Reciprocating Internal Combustion Engines

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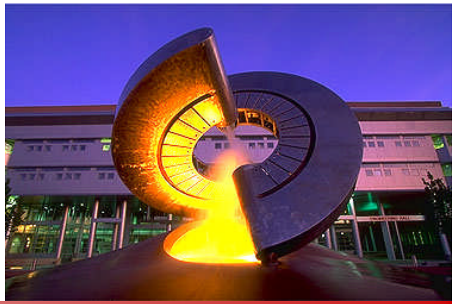
University of Wisconsin-Madison

2012 Princeton-CEFRC
Summer Program on Combustion
Course Length: 9 hrs

(Wed., Thur., Fri., June 27-29)

Hour 9



Short course outine:

Engine fundamentals and performance metrics, computer modeling supported by in-depth understanding of fundamental engine processes and detailed experiments in engine design optimization.

Day 1 (Engine fundamentals)
Hour 1: IC Engine Review, 0, 1 and 3-D modeling
Hour 2: Turbochargers, Engine Performance Metrics
Hour 3: Chemical Kinetics, HCCI & SI Combustion

Day 2 (Spray combustion modeling)
Hour 4: Atomization, Drop Breakup/Coalescence
Hour 5: Drop Drag/Wall Impinge/Vaporization
Hour 6: Heat transfer, NOx and Soot Emissions

Day 3 (Applications)
Hour 7: Diesel combustion and SI knock modeling
Hour 8: Optimization and Low Temperature Combustion
Hour 9: Automotive applications and the Future

Light-duty automotive drive-cycle performance

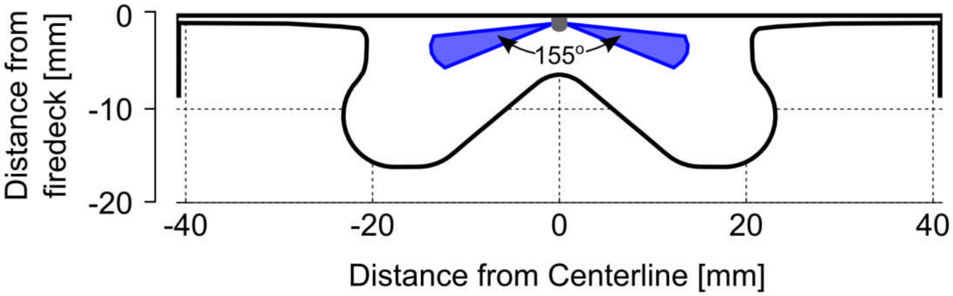
Compare conventional diesel combustion (CDC) and Reactivity Controlled Compression Ignition (RCCI) combustion

Compare at same operating conditions (CR, boost, IMT, swirl..)

ERC KIVA-Chemkin Code

- Reduced primary reference fuel used to model diesel and gasoline kinetics
- Suite of improved ERC spray models

Combustion Chamber Geometry



Engine specifications

Base engine type	GM 1.9 L
Bore (mm)	82
Stroke (mm)	90.4
Connecting rod length (mm)	145.5
Squish height (mm)	0.617
Displacement (L)	0.4774
Compression ratio	16.7:1
Swirl ratio	1.5 to 3.2
IVC (°ATDC)	-132°
EVO (°ATDC)	112°

Diesel fuel injector specifications

Type	Bosch common rail
Actuation type	Solenoid
Included angle	155°
Number of holes	7
Hole size (µm)	141

Kokjohn, PhD thesis 2012

Comparison between RCCI and Conventional Diesel

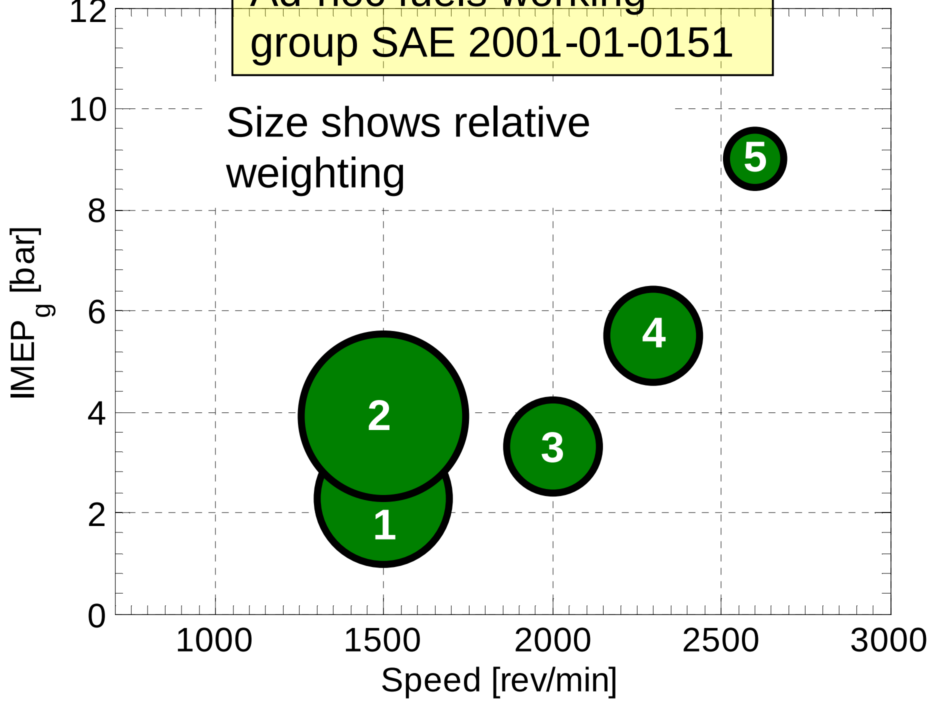
Five operating points of Ad-hoc fuels working group

Tier 2 bin 5 NOx targets from

Cooper, SAE 2006-01-1145

(assumes 3500lb Passenger Car)

Evaluate NOx / fuel efficiency tradeoff using SCR for CDC



Mode	Speed (rpm)	IMEP (bar)	CDC Baseline NOx (g/kgf) *	NOx Target (g/kgf)
1	1500	2	1.3	0.2
2	1500	3.9	0.9	0.4
3	2000	3.3	1.1	0.3
4	2300	5.5	8.4	0.6
5	2600	9	17.2	1.2

Assumptions

Diesel exhaust fluid (DEF) consumption is 1% per g/kW-hr NOx reduction

Johnson, SAE 2011-01-0304

No penalty for DPF regeneration

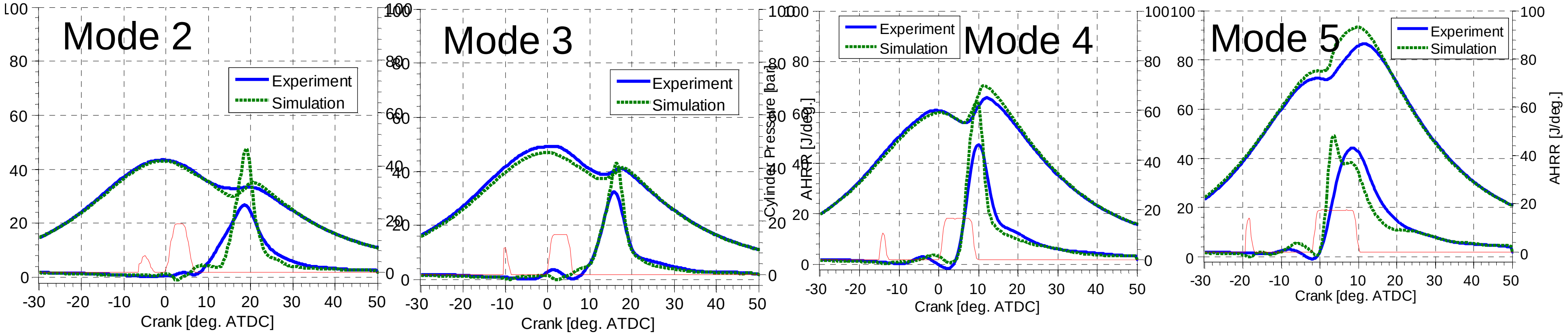
UHC and CO only contribute to reduced work

Kokjohn, PhD thesis 2012

* Baseline CDC Euro 4: Hanson, SAE 2012-01-0380

Euro 4 operating conditions - Conventional Diesel

Model validation	CDC Operating Conditions *				
Mode	1	2	3	4	5
IMEPg (bar)	2.3	3.9	3.3	5.5	9
Speed (rev/min)	1500	1500	2000	2300	2600
Total Fuel (mg/inj.)	5.6	9.5	8	13.3	20.9
Intake Temp. (deg. C)	60	60	70	67	64
Intake Press. (bar abs.)	1	1	1	1.3	1.6
EGR Rate (%)	47	38	42	25	15
CR Inj. Pressure (bar)	330	400	500	780	1100
Pilot SOI advance (°CA)	7	7	11	15	18
Main SOI (° ATDC) (actual)	-0.9	0	0.1	0.5	-1.8
Percent of DI fuel in Pilot (%)	20	15	15	10	10



Kokjohn, PhD thesis 2012

* Baseline CDC Euro 4: Hanson, SAE 2012-01-0380

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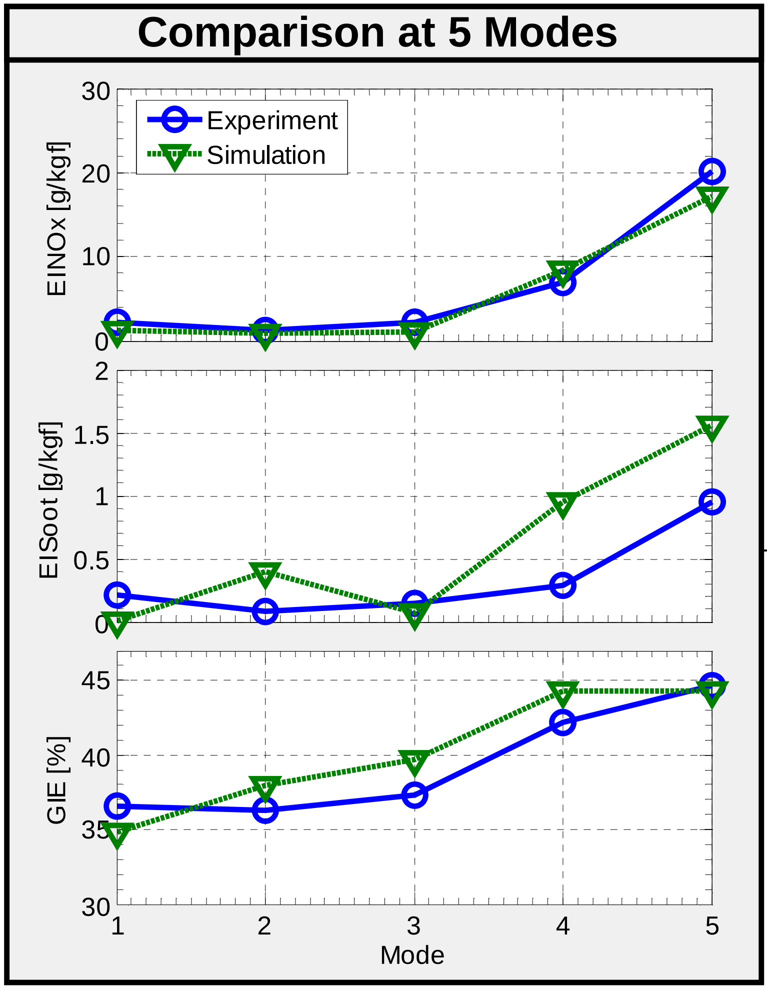
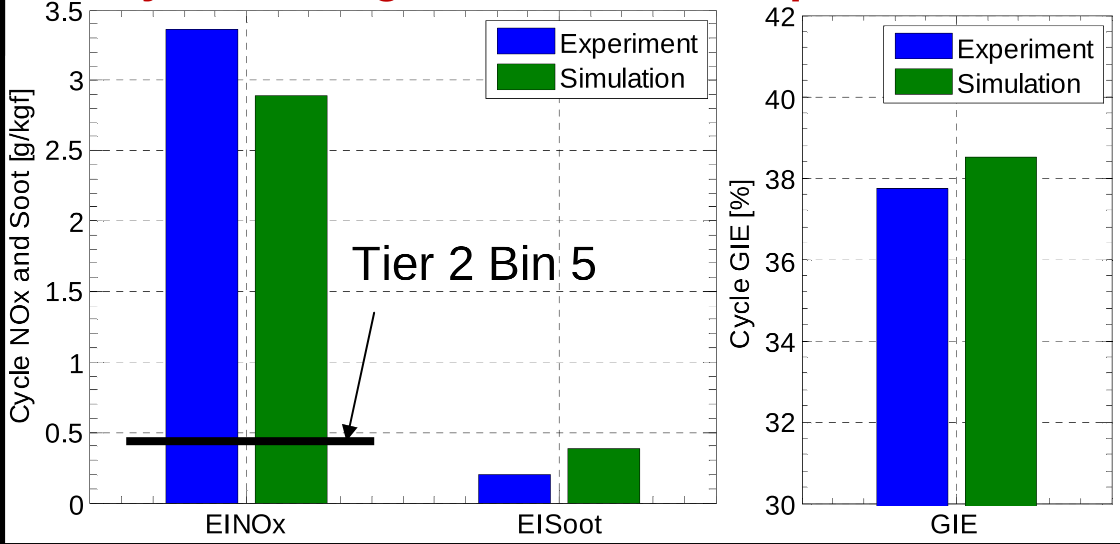
Model validation (Euro 4)


Comparison at 5 Modes

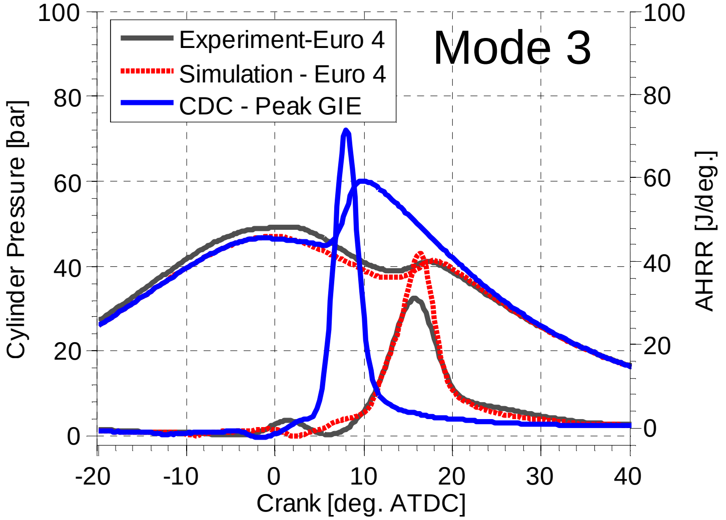
Weighted average:

$$E_{cycle} = \frac{\sum_{imode=1}^{5} E_{imode} Weight_{imode}}{\sum_{imode=1}^{5} Weight_{imode}}$$

Cycle average emissions and performance



Optimized CDC with SCR for Tier 2 Bin 5



CDC optimized GIE has higher allowable PPRR (advanced SOI) than Euro 4 calibration

Comparison between RCCI and Conventional Diesel

"CDC Peak GIE" point shown for reference (does not meet NOx target)

CDC and RCCI efficiency sensitive to selected value of peak PRR

- Maximum allowable PRR of CDC points set at 1.5 times higher than for RCCI

	CDC	RCCI	CDC	RCCI	CDC	RCCI	CDC	RCCI	CDC	RCCI
Mode	1		2		3		4		5	
IMEPg (bar)	2.3		3.9		3.3		5.5		9	
Speed (rev/min)	1500		1500		2000		2300		2600	
Total Fuel (mg/inj.)	5.6		9.5		8		13.3		20.9	
Intake Temp. (deg. C)	60		60		70		67		64	
Intake Press. (bar abs.)	1		1		1		1.3		1.6	
EGR Rate (%)	47	61	38	0	42	0	25	0	15	36
Premixed Gasoline (%)	0	0	0	65	0	48	0	79	0	90
CR Inj. Pressure (bar)	330	500	400	500	500	500	780	500	1100	500
Pilot SOI advance (°CA)	7	16	7	21	11	21	15	N/A	18	21
Main SOI (° ATDC) Baseline	-0.9	-17	0	-37	0.1	-37	0.5	-60	-1.8	-37
Main SOI (° ATDC) Peak GIE	-4.6	N/A	-1.3	N/A	-4.1	N/A	-3.6	N/A	-8	N/A
Main SOI (° ATDC) Bin 5 SCR	-4.6	N/A	-1.3	N/A	-4.1	N/A	**-2**	N/A	**-6.3**	N/A
Percent of DI fuel in Pilot (%)	20	42	15	60	15	60	10	0	10	60
DEF (%)	0.6	0	0.4	0	0.5	0	2.1	0	4.9	0

Comparison between RCCI and CDC plus SCR

CDC (with SCR)

Main injection timing swept

DEF consumption 1% per 1 g/kW-hr reduction in NOx

$$GIE_{Total} = \frac{Work_{-180\text{ to }180}}{\left(m_{DEF} + m_{Fuel}\right) * LHV_{Fuel}} \times 100$$

Peak efficiency at tradeoff between fuel consumption (SOI timing) and DEF consumption (engine-out NOx)

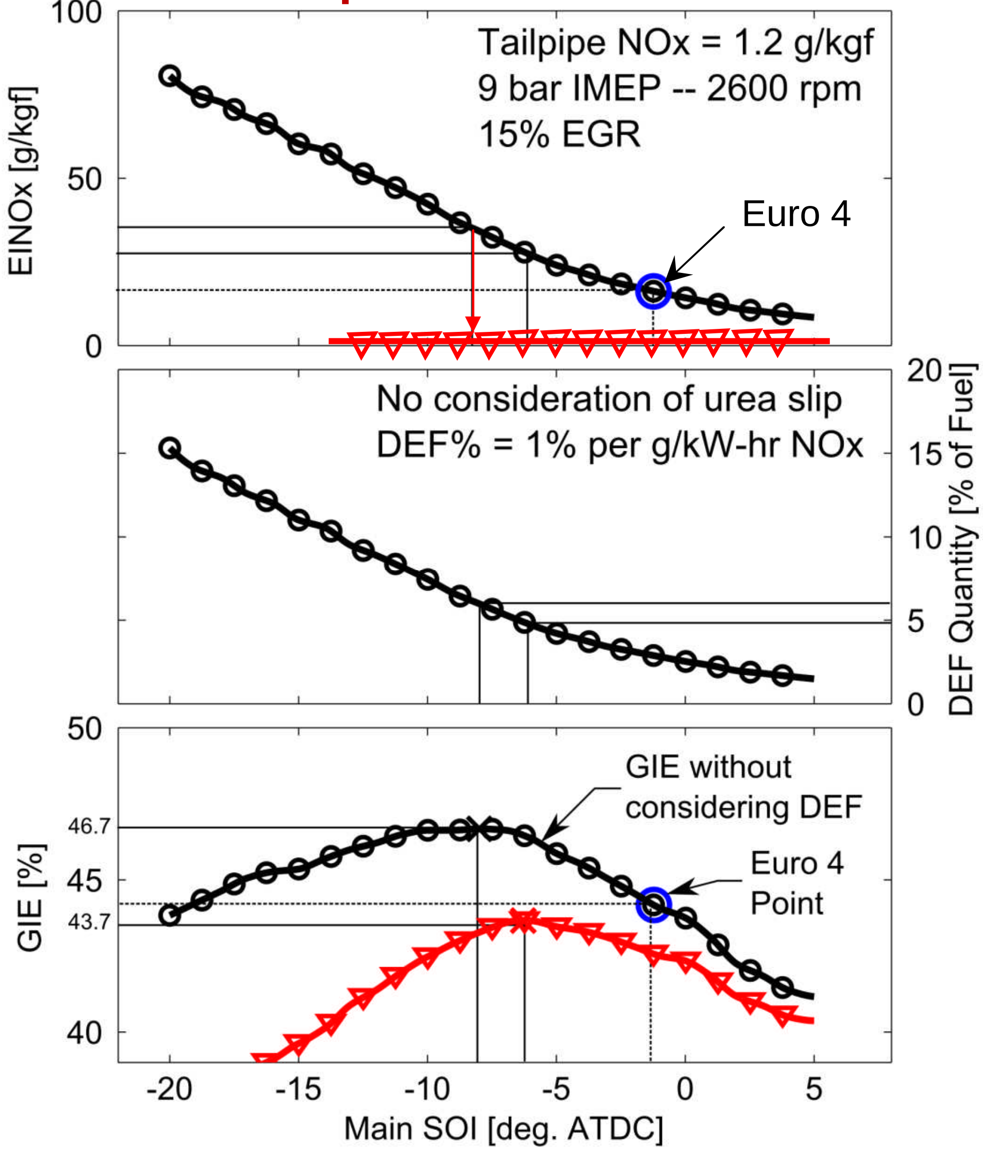
RCCI (No SCR needed)

Gasoline amount controls CA50 to meet NOx/PRR constraints

Mode 1 uses diesel LTC (i.e., no gasoline and EGR is added)

Mode 5 has EGR for phasing control

CDC optimization with SCR



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Comparison of Efficiency, NOx and PRR

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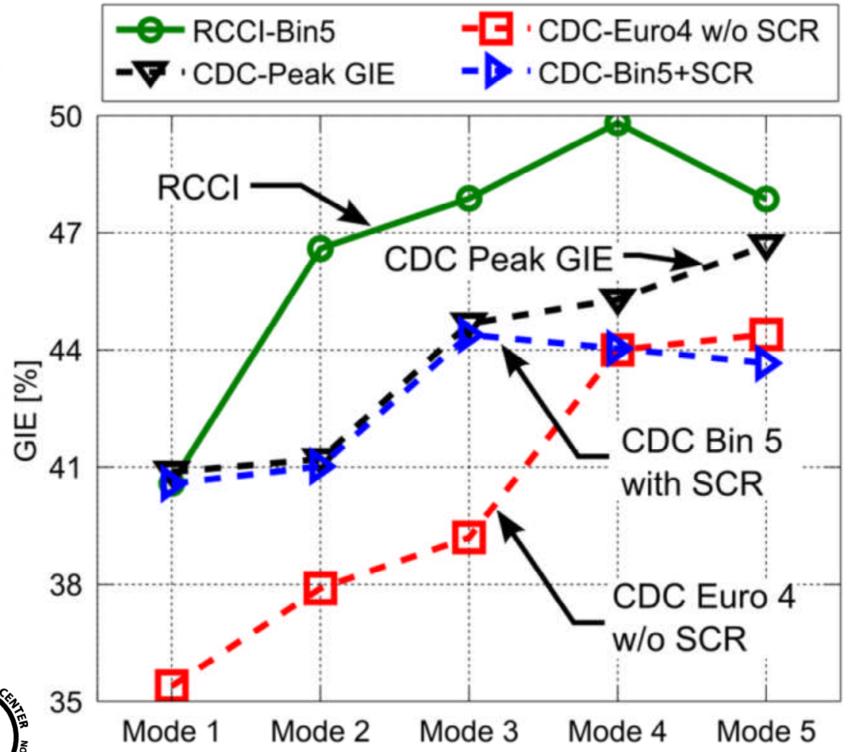
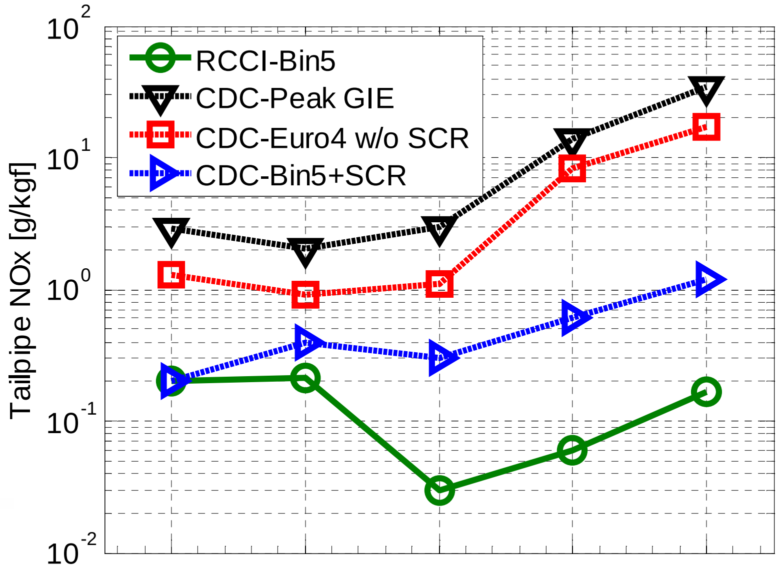
Target NOx at Tier 2 Bin 5

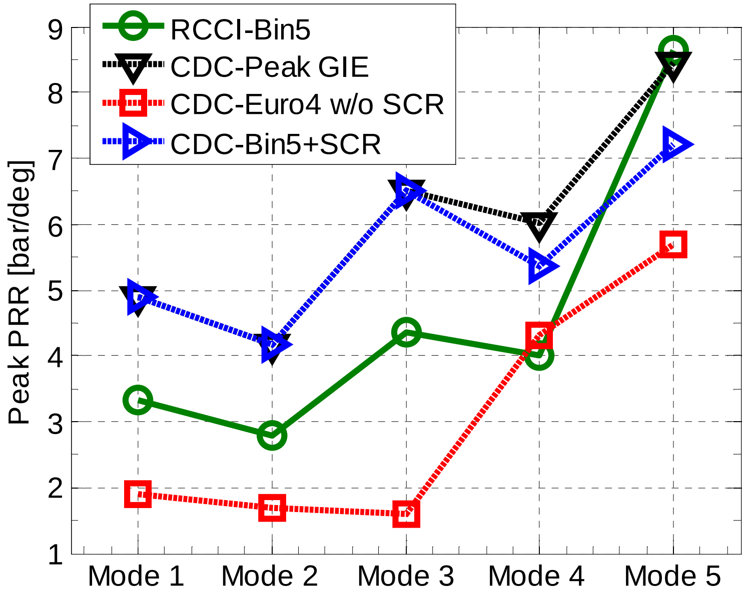
RCCI meets NOx targets without DEF

DEF NOx after-treatment has small efficiency penalty at light-load (2 to 4 bar IMEP) and moderate EGR (~40%)

DEF penalty is larger above 5 bar IMEP where EGR is below 40%







Cycle averaged NOx, Soot and GIE

RCCI and CDC compared at baseline and Tier 2 Bin 5 NOx

- CDC NOx-GIE tradeoff controlled by main injection timing

RCCI meets NOx targets without after-treatment

RCCI gives ~8% improvement in fuel consumption over CDC+SCR

RCCI soot is an order of magnitude lower than CDC+SCR

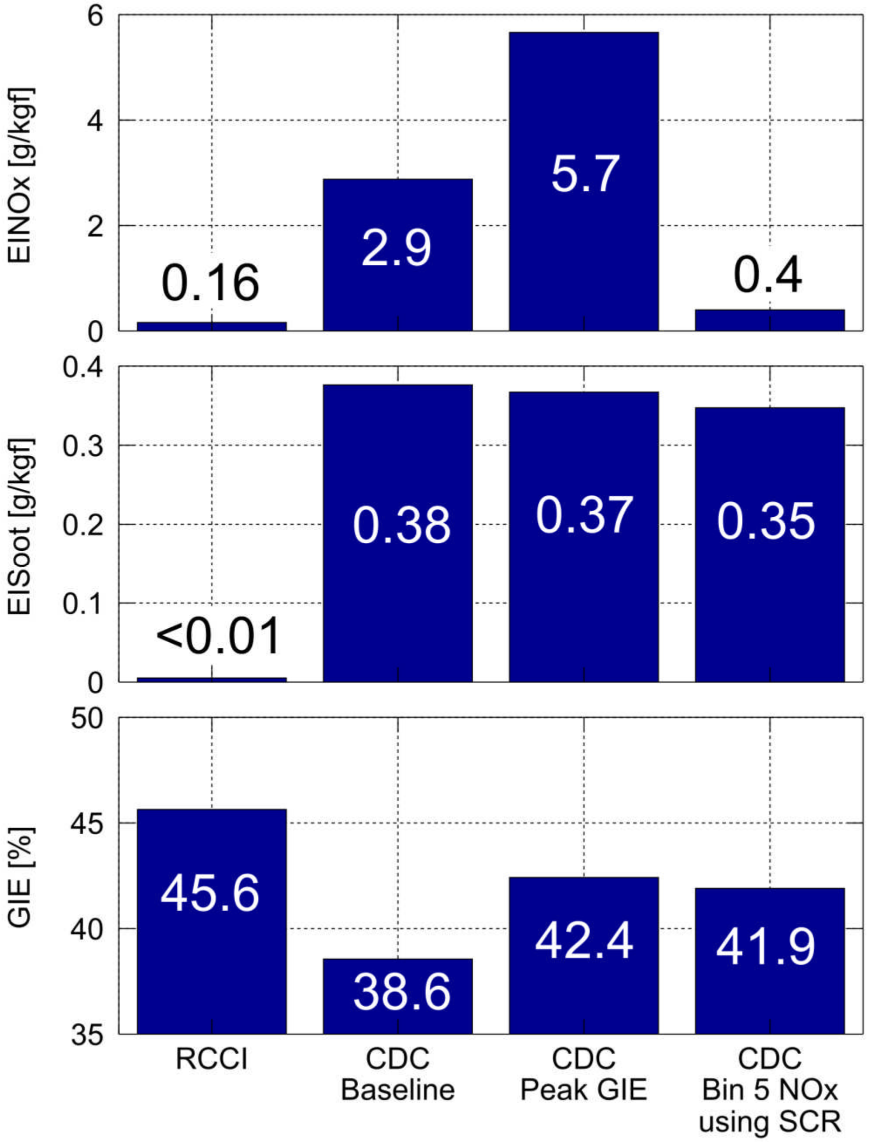
RCCI HC is ~5 times higher than CDC+SCR

- Currently addressing methods to reduce HC emissions
- Crevice-originated HC emissions

Splitter, SAE 2012-01-0383

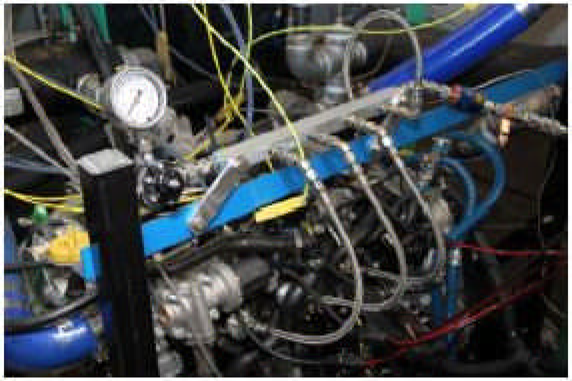
- Thermal barrier coated piston

Kokjohn, PhD thesis 2012



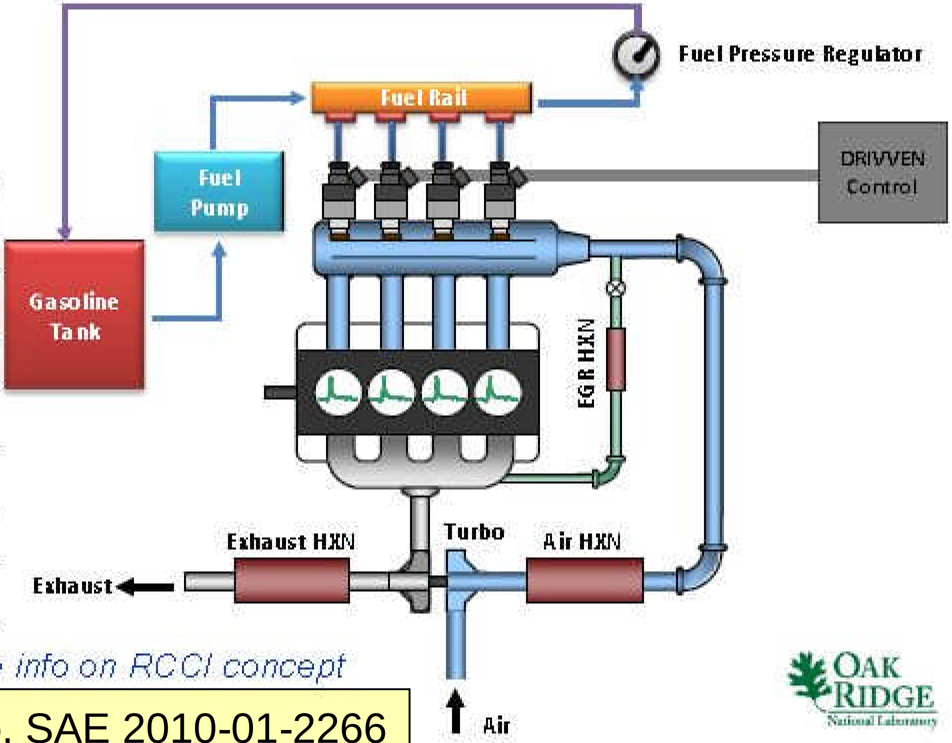
Collaboration with Oak Ridge – GM 1.9L Multi-cylinder engine

- **SAE 2010 RCCI ("dual-fuel") approach from Univ. of Wisconsin (UW) demonstrated on ORNL multi-cylinder engine**
  - +1.5% efficiency (η_T) and low NOx demonstrated
- **ORNL collaborating with UW to compare UW model to ORNL multi-cylinder experimental results**



2300 rpm, 4.2 bar BMEP condition (no EGR)

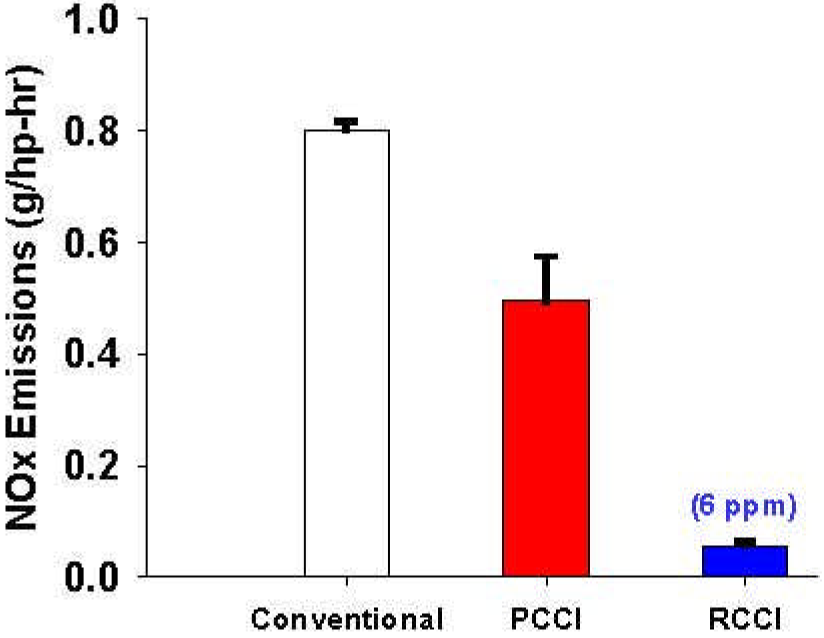
	Conventional Diesel	RCCI (77% Gasoline)
BTE (%)	32.1	33.6
NOx (ppm)	94	7.5
FSN	1.78	0.02
CO (ppm)	423	1512
HC (ppm)	296	2581
Exhaust T (C)	412	260

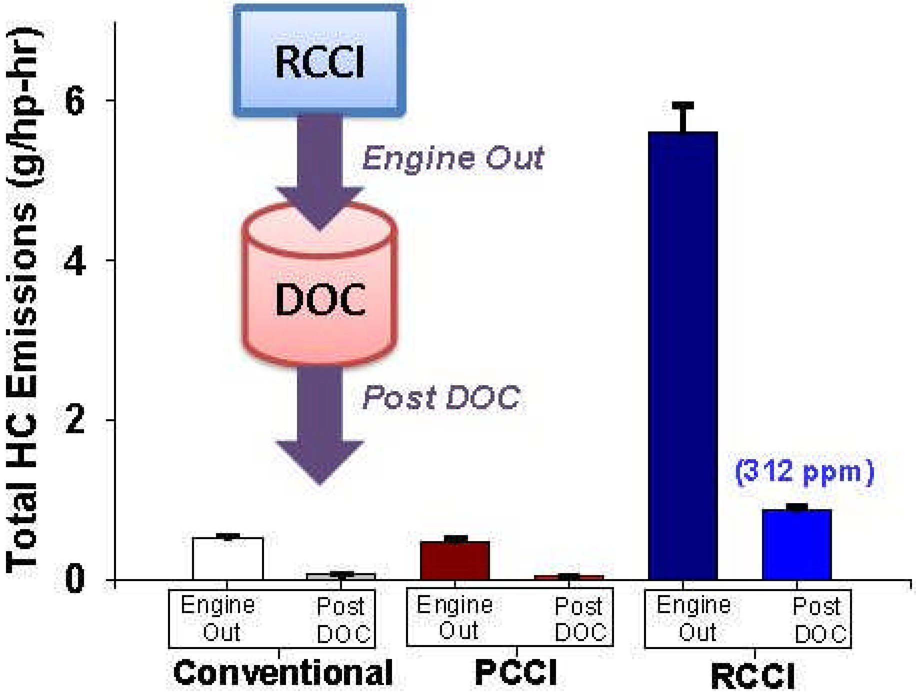


See Kokjohn et al. SAE 2009-01-2647 for more info on RCCI concept

Prikhodko, SAE 2010-01-2266

Collaboration with Oak Ridge – GM 1.9L Multi-cylinder engine





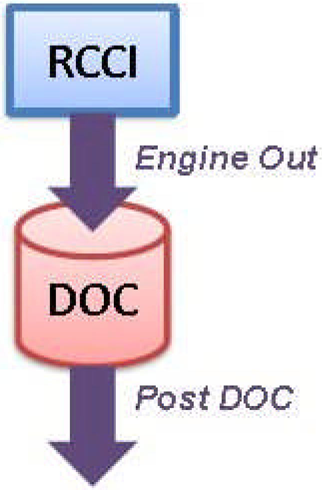
- **RCCI PM has high organic content and small size indicative of hydrocarbon-heavy aerosols**
- **DOC found to be effective in reducing PM emissions and hydrocarbon emissions from RCCI**
- **Resulting RCCI tailpipe emissions are very low for NOx without NOx catalyst**

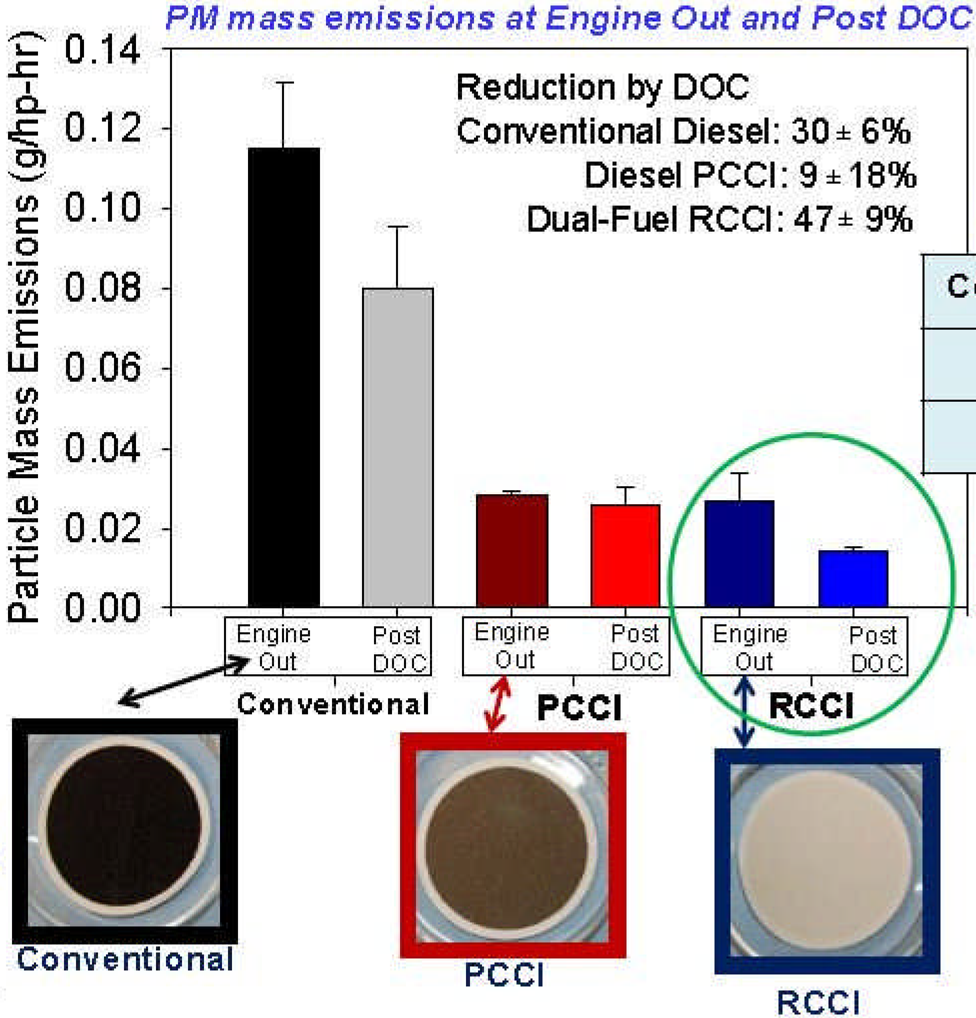
RCCI is fuel-efficient with emissions that can largely be controlled with DOC alone thus reducing the fuel penalty and cost of the aftertreatment system

Prikhodko, SAE 2010-01-2266

RCCI Emissions

- **RCCI particulate matter (PM) found to be very different from conventional and PCCI PM**
- **PM filter images and size distribution data suggested high organic content in PM from RCCI**
- **DOC reduces RCCI PM mass significantly**





Reduction by DOC
Conventional Diesel: 30 ± 6%
Diesel PCCI: 9 ± 18%
Dual-Fuel RCCI: 47 ± 9%

PM filter samples at Engine Out

Exhaust Temperature

Conventional	415°C
PCCI	420°C
RCCI	250°C

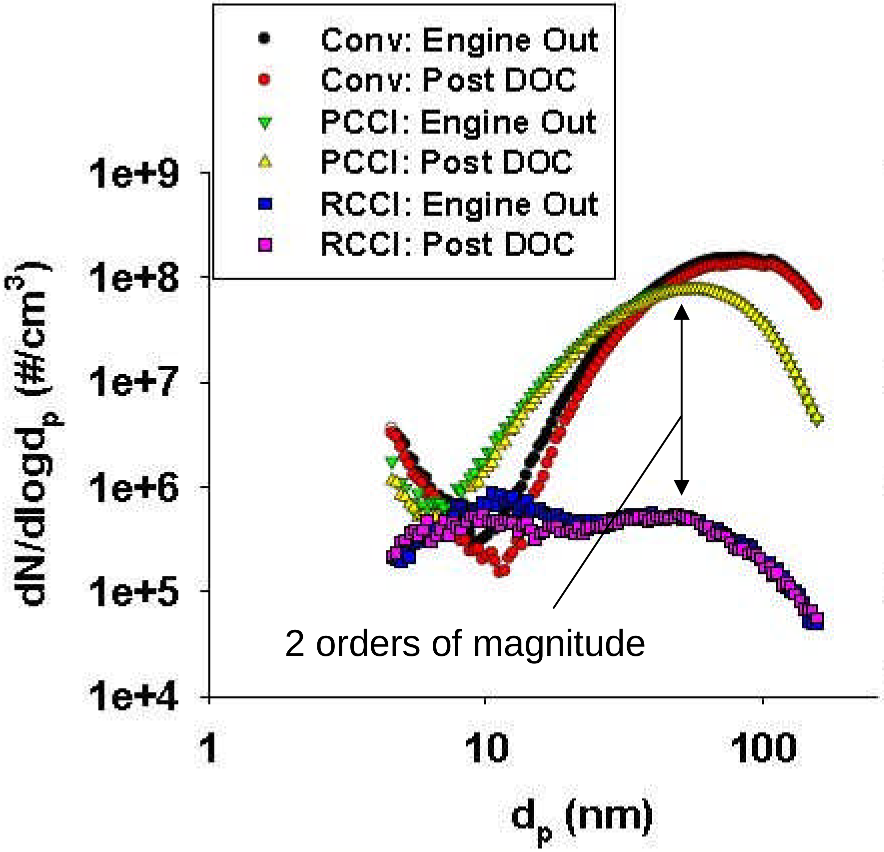
DOC effective for RCCI PM even though exhaust temperature lower

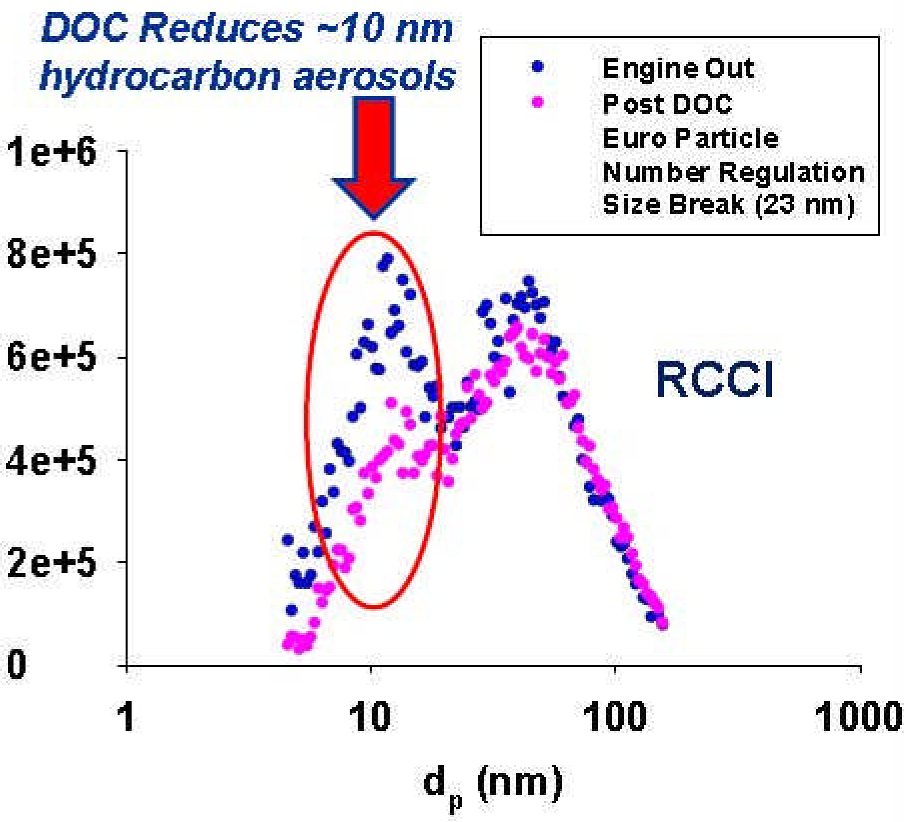
Prikhodko, SAE 2010-01-2266

RCCI - low particle number

Prikhodko, SAE 2010-01-2266

- **Scanning Mobility Particle Sizer (SMPS) shows PM size distribution differs for conventional, PCCI, and RCCI particulate**
- **RCCI PM has bimodal distribution**
- **DOC effective at reducing RCCI PM in ~10 nm range but not ~60 nm range**





Note: log y-axis for plot on left __but__ linear y-axis for plot on right

Light- and heavy-duty engine RCCI

HD and LD engines compared over gasoline/diesel fuel ratio sweep at 9 bar IMEP

LD engine intake temperature and pressure adjusted in to match HD compression stroke

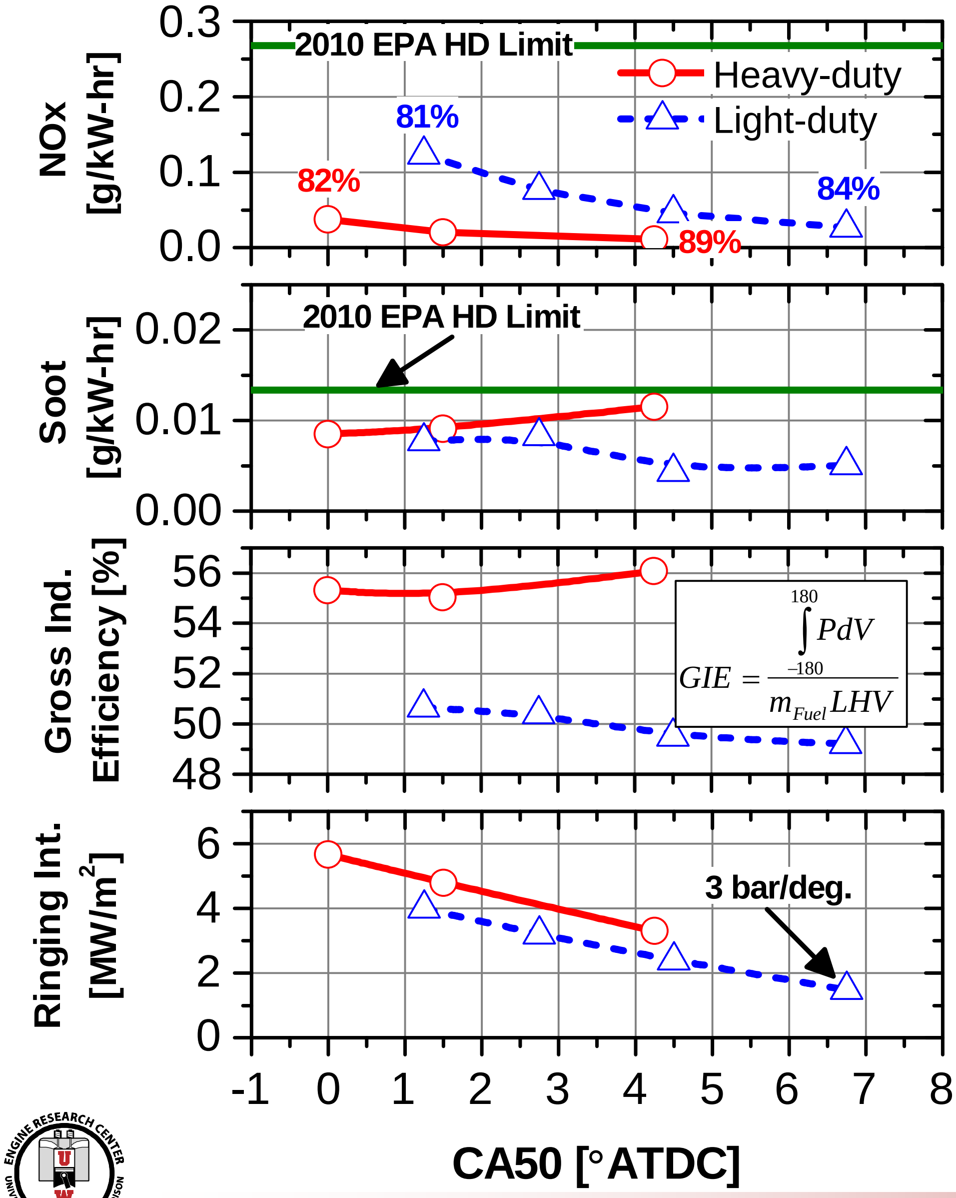
Engine size scaling laws do not provide a scaling parameter for engine speed

- Kinetics implies speeds should be equal (equal ignition delay)
- To scale convective heat transfer, LD engine should be operated at ~3800 rev/min
- Intermediate speed of 1900 rev/min selected

	Heavy Duty	**Light Duty**
Engine	CAT	GM 1.9 L
IMEP (bar)	9	
Engine speed (rev/min)	1300	1900
Mean piston speed (m/s)	7.2	5.7
Total fuel mass (mg)	94	20.2
EGR (%)	41	
Premixed gasoline (%)	82 to 89	81 to 84
Diesel SOI 1 (° ATDC)	-58	-56
Diesel SOI 2 (° ATDC)	-37	-35
Diesel inj. pressure (bar)	800	500
Intake pressure (bar)	1.74	1.86
Intake runner temp. (° C)	32	39
Air flow rate (kg/min)	1.75	0.46
Abs. exhaust back pressure (bar)	1.84	1.98
Ave. exhaust temperature (° C)	271	319
Equivalence ratio (-)	0.52	0.62
Port-injected fuel	Gasoline	
Direct-injected fuel	Diesel Fuel	

Kokjohn, IJER 2011
Kokjohn, SAE 2011-01-0357

Light- and heavy-duty engine RCCI

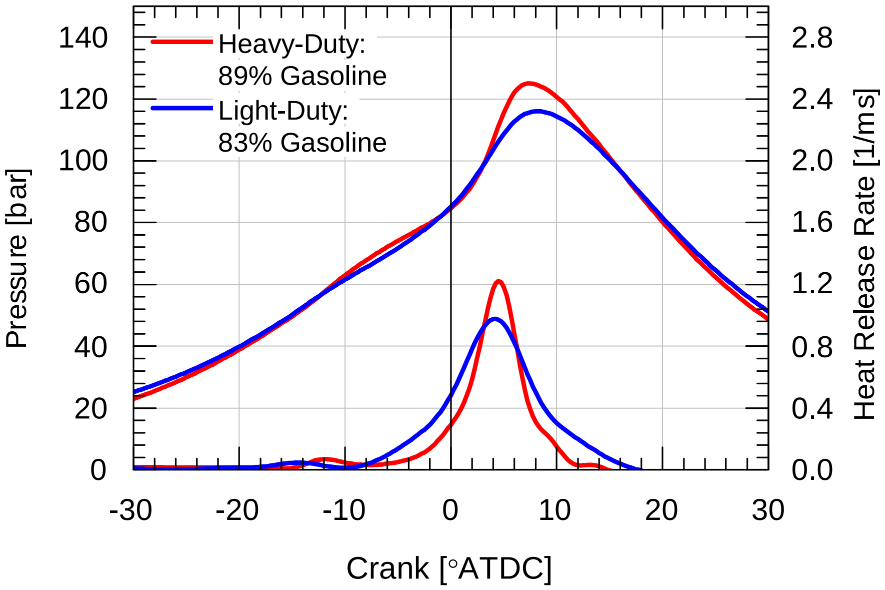


$$GIE = \frac{\int_{-180}^{180} PdV}{m_{Fuel} LHV}$$

Low NOx and soot emissions achieved for both HD and LD engines

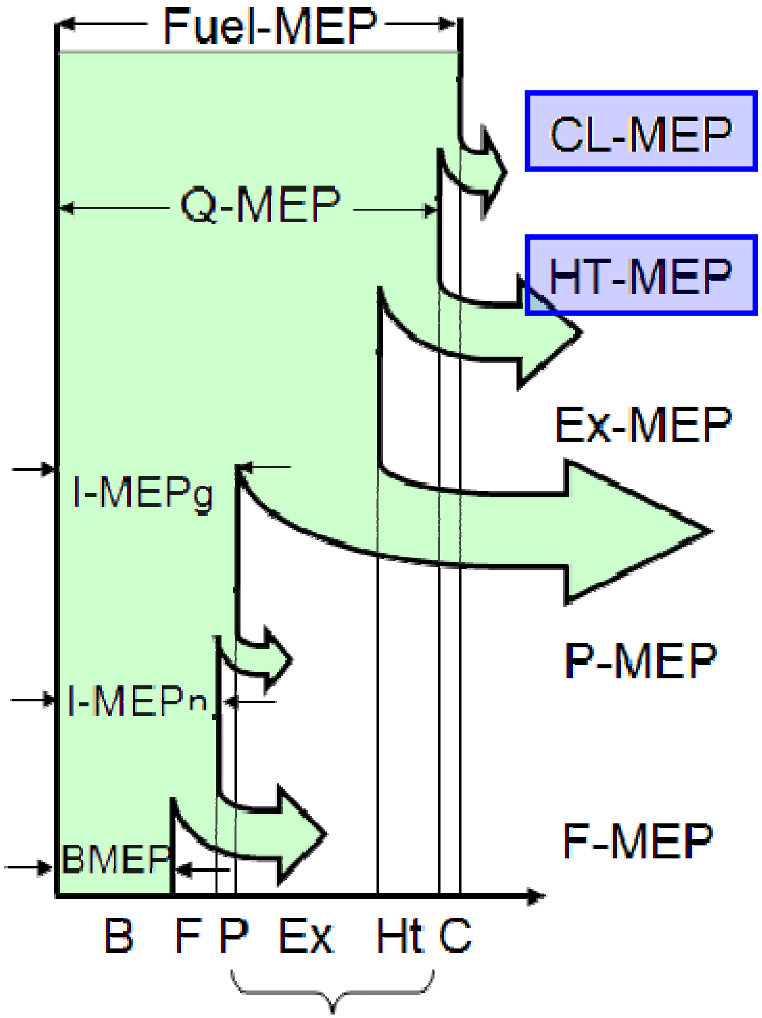
Ringing intensity (noise) easily controlled by combustion phasing (via gasoline-diesel ratio) with only minimal effect on efficiency

Both engines achieve high efficiency; however, **HD engine shows 5 to 7% higher gross indicated efficiency**

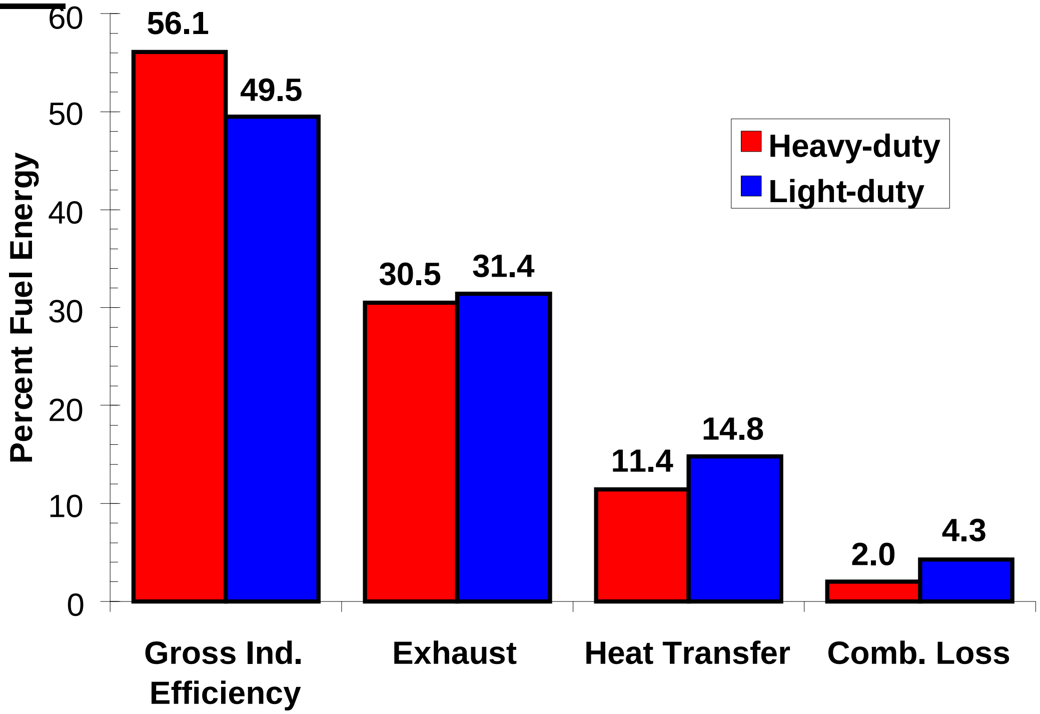


HD Conv. Diesel Efficiency = 48%
LD Conv. Diesel Efficiency = 45%

Light- and heavy-duty engine RCCI



Kokjohn, IJER 2011
Kokjohn, SAE 2011-01-0357



Gross indicated efficiency is lower in LD engine due to lower combustion efficiency and higher heat transfer losses

Combustion efficiency is ~2% lower in LD engine

3.4% more of the fuel energy is lost to heat transfer in LD engine.

CFD modeling used to explain losses

Combustion Losses

CFD modeling predicts that the highest levels of late cycle CO and UHC are located in the ring-pack crevice and near liner region

- Reducing ring-pack crevice volume improves combustion efficiency

  (SAE 2012-01-0383)

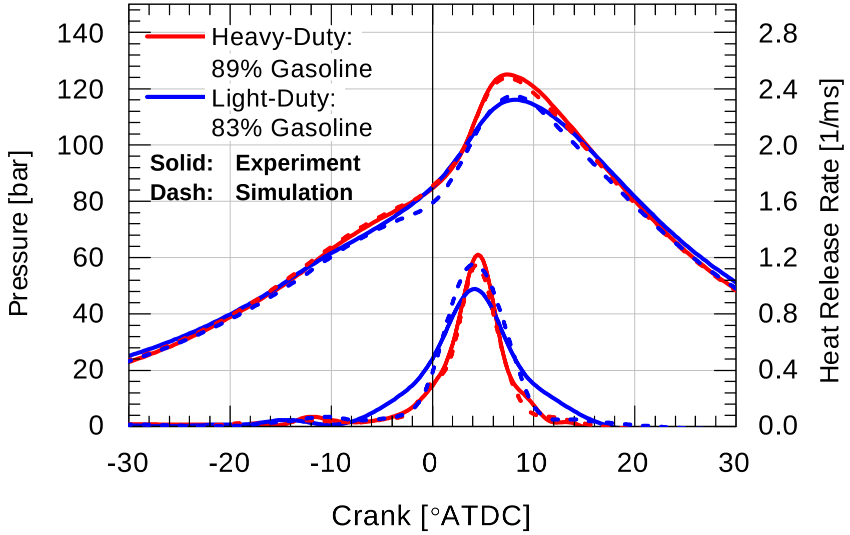
Heat Transfer Losses

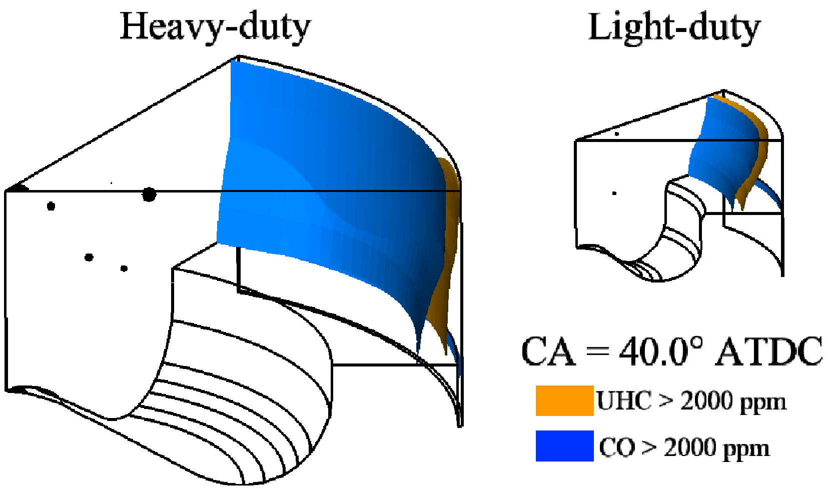
LD engine heat transfer is higher due to

- Higher swirl (**LD: 2.2** **HD: 0.7**)
- Increased surface area-to-volume ratio (**LD: 5.6** **HD: 2.7**)
- Lower mean piston speed (**LD: 5.7 m/s** **HD: 7.2 m/s**)

Kokjohn, IJER 2011
Kokjohn, SAE 2011-01-0357

CFD simulations with KIVA-Chemkin code and reduced PRF mechanism





Future research directions

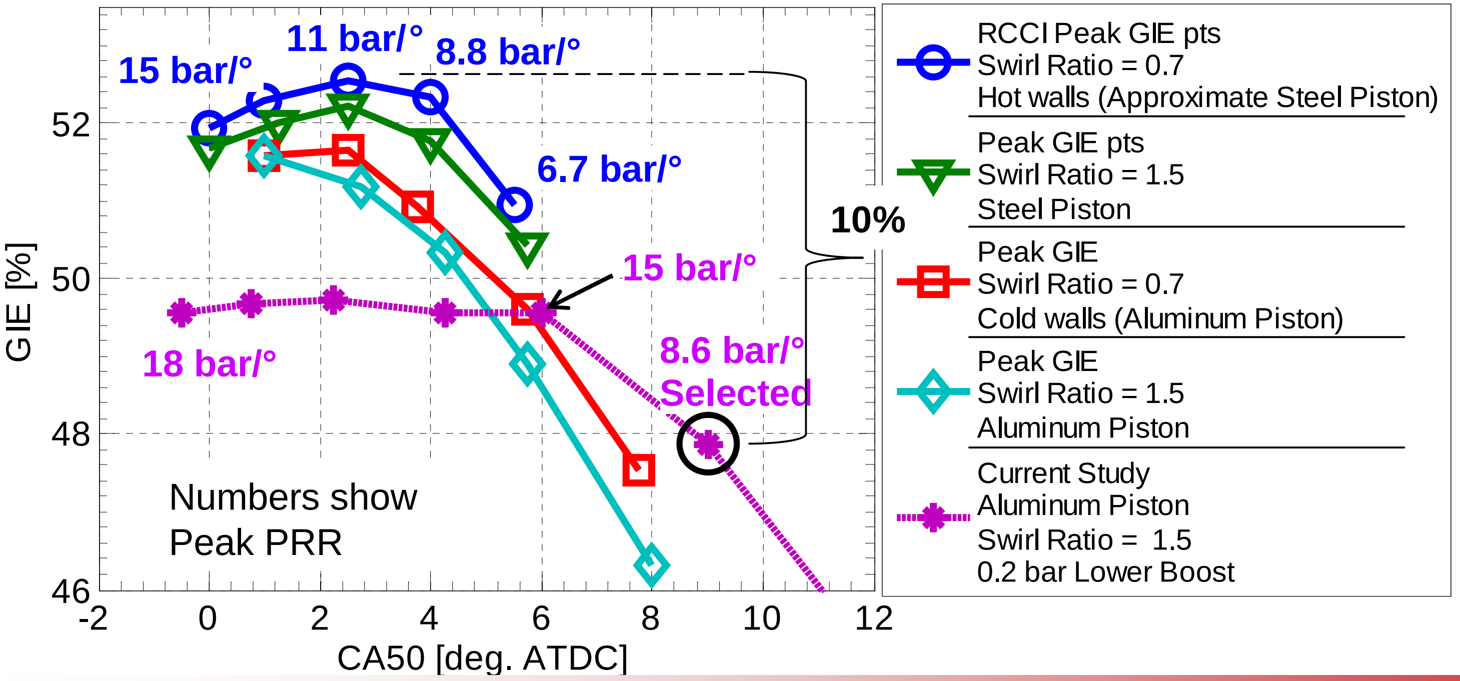
Kokjohn, PhD thesis 2012

LD RCCI further improved by relaxing constraints (Euro 4 boost, IMT, swirl..)

Peak efficiency at Mode 5 is 47.9% → CFD says can be increased to ~53%

Improve heat transfer losses and combustion phasing

- Higher boost (1.86 bar vs. 1.6 bar) allows CA50 advance with same PRR and lowers heat transfer losses due to lower Φ (lower temps)
- Lower swirl reduces convective heat transfer losses
- Higher wall temps improve combustion efficiency (steel piston)
- 8% + 10% ~ consistent with DOE goals of 20-40% improvement



Numbers show Peak PRR

Summary and Conclusions

RCCI shown to yield clean, quiet, and efficient combustion over wide load/speed range (HD: 4 to 23 bar IMEP, 800 to 1800 rev/min).

HD: EPA 2010 NOx/PM emissions met in-cylinder with peak GIE >55%

LD: Low NOx and PM emissions with less EGR needed over FTP cycle

Suggested RCCI strategy uses optimized high EGR diesel combustion at low load (idle) and then no EGR up to Mode 5 (~9 bar IMEP)

RCCI LD modeling indicates ~8% improvement in fuel consumption over CDC+SCR over FTP cycle using same engine and conditions.

RCCI meets Tier 2 bin 5 without need for NOx after-treatment or DPF, but DOC will likely be needed for UHC reduction

Modeling indicates that further RCCI optimization requires:

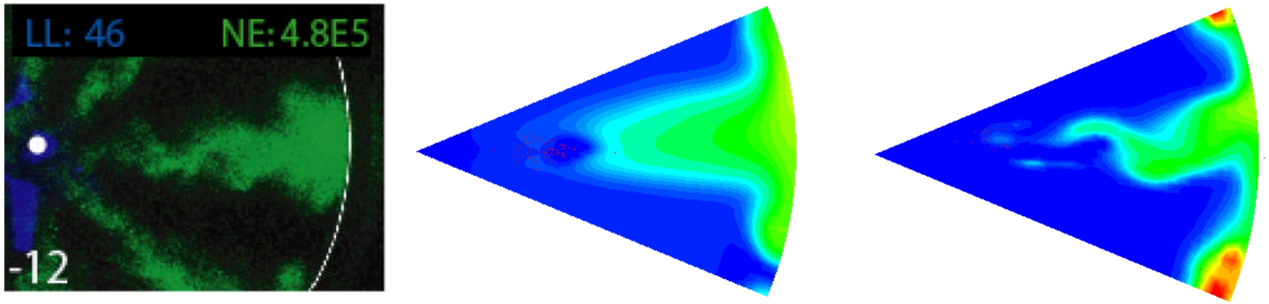
higher boost pressure, higher piston temps,
reduced swirl, reduced surface area
steel piston, optimized crevice design

Future experiments/modeling in HD and LD engines will continue to explore RCCI with optimized pistons and alternative fuels.

And vehicle tests are in progress! →

Future of engine CFD modeling

Incrementally improved models, used for engine design with less engine testing.


Experiment RANS CHEMKIN LES CHEMKIN

Hu, SAE
2007-01-0163

Models are a storehouse of current knowledge

Engine CFD Timeline

(1960’s) - no local resolution

(1970-80’s) - 1&2-D
physics sub-grid scale

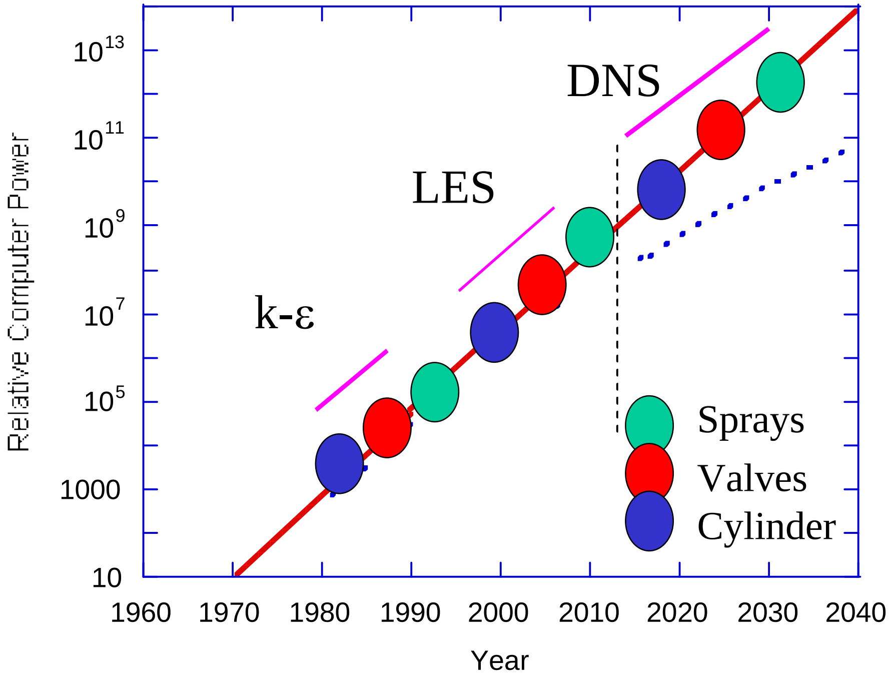
(1990’s) - 3D 1-mm grids
subgrid scale models

(2000’s) - all relevant gas-phase
scales resolved

(2020’s) - all liquid and gas
scales resolved

+ Detailed kinetics + nozzle processes

Computer Speed and CFD (C. Rutland)



The long term future:

How Do We Supply the World's Energy Needs?

Derek Abbott, University of Adelaide, Australia

"ABSTRACT

We take a fresh look at the major nonrenewable and renewable energy sources and examine their long-term viability, scalability, and the sustainability of the resources that they use.

We achieve this by asking what would happen if each energy source was a single supply of power for the world, as a gedanken experiment.

From this perspective, a solar hydrogen economy emerges as a dominant solution to the world's energy needs."

Abbott, 2010

How much energy do we use? - 15 TeraWatts

We use the equivalent energy of every person on earth (6 billion) running 25, 100 W light bulbs.

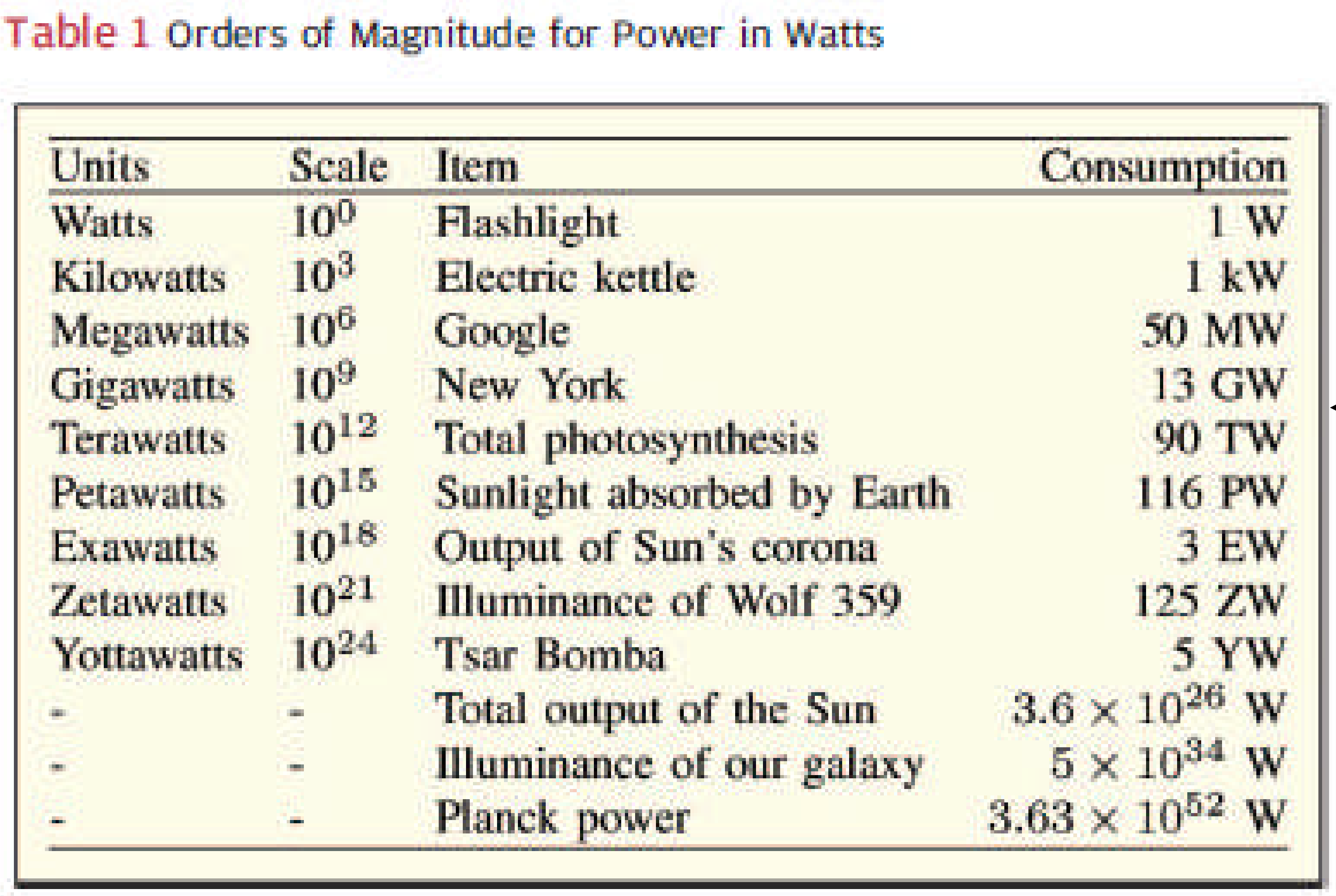


Table 1 Orders of Magnitude for Power in Watts

Units	Scale	Item	Consumption
Watts	10^{0}	Flashlight	1 W
Kilowatts	10^{3}	Electric kettle	1 kW
Megawatts	10^{6}	Google	50 MW
Gigawatts	10^{9}	New York	13 GW
Terawatts	10^{12}	Total photosynthesis	90 TW
Petawatts	10^{15}	Sunlight absorbed by Earth	116 PW
Exawatts	10^{18}	Output of Sun's corona	3 EW
Zetawatts	10^{21}	Illuminance of Wolf 359	125 ZW
Yottawatts	10^{24}	Tsar Bomba	5 YW
-	-	Total output of the Sun	3.6×10^{26} W
-	-	Illuminance of our galaxy	5×10^{34} W
-	-	Planck power	3.63×10^{52} W

Abbott, 2010

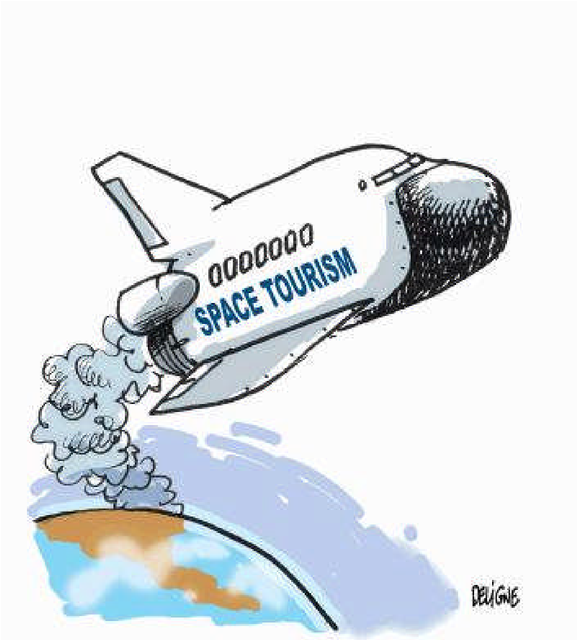
“How to supply World’s 15 TeraWatt energy needs?”

At current rates, to supply the world’s energy use, we have enough:

uranium for nuclear for 5 years,
fossil oil for 42 years,
natural gas 60 years,
and coal for 130 years.

But, centuries from now we will still need fuels to make fertilizers, plastics and to lubricate machinery,

And a billion years from now when sun turns into a red giant, we will probably need nuclear so some of us can escape to a new solar system.



Abbott, 2010

Non-sustainability

Assume 5 billion people drive a car with a 50 kW engine for 1 hour per day
→ 10 TJ consumed in world each second
i.e., 10 TW: 2/3 current world energy consumption.

Abbott's point is that we cannot afford to recklessly deplete precious non-renewable sources of energy for man's continued survival on earth.

Abbott considers fossil, nuclear, wind, hydroelectric, wave, geothermal energy sources and concludes that the only sustainable long term energy scenario is a Solar Hydrogen Economy.

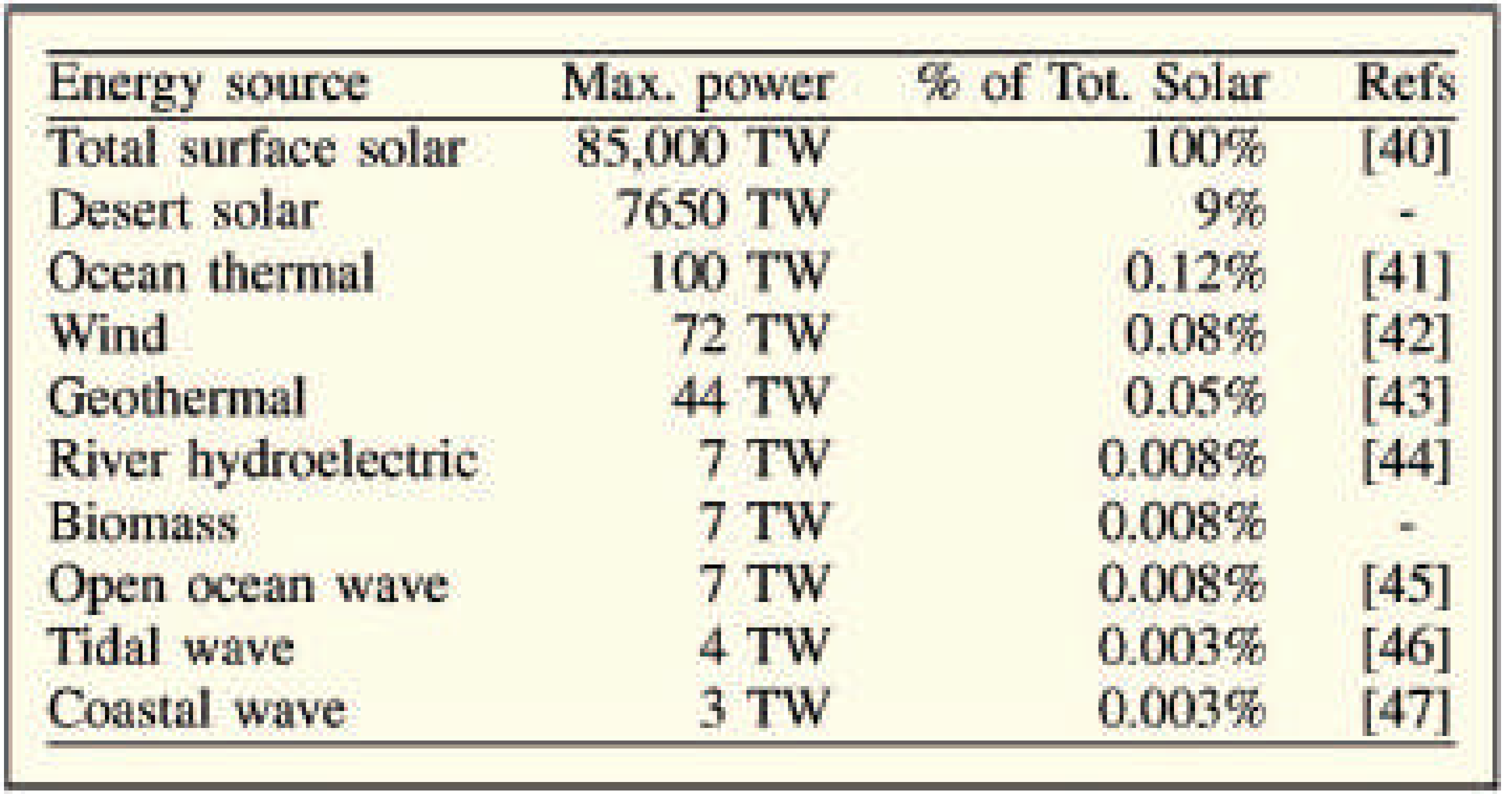
(wind, hydroelectric, wave come from the sun anyway, and the sun is a fusion reactor!)

Abbott, 2010

Hour 9: Automotive applications and the Future

Solar energy incident on the earth in one month is more than all the energy in the world's fuel resources combined.

Table 2 Power Available From Renewable Sources



Energy source	Max. power	% of Tot. Solar	Refs
Total surface solar	85,000 TW	100%	[40]
Desert solar	7650 TW	9%	-
Ocean thermal	100 TW	0.12%	[41]
Wind	72 TW	0.08%	[42]
Geothermal	44 TW	0.05%	[43]
River hydroelectric	7 TW	0.008%	[44]
Biomass	7 TW	0.008%	-
Open ocean wave	7 TW	0.008%	[45]
Tidal wave	4 TW	0.003%	[46]
Coastal wave	3 TW	0.003%	[47]

Abbott, 2010

Large amount of energy from the sun!

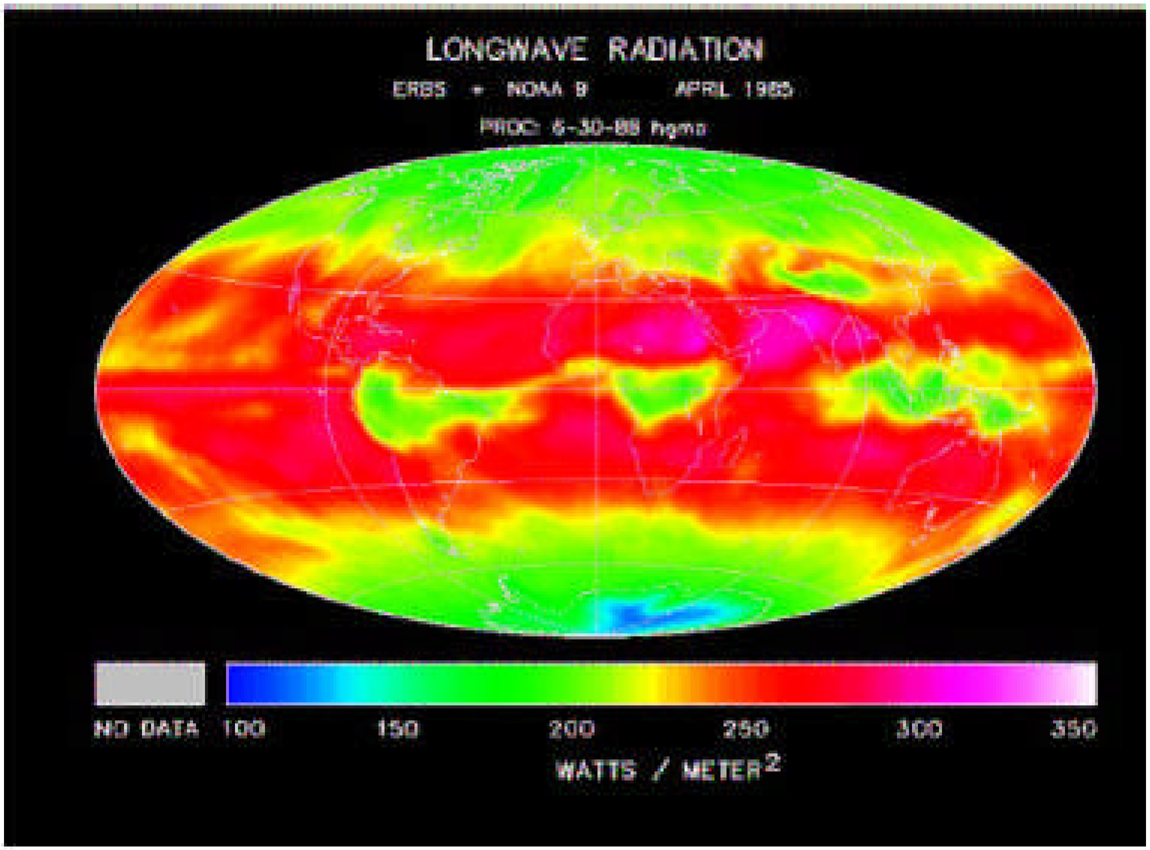


Fig. 2. *This Erbe satellite image clearly identifies the strategic regions for solar collector farms. Actual insolation (solar power per unit area) levels are not obtained from this image, but it can be used to estimate which regions are relatively hotter. Note that in the hottest regions insolation levels can exceed 1 kW/m^2.*

Usable Solar Power incident on earth is 5,000 times our global energy consumption.

Deserts are 9% of world's surface area

If we tap sunlight on 1% of earth's surface at conversion efficiency of 1%, we can meet current world energy demand.

Abbott, 2010

Abbott, 2010

Solar collection – proven technology!

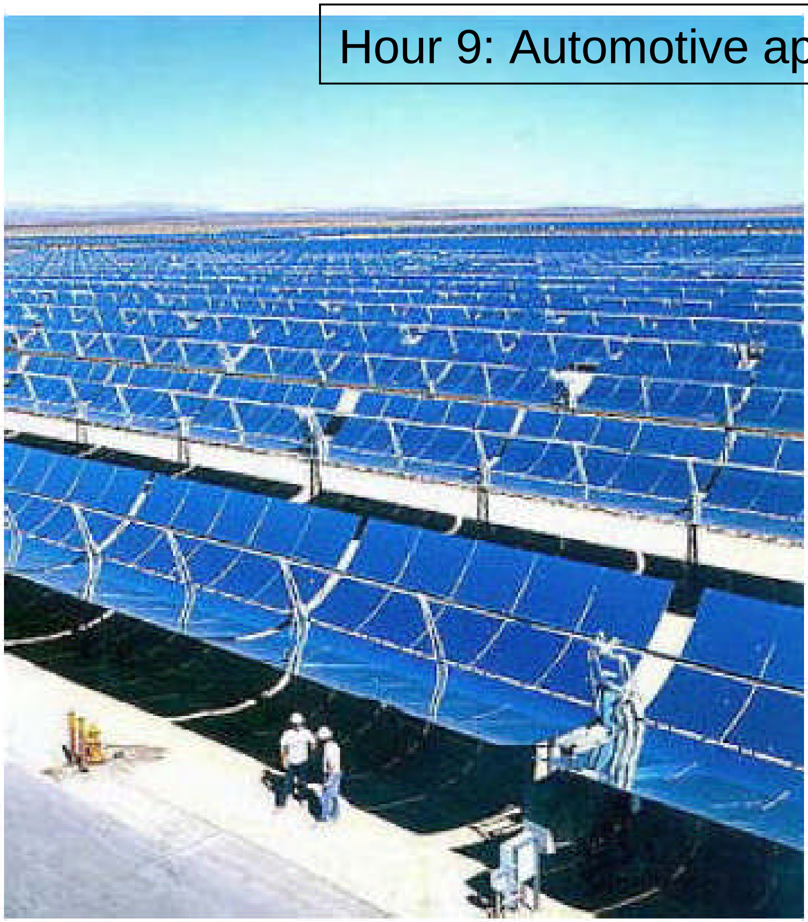
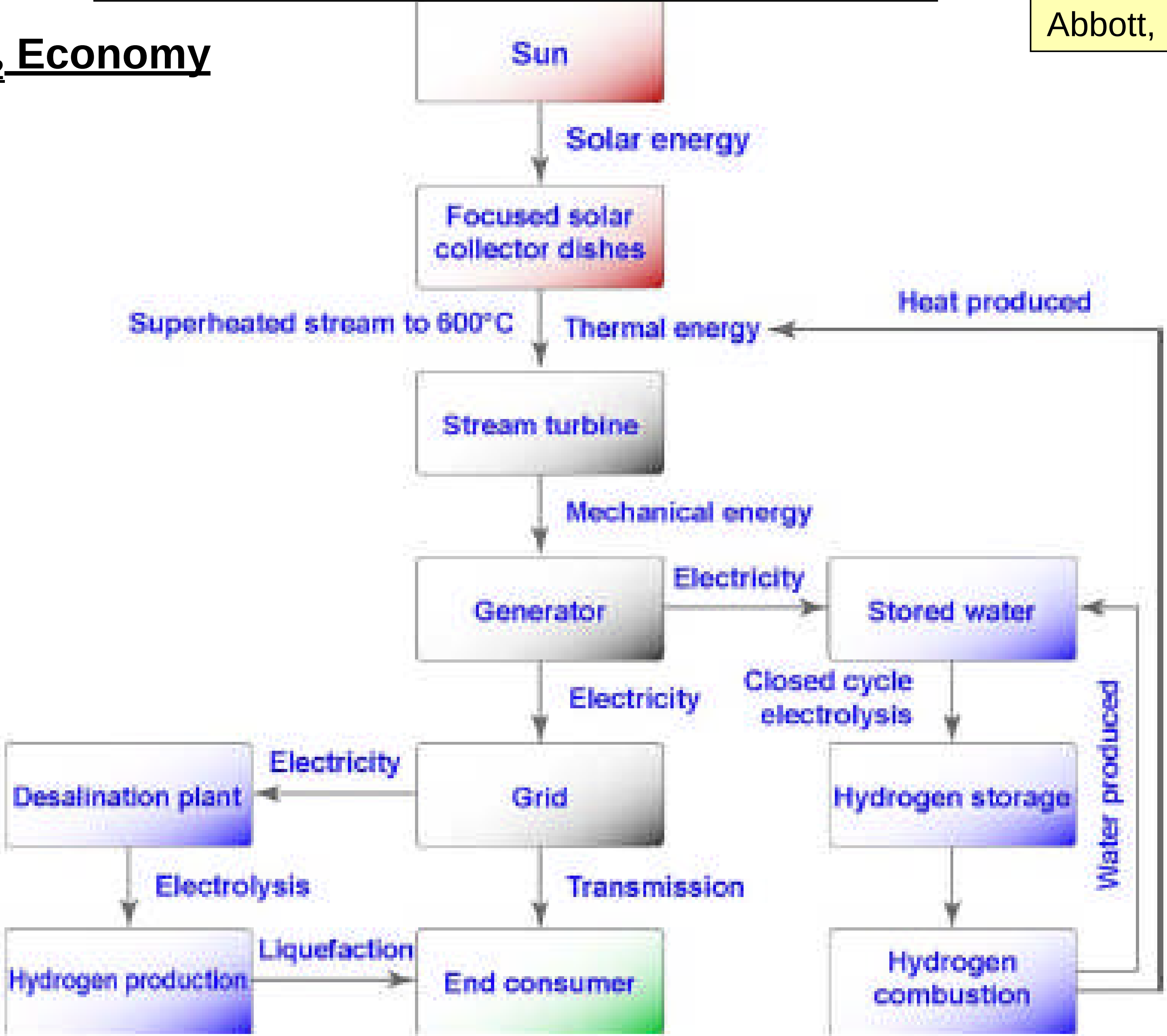


Fig. 3. *The Solar Energy Generating Systems (SEGS) solar trough farm at Kramer Junction, California. The concept is that the reflective troughs focus sunlight on a pipe containing oil in a closed-cycle, which heats water to create steam to turbines. In total there are nine SEGS farms, with two at Dagett, five at Kramer Junction, and two at Harper Lake; all in California's Mojave Desert. The total area occupied is 2.4 sq km, generating 354 MW of power. These figures scale up to a footprint of 320 km by 320 km, if we were to supply 15 TW with this method. The nine plants have gradually been installed from 1984 to 1990, demonstrating over 20 years of performance without malfunction. Source: Power Corp.*

Fig. 4. *The Stirling Energy Systems (SES) SunCatcher solar dish farm being developed in California. Each 11.6 m (38 ft) diameter dish automatically tracks the sun and powers a 25 kW Stirling cycle generator. Source: Stirling Energy Systems.*

Solar H_2 Economy

Abbott, 2010



Abbott, 2010

H_2 for transportation – infrastructure?

Fig. 7. *Henry Ford with his Model T, circa 1908. When the gasoline car was first introduced there was no infrastructure, were no sealed roads, and were no refueling stations. Typically a vehicle owner would purchase a can of gasoline at the local pharmacy. This is a salient reminder that the growth of infrastructure can coevolve with demand.*

60 million vehicles/year:

For battery electric we have enough lithium on earth for only 23 years

Fuel cells require exotic rare Materials

IC engine is sustainable
(available materials)

Liquid hydrogen engines & Hydrogen gas engines

BMW Hydrogen 7 (2006)
260 HP twelve-cylinder engine

17.6 lb of liquid H_2 storage tank,
cruising range 125 miles, 0-62.1 mph in 9.5s

Ford E-450 (2008)

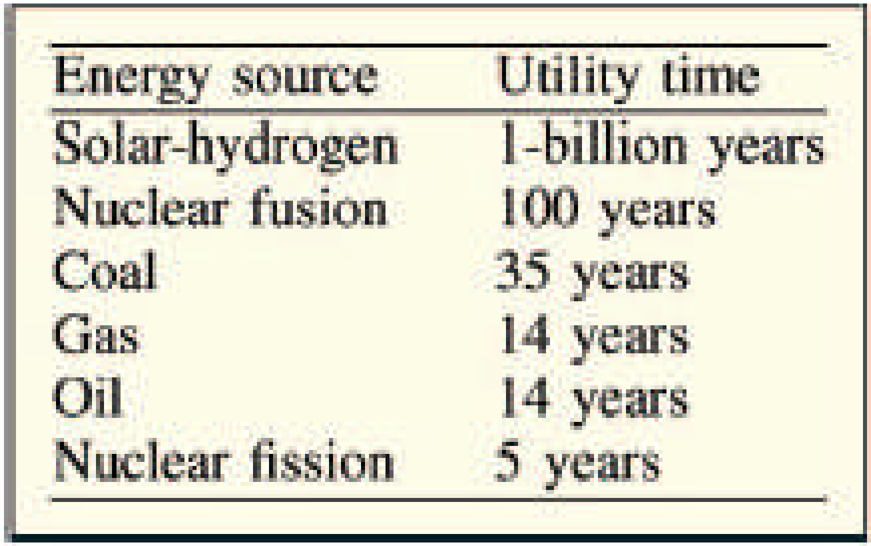
Mazda H_2 Rotary RX-8 (2008)

IC engine: transportation powerplant
- field of engine research will be alive for next billion or so years!

Solar Hydrogen Economy

- reversible, sustainable future
- with unlimited energy supply!

Table 3 Consolidated Utility Time (CUT)



Energy source	Utility time
Solar-hydrogen	1-billion years
Nuclear fusion	100 years
Coal	35 years
Gas	14 years
Oil	14 years
Nuclear fission	5 years

Abbott, 2010

Closure

Availability of cheap energy has led to distorted world economies/priorities

Next 30-40 years will require major innovations in IC engines

- dwindling resources and minimized environmental impact
- current energy usage rates are clearly unsustainable.

Many energy “solutions” (battery, fuel cell, nuclear) are only short term and resources are better saved for future generations

The only long-term sustainable energy source is solar hydrogen

Research will be needed to improve efficiency of electricity generation, H_2 production/storage and engine efficiency

The switch to the H_2 economy will take considerable time and effort

Until this occurs, research on more efficient usage of fossil and other fuels is urgently needed!

> “I’d put my money on the sun and solar energy.   What a source of power!
> I hope we don’t have to wait until oil and coal run out before we tackle that.”
> Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone.