Thermoelectrics for Cars

Jane Philbrick
Harvard Energy Journal Club
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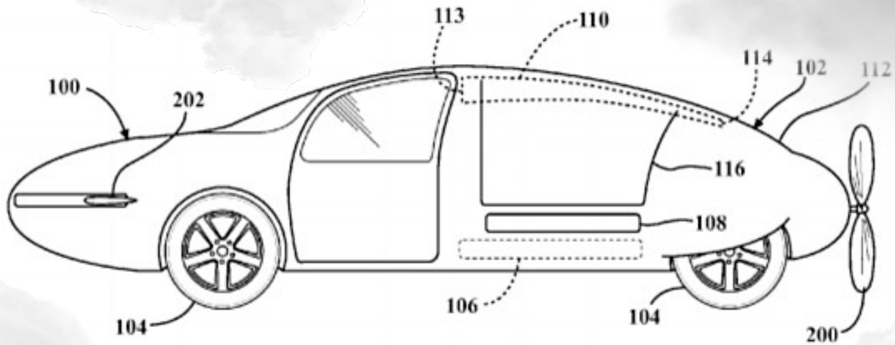

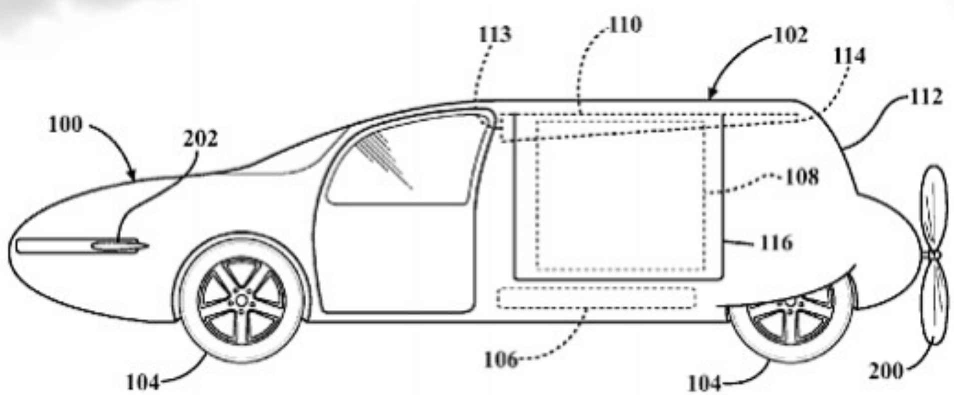

Source: US 2016/0176256 A1, June 23, 2016

The **thermoelectric effect** enables direct and reversible conversion between thermal and electrical energy, and provides a viable route for **power generation from waste heat**.

Source: "Ultralow Thermal Conductivity and High Thermoelectric Figure of Merit in SnSe Crystals," *Nature* Materials, 2014

Thermoelectric Technology

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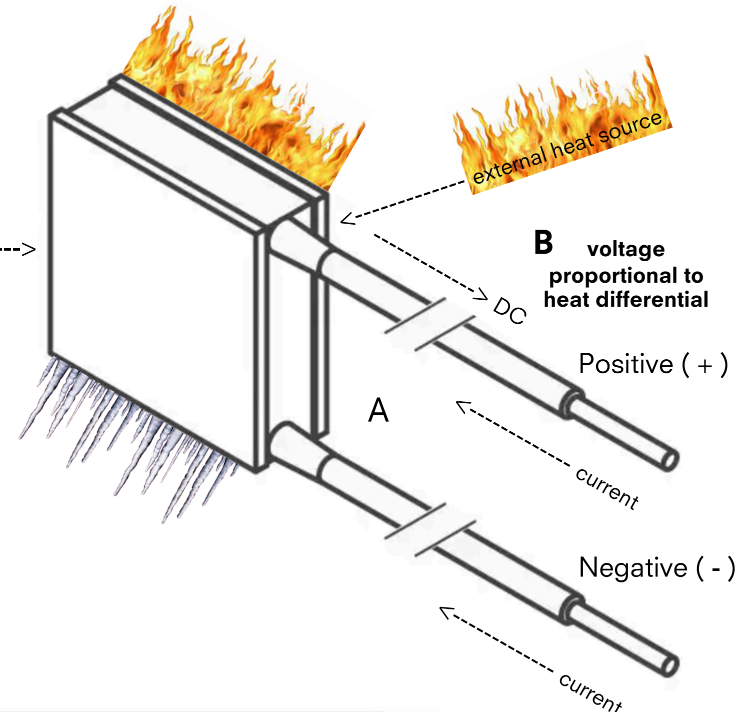
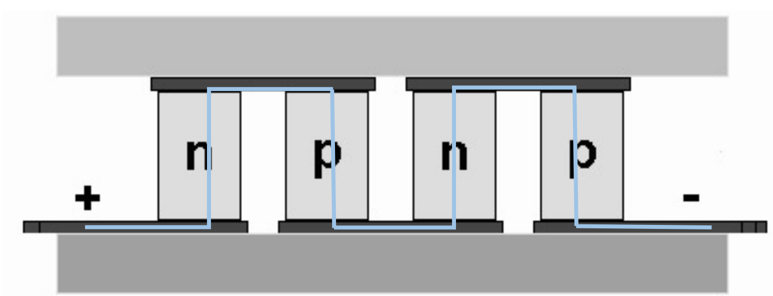




Heat ⟺ Electricity

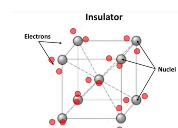
A

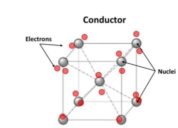
A thermoelectric device is a solid-state, semiconductor-based electronic component capable of converting a voltage input into a temperature difference which can be used for either heating or cooling.

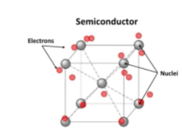
Conversely, **when a temperature difference is applied to the device, it has the capability of producing DC electrical power**.

B

Thermoelectric devices rely on the ability of dissimilar materials to generate an electric current when exposed to a temperature gradient.







Source: US 2016/0176256 A1, June 23, 2016

Figure of Merit

$$ZT = \frac{S^2 \sigma}{\kappa} T$$

Seebeck coefficient

electrical conductivity

figure of merit

absolute temperature

thermal conductivity

$k = k_e + k_g$

k_e = electronic component
k_g = lattice component

Seebeck coefficient (S) is a measure of how readily the respective carriers (electrons or holes) can transfer energy as they move through a thermoelectric element which is subjected to a temperature and electric potential gradient.

The type of carrier (electron or hole) is a function of the materials selected to form each thermoelectric element.

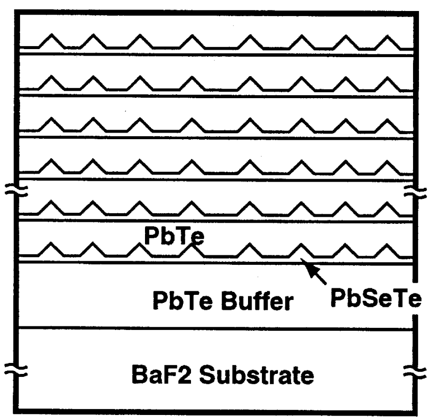
Source: US 6399871 B1, June 4, 2002

Thermoelectric Technology

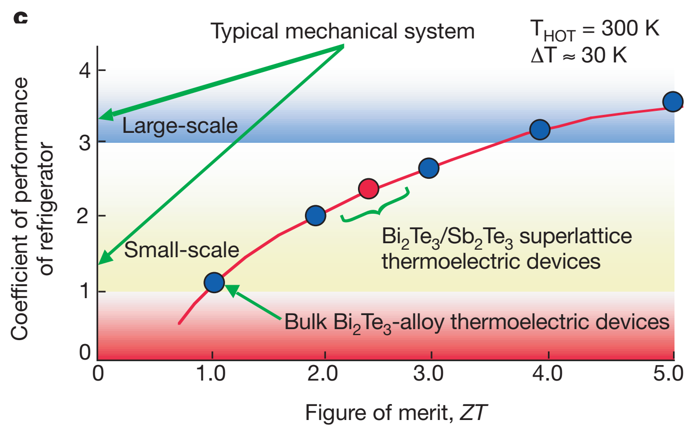
l: T.C. Harman's quantum-dot superlattice with a reported ZT ~3.5 at 575 K

c: Rama Venkatasubramanian's superlattice with reported ZT ~2.4 at 300 K and ZT ~2.9 at 400 K

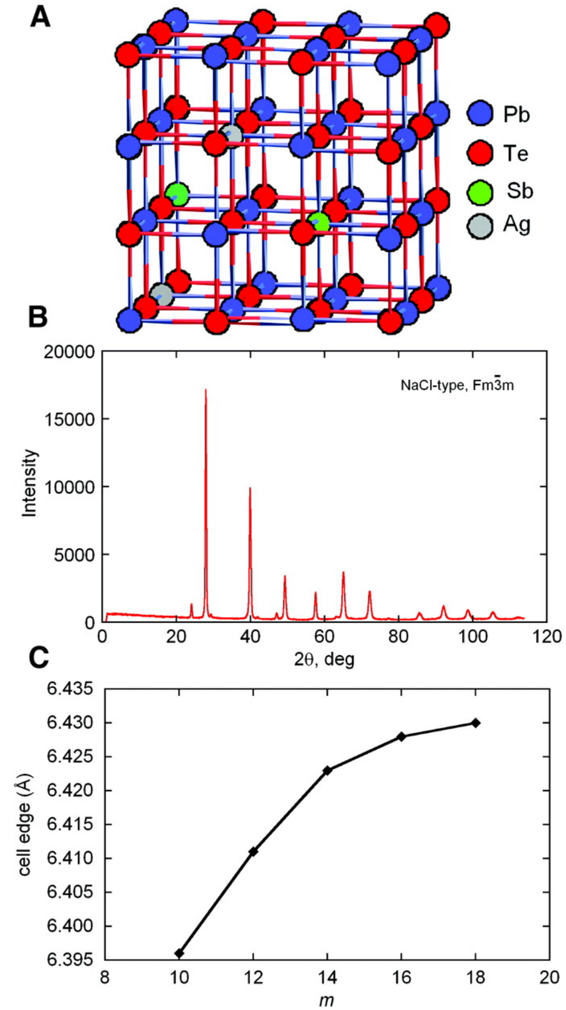
r: Keu Fang Hsu's lead antimony silver telluride (LAST) bulk/'nanodot' material with a reported ZT ~2.2 at 800 K



Schematic cross section of the quantum-dot superlattice structure



Potential COP as a function of *ZT* with various technologies. T_{HOT} refers to the heat-sink temperature



(A) Average ideal *Fm*3*m* crystal structure of $AgPb_mMTe_{2+m}$ (M=Sb, Bi) series;
(B) X-ray diffraction pattern (Cu Ka radiation) of $AgPb_{10}SbTe_{12}$;
(C) Lattice parameter variation of $AgPb_mSbTe_{2+m}$ as a function of *m*.

The elemental formulae are nominal, but they have been confirmed with microprobe energy-dispersive spectroscopic analysis.

Source: "Thermoelectric Quantum-Dot Superlattices with High ZT," *Journal of Electronic Materials*, 2000; "Thin-Film Thermoelectric Devices with High Room-Temperature Figures of Merit," *Nature*, 2001; "Cubic AgPb(m)SbTe(2+m): Bulk Thermoelectric Materials with High Figure of Merit," *Science*, 2004

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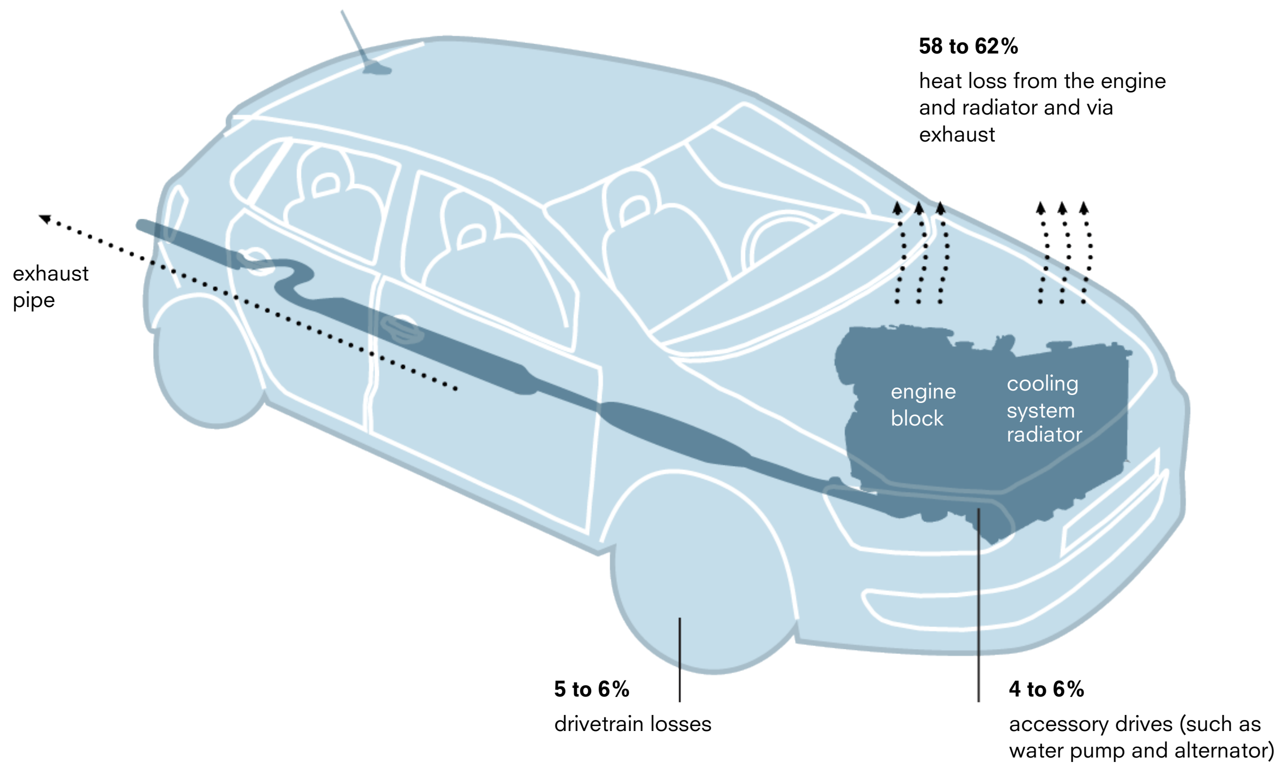
Thermoelectric Technology

Benefits

- solid state construction (no moving parts)
- vibration-free operation
- chloro-fluorocarbon free
- scalable microW to kW of heat or power output
- no acoustical or electrical noise
- performs in any physical or gravitational orientation
- operates in zero-gravity
- withstands the high g-forces of space and military applications
- size and performance output highly scalable -- 2mm to 60mm

Estimates of Energy Losses Occurring in Combined City and Highway Driving



Source: Marlowe Industries; "New Frontier in the Efficiency Quest: Cutting Heat Losses," *The New York Times*, 2014

Efficiency

- 2/3 of energy produced in power stations lost in "waste heat"

  inefficiency of converting heat (burning fuel) ⟹ mechanical energy (spinning turbines) ⟹ electricity (generator)

- harvesting energy lost in "waste heat" means less fuel needs to be burned, reducing CO_2 emissions
- thermoelectric generators (TEGs) directly convert heat into energy without moving parts, such as turbines
- automotive thermoelectric generators (ATEGs) capture waste heat from the exhaust system of internal combustion engines
- Goodyear concept tire BH03, debuted at the Geneva auto show 2014, embeds thermoelectrical material in the tire to capture heat from normal driving

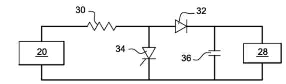


Fig. 3

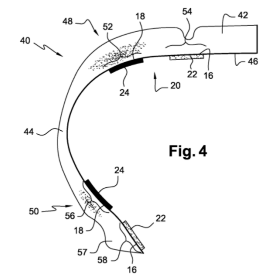
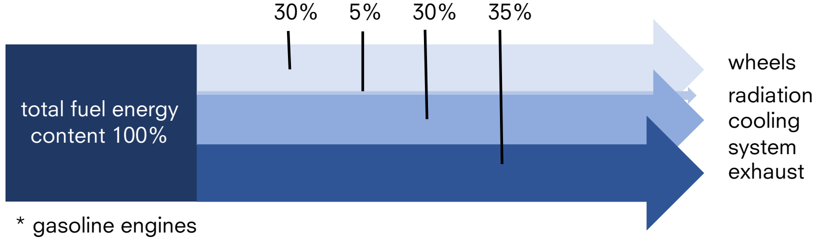


Fig. 4

Source: US 20090151440 A1, June 18, 2009

Efficiency

Typical Power Flows in an Internal Combustion Engine (ICE)*



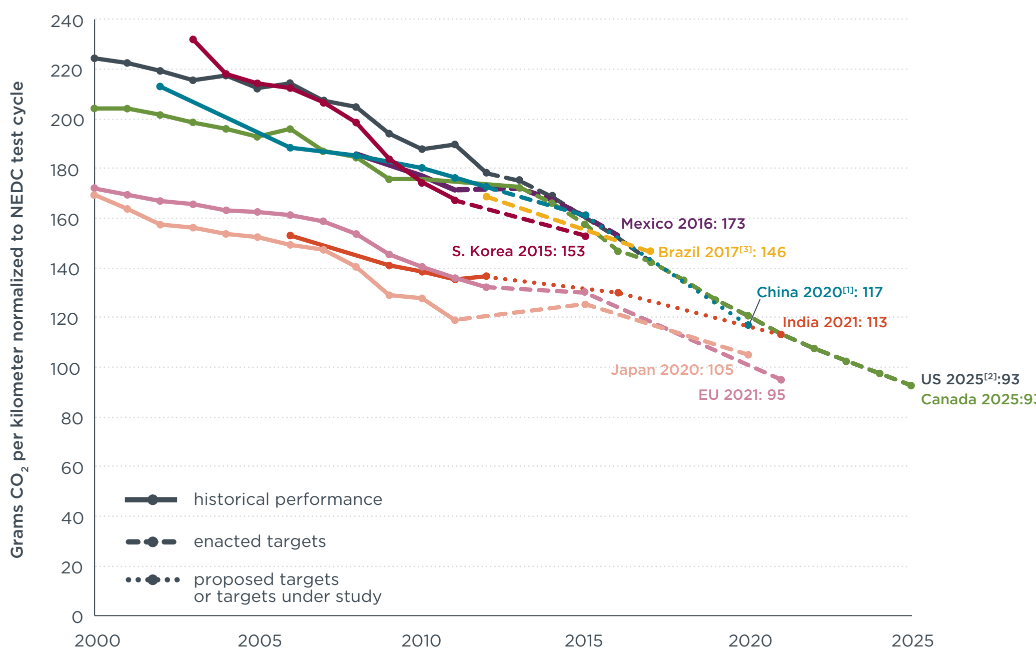
* gasoline engines

US

Projected Emissions Targets Under the Greenhouse Gas Standards (g CO_2e/mi)

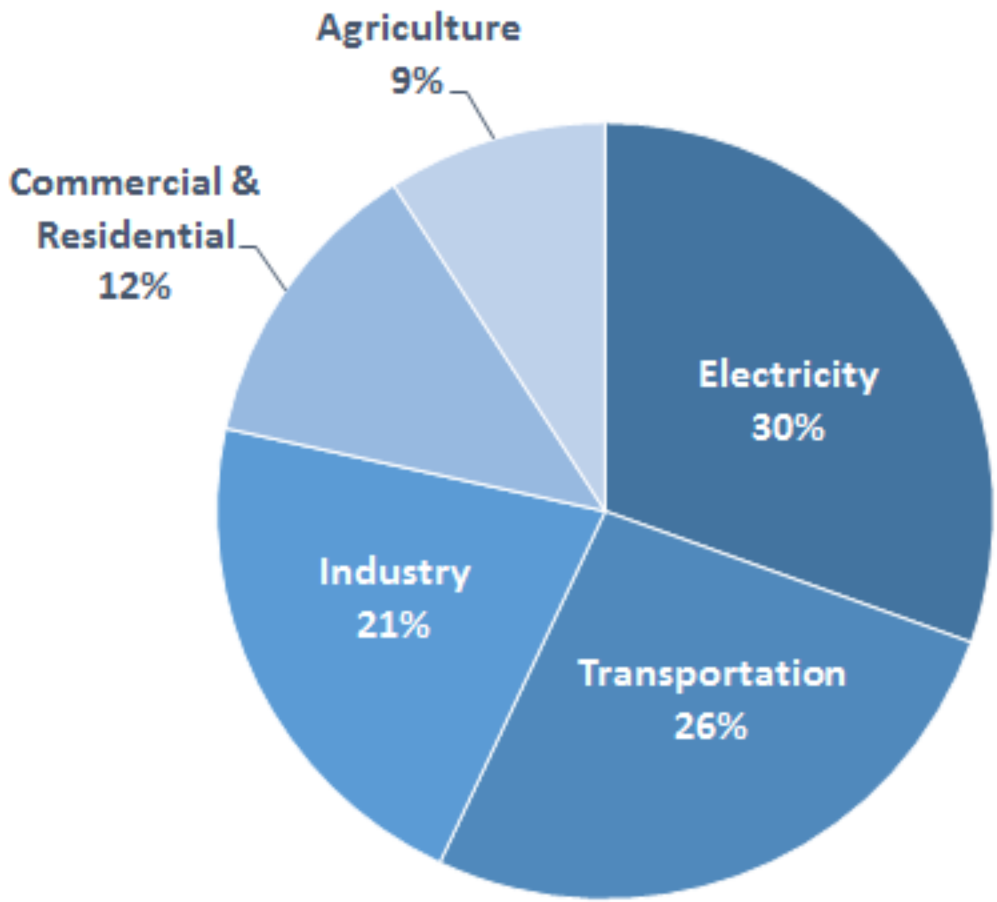
	2017 I 2025
Passenger Cars	261 I 143
Light Trucks	352 I 203
Combined Cars + Light Trucks	295 I 163

Global



Source: Center for Climate and Energy Solutions; The International Council on Clean Transportation

Total US Greenhouse Gas Emissions by Economic Sector 2014



Source: *US Greenhouse Gas Inventory Report: 1990-2014*, US Environmental Protection Agency, 2014

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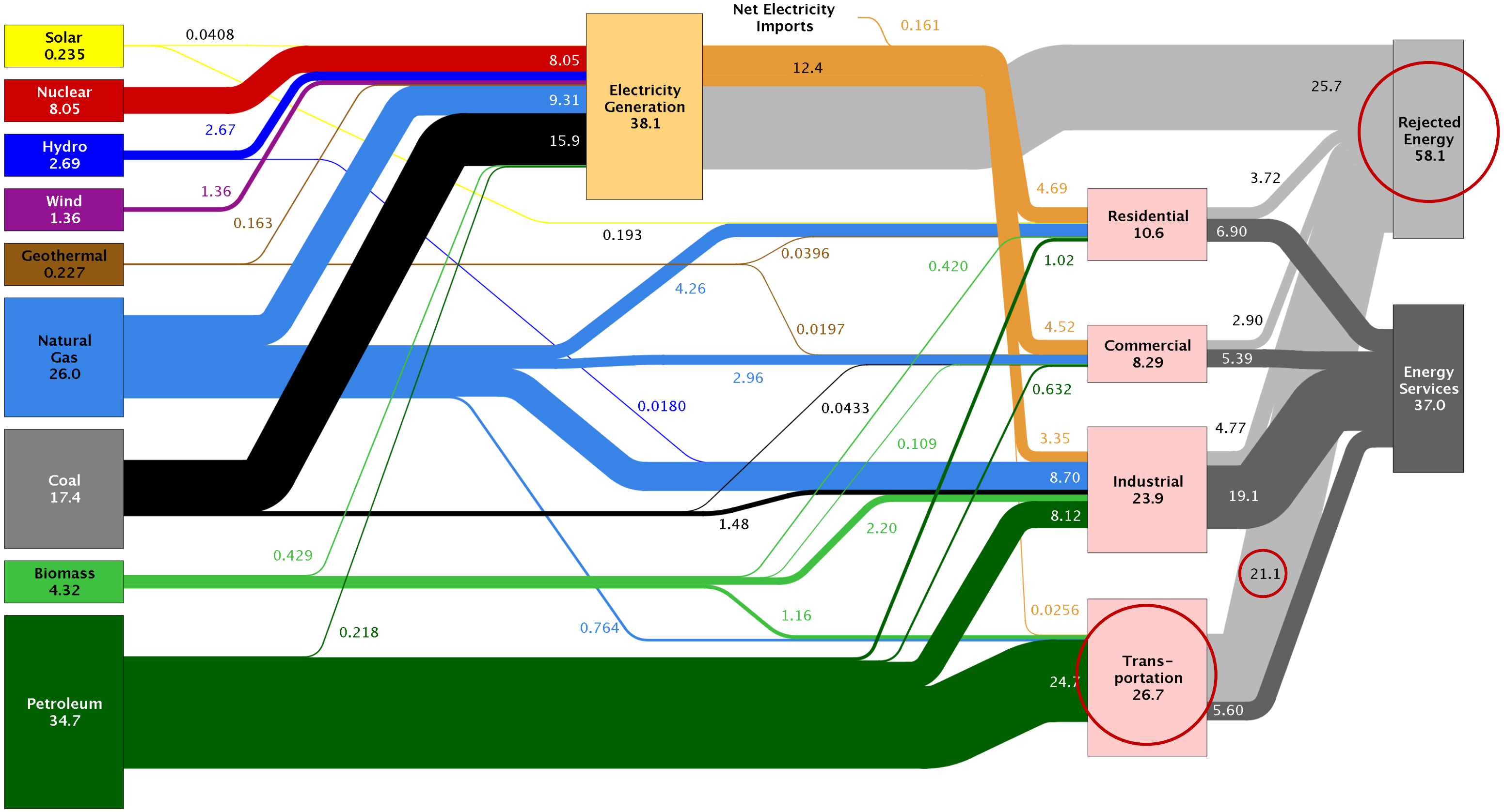
Estimated US Energy Use 2012 ~ 95.1 Quads



Source: Lawrence Livermore National Laboratory

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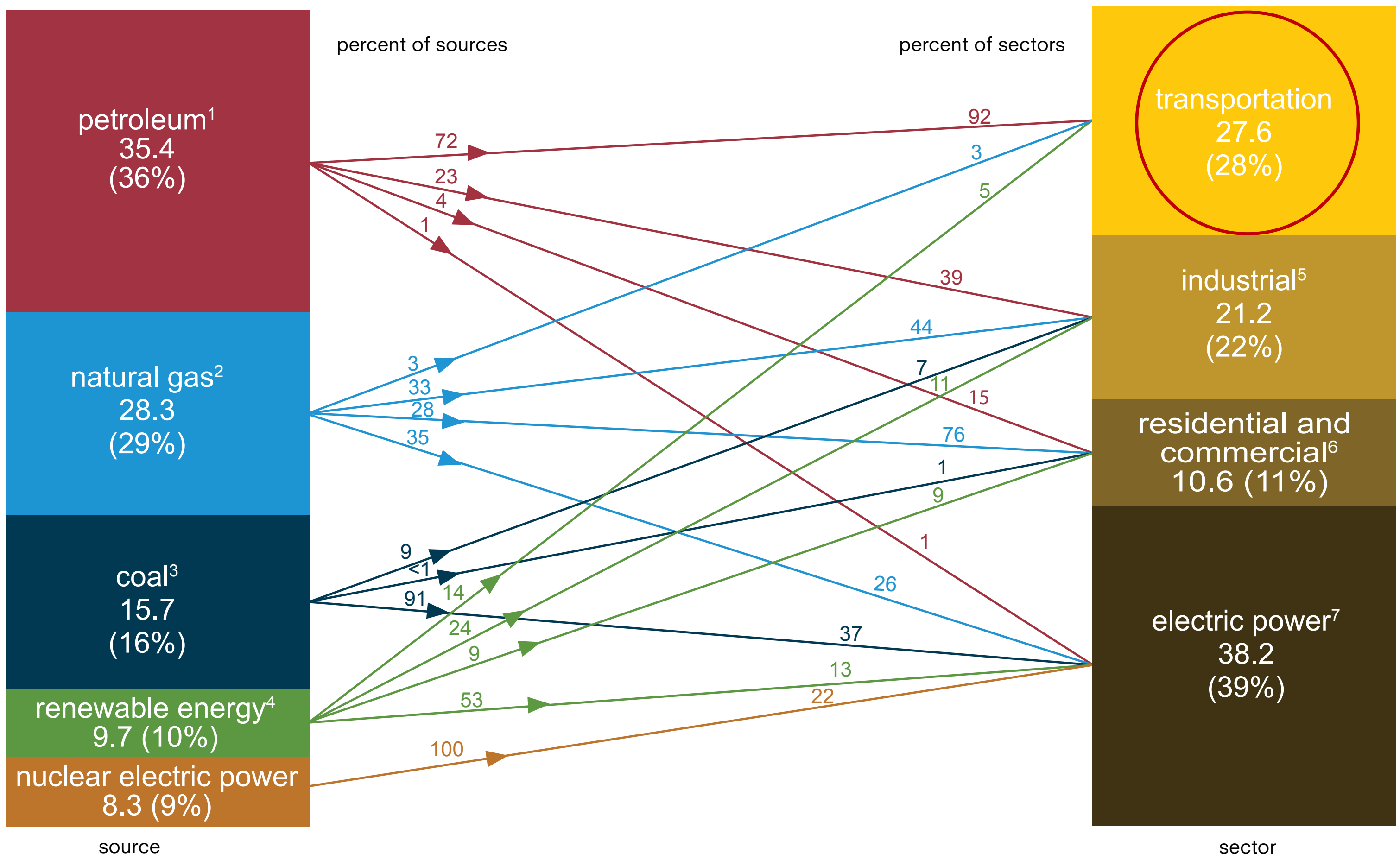
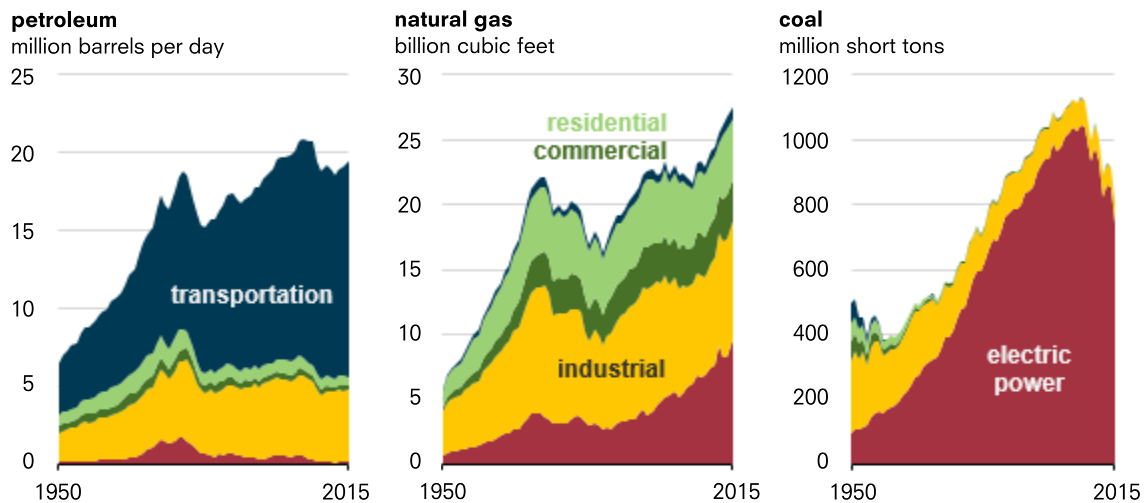
US Energy Use 2015
Total = ~ 97.7
quadrillion British
thermal units (Btu)



Source: US Energy Information Administration; *Monthly Energy Review* (April 2016), Tables 1.3, 2.1-2.6

US Consumption of Selected Energy Commodities by Sector 1950-2015
quadrillion Btu



ATEGs mounted on a car's exhaust stream could eventually replace alternators and run electrical water and oil pumps, boosting performance and saving fuel.

In 2006, John Fairbanks, technology development manager, US DoE, speculated that **if all GM cars alone used TEG, it would save roughly 100 million gallons of gas per year.**

Source: US Energy Information Administration; "Free Power for Cars: Automakers Look to Thermoelectrics to Help Power Tomorrow's Vehicles," *MIT Technology Review*, 2006

Brief History

$$ZT = \frac{S^2\sigma}{\kappa}T$$

1820-1920

"Seebeck Effect"

- Power generation

"Peltier Effect"

- Heating and cooling

"Thomson Effect"

- Heat absorbed or produced is proportional to the heat differential

1920-1970

"Figure of Merit zT," Abram Fedorovich Ioffe, 1949

- The higher this figure, the more effective the material
- Commercial thermoelectric materials today achieve a ZT of more than 1

1970-2000

Niche Applications

- Optoelectronics, small refrigerators, seat heating/cooling

Thermoelectric Generators for Space

- Multihundred-Watt radioisotope thermoelectric generators (MHW RTG) – nuclear heat source + heat sink (space)
- Developed for Voyager program (1977)

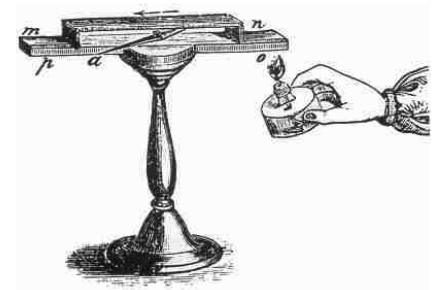
1990s Optimism for High Efficiencies through Nanostructural Engineering

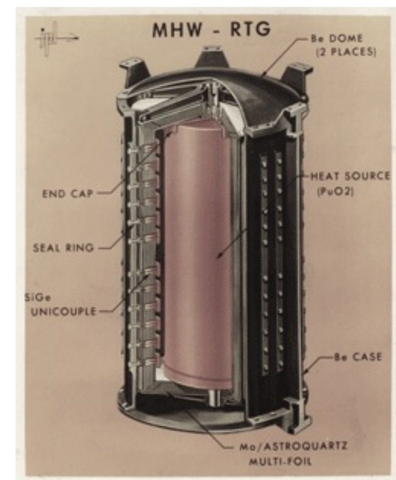
- Skutterudites, clathrates, zintl phases

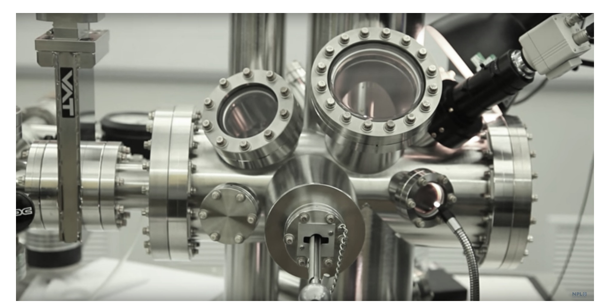
2000-

Nanoscale

- Engineering thermoelectric material to improve efficiency
- Scanning Thermoelectric Microscopy (SThEM)
- High electrical conductivity but low thermal conductivity
- US Department of Energy's 'FreedomCar' programme, teams assembled to pursue harvesting vehicle waste heat, usually from the exhaust, which is redirected to a TEG to produce electricity
- FreedomCar target is for cars and trucks to improve overall fuel economy by 10% and aims to reach production in the 2011–2014 timeframe

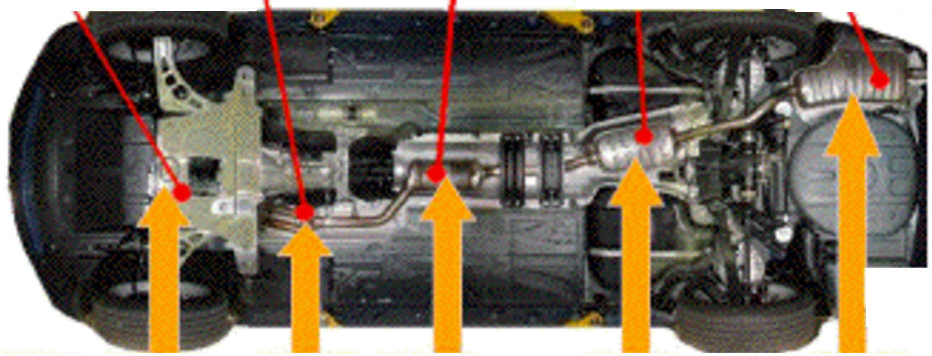






Source: Jeff Snyder Thermoelectrics Group, Northwestern Materials Science and Engineering; National Physical Laboratory, 2012; IAV Automotive Engineering; "Complex Thermoelectric Materials," *Nature Materials*, 2008; "Inconvenient Truth"

Automotive Thermoelectric Generators (ATEGs)



318i	full load	780 ˚C	620 ˚C	550 ˚C	480 ˚C	430 ˚C	(806 ˚F)
330i	part load	550 ˚C	380 ˚C	320 ˚C	240 ˚C	190 ˚C	

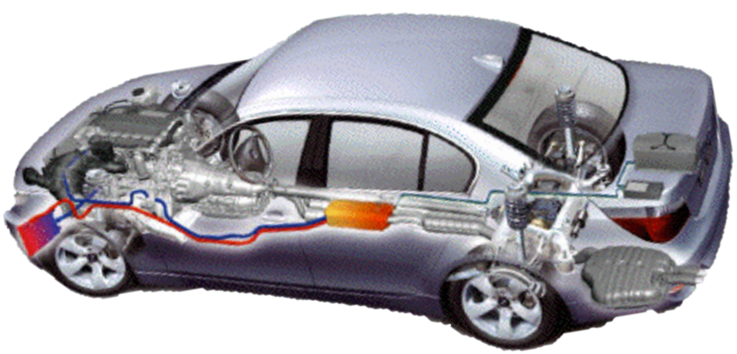
Automobiles are **high energy usage, low efficiency**.

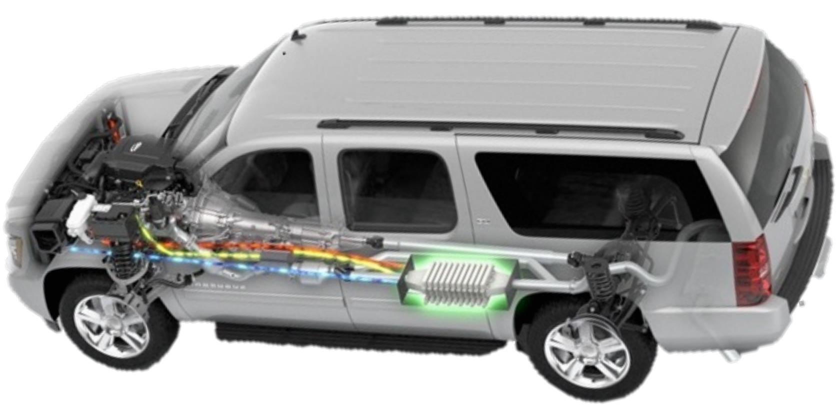
75% of the energy produced during combustion is lost in the exhaust or engine coolant in the form of heat.

Harvesting a portion of the lost thermal energy to charge

- EV battery
- ac
- seat heating
- lights

instead of using an alternator (adds drag on the engine), **overall fuel economy can be increased by 10%.**

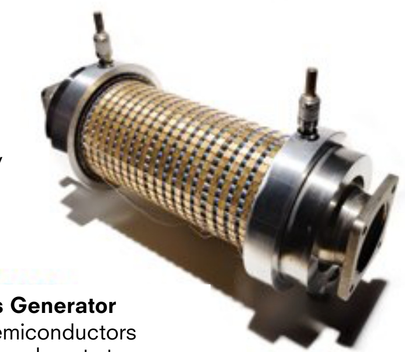




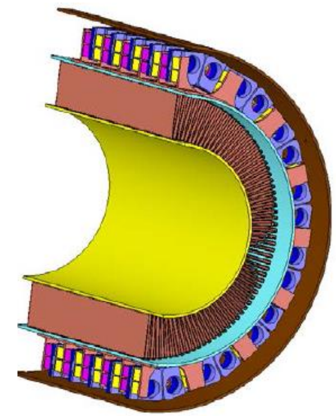
Source: Jeff Snyder Thermoelectrics Group, Northwestern Materials Science and Engineering; *MIT Technology Review*

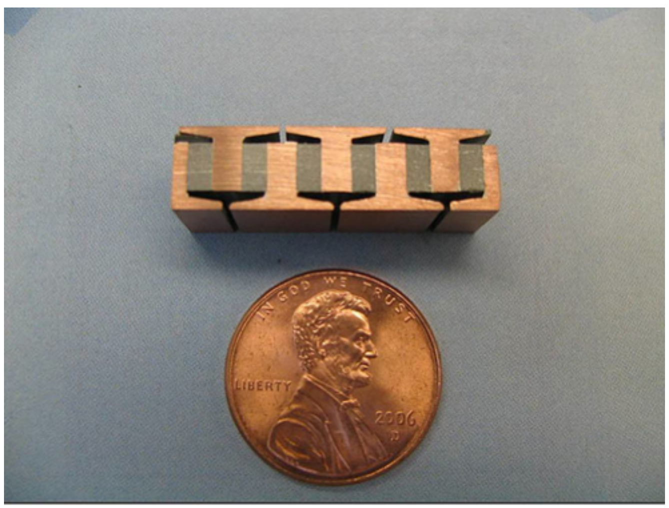
Automotive Thermoelectric Generators (ATEGs)

cylindrical TEG hot-side heat-exchanger body with fins and internal bypass

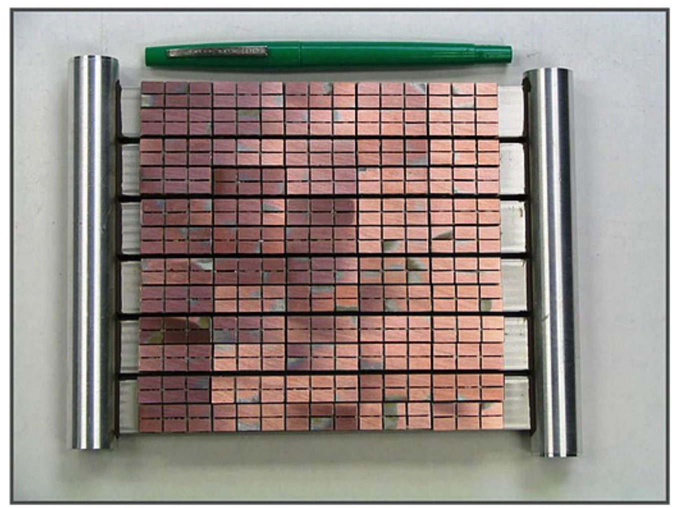


Amerigon's Generator positions semiconductors between the exhaust stream and a cooled outer surface to produce electricity





single-watt stack design

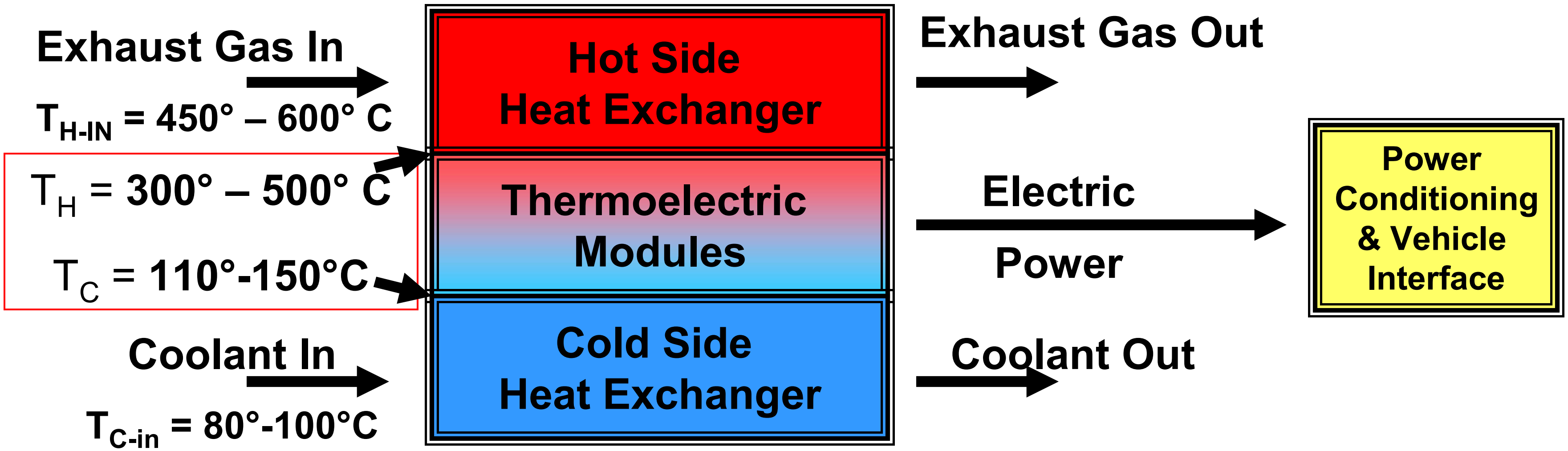


Amerigon's prototype array of single-watt elements can generate 100 W of power when subjected to a strong temperature gradient

Source: "Recovery Exhaust Heat to Generate Electricity and Boost Efficiency," SAES International, 2011; Dr. HoSung Lee,"Exhaust Waste Heat Recovery," 2016

Generic Exhaust Gas TEG

Representative TEG Temperatures for a Gasoline Fueled Vehicle



Typical Heat Exchanger Loses

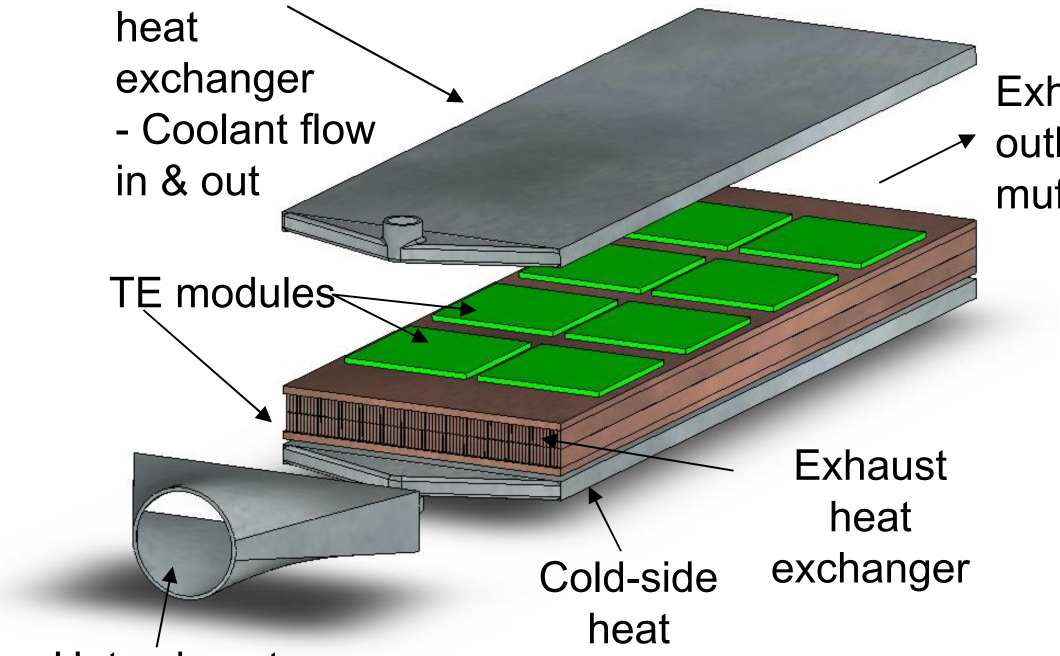
ΔT_{HS} = 100° to 150° C

ΔT_{CS} = 30° to 50° C

Start up temperatures lower

Peak temperatures higher

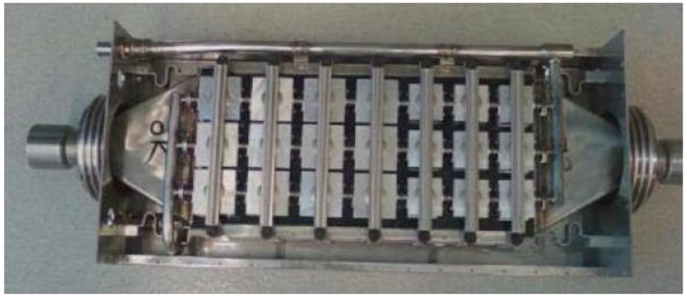
Example of Exhaust TEG Basic Geometry



- High performance compact exhaust gas heat exchanger
  - high heat transfer coefficient at average flow
  - high surface area
  - meets pressure drop requirements at max flow
- Dual surface configuration
- Scalable, manufacturable design
- Geometrically compatible with vehicle

Slide courtesy of General Motors Corp. **2009**

Automotive Thermoelectric Generators (ATEGs)



Source: Dr. HoSung Lee,"Exhaust Waste Heat Recovery," 2016

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Automotive Thermoelectric Generators (ATEGs)

Timeline

1990s-2014

Limited interest in thermoelectric harvesting in general and its use in automotive applications in particular

For instance, BMW had worked on it for 20 years without bringing anything to market

The theoretical maximum attainable efficiency was known to be one half of that for photovoltaics and some other options and the actual achievement was around one tenth of theoretical at 3%

2008

First IAV "Thermoelectrics Conference"

"Material zoo": no one knew which thermoelectric material would make the race for use in motor vehicles

- no volume production
- difficult to find test modules for medium temperatures
- **unusual for automotive industry to address fundamental issues of materials science**
- **funding has remained relatively modest, particularly when compared with photovoltaics or fuel cells**

2014

Interest in TE picks up

- Komatsu KELK in Japan trials 1.5 kW thermoelectric modules on its huge construction vehicles showing, that thermoelectric harvesting was no longer just about providing signal power
- predicts thermoelectric harvesting will be in on-road vehicles in 2018
- selling point: cost of ownership and green credentials

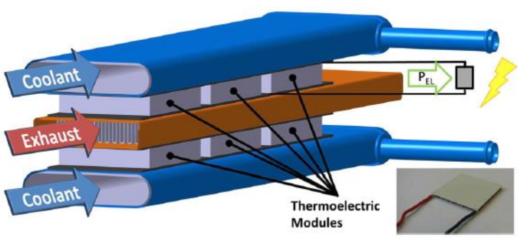
Mercouri Kanatzidis from Northwestern University has discovered that **tin selenide**, a well-known crystalline material long dismissed by experts in the field, is actually exceptionally efficient at converting heat into electricity; **ZT=2.6**; in 2012 he reported lead telluride with ZT=2.2

- Kanatzidis: "Tin selenide has a layer structure and each layer is corrugated like an accordion. We thought maybe this will make the material so soft that it might have a very low thermal conductivity, and we could do some neat fundamental science"

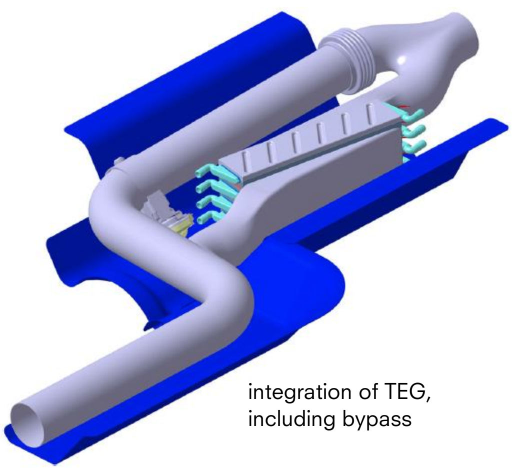
2015

Forecast:

- "Thermoelectric harvesting on production hybrid electric on-road vehicles from 2018"
- TE commonplace on hybrids in 2020 and almost entirely to charge the battery, or increasingly supercapacitor or supercabattery used for power
- Future market – hybrid cars; approx 9 million units in 2025 with possibility of application in conventional cars, adding tens of millions for addressable market in 2025



single-channel TEG


integration of TEG, including bypass

materials – nanostructured thermoelectric materials, which convert heat to electricity

modules

system integration

durability

BMW has said that it developed a thermoelectric device positioned in the exhaust system that provides 200 watts of power. The latest generation of the device uses more advanced materials to generate 600 watts. The automaker's goal is 1,000 watts of thermoelectric power.

Military use to solve fuel logistics and security propulsion.

Heat travels through a material as vibrations in the structure, so the more rigid a material is the better it conducts heat.

To become comparable to a car engine, you would need a ZT of about 3.

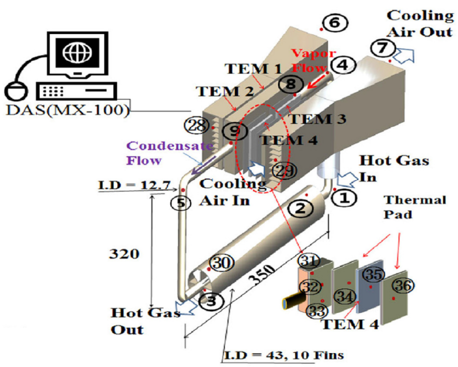
Source: SAE International; IAV Automotive Engineering; "Waste Not, Want Not," Energy from Thermoelectrics, *Cosmos Magazine,* 2014; Dr. HoSung Lee,"Exhaust Waste Heat Recovery," 2016

Automotive Thermoelectric Generators (ATEGs)

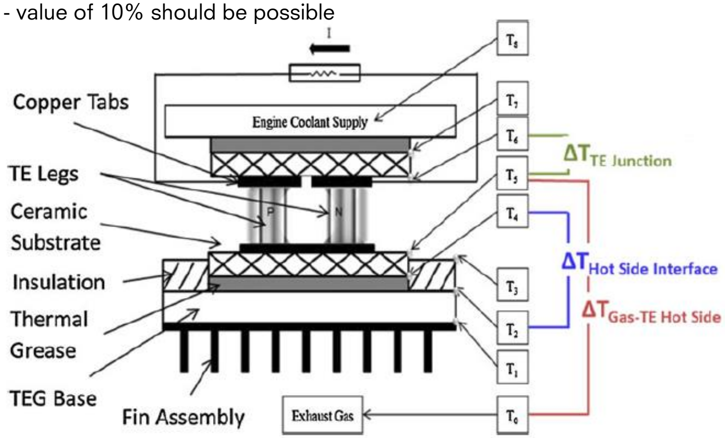
2015 (cont'd)

Today **skutterudites**, **silicides**, and **half-Heusler alloy**s are presumed to be the best candidates for use in motor vehicles.

- good ZT figures: more than1 in the lab and already manage ZT figures of about 1 in production
- maximum ZT figures of 1.6 are probable for all three materials in the medium term
- relatively easily available:
    - skutterudites can be produced in the larger kilogram scale
    - half-Heusler alloys are easily available in the kilogram scale
    - silicides is not so good – available in quantities of a few hundred grams, production of larger quantities in development
- progress contradicts the fear that high material costs make thermoelectrics too expensive for use in motor vehicles
- possible to generate several hundred watts in power per kilogram of material
    - skutterudites currently produce about 0.8 kW per kg
    - silicides produce 1.8 kW per kg
    - TEG in a vehicle should produce about 600 watt
    - automotive industry aims to keep system costs below one euro per watt
- thermoelectric modules made of silicide and half-Heusler alloys currently achieve efficiency rates of 5-6 %, while modules with skutterudites even manage up to 8%
    - difference between material efficiency and module efficiency is currently less than 10%
    - value of 10% should be possible

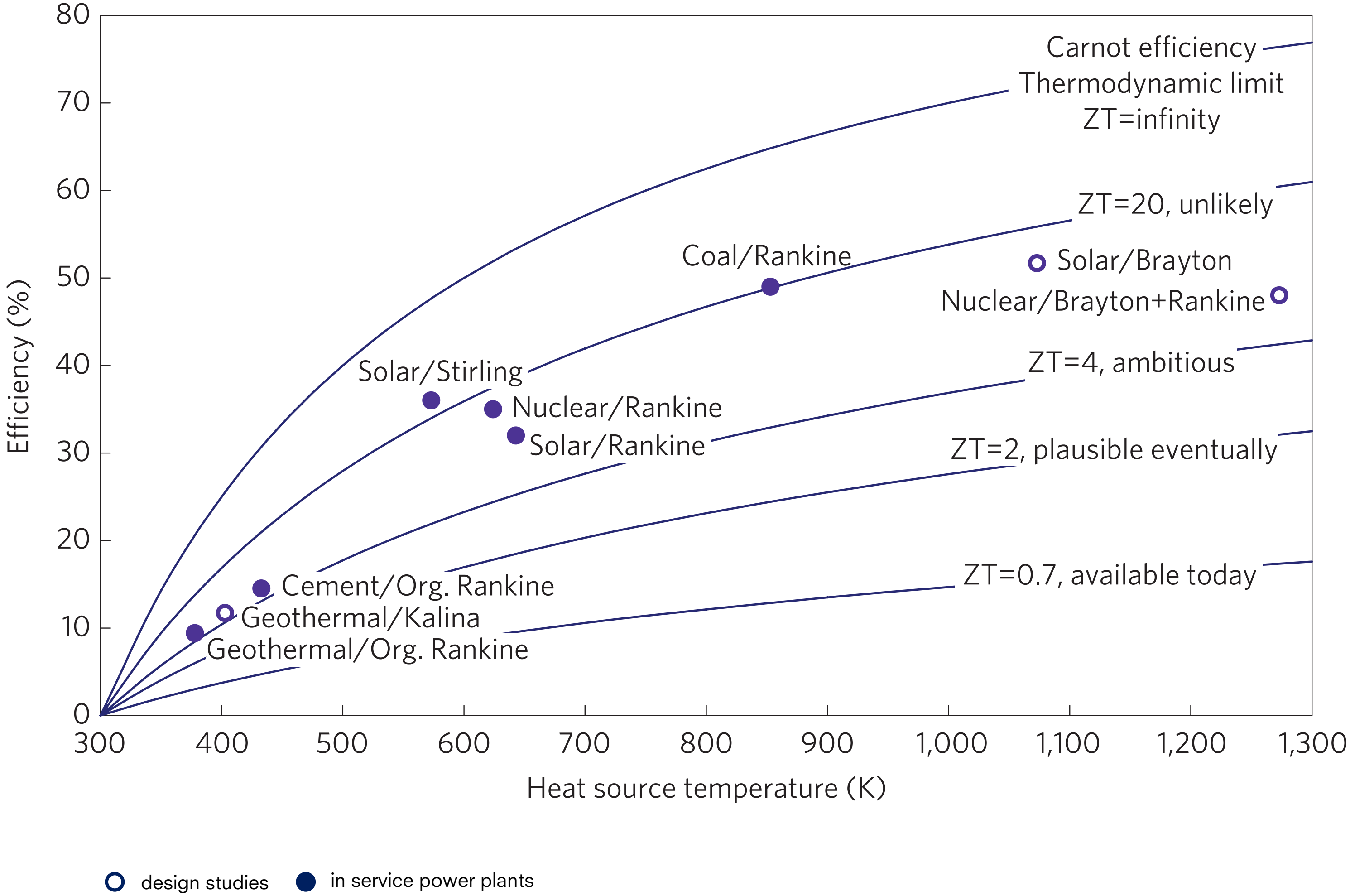


exhaust heat recovery system using a loop heat pipe to extract the heat



Source: IAV Automotive Engineering; Dr. HoSung Lee,"Exhaust Waste Heat Recovery," 2016; A Review of Car Waste Heat Recovery Systems Utilising Thermoelectric Generators and Heat Pipes," *Applied Thermal Engineering,* 2016

Challenges +
Competitors



Source: "An Inconvenient Truth About Thermoelectrics," *Nature* Materials, 2009

Climate Crisis Impact of Thermoelectric Technology

Power Scale (kW_e)	Examples	Required ZT	Impact on Climate Crisis
> 1,000s	Solar thermal "engine" replacement	> 8-20	Highly unlikely
> 10s	Industrial waste heat, geo-thermal bottoming cycles	> 4	Unlikely
0.5-several	Vehicle waste heat, car cooling/heating, home co-generation	>1.5-2	To be determined
< 0.5	Remote power, "personal" micropower, all existing applications	> 0.5-1	(almost) None

"Even if future R&D achieves a fully edged, device-level average of ZT = 4, it is still probably insufficient to displace mechanical engines for large-scale applications. Of course, ZT = 4 should greatly enhance the range and performance of niche applications that thermoelectric technology serves so well today.

But the impact on the climate crisis, even with ZT = 4, seems limited to the smaller scale, decentralized applications, the **most promising of which appears to be vehicle exhaust heat recovery**. Even there, the benefit is potentially around 10% improved fuel economy assuming all the hurdles to market penetration are overcome.

The opportunity for thermoelectric technology to help in the climate crisis seems limited."

Source: "An Inconvenient Truth About Thermoelectrics," *Nature Materials*, 2009

Challenges + Competitors

Speed	Horsepower	Watts	BTU/min
35 mph	6.15	4586	261
40 mph	7.94	5920	337
50 mph	12.64	9425	536
55 mph	15.66	11677	664
60 mph	19.17	14295	813
65 mph	23.23	17322	985
70 mph	27.87	20782	1182
80 mph	39.12	29171	1660

Test Subject

Late Model **Chevy Malibu**, a mid-sized four passenger sedan.

It weighs 3,460 pounds, has a frontal area of 24.1 square feet, and a Coefficient of Drag of .37.

www.ecomodder.com

For steady speed!

- “At a steady speed on a level road in a Chevy Malibu it only takes 27.87 h.p. to move our butts down the road at 70 mph. Yet we have cars with 350 cu. in. engines producing 300 h.p. for what purpose - just so we can burn rubber every once in a while? Of course if your really watch how you drive that 300 h.p. monster you can maybe squeeze what, 20-22 mpg out of it.”

- “350 watts! Oh my, I'm so impressed! 350 watts extracted from the waste heat of a 320 hp engine. That's a whole extra 0.5 hp. Admittedly, this is a bigger savings since most of that 320 hp is lost. The 350 watts seems to be about 10% of what the alternator generates.”

- “More or less have to agree with you that 350 watts seems like a joke. If I look at some of the technology developed in the last year or two like Transsonic injectors or the OPEC engine with potential gains of 20-40% why are we fiddling around with this. Oh sure someday when it becomes 10X more efficient maybe. If as stated elsewhere, series hydraulic hybrids can be 30-60% more efficient without the high cost of the batteries, what are we waiting for?”

Energy Harvest Trivial:

generating 350 watts, improving fuel economy by 3%

Amerigon ATEG improves fuel efficiency by 5%

“Adding any ernergy conversion system to a car adds **weight, cost, and complexity**.”

Source: IAV Automotive Engineering; IDTechEx, “CAFE Tenth Electric Aircraft Symposium Report: Overview,” May 24, 201; “Powering Your Car with Waste Heat,” *MIT Technology Review,* 2011 and “*Comments*”

Challenges + Competitors

Even for vehicle waste heat, competition from mechanical engines can be expected to be fierce. **Honda**, for example, have tested a system using a **Rankine steam engine** to generate electricity from waste heat in a hybrid vehicle, increasing overall engine efficiency by 3.8% .

BMW have for some years had a similar effort called **Turbosteamer**, but their added device is used to supplement the power train (rather than to generate electricity), improving fuel efficiency by 15%.

Either of these projects seems to surpass the FreedomCar goal of 10% fuel savings.

Significant barriers remain before deployment including:

- costs
- scaling of the nanomaterials
- heat transfer to thermoelectric modules
- dedicated radiators
- system weight
- acceptance of change
- competition with alternate conversion technologies
- all other means of increasing fuel efficiency

Between 2008 and 2013, around 250 million euro were spent on thermoelectric research worldwide

- in ten years, the football club Real Madrid spent around one billion euro on new players
- "**money scores goals** (applies figuratively speaking to research and development)

Historic limitations of **low efficiency** and **high cost per watt of power conversion** that have limited its applications in the past

"Right now, the device is just inserted into the exhaust system," GM scientist Gregory Meisner says. "**A section of pipe is cut out and the device, which looks like a muffler, is inserted. We need to design something that's more integrated into the vehicle system rather than an add-on device**."

rankine, sterling, thermoacoustics, alternative fuels, flexible fuel vehicles, triboelectrics, magnetostrictive harvesting, wind turbines that erect when parked

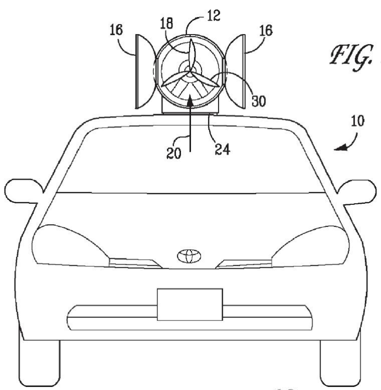
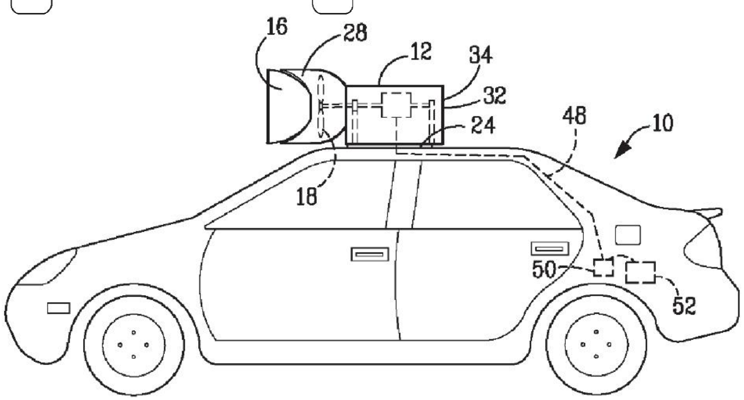
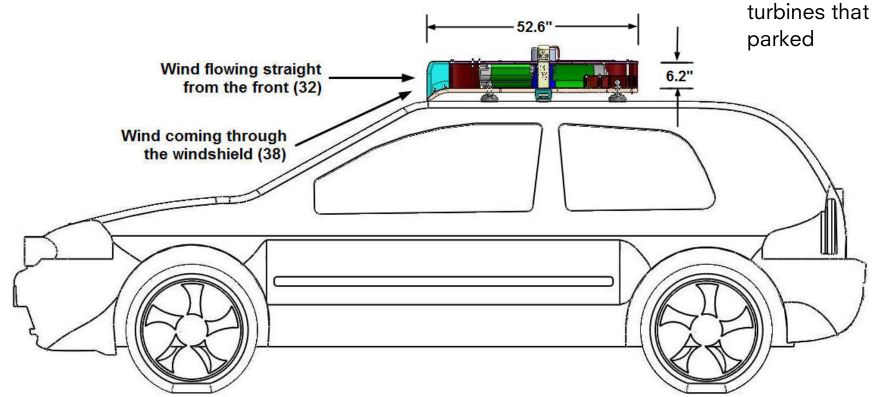


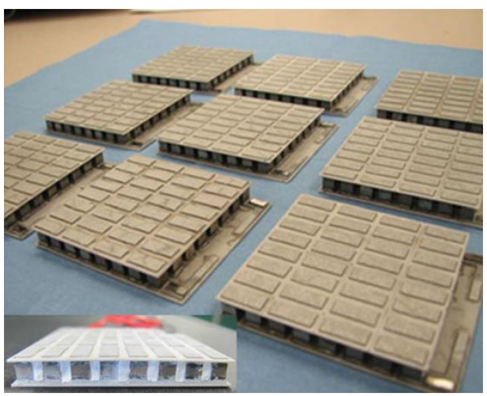
FIG. 3





Source: "An Inconvenient Truth About Thermoelectrics," *Nature* Materials, 2009; "Cooling, Heating, Generating Power, and Recovering Waste Heat with Thermoelectric Systems," *Science*, 2008; IAV Automotive Engineering

Current Research



full-sized skutterudite modules, fabricated by Marlow Industries, after encapsulation with aerogel

Band Structure Engineering of PbTe-based Alloys for Thermoelectrics

- high valley degeneracy is one of the peculiar features of PbTe based materials that makes them the most efficient thermoelectric materials for waste heat recovery
- alloying can finely tune the band structure to enhance thermoelectric performance as well as control doping and reduce thermal

Thermoelectric Materials from Zintl Compounds

- rich solid-state chemistry of Zintl phases enables a directed search and optimization of new complex thermoelectric materials
- complex crystal structures of Zintl Phases lead to low phonon velocity and therefore low thermal conductivity while the chemistry of Zintl phases facilitates strategies for tuning the electronic transport

Skutterudites

- skutterudites, based on $CoSb_3$, are the new thermoelectric materials most developed to supplant Bi_2Te_3 and PbTe based materials in space and commercial applications
- their complex electronic and atomic structures gives them ideal eletrical and thermal properties for thermeoelectrics

Liquid Like Thermoelectric Materials

- some thermoelectric materials contain fast-diffusing, even 'super-ionic' atoms within a crystalline sublattice of another type of atom
- 'liquid-like' behaviour results in an intrinsically low lattice thermal conductivity which enables
- high zT in an otherwise simple semiconductor

Thermoelectric Nanomaterials

- interfaces at the nanometer scale used to scatter long mean-free-path phonons to reduce phonon or lattice thermal conductivity and increase zT

October 14, 2016

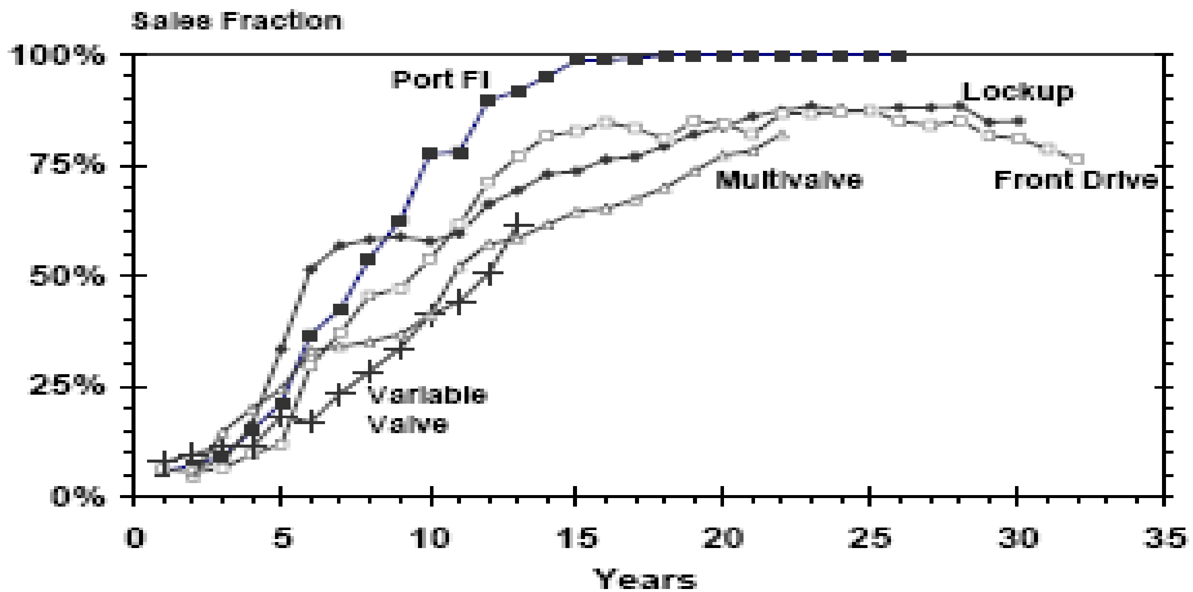
Northwestern University's **Mercouri G. Kanatzidis** receives prestigious 2016 Samson-Prime Minister's Prize for Innovation in Alternative Fuels for Transportation, shared with **Gregory Stephanopoulos**, a chemical engineer at MIT

- recognized for their research on automobile fossil fuel reduction and thermoelectrics
- Eric and Sheila Samson Prize is the world's largest monetary award ($1mm) for alternative fuel research

Modern Electron

A start-up company based in the Seattle area. Its mission is to generate cheap, modular, and reliable electricity for all. Expensive mechanical engines and turbines based on 19th-century technology are still used to generate the majority of today's electricity worldwide. **Modern Electron** seeks to revolutionize the industry via direct heat-to-electricity generation with advanced thermionic energy converters. Over $10 MM of venture capital funding with technology supported by 14 issued patents, with 20+ more patents pending in the US and worldwide.

Source: IAV Automotive Engineering;



It takes about 15 years for a technology to reach maximum penetration in new vehicle sales and another 15 years for the technology to be ubiquitous

Source: "Light-Duty Automotive Technology and Fuel Economy Trends: 1975 through 2006," *EPA420-R-011, July 2006*

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Source: US 2016/0176256 A1, June 23, 2016

Thermoelectrics for Cars

What

Why

Then

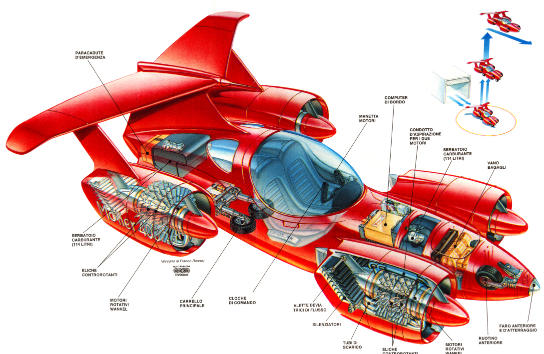
How

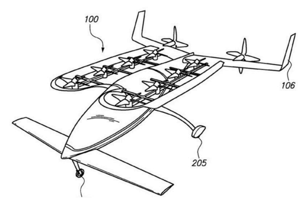
Not

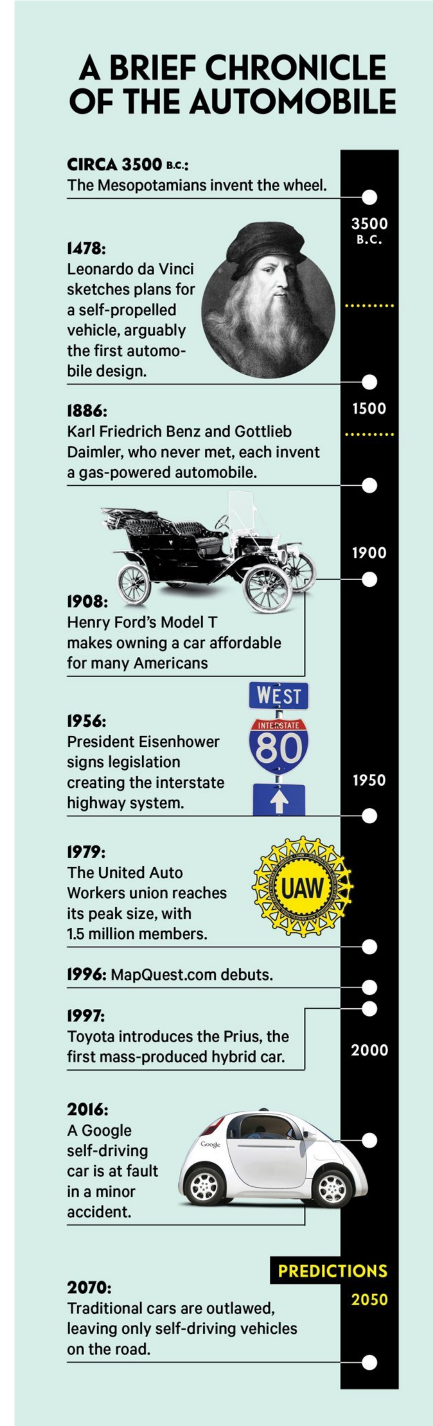
Now

Future . . .

Thank you







Source: Terrafugia; Inhabitat; "When Cars Fly: How Driverless Cars Could Change Meetings, Manufacturing, Safety, and More," *The Atlantic*, 2016