transit	heavy rail (electricity)	-66%	-86%	-80%	-49%	-17%	-86%
rail transit	light rail (electricity)	-64%	-87%	-88%	-82%	-62%	-88%
mini-bus	diesel (crude oil)	-69%	-74%	-70%	-68%	-61%	-87%
mini-bus	LPG (oil and NG)	-76%	-82%	-78%	-76%	-71%	-90%
mini-car	RFG (crude oil)	-58%	-53%	-42%	-50%	-42%	-60%
mini-car	electricity (national mix)	-76%	-76%	-77%	-70%	-53%	-73%
scooter 2-str.	gasoline (crude oil)	-71%	-64%	-52%	-37%	-54%	-75%
scooter 4-str.	RFG (crude oil)	-82%	-78%	-71%	-60%	-71%	-85%
scooter	electricity (national mix)	-81%	-79%	-79%	-54%	-61%	-81%
non-motorized	bicycles	-92%	-91%	-88%	-79%	-82%	-93%
non-motorized	walking	-100%	-100%	-100%	-100%	-100%	-100%

Lifecycle air pollution and GHG emissions from the perspective of social cost: External costs of motor-vehicle use in the U. S., 1990-91 (10^9 1991 $)

Cost Item	*Low*	*High*
Air pollution: human mortality, morbidity from PM emissions from vehicles	17	266
Air pollution: human mortality, morbidity from all other pollutants from vehicles	2.3	17
Air pollution: human mortality, morbidity, from ŅupstreamÓ pollutants	2.3	13
Air pollution: human mortality, morbidity, due to road dust	3.0	154
Air pollution: loss of visibility, due to all pollutants attributable to motor vehicles	5.1	37
Air pollution: damage to agricultural crops, due to ozone from motor vehicles	3.3	5.7
Air pollution: damages to materials, due to all pollutants from motor vehicles	0.4	8.0
Air pollution: damage to forests, due to all pollutants from motor vehicles	0.2	2.0
Climate change damages in U.S. from U.S. motor-vehicle lifecycle GHGs	0.0	25
Climate change damages globally from U.S. motor-vehicle lifecycle GHGs	2.4	201
Noise from motor vehicles	0.5	15
Water pollution: leaking tanks, urban runoff, highway de-icing	0.8	2.2
Water pollution: environmental and economic impacts of large oil spills	0.2	0.5
External non-market costs of motor-vehicle accidents (death, suffering, etc.)	9.5	98
External costs of motor-vehicle travel delay	23	99

Source: M. A. Delucchi et al., *The Social Cost of Motor-Vehicle Use in the U. S. in 1990-1991*, see reports at www.its.ucdavis.edu/people/faculty/deluccchi. See also M. A. Delucchi and D. M. McCubbin, “External Costs of Transport in the U. S.,” Chapter 9 of the *Handbook in Transport Economics,* edited by A. de Palma, R. Lindsey, E. Quinet, and R. Vickerman, Edward Elgar Publishing, in press (2010).

Lifecycle air pollution and GHG emissions from the perspective of social cost: external costs of EVs versus gasoline ICEVs in the US (cents/mile)

	Battery EVs			**Gasoline ICEVs**		
	low	*high*	*best*	*low*	*high*	*best*
Noise	0.00	1.20	0.04	0.00	1.60	0.05
Externalities of oil use	0.02	0.12	0.04	0.22	1.25	0.40
Climate change	0.00	0.08	0.03	0.00	0.10	0.04
Air pollution	0.02	0.21	0.07	0.19	2.32	0.75
TOTAL	0.05	1.62	0.18	0.40	5.27	1.24

Gasoline vehicle ca. year 2005 US, at 25 mpg, CO2 damages US only; global about 10 x higher. External costs estimates from various studies conducted at ITS-UC Davis.

Social cost of EVs vs. gasoline vehicles (cents/mi)

	EV cost minus gasoline cost		
	low	*high*	*best*
Private lifecycle costs	0.0	30.00	10.00
Noise	0.00	-0.40	-0.01
Externalities of oil use	-0.20	-1.12	-0.36
Climate change	-0.00	-0.02	-0.01
Air pollution	-0.17	-2.11	-0.69
Total externalities	-0.37	-3.69	-1.09
Social cost	-4	30	9

External costs from previous slide

LCA of air pollution and GHGs: what we know reasonably well

- Some of the basic building blocks of LCAs are reasonably well known, for example: emissions from conventional vehicles over standard test cycles; emissions from conventional power plants; energy use of conventional transport and electricity-generation technologies.

An important thing that we think we think we are reasonably sure of

- It does appear that battery and hydrogen fuel-cell electric vehicles powered entirely by wind, water, or solar (WWS) power, either directly or via electrolysis of water to produce hydrogen, would have zero or very near zero emissions of air pollutants and greenhouse gases over the entire lifecycle -- especially in a world where other sectors (buildings, industry) use WWS power. This means that we probably don’t need to do any more analyses to know that a 100% WWS/EV world will essentially eliminate air-pollution problems and climate -change problems (and other environmental problems too).

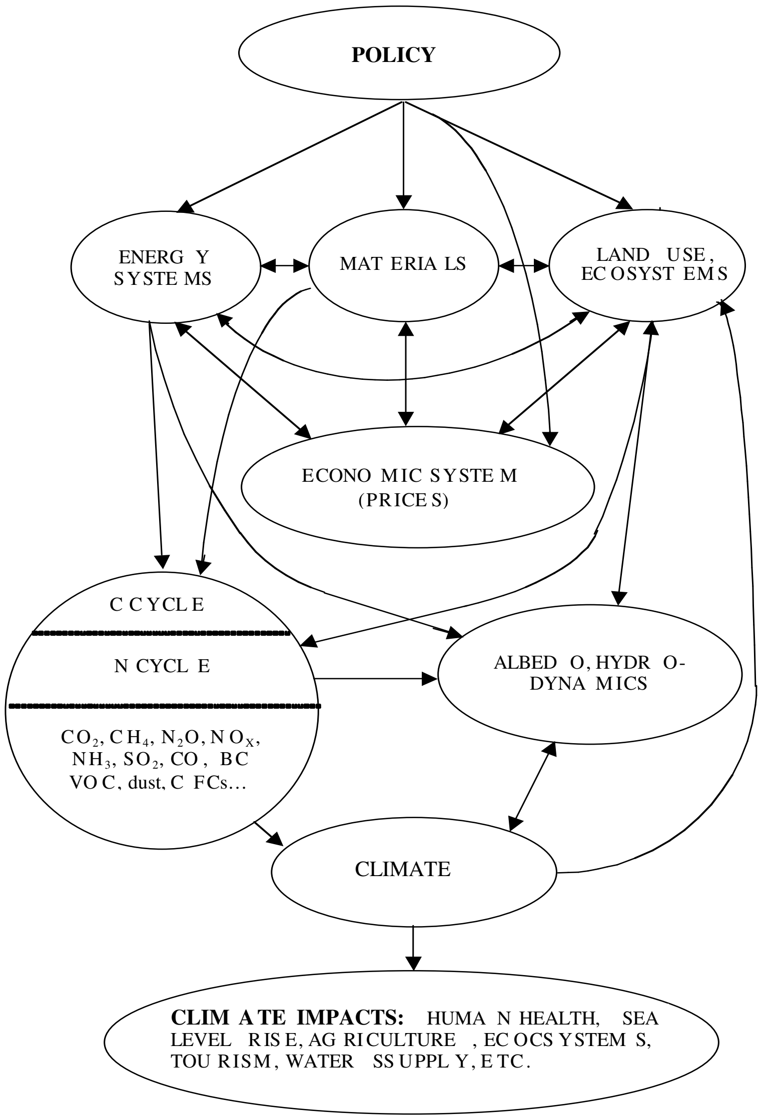
- (As we have seen, our state of understanding regarding biofuels is essentially the opposite.)

What we know less well

- Emissions in “real world” conditions.
- Emissions from new vehicle or fuel production technologies that are still under development (in some cases, we know almost nothing at all).
- Emissions that we have only recently begun to measure (e.g., N_2O).
- Non-combustion sources of pollutants (e.g., from chemical processes, agriculture, land-use change).
- Performance and energy use of new technologies.
- The relationships between emissions and the impacts we care about -- e.g., PM emissions → PM concentrations → exposure to PM → health effects of PM.
- The climate, air-quality, and water-quality impacts of perturbations to nitrogen cycles or hydrologic cycles.
- Climate and hydrologic impacts of biogeophysical changes (e.g., changes in albedo due to changes in land use)
- The interaction of economic, social, and political systems with “technological” systems and the ultimate effects of this interaction on activity, technology choice, performance, and emissions.

Conventional LCA vs. ideal LCA, revisited

REALITY (IDEAL)



POLICY

ENERGY SYSTEMS

MATERIALS

LAND USE, ECOSYSTEMS

ECONOMIC SYSTEM (PRICES)

C CYCLE

N CYCLE

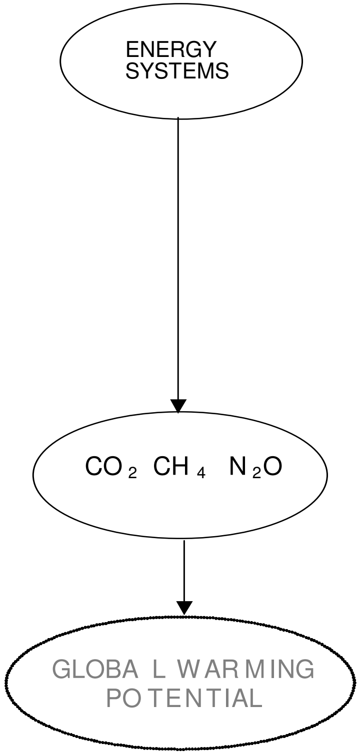
CO_2, CH_4, N_2O, NO_X, NH_3, SO_2, CO, BC VOC, dust, CFCs…

ALBEDO, HYDRO-DYNAMICS

CLIMATE

CLIMATE IMPACTS: HUMAN HEALTH, SEA LEVEL RISE, AGRICULTURE, ECOSYSTEMS, TOURISM, WATER SUPPLY, ETC.

CONVENTIONAL LCA



ENERGY SYSTEMS

CO_2 CH_4 N_2O

GLOBAL WARMING POTENTIAL

CONVENTIONAL LCA VS. REALITY

No policy analysis: conventional LCA assumes that one set of activities replaces another.

Energy systems are well represented (~90%), but materials life cycle, infrastructure, and land-use usually are not.

Conventional LCAs do not model price changes and their effects.

Some CH_4, N_2O omitted. CO, NO_X, SO_X,, PM, O_3, etc., omitted. C cycle and N cycle are incomplete. Albedo, water cycle not modeled.

GWPs are simplistic and do not capture several important aspects of climate change

Conventional LCA does not model impacts of climate change.

Recap

- Not surprisingly, the broader, more complex, more multi-faceted, more dynamic, and less well tested the system being analyzed, the less well we know the impacts.
  - Breadth concerns the geographic or sectoral scope, complexity is the number of constituents and interactions in the system, facets are kinds of subsystems (economic, political, technical, environmental, etc.), dynamic means changing over time.
- Conventional LCA of energy use and emissions can reasonably well represent differences in air-pollutant and (to a lesser extent) GHG emissions between near-term alternatives that are similar to current fuels, but generally needs considerable further development to adequately represent differences between future transport modes or dissimilar fuel production pathways (such as biofuels vs. fossil fuels).
  - Problems are especially pronounced in the case of biofuels, which affect the nitrogen cycle, land use, biogeophysical parameters, a wide range of air-pollutant emissions, the use of agricultural chemicals, and global economies.

Final thought

- To make significant further progress in LCA of air-pollutant and GHG emissions, we need to combine engineering, environmental, and economic models to estimate the costs and benefits of energy and environmental policies, considering all important impact pathways of all pollutants.
  - These might be similar to “Integrated Assessment Models” (IAMs).

Thanks for your attention!

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