Tackling Energy Sector Challenges by Intersecting Materials, Manufacturing, and Systems

Defense Energy Seminar
Naval Postgraduate School
May 28, 2024

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Energy Flows

Resources

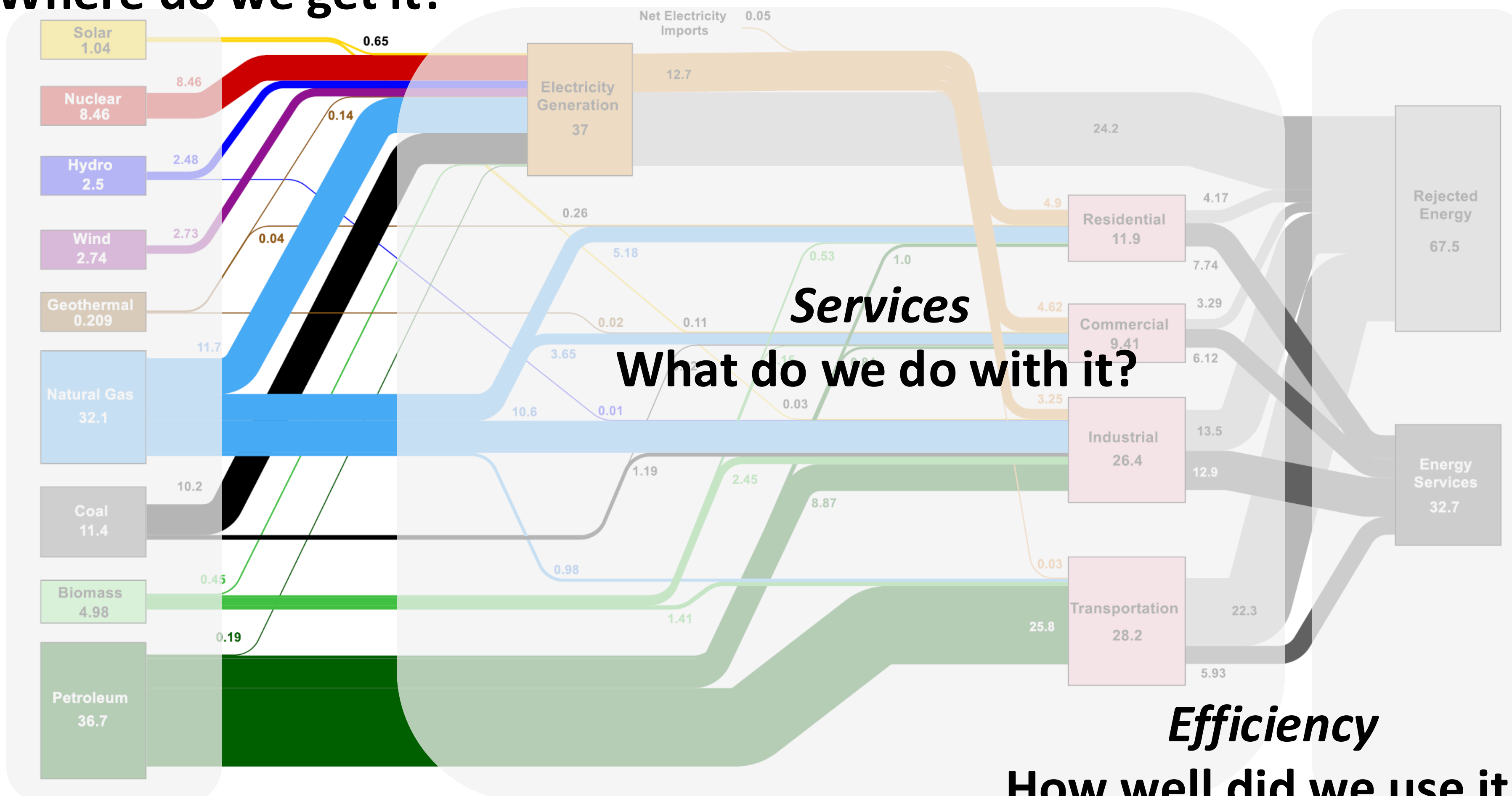
Where do we get it?

Services

What do we do with it?

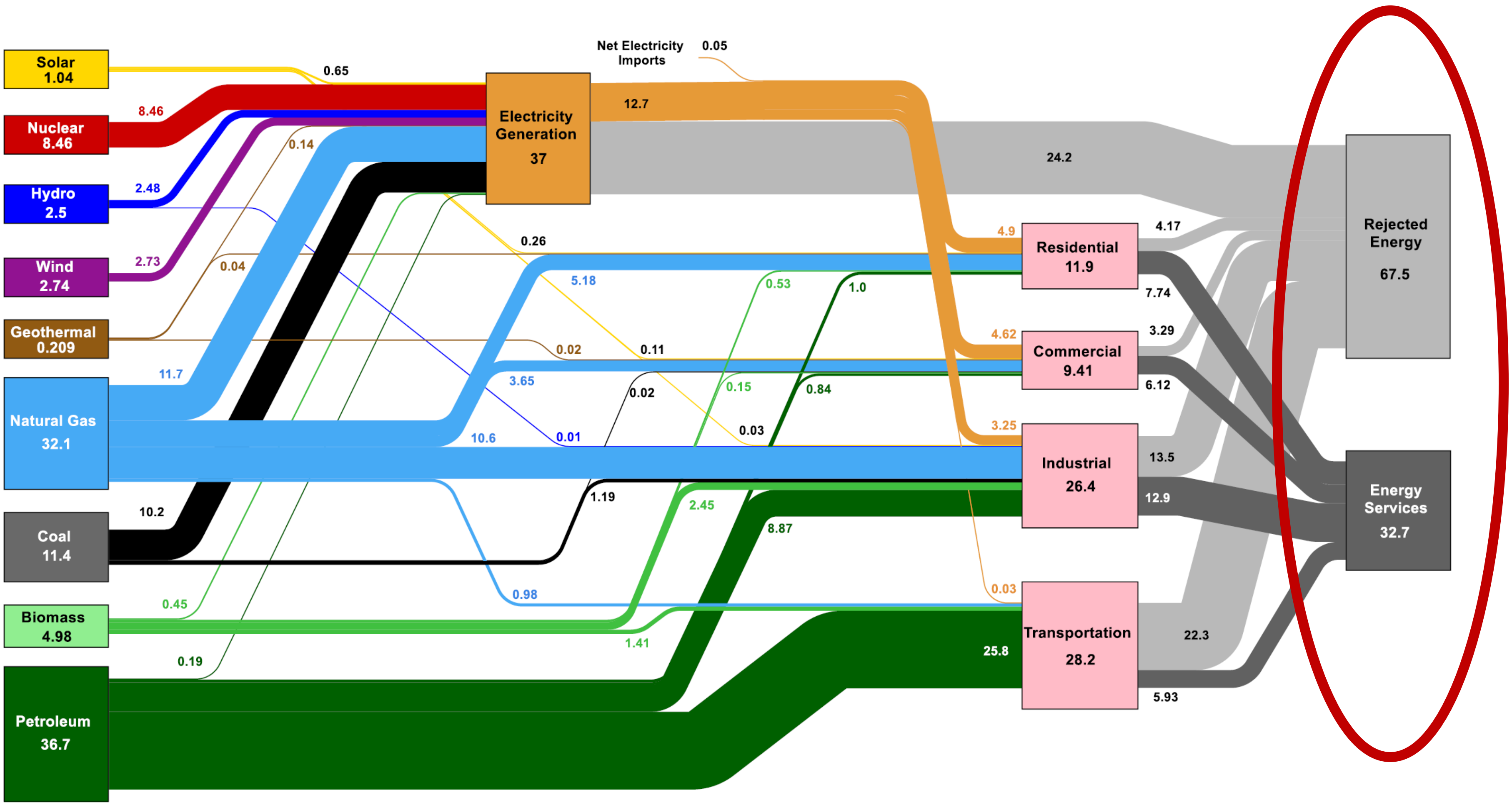
Efficiency

How well did we use it?



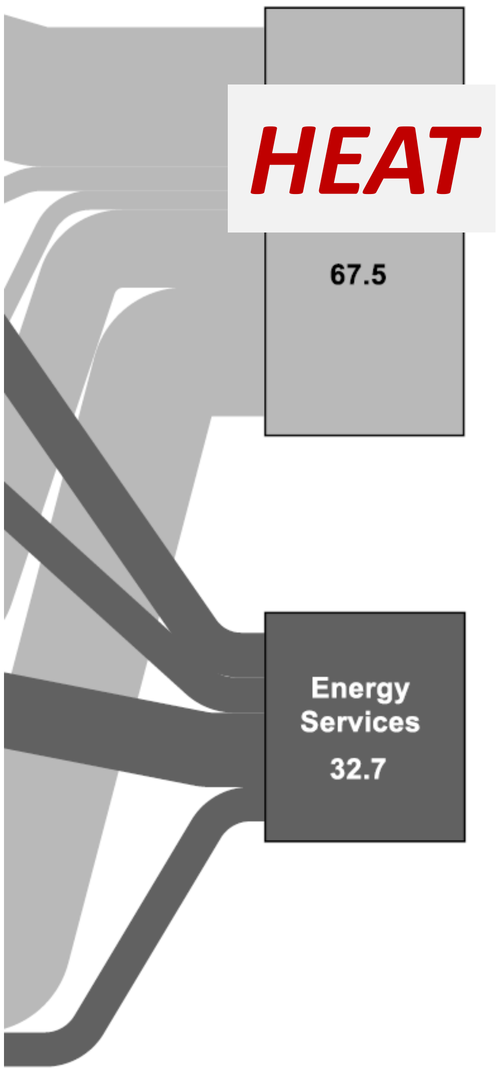
https://flowcharts.llnl.gov/commodities/energy

Where did all that energy go?

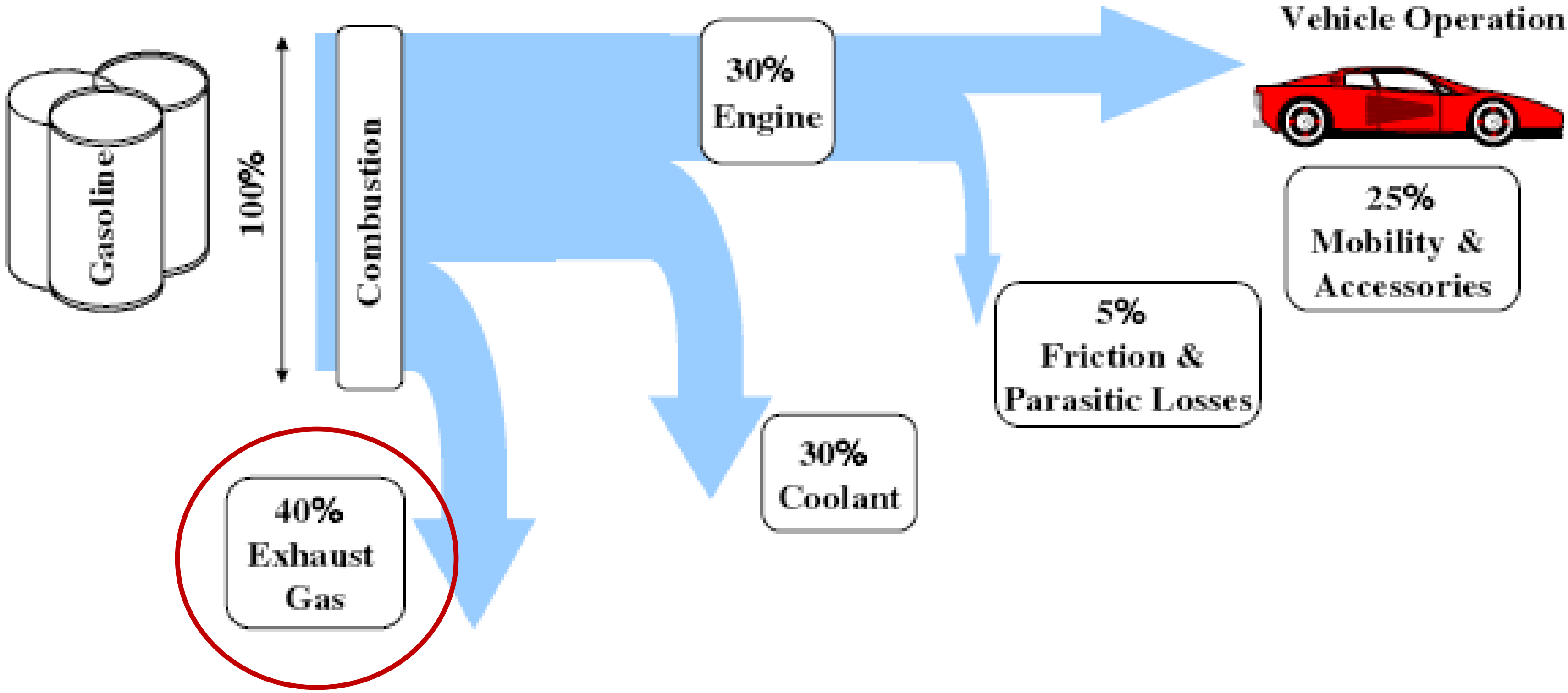


https://flowcharts.llnl.gov/commodities/energy

Where did all that energy go?



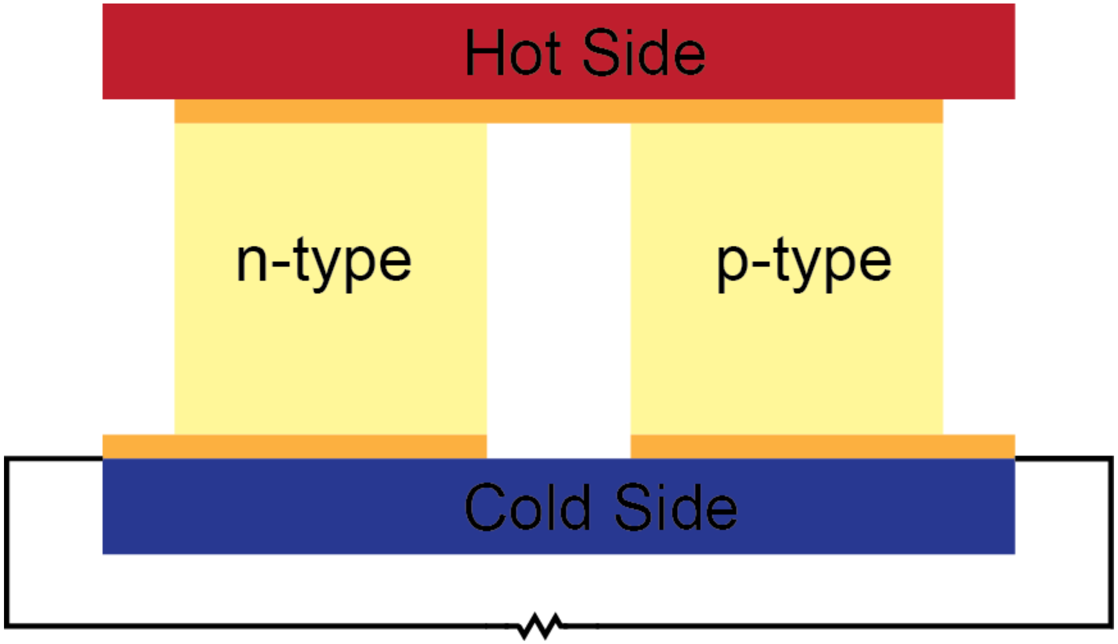
Efficiency Example



J. Yang and F. Stabler, *J. of Electronic Materials* (2009)

Thermoelectric Energy Conversion

Power generation & Heat pumping



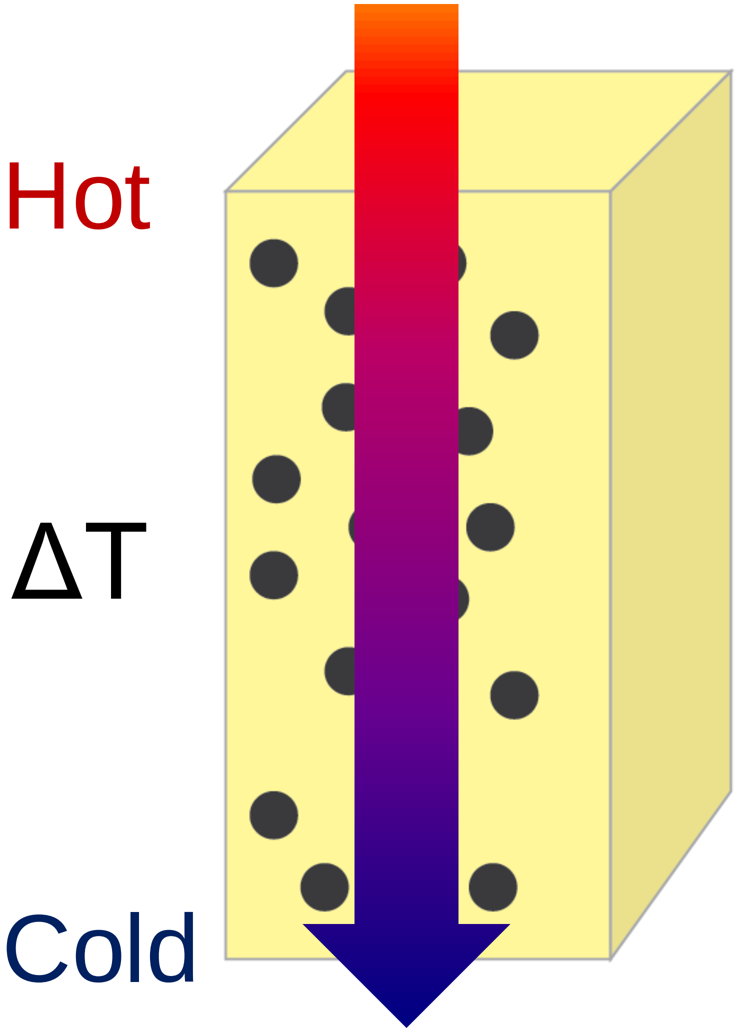
<u>Advantages:</u>

Distributed generation
Localized control of energy transfer
Reliable
No moving parts
Silent

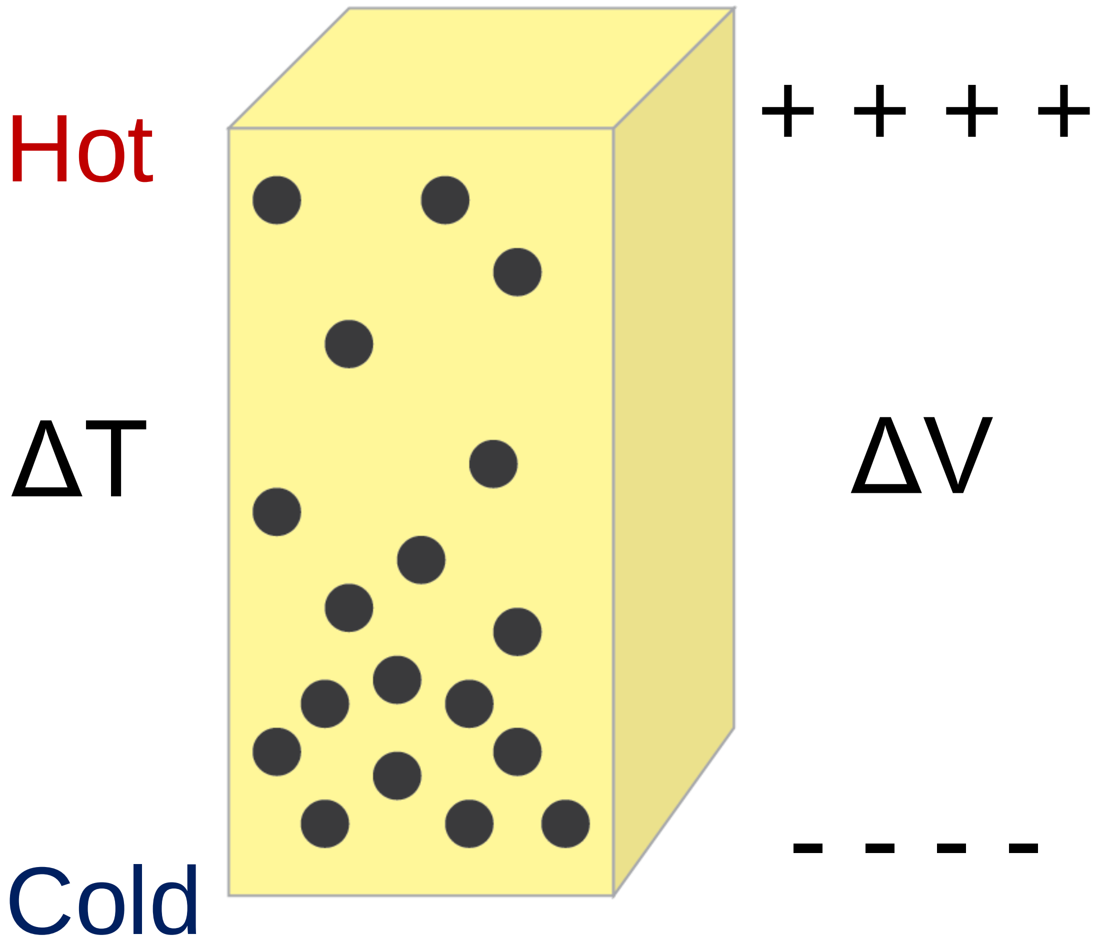
<u>Challenges:</u>

System integration
Conversion efficiency
Operating temperatures

Thermoelectric Effect



Thermoelectric Effect



Thermoelectric Figure of Merit

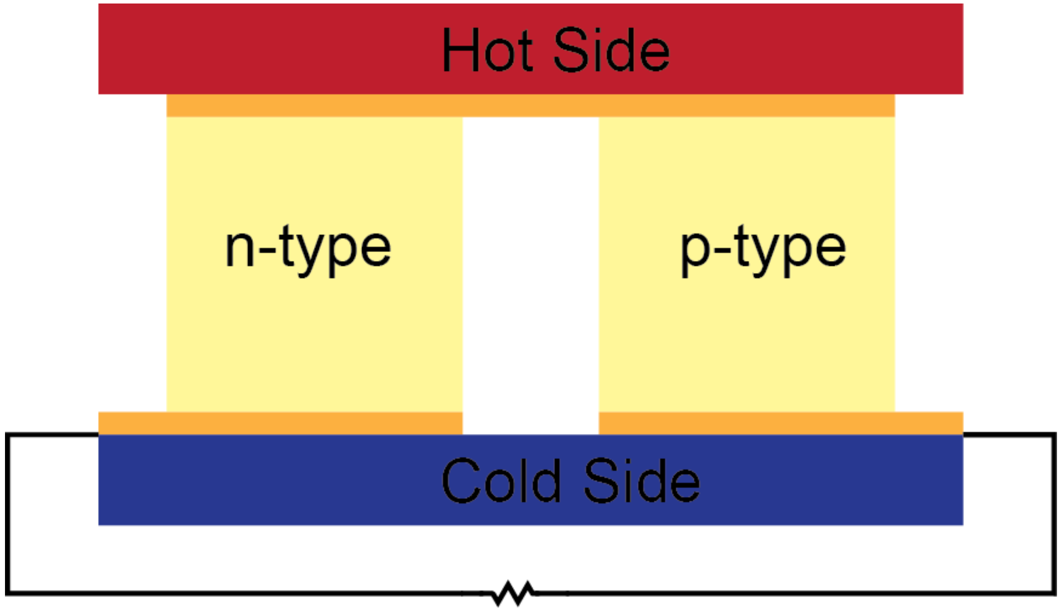


Figure-of-merit:

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

S = Seebeck coefficient
σ = electrical conductivity
k = thermal conductivity

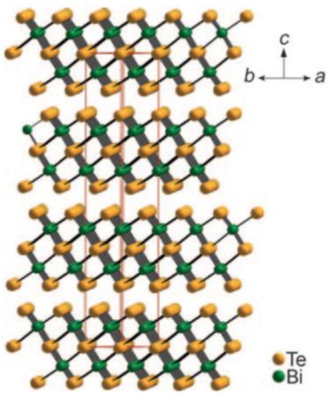
Thermoelectric material:

Requires good charge transport while minimizing thermal energy carrier transport.

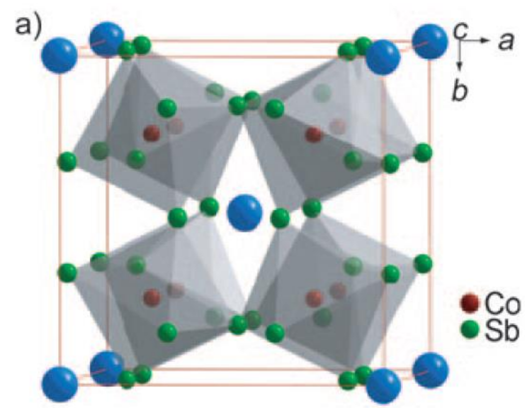
High S,σ **Low** k

Thermoelectric Materials

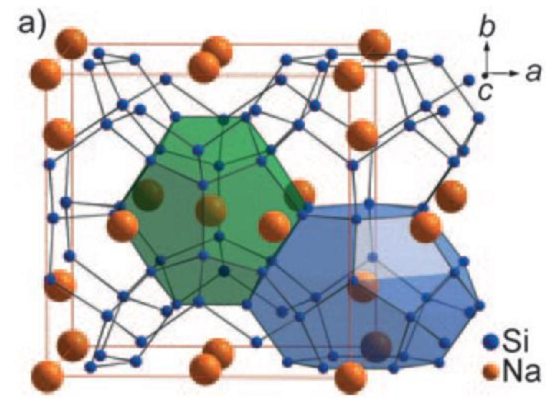
Chalcogenide



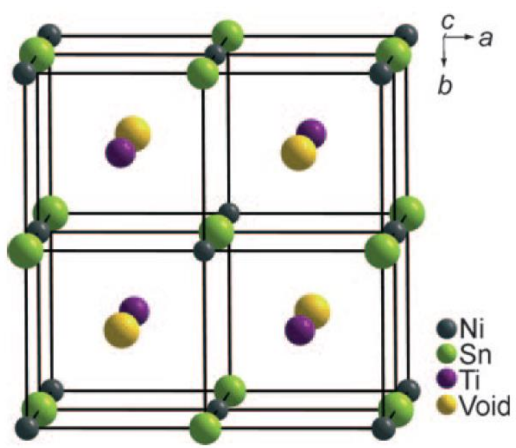
Skutterudite



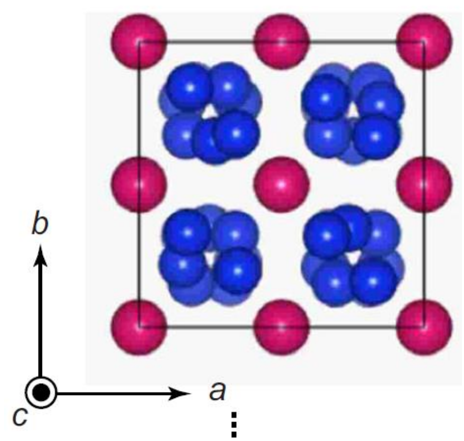
Clathrate



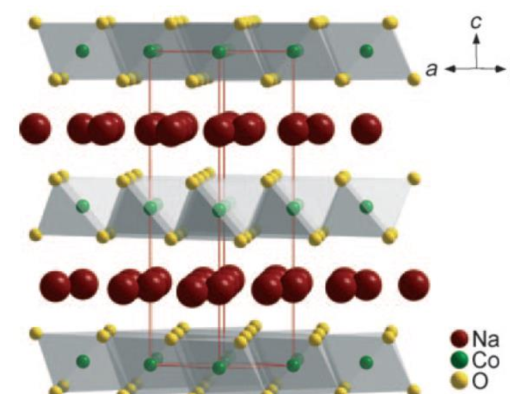
Half Heusler



Silicide



Metal Oxide

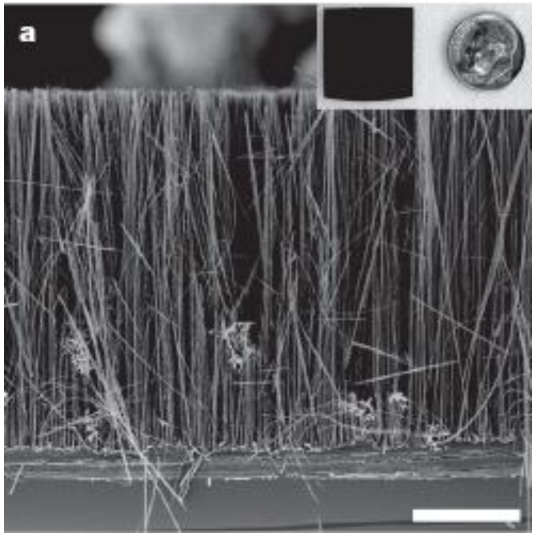


Sootsman *et al.*, *Angew .Chem.* (2009)

Miyazaki *et al.*, *Phys. Rev. B* (2008)

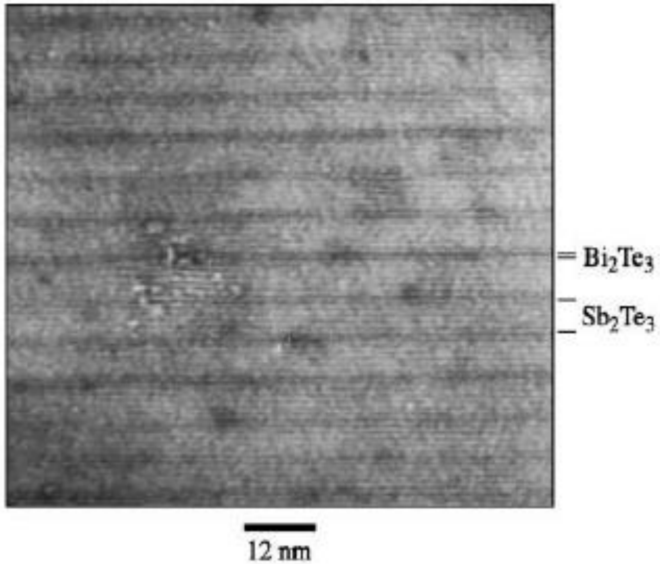
Nanostructured Materials

Wires:



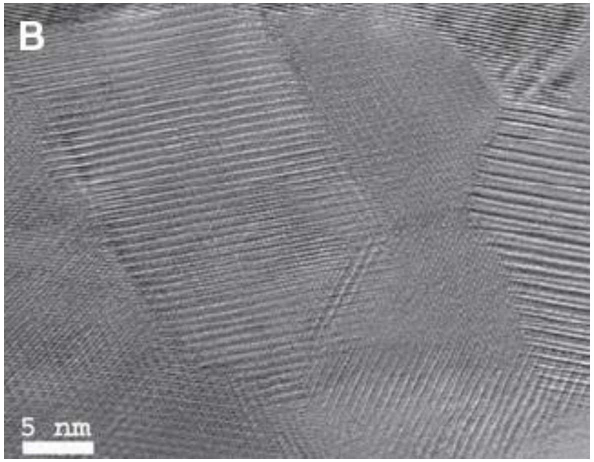
Hochbaum *et al.*, *Nature* (2008)

Superlattices:



Bottner *et al.*, *MRS Bul.* (2006)
Harman *et al., J. Elec. Matl. (2000)*

Particles:

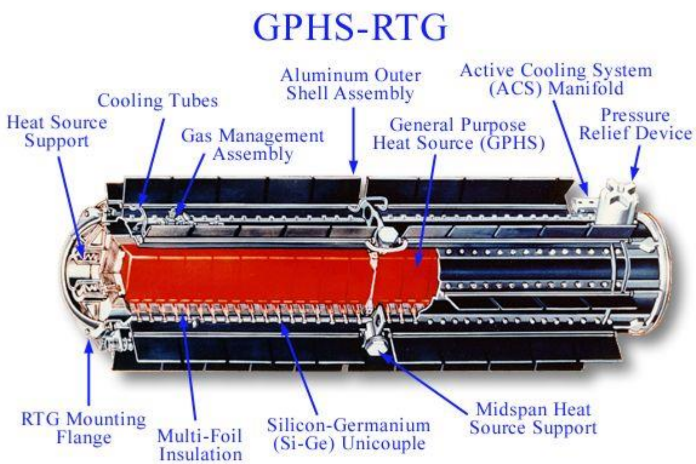


Poudel *et al.*, *Science* (2008)

Thermoelectrics Applications

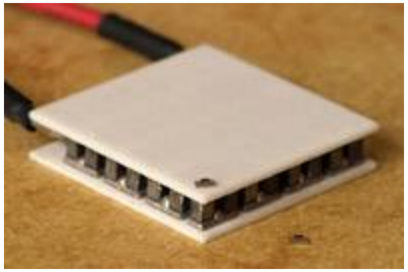
Current

Space exploration:



www.nasa.gov

Electronics cooling:



www.micropelt.com

Future

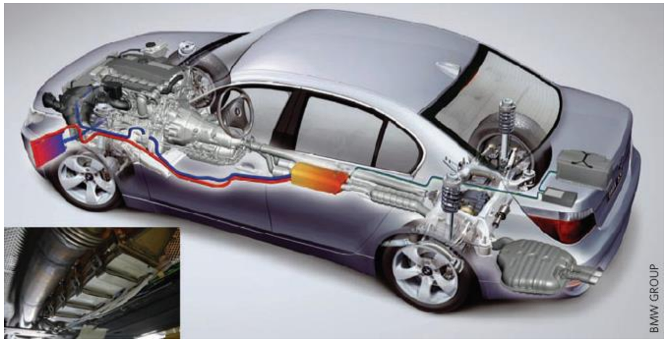
Industrial furnaces:

www.fuelsavessystems.com

Appliances:

www.boschappliances.com

Automotive exhaust:

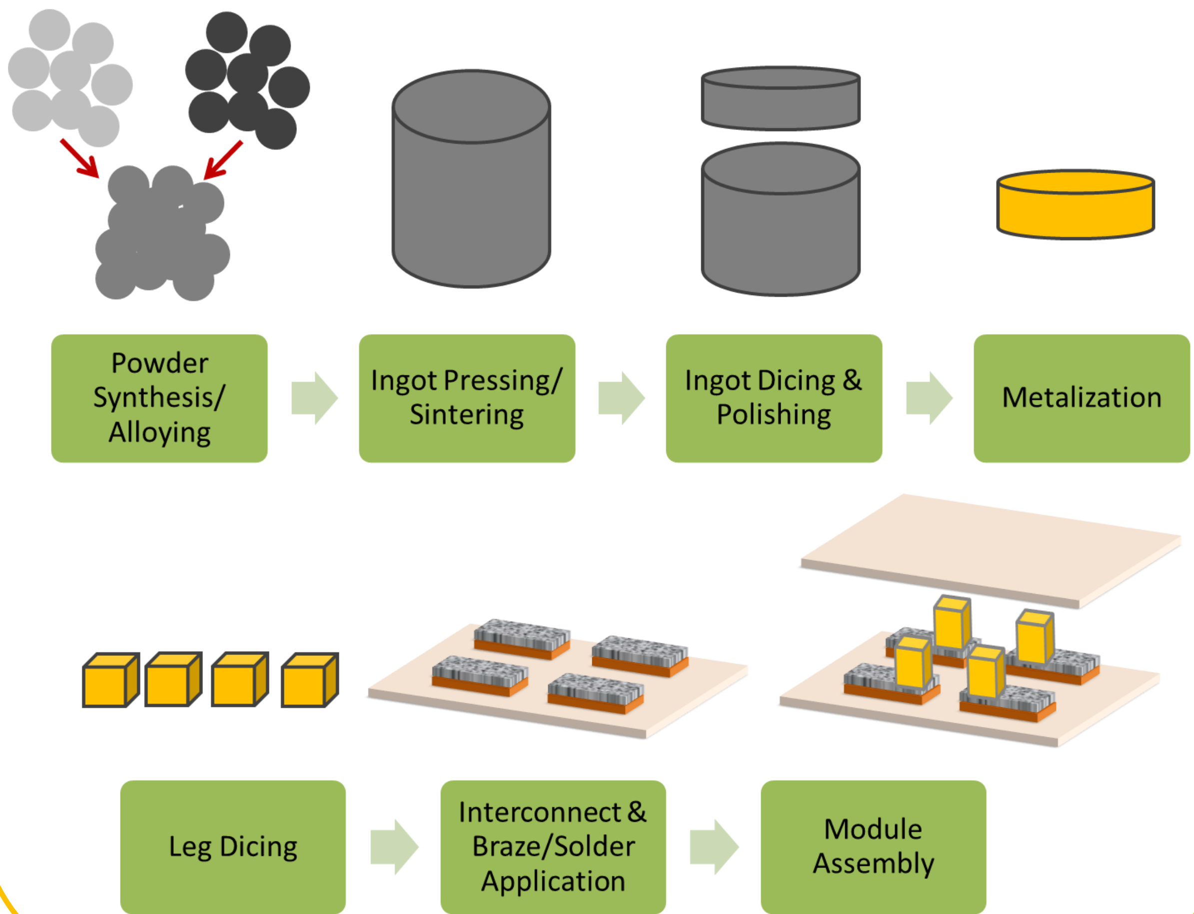


Vining, *Nature Materials*, 2009

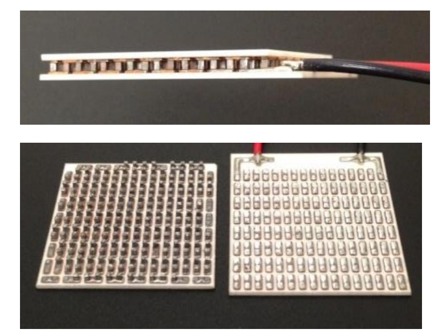
Body heat:

Manufacturing Process

Traditional Manufacturing



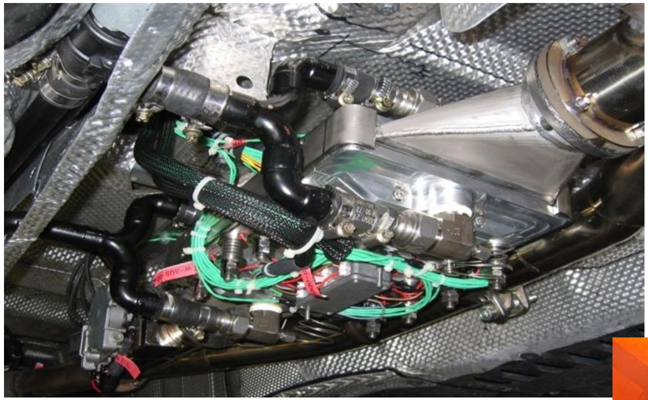
Thermoelectric Module



S. LeBlanc, “Thermoelectric Generators: Linking Material Properties and Systems Engineering for Waste Heat Recovery,” *Sustainable Materials & Technologies* (2014)

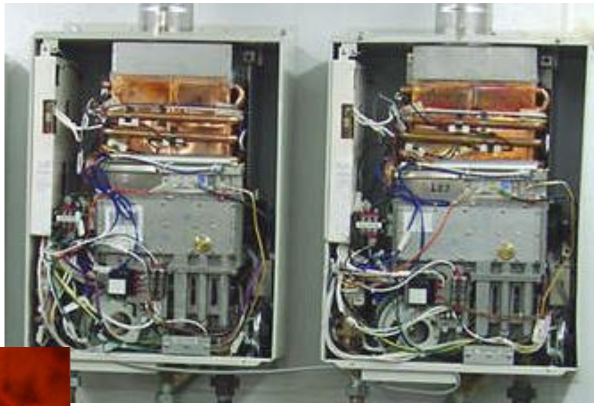
Potential Applications

Automotive Exhaust



www.bosch.com

Water Heater



www.water.arredemo.org

Industrial Furnace

www.risenterprises.com

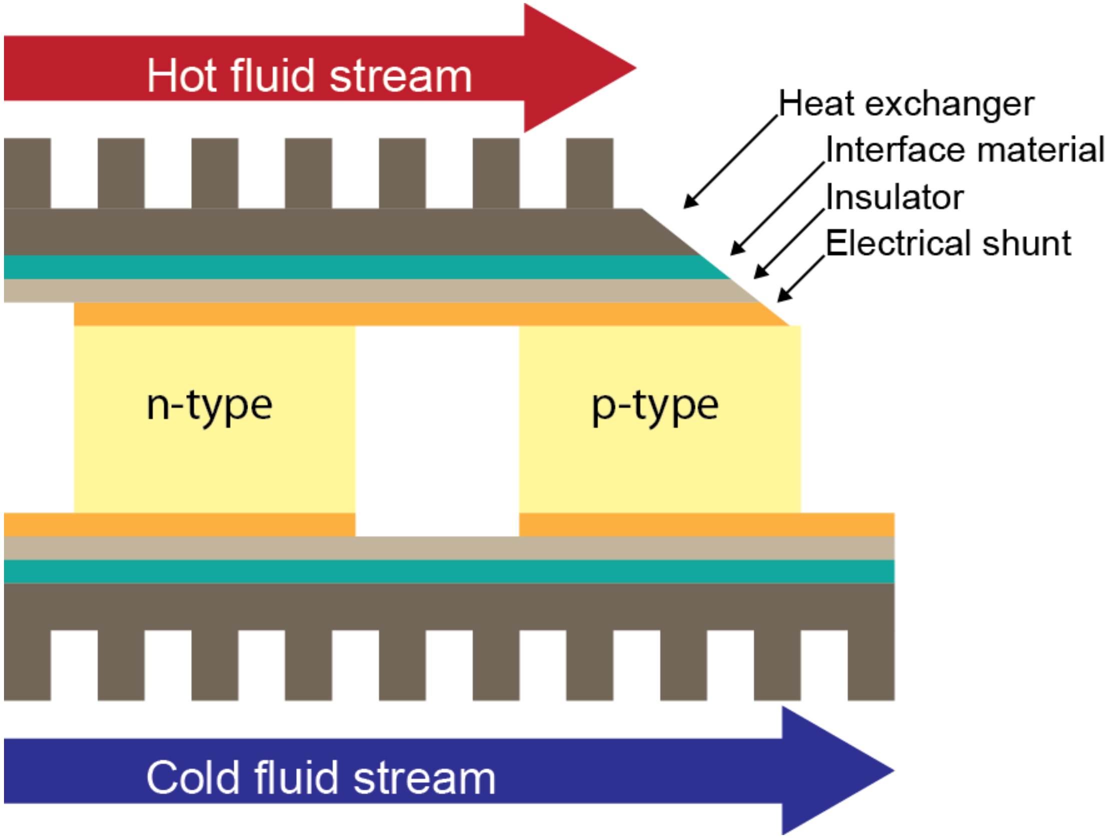
Gas Turbine

www.usa.siemens.com

Glass Lehr

www.glassfurnacemaker.com

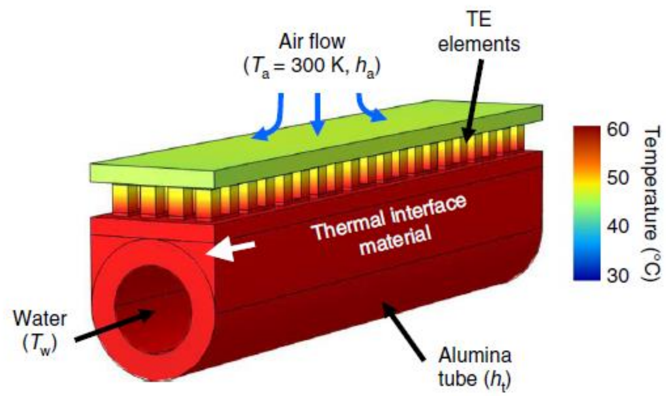
System Figure-of-Merit

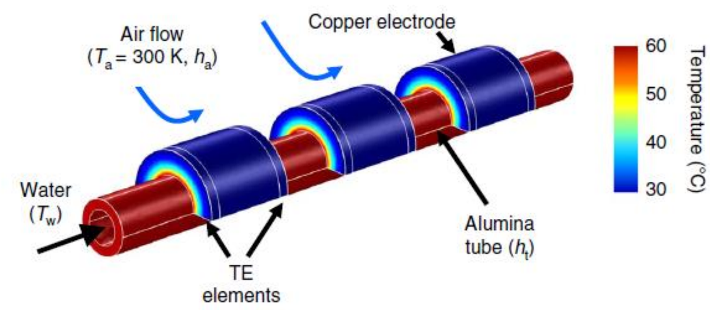


$$ZT = \frac{S_{pn}^{\ 2}}{KR} T$$

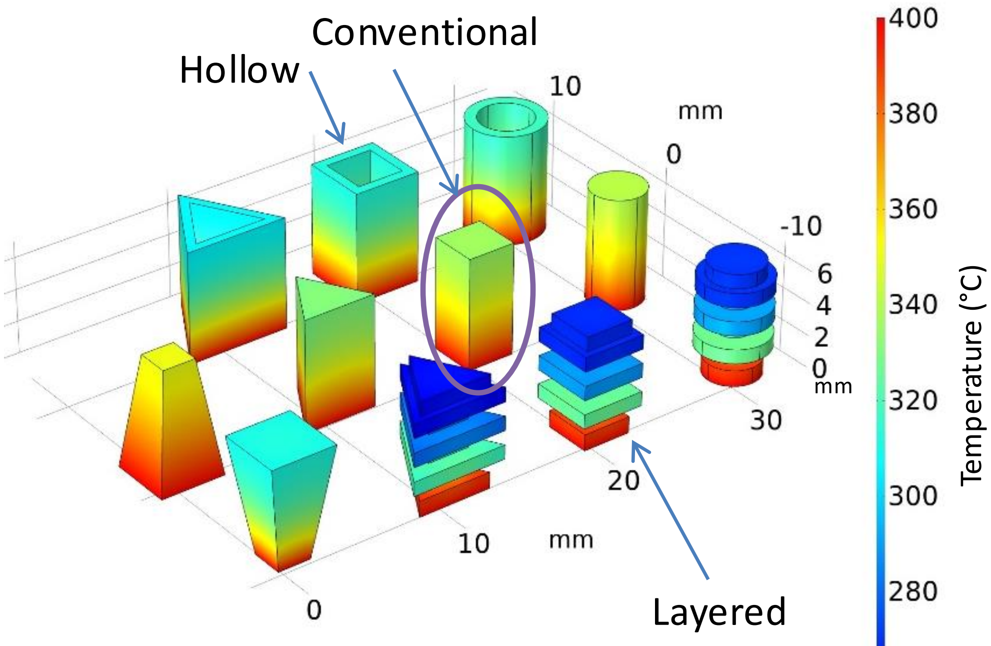
S = combined Seebeck coefficient
R = electrical resistance
K = thermal conductance

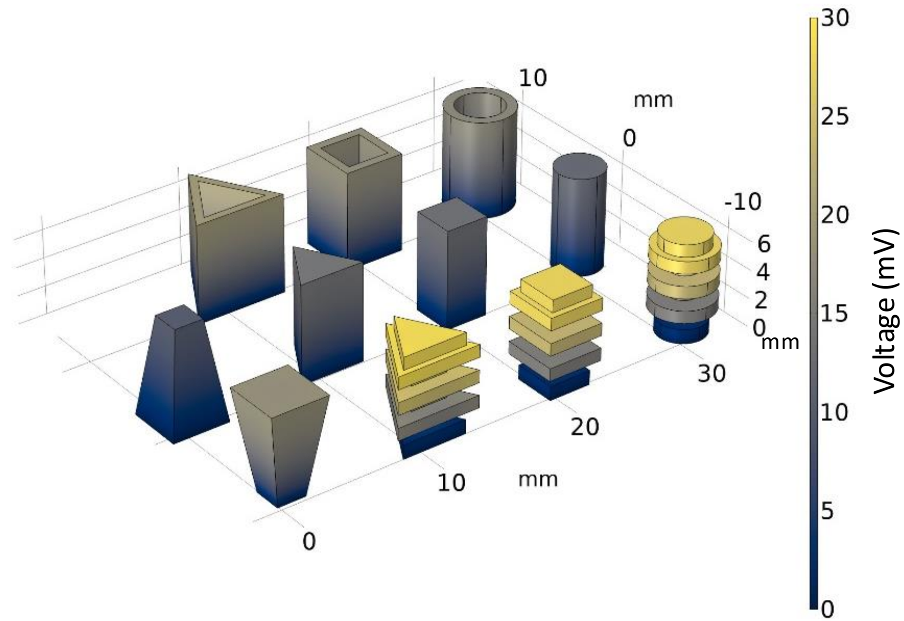
System Integration & Adaptability





F. Kim et al., *Nature Energy* (2018)

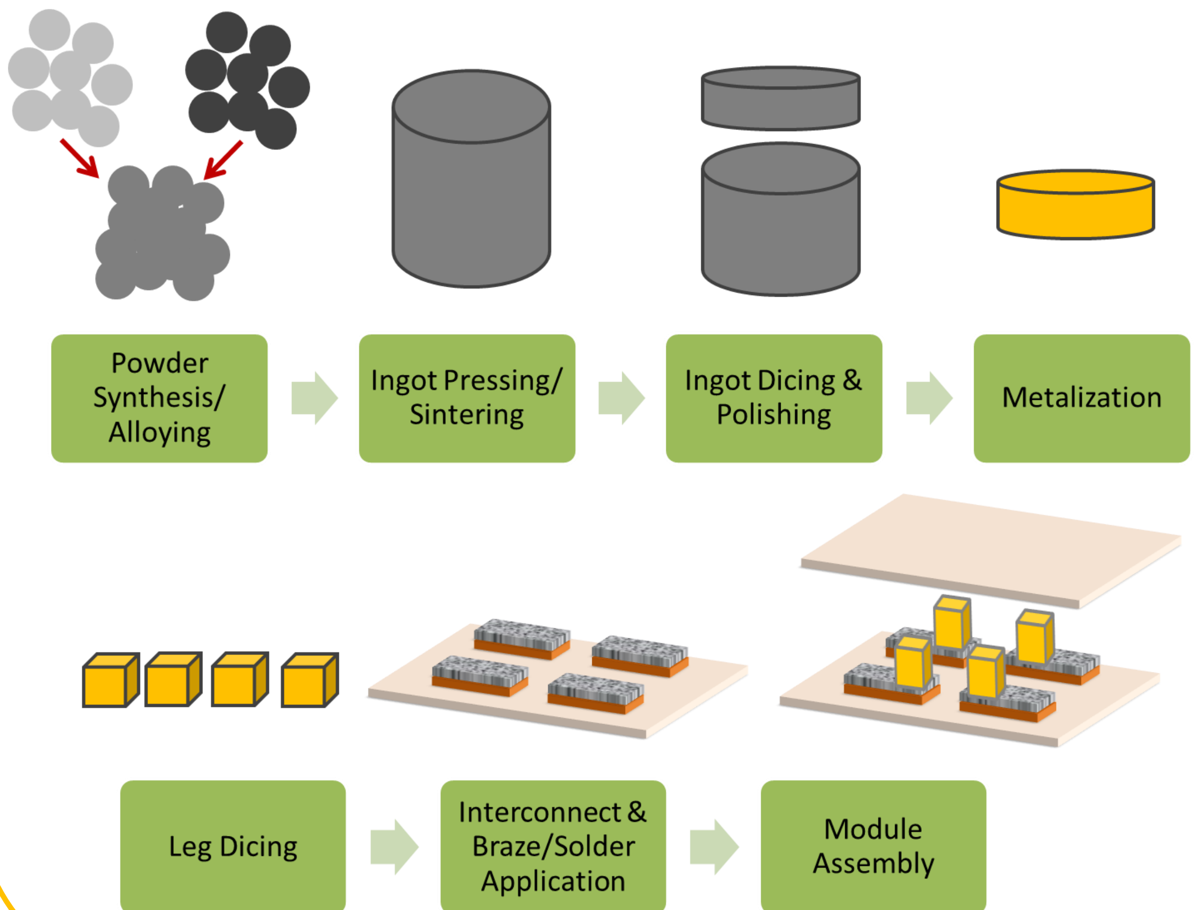




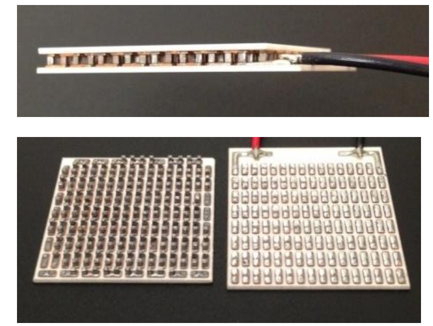
Y. Thimont, S. LeBlanc, *J. Applied Physics* (2019)

Manufacturing Challenges

Traditional Manufacturing



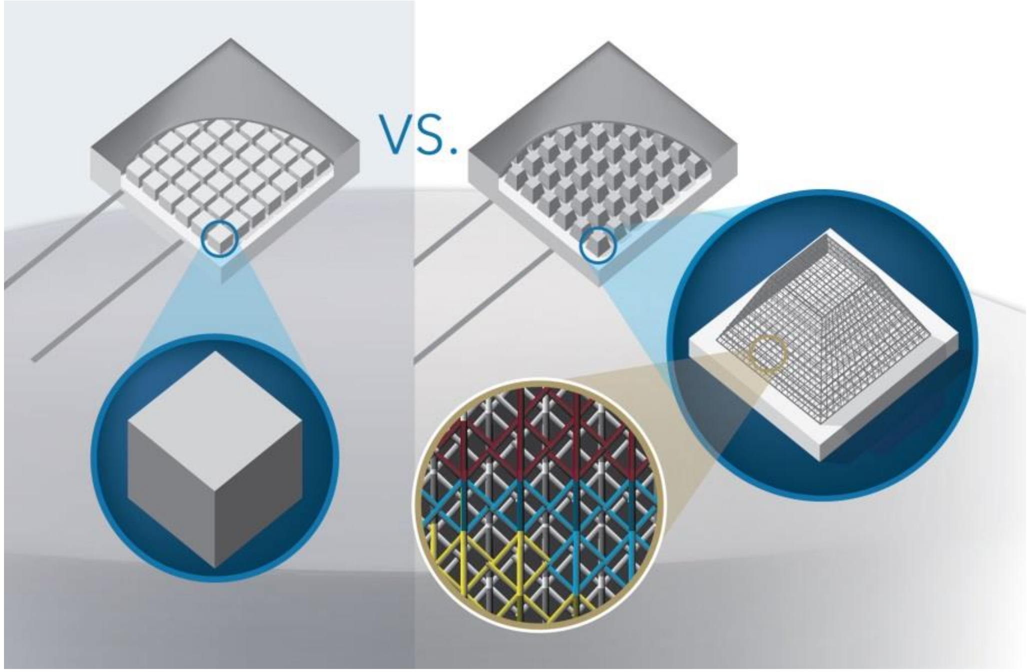
Thermoelectric Module



- ***Limited geometries***
- ***Significant material loss***
- ***Interface & integration challenges***
- ***Lengthy processing time***
- ***Rudimentary assembly***

S. LeBlanc, "Thermoelectric Generators: Linking Material Properties and Systems Engineering for Waste Heat Recovery," *Sustainable Materials & Technologies* (2014)

Materials-to-Device Integration



Materials

- *Engineer material composition*
- *Control material structure from nano- to meso-scale*

Manufacturing

- *Enable new, tunable device geometry beyond solid block-like "legs"*
- *Eliminate assembly steps*

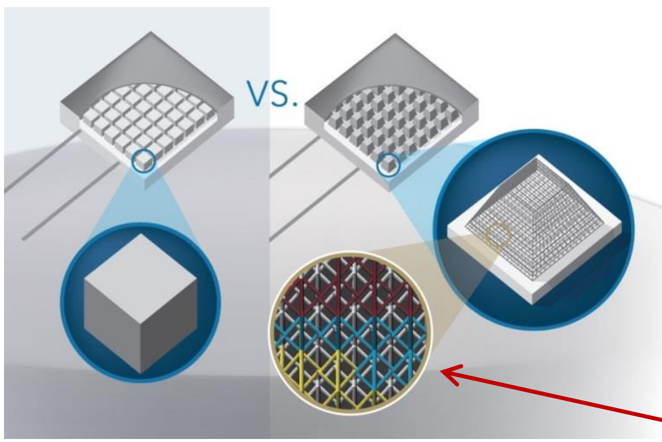
System integration

- *Build thermoelectric materials and device into system-level components (electrical shunts, substrates, heat exchangers)*
- *Engineer interfaces between materials and components*

Re-envision Thermoelectric Module

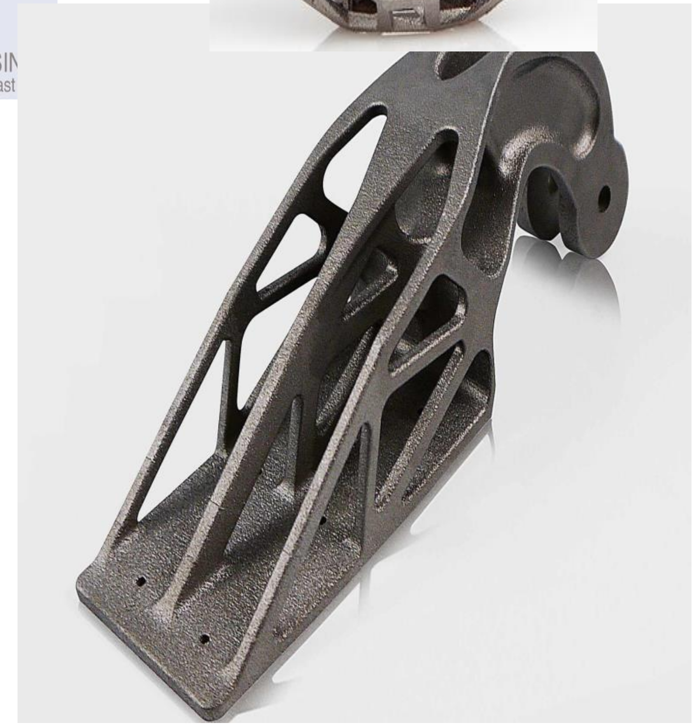
Enable multifunctional materials:

"Sheets" of thermoelectric material with <u>hierarchical structure</u> and <u>engineered composition</u> to enable integrated thermal management and power generating panels.

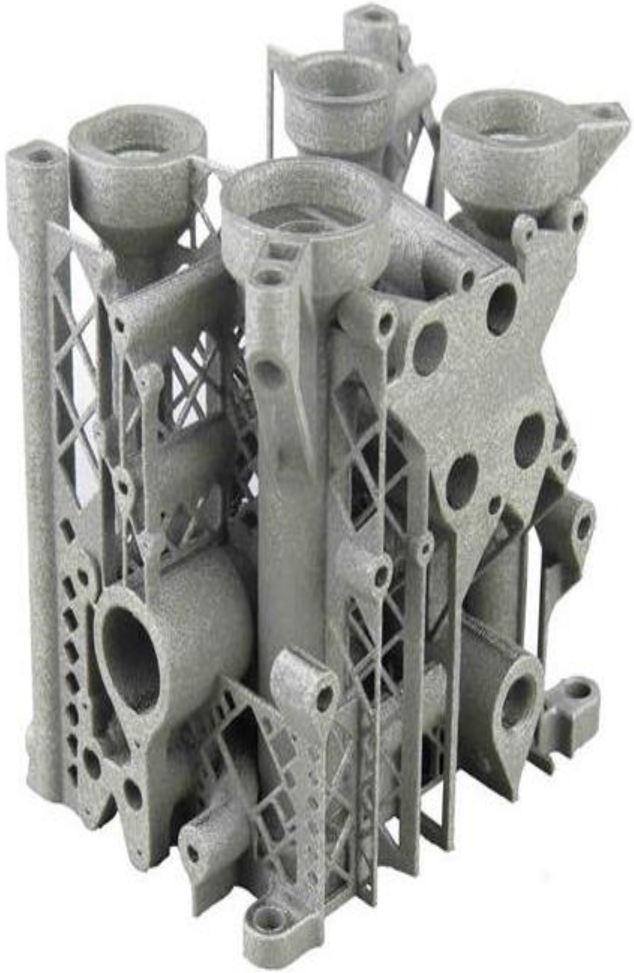


darpa.mil

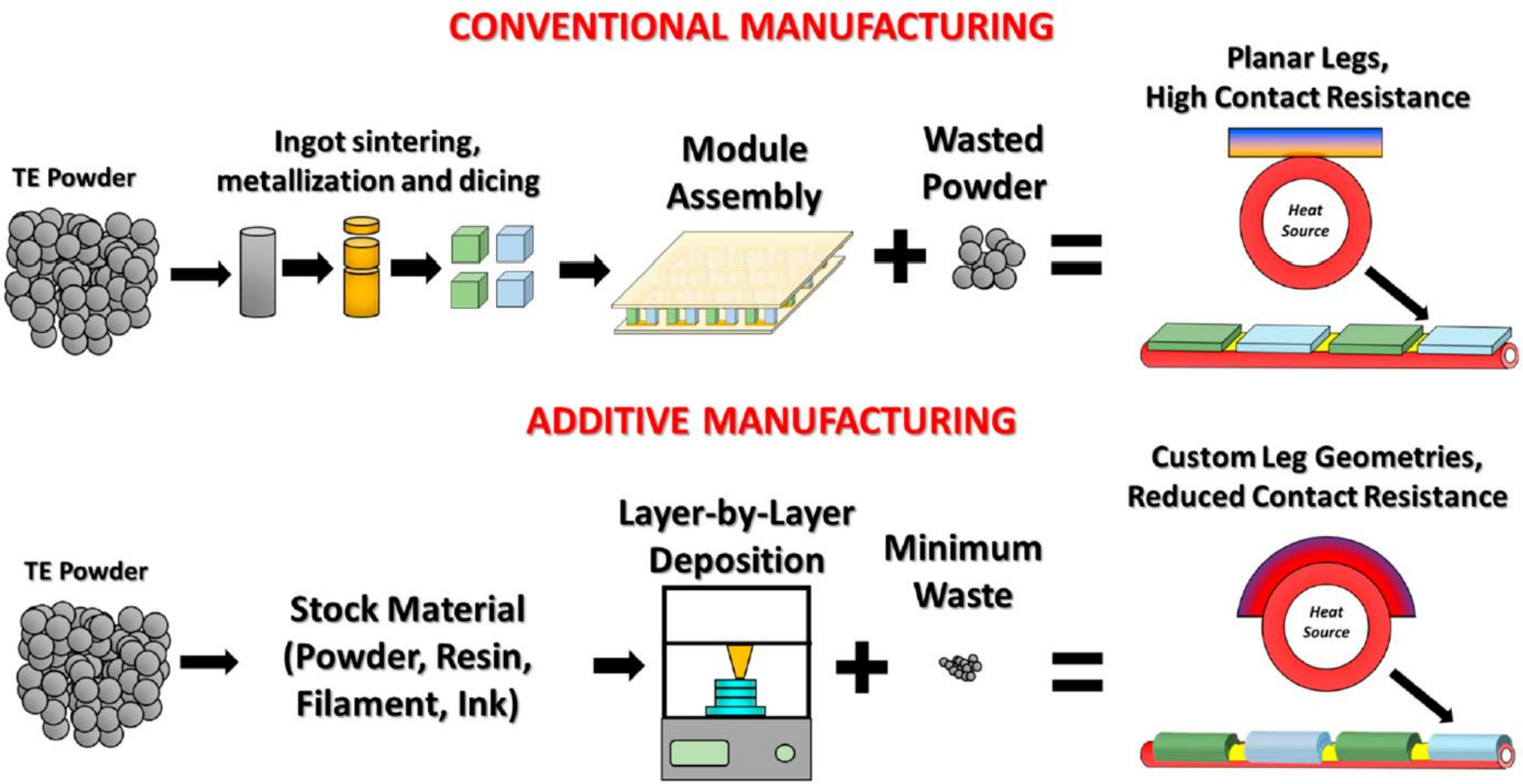
Strong, Lightweight, Customized Parts



…with Small, Complex Features

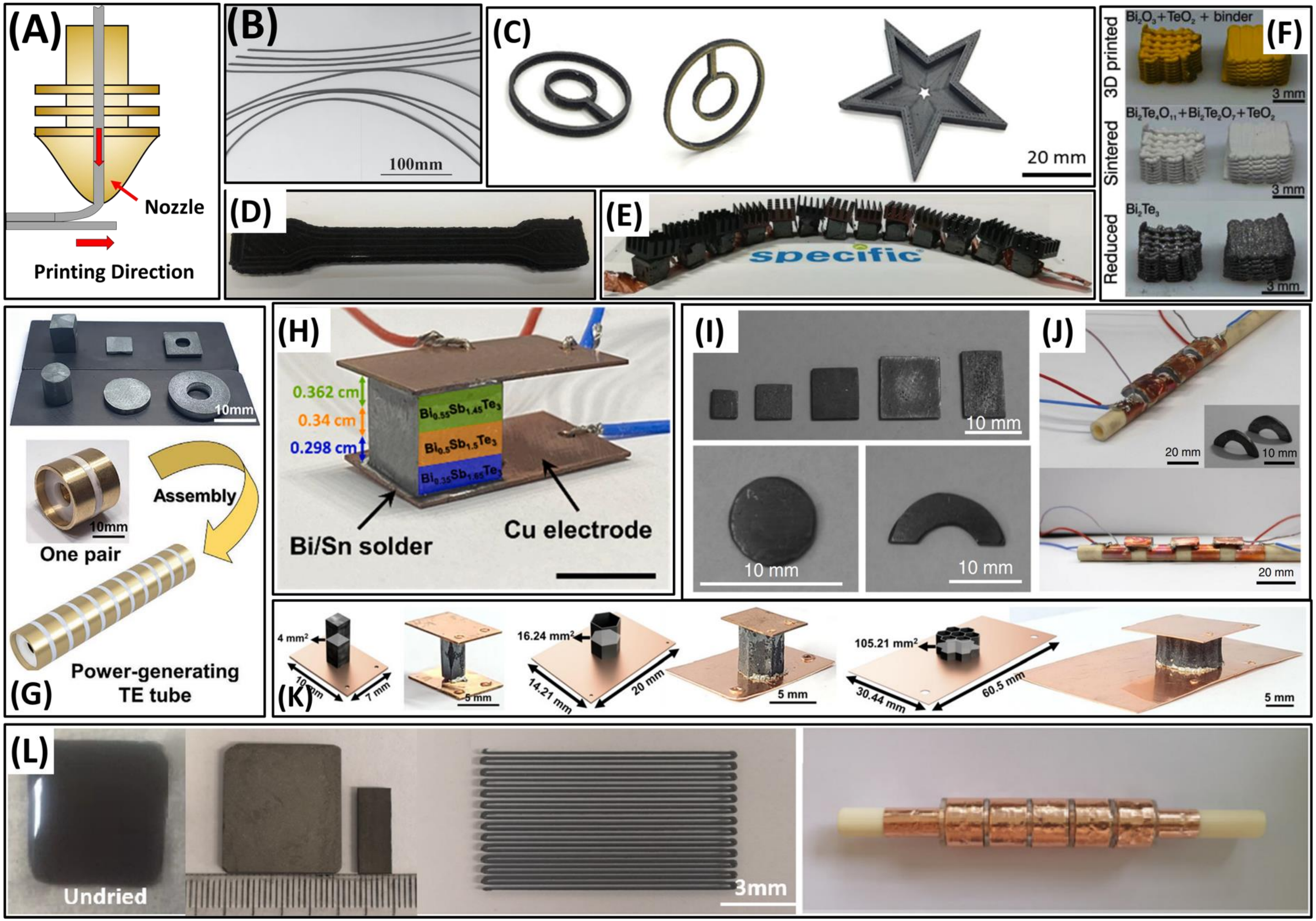


Additive Manufacturing as a Tool



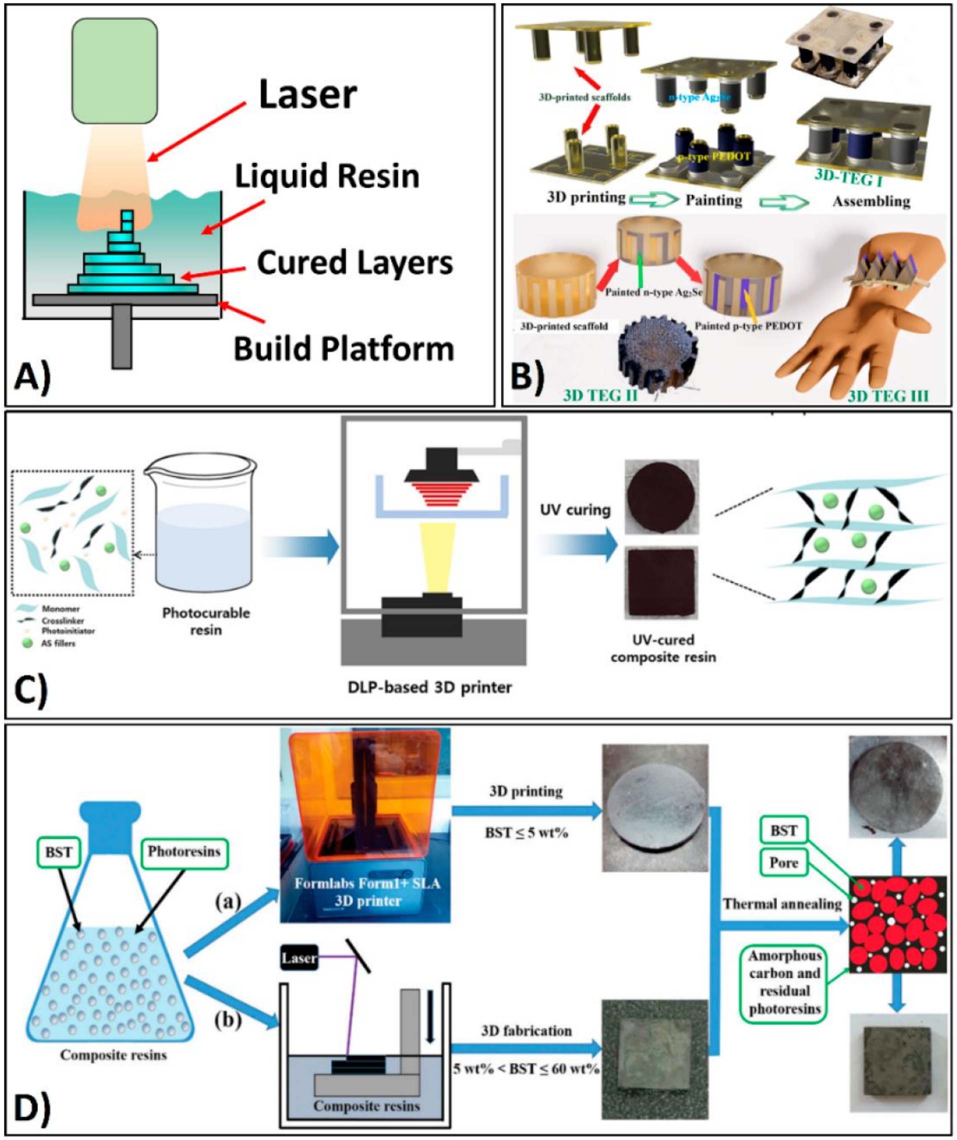
C. Oztan, S. LeBlanc, *Energies* (2022)

Material Extrusion



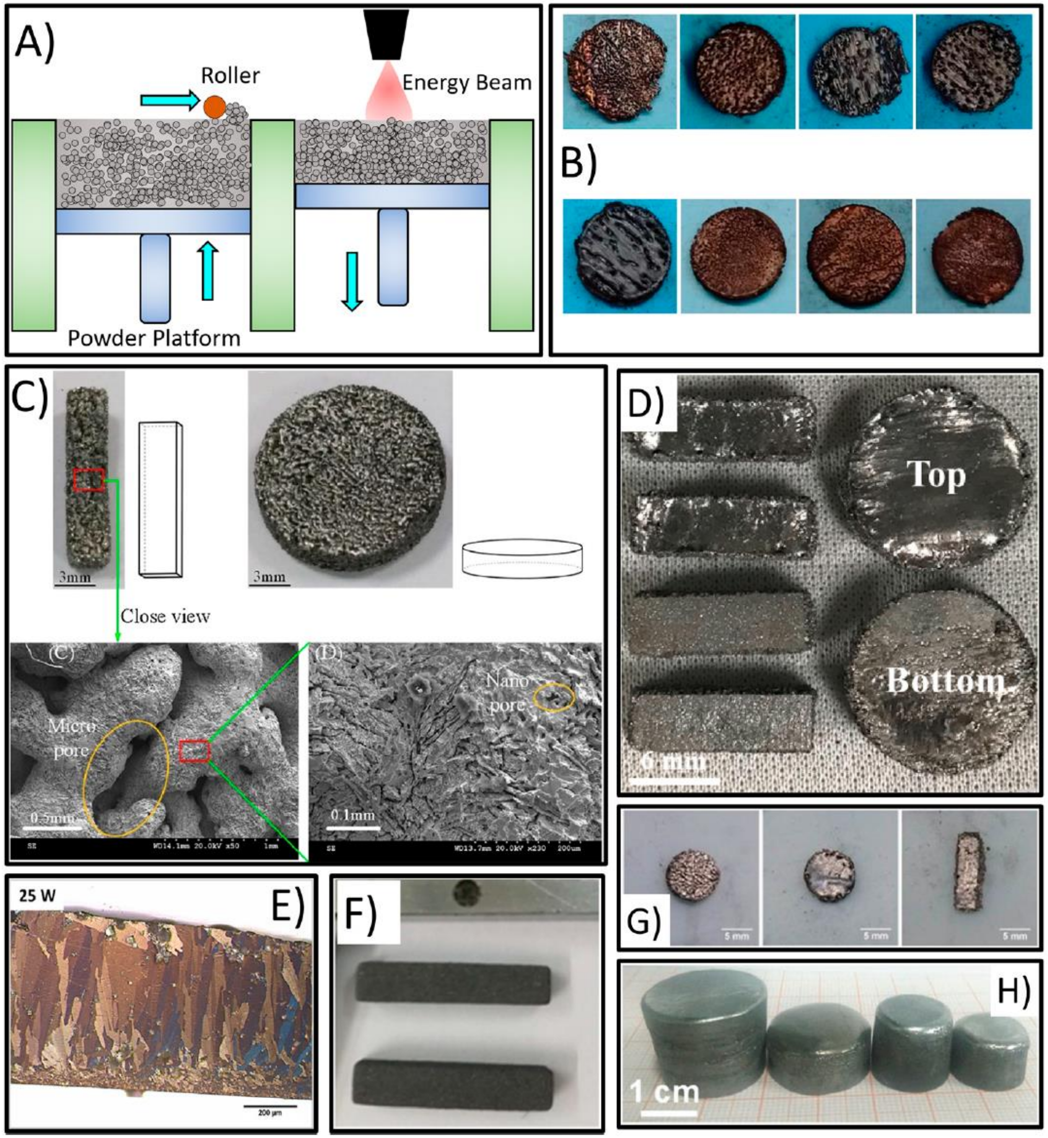
C. Oztan, S. LeBlanc, *Energies* (2022)

Vat Polymerization



C. Oztan, S. LeBlanc, *Energies* (2022)

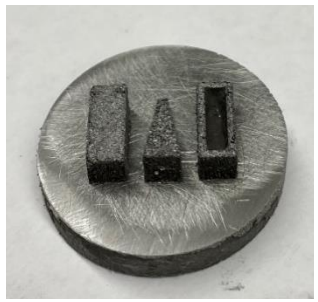
Powder Bed Fusion



C. Oztan, S. LeBlanc, *Energies* (2022)

Custom Shapes & Properties

Laser powder bed fusion (selective laser melting):

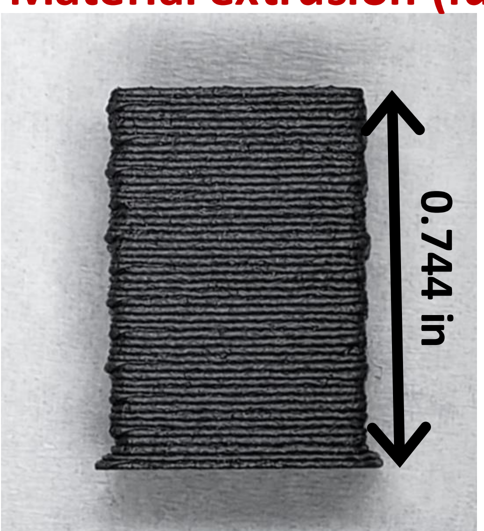


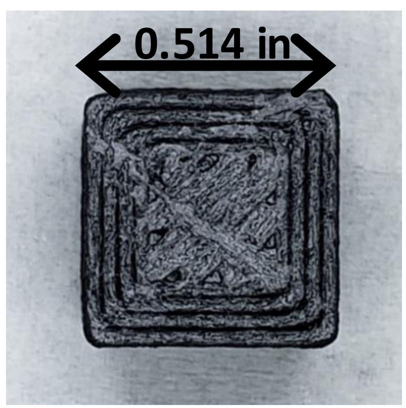
Collaboration with Prof. Ji Ma

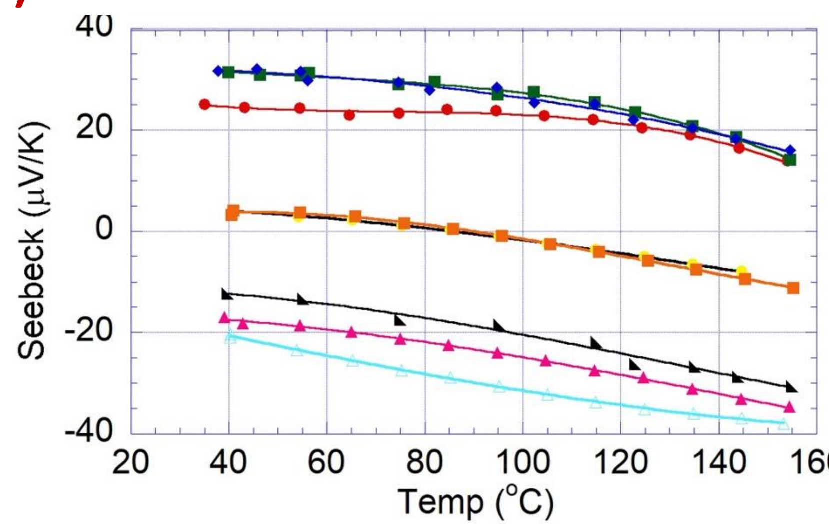
UNIVERSITY of VIRGINIA

OPEN ADDITIVE™

Material extrusion (fused filament fabrication):

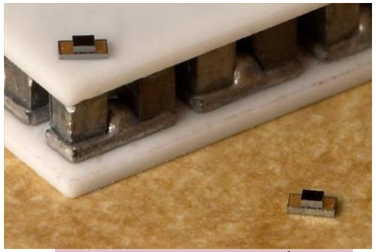




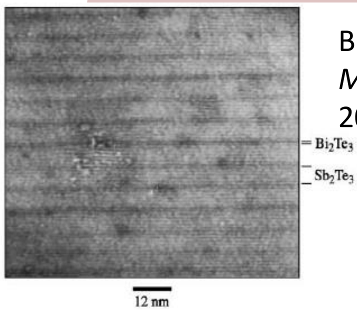


Energy Systems Materials to Devices

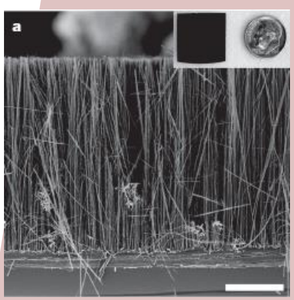
Thermoelectrics



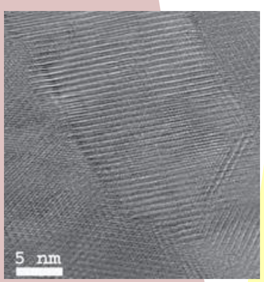
www.micropelt.com



Böttner *et al.*, *MRS Bulletin*, 2006



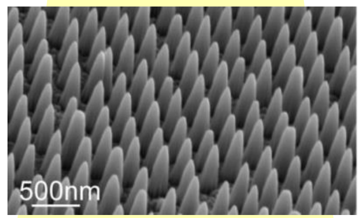
Hochbaum *et al.*, *Nature*, 2008



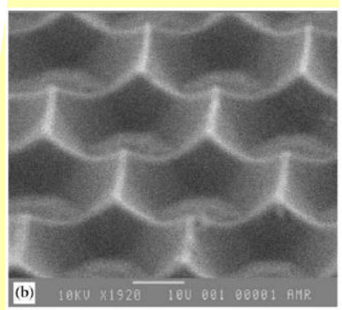
Poudel *et al.*, *Science*, 2008

Solar cells

www.soultek.com



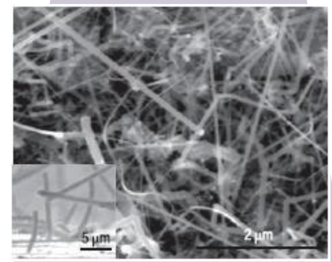
Zhu *et al.*, *Nano Letters*, 2009



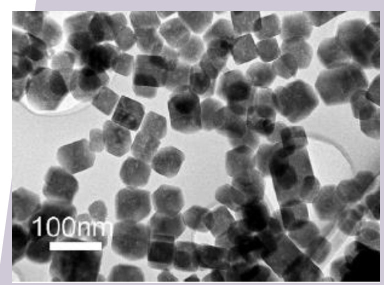
Manea *et al.*, *Solar Energy Matls. & Solar Cells*, 2005

Batteries

www.teslamotors.com

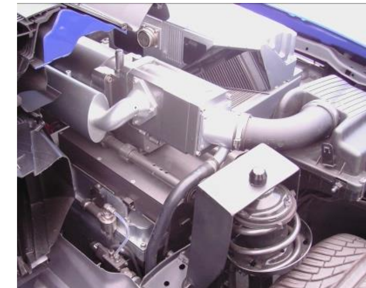


Chan *et al.*, *Nature Nanotech*., 2008

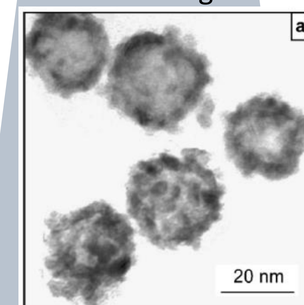


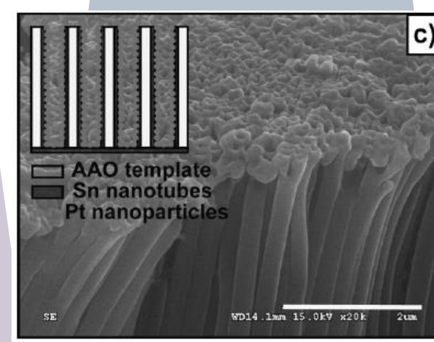
Xiao *et al.* , *Electrochimica Acta*, 2009

Fuel cells



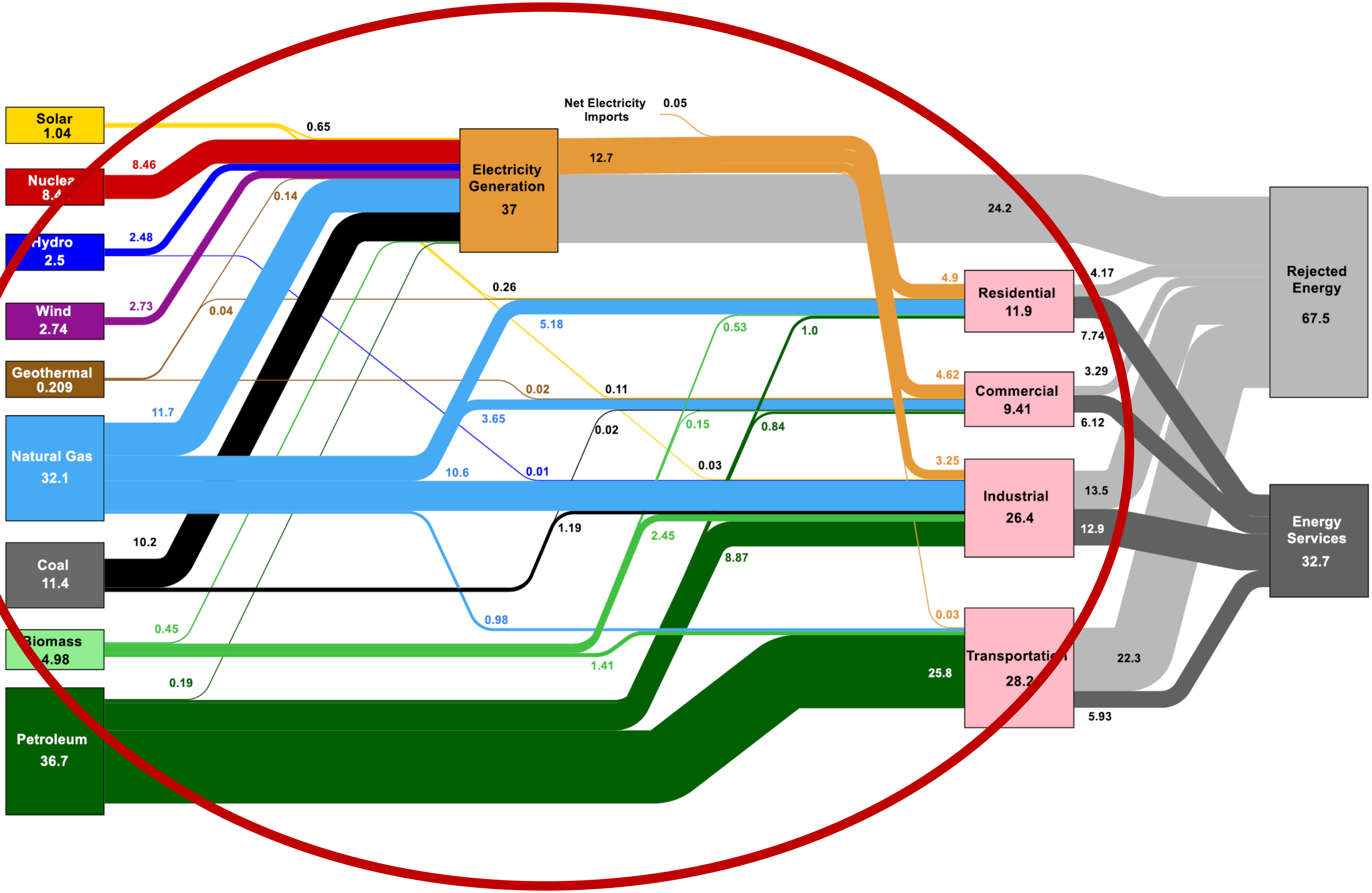
www.gm.com





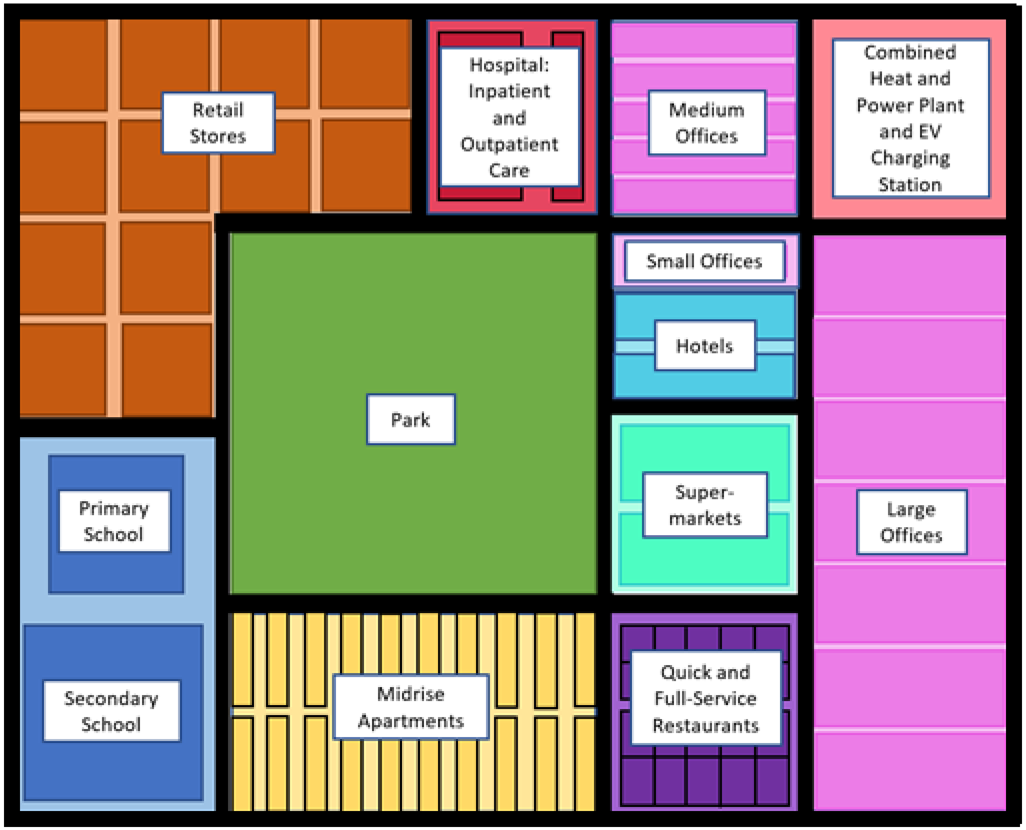
Guo *et al. Adv. Mater.*, 2008

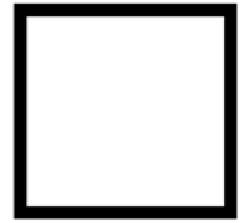
How do we manage all that energy?



https://flowcharts.llnl.gov/commodities/energy

Example Community's Energy Systems



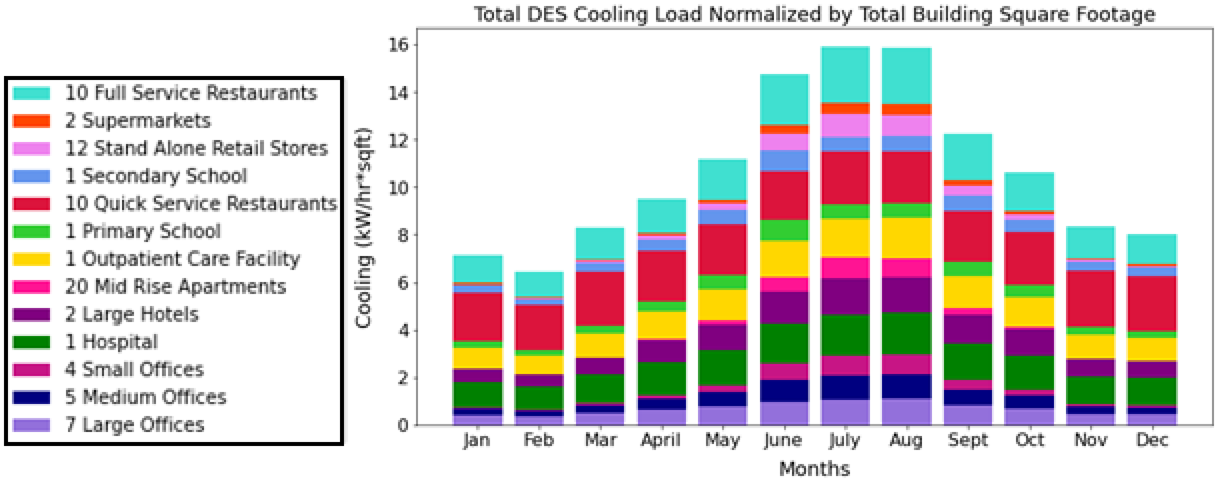


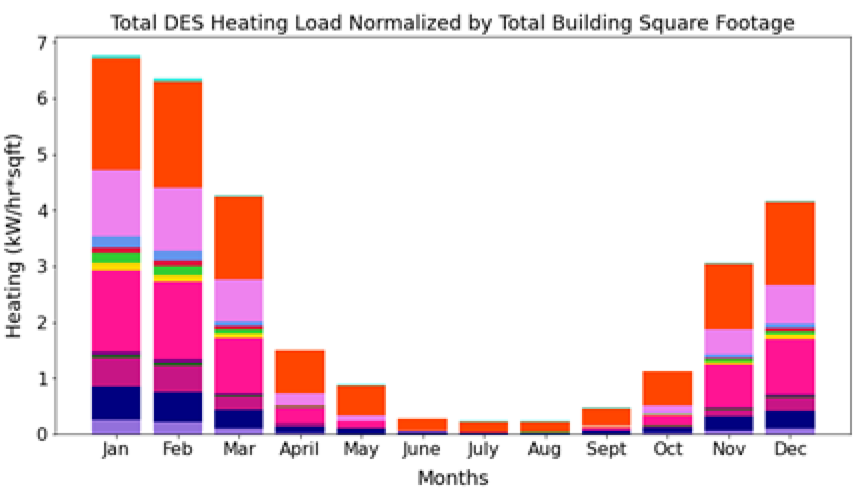
= One City Block (100,000 square feet)

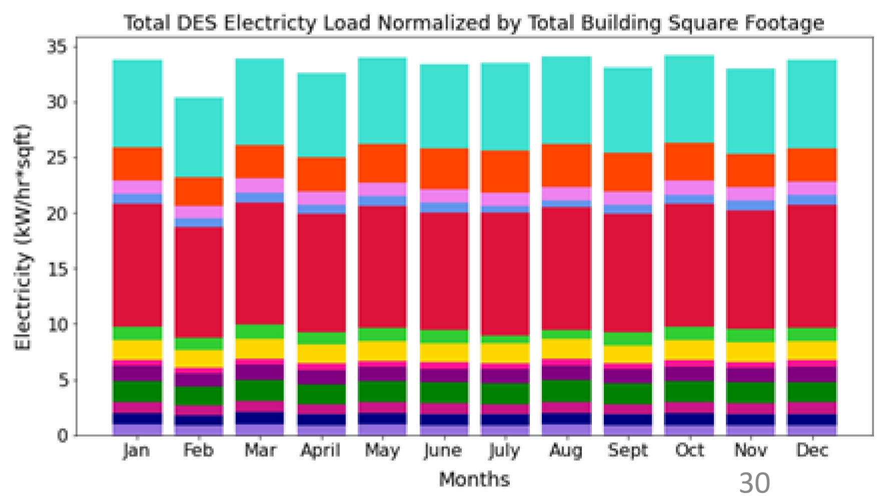
- 1 Primary and 1 Secondary School
- 20 Midrise Apartments
- 10 Quick Service and 10 Full-Service Restaurants
- 7 Large, 5 Medium, and 4 Small Office Buildings
- 2 Supermarkets
- 2 Hotels
- 1 Combined Heat and Power Plant, and 1 EV Charging Station
- 1 Hospital with Inpatient and Outpatient Care
- 12 Retail Stores

- Climate Zone 4A
- Combined Heat and Power Plant
- Hot and Chilled Water Thermal Storage
- Battery Storage
- Solar Photovoltaic Panels
- Electric Vehicle Charging Station

Energy Loads



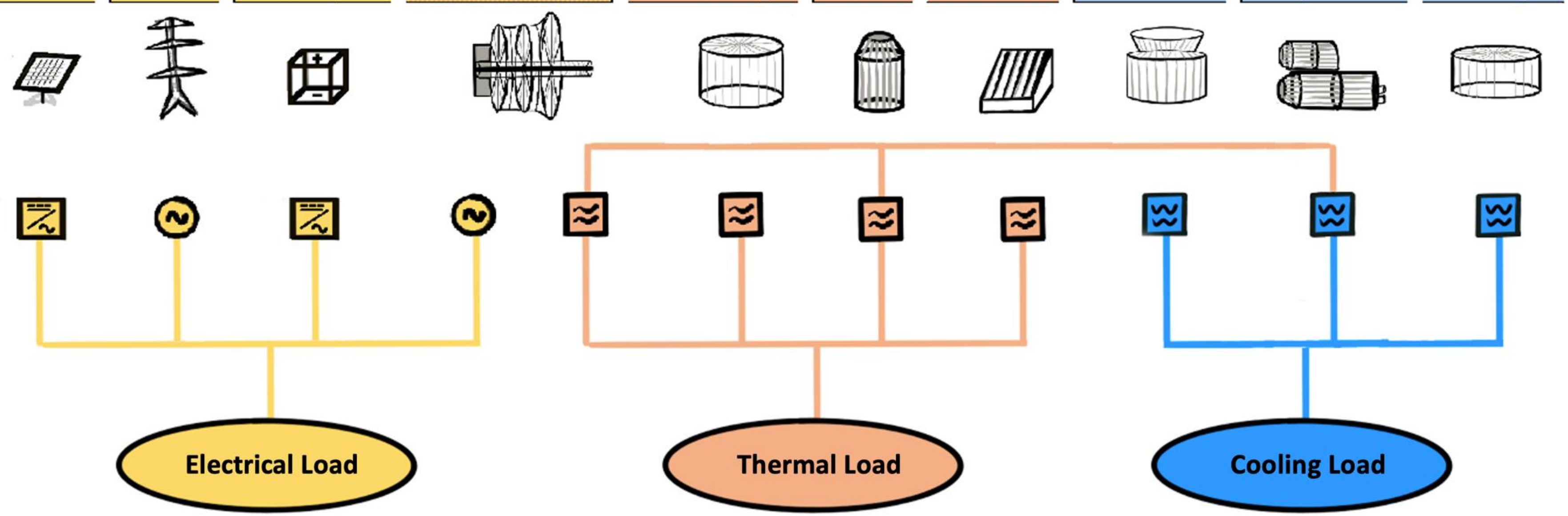




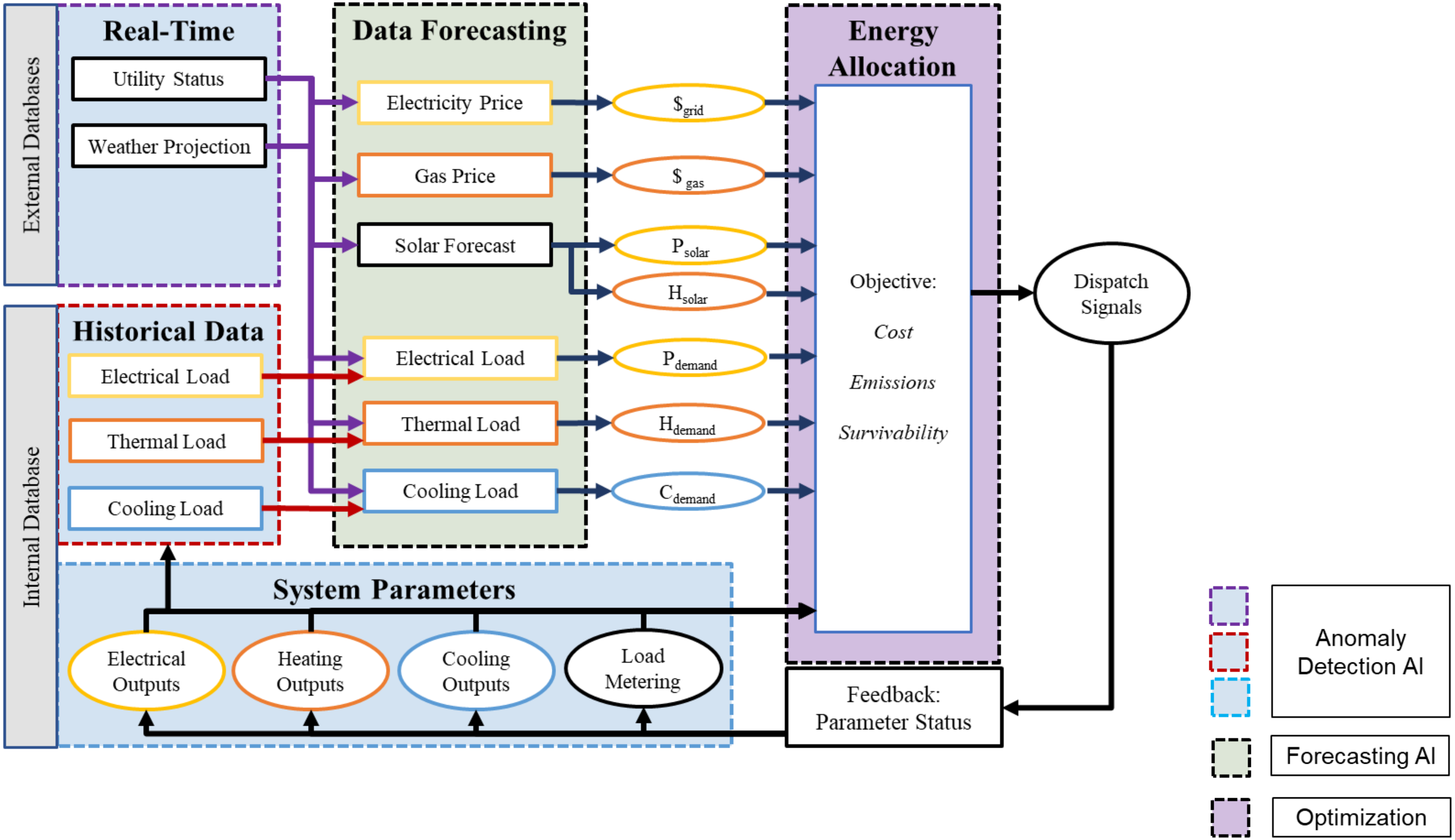
(normalized by building square footage)

Energy System Mix

	Solar	Grid	Battery	CHP	Thermal Storage	Boiler	Solar Heater	Towers & Chiller	Absorption Chiller	Ice Storage
Parameter	Power Output	Max In/Out	Capacity	Heat Output	Capacity	Heat Output	Heat Output	Output Max	Output Max	Capacity
	[kW]	[kW]	[kWh]	[kW]	[kWh]	[kW]	[kW]	[gpm]	[gpm]	[gal]
	5491	5000	24071	1538	19569	23503	0	26024	2246	1754995
Sizing	Area	Min In/Out	Critical Load Support	Heat Load Percentile	Critical Load Support	% Peak Heat	Area	% Peak Cooling	% CHP Peak Heat	Critical Load Support
	[m^2]	[kW]	[days]	[%]	[days]	[%]	[m^2]	[%]	[%]	[days]
	49139	0	0.50	75	0.50	125	0	125	100	0.50
Energy Resource	Solar	Grid	Battery	CHP	Thermal Storage	Boiler	Solar Heater	Towers & Chiller	Absorption Chiller	Ice Storage



Energy Management System: Design



Baseline & Emergency Operation

EMS Baseline Operation Objective Function:

- Minimizes energy resource operational cost
- Heavy penalty (outage cost) on any load shed, both critical and non-critical load

$$\min \sum_{t \in \mathbf{T}} \Bigg[\underbrace{C^{GR}(P_t^{GRb}, P_t^{GRs})}_{\text{Grid}} + \underbrace{\sum_{i \in \mathbf{I}} C^{HP}(P_{i,t}^{HP}, H_{i,t}^{HP}, x_{i,t}, y_{i,t}, z_{i,t})}_{\text{CHP}} + \underbrace{\sum_{k \in \mathbf{K}} C^{BO}(H_{k,t}^{BO}, u_{k,t})}_{\text{Boilers}} + \underbrace{\sum_{e \in \mathbf{E}} C^{BS}(P_{e,t}^{BSc}, P_{e,t}^{BSd})}_{\text{Battery}} + \underbrace{\sum_{s \in \mathbf{S}} C^{TS}(H_{s,t}^{TSc}, H_{s,t}^{TSd})}_{\text{Thermal Storage}}$$

$$+ \underbrace{\sum_{c \in \mathbf{C}} C^{IS}(C_{c,t}^{ISc}, C_{c,t}^{ISd})}_{\text{Grid}} + \underbrace{\sum_{a \in \mathbf{A}} C^{CT}(C_a^{CT}, l_a)}_{\text{Towers \& Chillers}} + \underbrace{\sum_{b \in \mathbf{B}} C^{SC}(j_b)}_{\text{Steam Chiller}} + \underbrace{C^{ls}(P_t^{ls}, H_t^{ls}, C_t^{ls})}_{\text{Load Shed}} + \underbrace{C^{lsc}(P_t^{lsc}, H_t^{lsc}, C_t^{lsc})}_{\text{Critical Load Shed}} \Bigg]$$

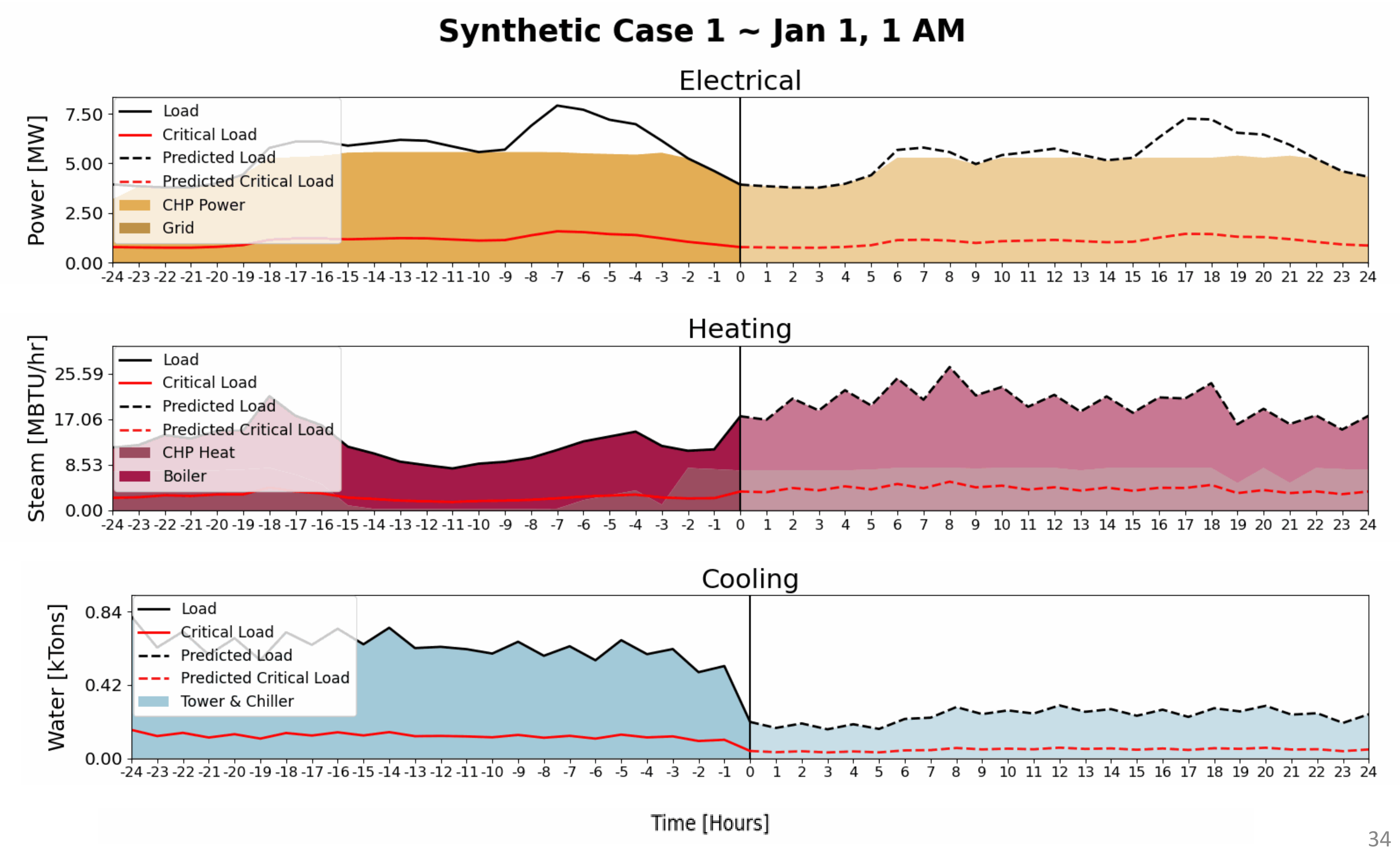
EMS Emergency Operation Objective Function:

- Minimizes energy resource operational cost
- Heavy penalty (outage cost) for critical load shed
- Mild penalty (lack of storage cost) for not having stored energy

$$\min \sum_{t \in T} \Bigg[\underbrace{C^{GR}(P_t^{GRb}, P_t^{GRs})}_{\text{Grid}} + \underbrace{\sum_{i \in I} C^{HP}(P_{i,t}^{HP}, H_{i,t}^{HP}, x_{i,t}, y_{i,t}, z_{i,t})}_{\text{CHP}} + \underbrace{\sum_{k \in K} C^{BO}(H_{k,t}^{BO}, u_{k,t})}_{\text{Boilers}} + \underbrace{\sum_{e \in E} C^{BS}(P_{e,t}^{BSc}, P_{e,t}^{BSd})}_{\text{Battery}} + \underbrace{\sum_{s \in S} C^{TS}(H_{s,t}^{TSc}, H_{s,t}^{TSd})}_{\text{Thermal Storage}}$$

$$+ \underbrace{\sum_{c \in C} C^{IS}(C_{c,t}^{ISc}, C_{c,t}^{ISd})}_{\text{Grid}} + \underbrace{\sum_{a \in A} C^{CT}(C_a^{CT}, l_a)}_{\text{Towers \& Chillers}} + \underbrace{\sum_{b \in B} C^{SC}(j_b)}_{\text{Steam Chiller}} + \underbrace{C^{lsc}(P_t^{lsc}, H_t^{lsc}, C_t^{lsc})}_{\text{Critical Load Shed}} + \underbrace{\sum_{e \in E} \left(C^{BSe}(E_{e,t}^{BS})\right)}_{\text{Electrical Storage Penalty}} + \underbrace{\sum_{s \in S} \left(C^{TSe}(E_{s,t}^{TS})\right)}_{\text{Thermal Storage Penalty}} + \underbrace{\sum_{c \in C} \left(C^{ISe}(E_{c,t}^{IS})\right)}_{\text{Cold Storage Penalty}} \Bigg]$$

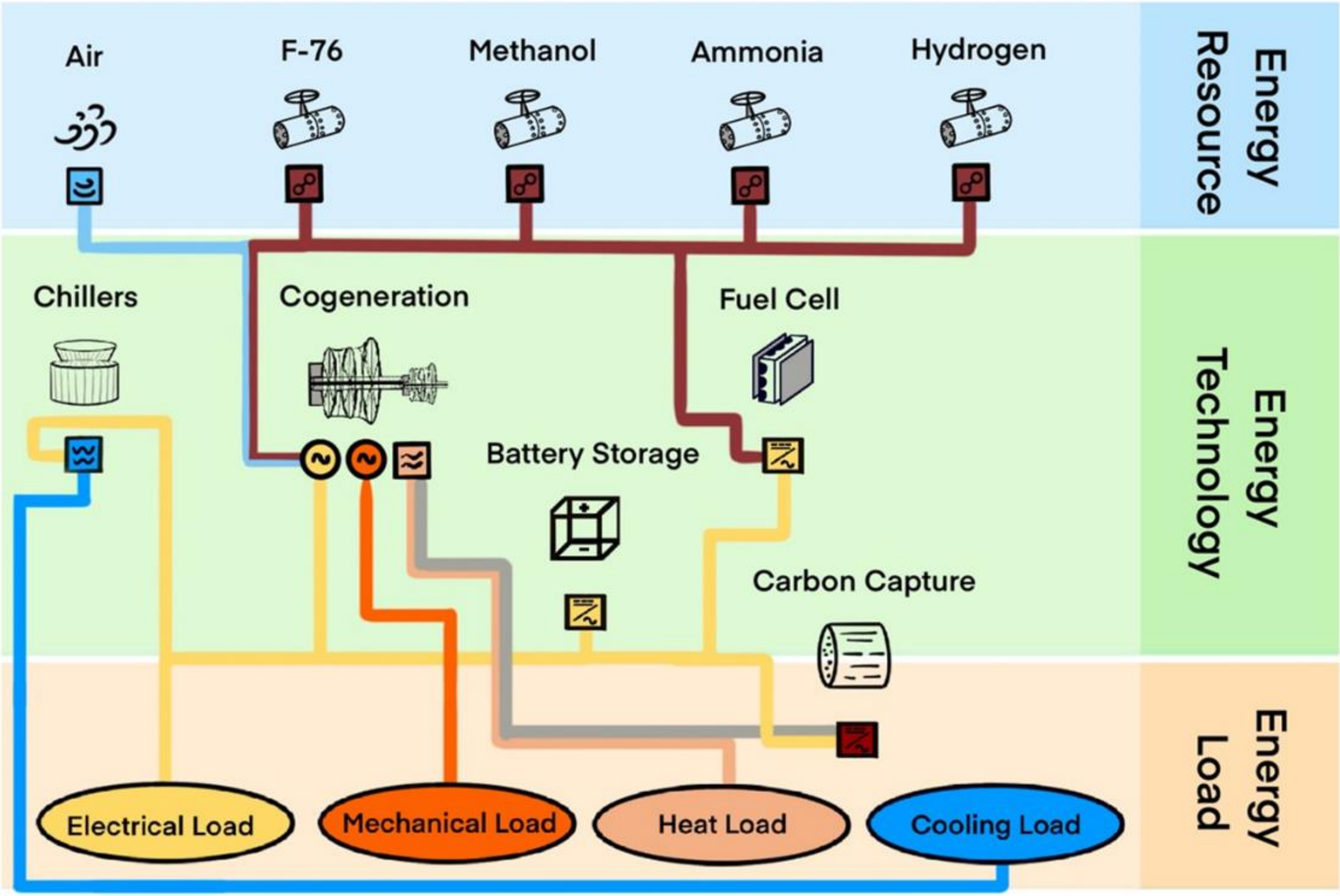
Energy Management System: Operation



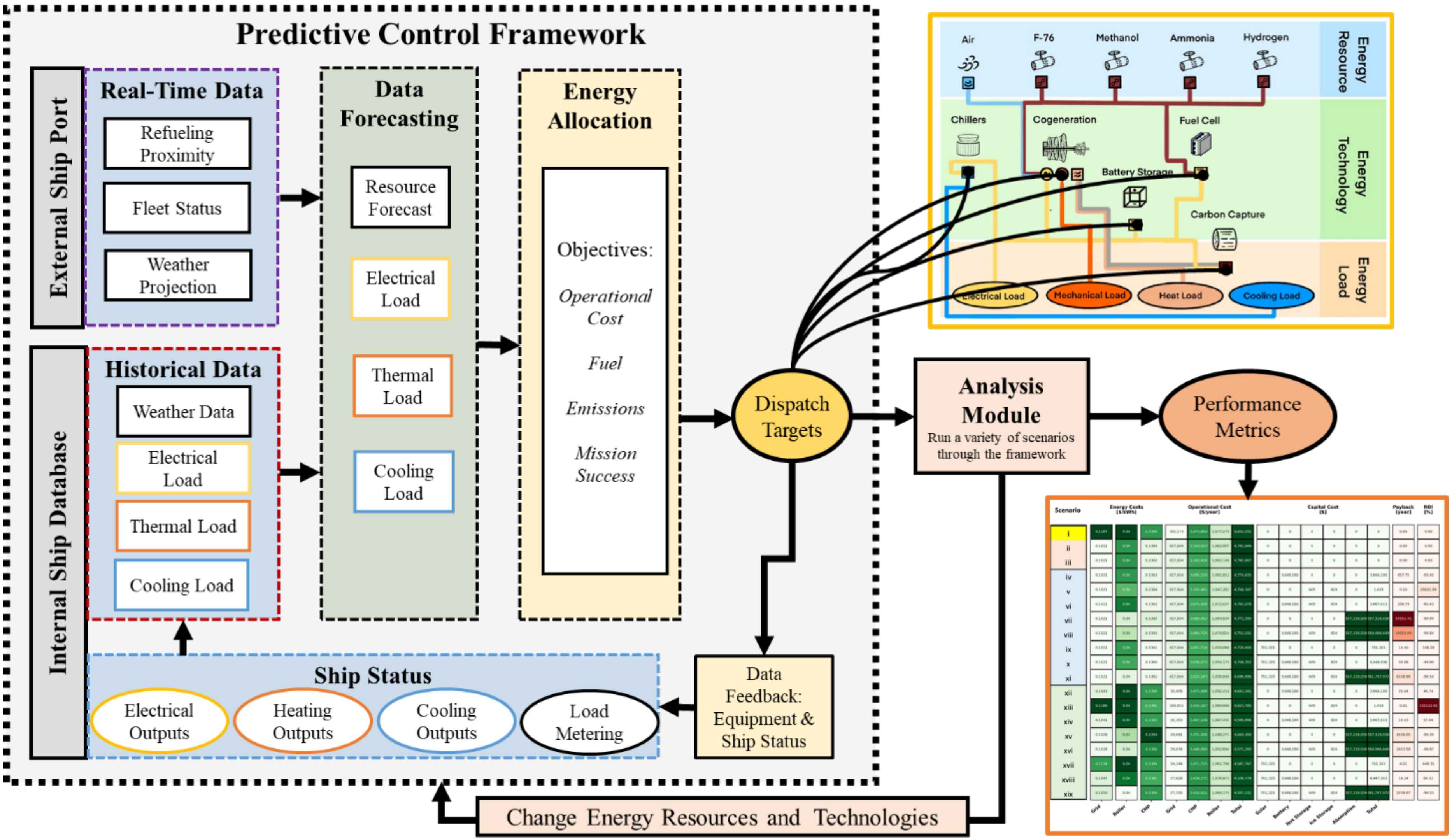
Scenarios Evaluated by Costs

Name	Grid Buy	Grid Sell	Techologies	Energy Costs [$/kWh] Grid	Energy Costs [$/kWh] Boiler	Energy Costs [$/kWh] CHP	Operational Cost [$/year] Grid	Operational Cost [$/year] CHP	Operational Cost [$/year] Boiler	Operational Cost [$/year] Total	Capital Cost [$] Solar	Capital Cost [$] Battery	Capital Cost [$] Hot Storage	Capital Cost [$] Ice Storage	Capital Cost [$] Absorption	Capital Cost [$] Total	Payback [year]	ROI [%]
i	**Yes**	**No**	**Base: CHP, Boiler, and Chiller**	0.1088	0.24	0.0815	7,196,547	1,006,820	773,031	8,976,397	0	0	0	0	0	0	0.00	0.00
ii	Yes	Yes	Base: CHP, Boiler, and Chiller	0.1087	0.24	0.0818	7,215,898	992,942	772,289	8,981,129	0	0	0	0	0	0	0.00	0.00
iii	Yes	No	Base + Battery	0.1057	0.25	0.0731	7,324,488	967,034	769,023	9,060,545	0	26,981,656	0	0	0	26,981,656	-320.65	-1.09
iv	Yes	No	Base + Hot + Ice	0.1084	0.21	0.0807	7,264,084	938,866	670,561	8,873,511	0	0	966	390,328	0	391,294	3.80	6.89
v	Yes	No	Base + Battery + Hot + Ice	0.1055	0.22	0.0712	7,372,051	927,773	658,344	8,958,168	0	26,981,656	966	390,328	0	27,372,950	1501.57	-0.98
vi	Yes	No	Base + Solar	0.1092	0.26	0.0770	6,736,123	815,563	742,066	8,293,751	5,338,792	0	0	0	0	5,338,792	7.82	2.84
vii	Yes	No	Base + Solar + Battery	0.1092	0.26	0.0770	6,736,123	815,563	742,066	8,293,751	5,338,792	26,981,656	0	0	0	32,320,448	47.35	-0.37
viii	Yes	No	Base + Solar + Battery + Hot + Ice	0.1055	0.22	0.0712	7,372,051	927,773	658,344	8,958,168	5,338,792	26,981,656	966	390,328	0	32,711,742	1794.43	-0.98
ix	Yes	No	Base + Absorption	0.1090	0.24	0.0810	7,166,456	1,033,177	773,419	8,973,052	0	0	0	0	4,643,355	4,643,355	1387.96	-0.98
x	Yes	No	Base + Solar + Battery + Hot + Ice + Absorption	0.1056	0.25	0.0760	6,666,833	885,153	622,238	8,174,224	5,338,792	26,981,656	966	390,328	4,643,355	37,355,097	46.57	-0.36
xi	Yes	Yes	Base + Battery	0.1057	0.25	0.0732	7,340,397	950,164	769,114	9,059,675	0	26,981,656	0	0	0	26,981,656	-343.52	-1.09
xii	Yes	Yes	Base + Hot + Ice	0.1083	0.21	0.0832	7,296,713	920,750	691,254	8,908,717	0	0	966	390,328	0	391,294	5.40	4.55
xiii	Yes	Yes	Base + Battery + Hot + Ice	0.1055	0.24	0.0716	6,685,617	874,659	627,589	8,187,864	0	26,981,656	966	390,328	0	27,372,950	34.51	-0.13
xiv	Yes	Yes	Base + Solar	0.1090	0.26	0.0779	6,757,147	799,135	744,394	8,300,676	5,338,792	0	0	0	0	5,338,792	7.85	2.82
xv	Yes	Yes	Base + Solar + Battery	0.1057	0.27	0.0728	6,650,264	921,375	742,562	8,314,201	5,338,792	26,981,656	0	0	0	32,320,448	48.46	-0.38
xvi	Yes	Yes	Base + Solar + Battery + Hot + Ice	0.1055	0.24	0.0716	6,685,617	874,659	627,589	8,187,864	5,338,792	26,981,656	966	390,328	0	32,711,742	41.24	-0.27
xvii	Yes	Yes	Base + Absorption	0.1093	0.24	0.0799	7,106,630	1,084,474	768,762	8,959,867	0	0	0	0	4,643,355	4,643,355	218.38	-0.86
xviii	Yes	Yes	Base + Solar + Battery + Hot + Ice + Absorption	0.1056	0.25	0.0784	6,657,776	904,798	627,246	8,189,820	5,338,792	26,981,656	966	390,328	4,643,355	37,355,097	47.21	-0.36

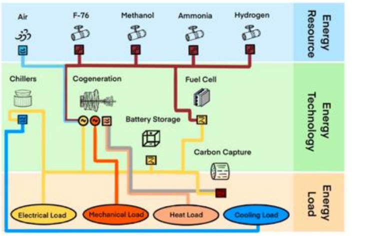
Energy Analysis for Future Navy Ships



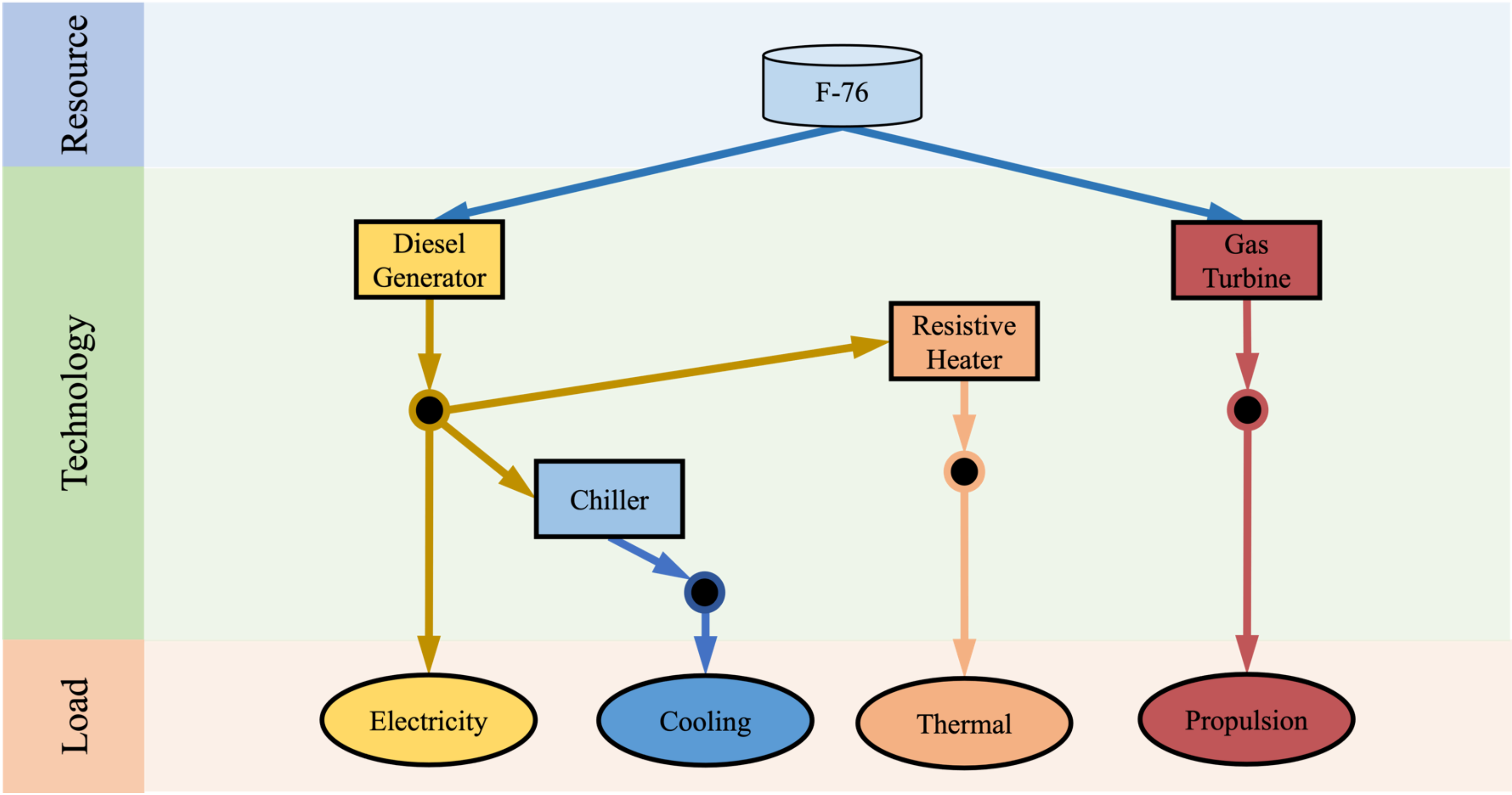
Ship Energy Analysis Tool



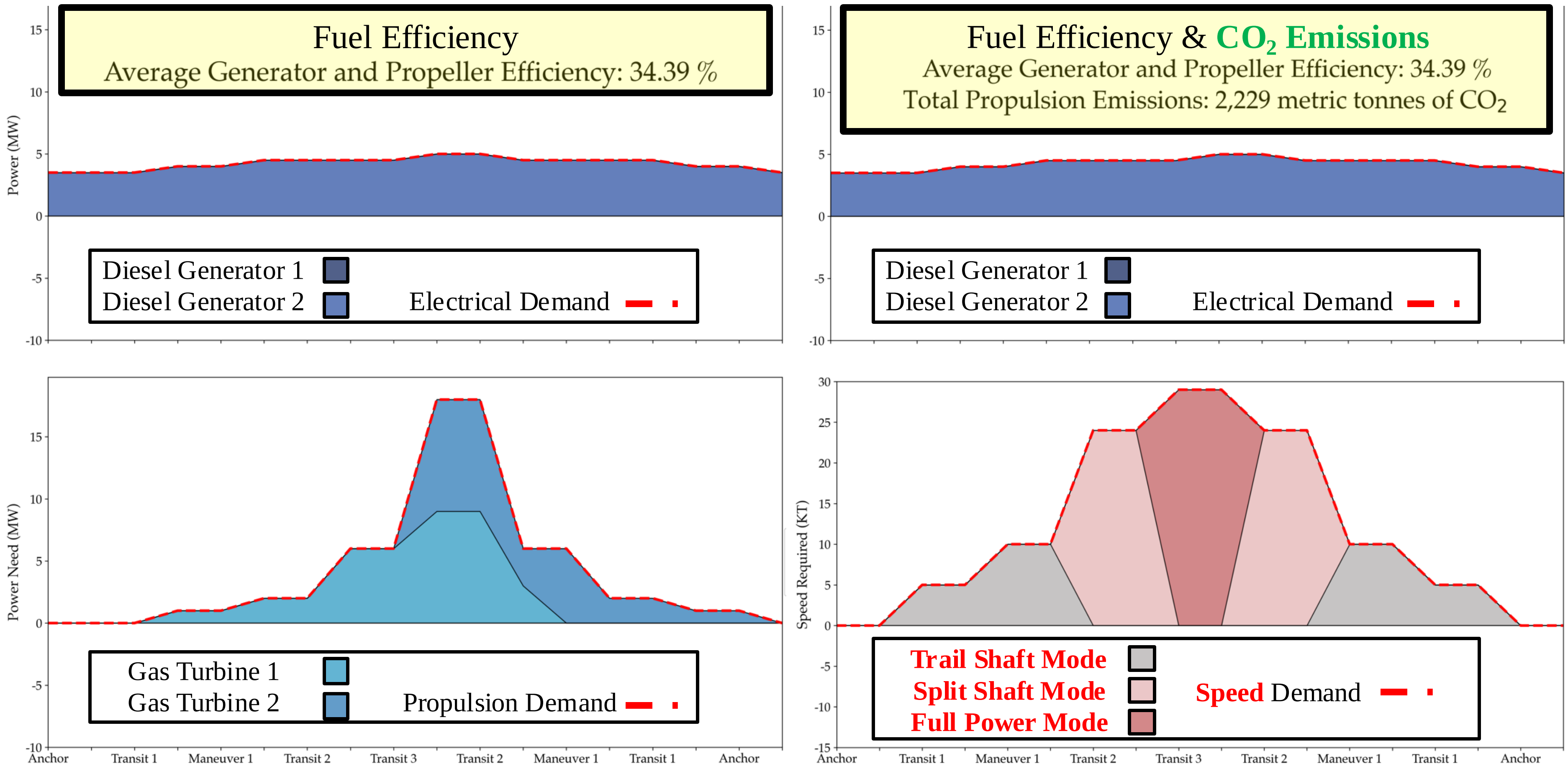
Example Ship Energy System Model



building a base model

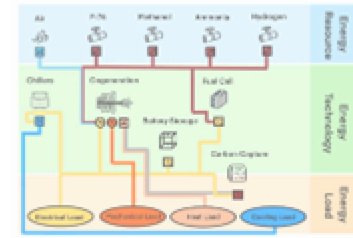


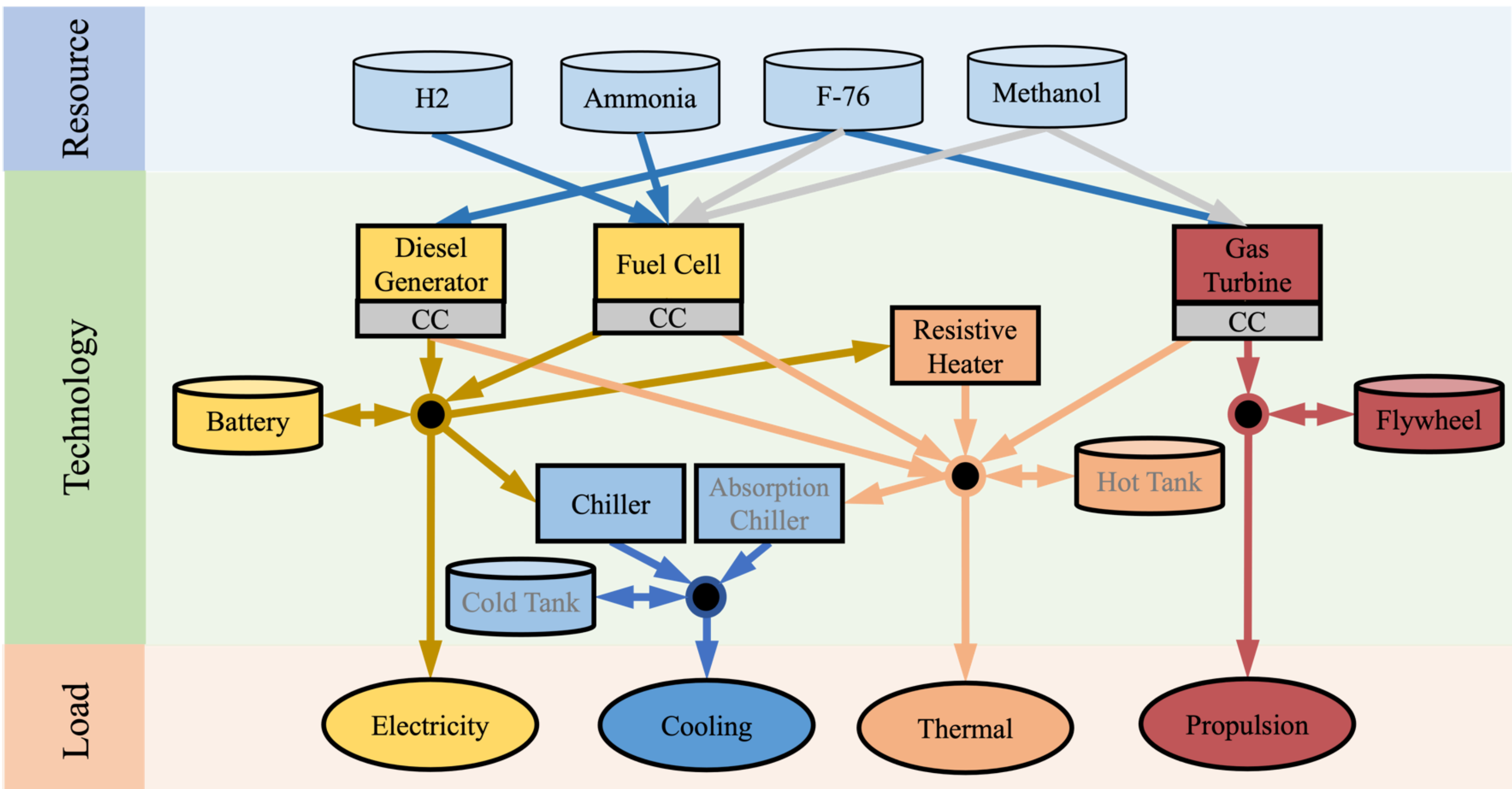
Energy System Analysis Tool Sample Output



Example Ship Energy System Model

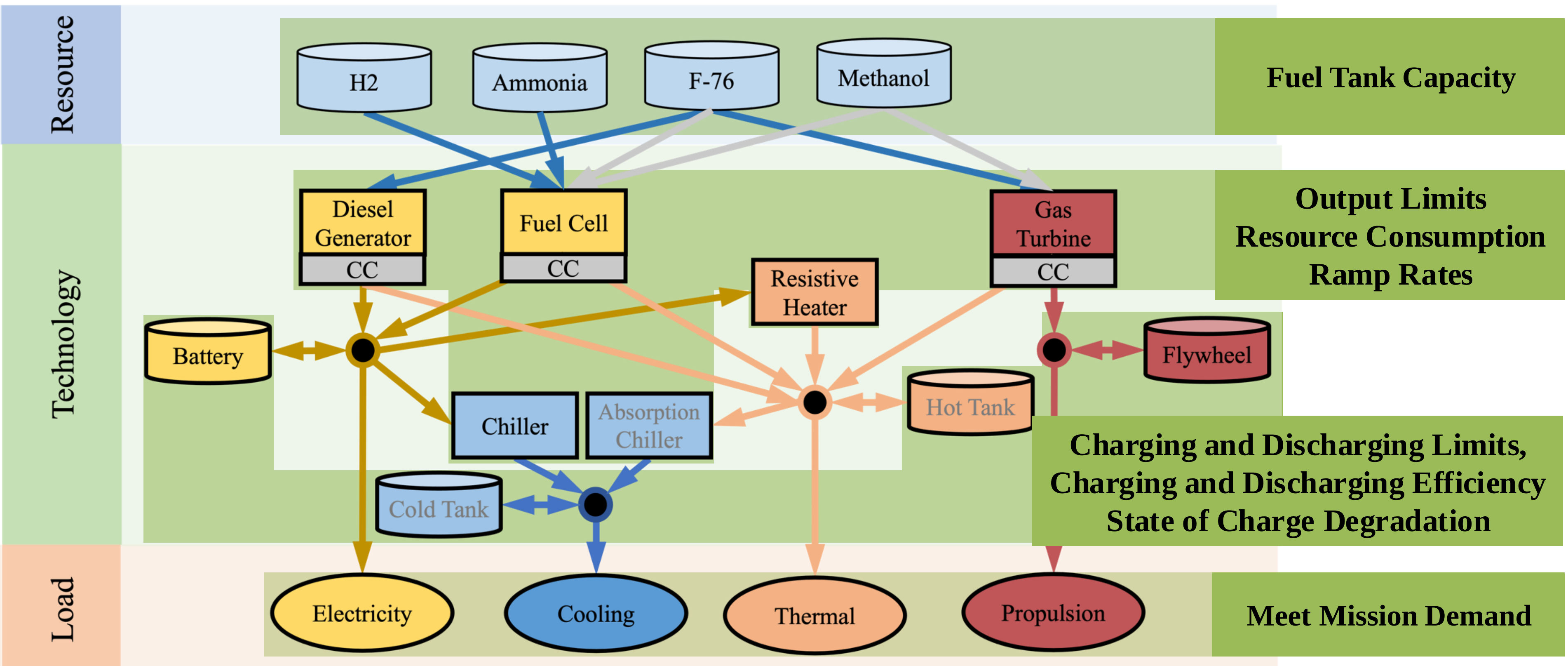
adding storage, alternative fuels, fuel cell, carbon capture, and heat recovery.





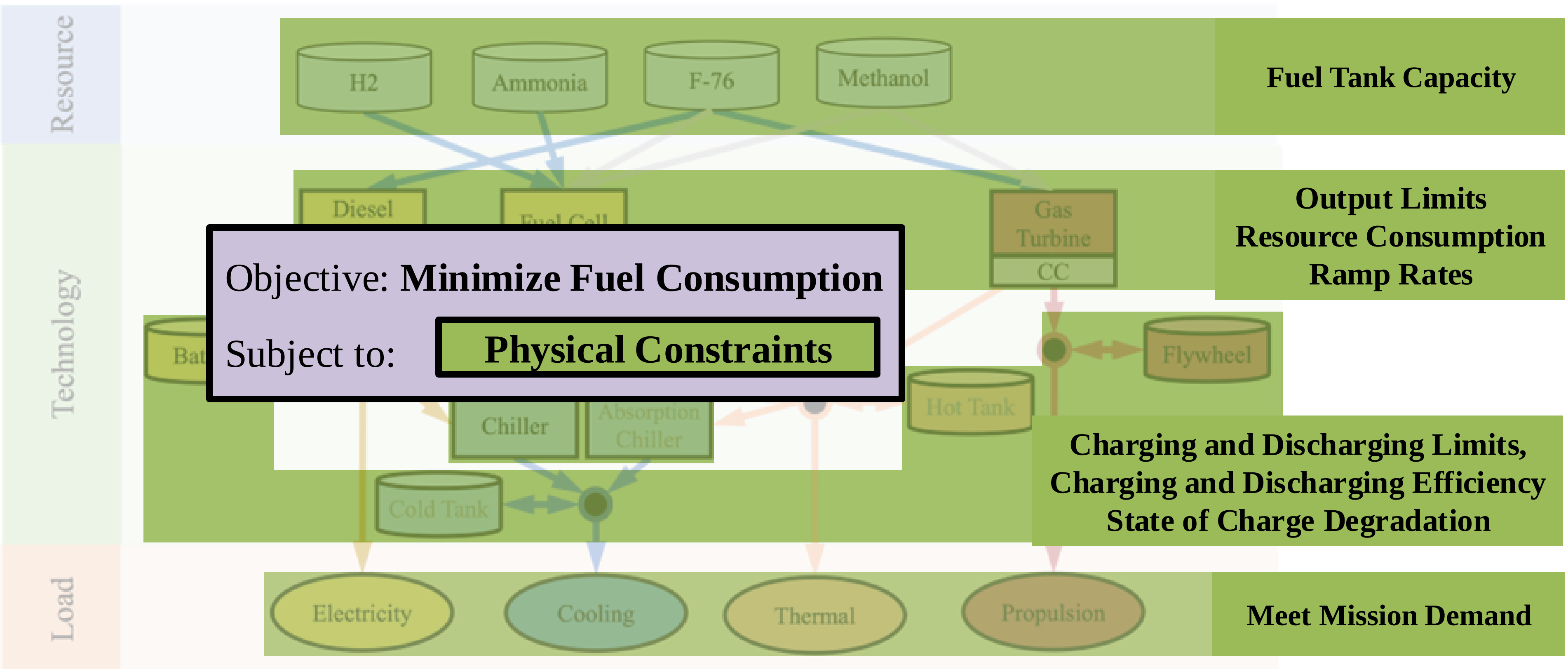
Example Ship Energy System Model

physical constraints & system objective



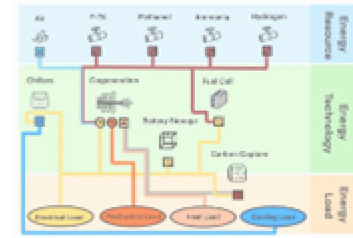
Example Ship Energy System Model

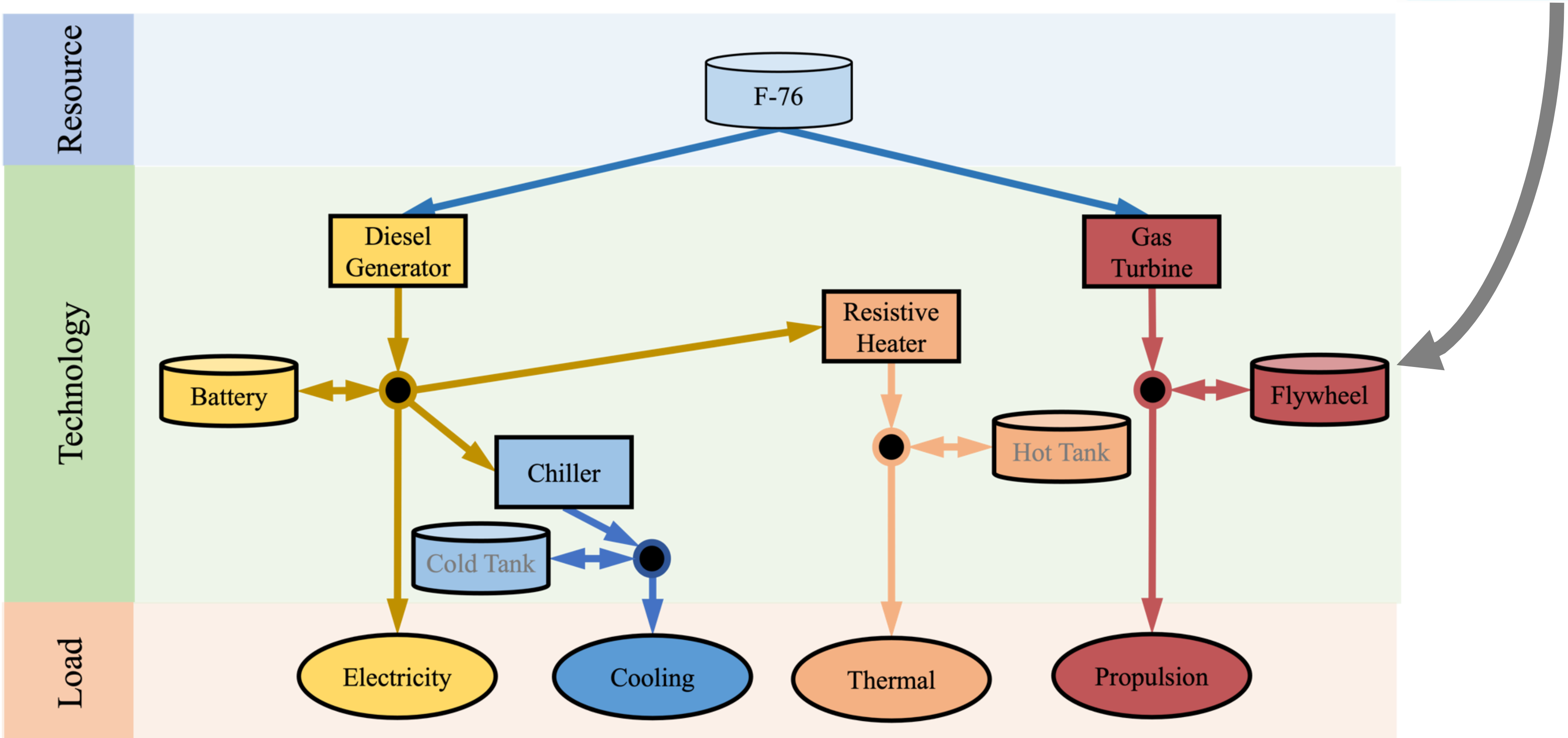
physical constraints & system objective



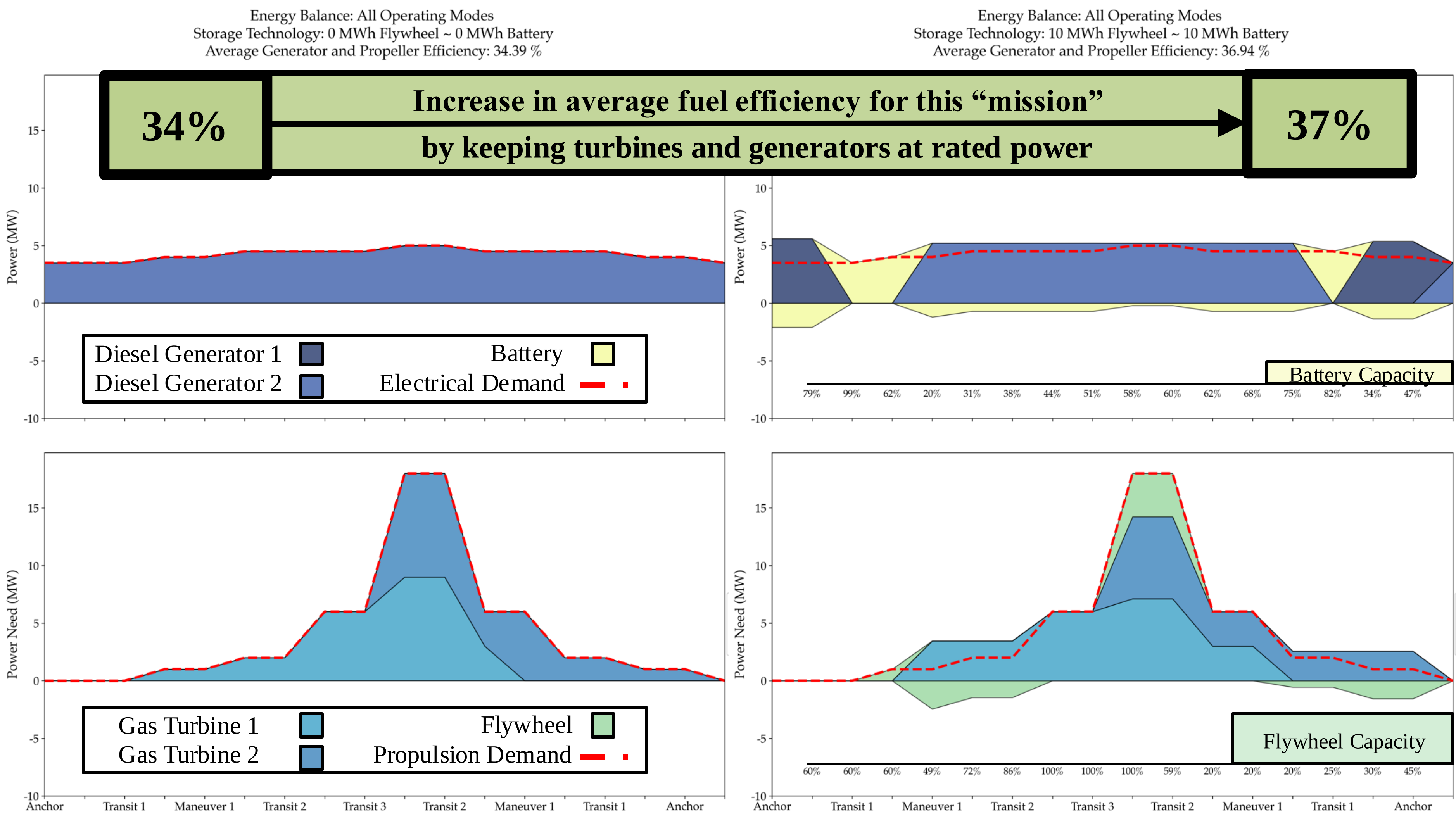
Example Ship Energy System Model

adding storage



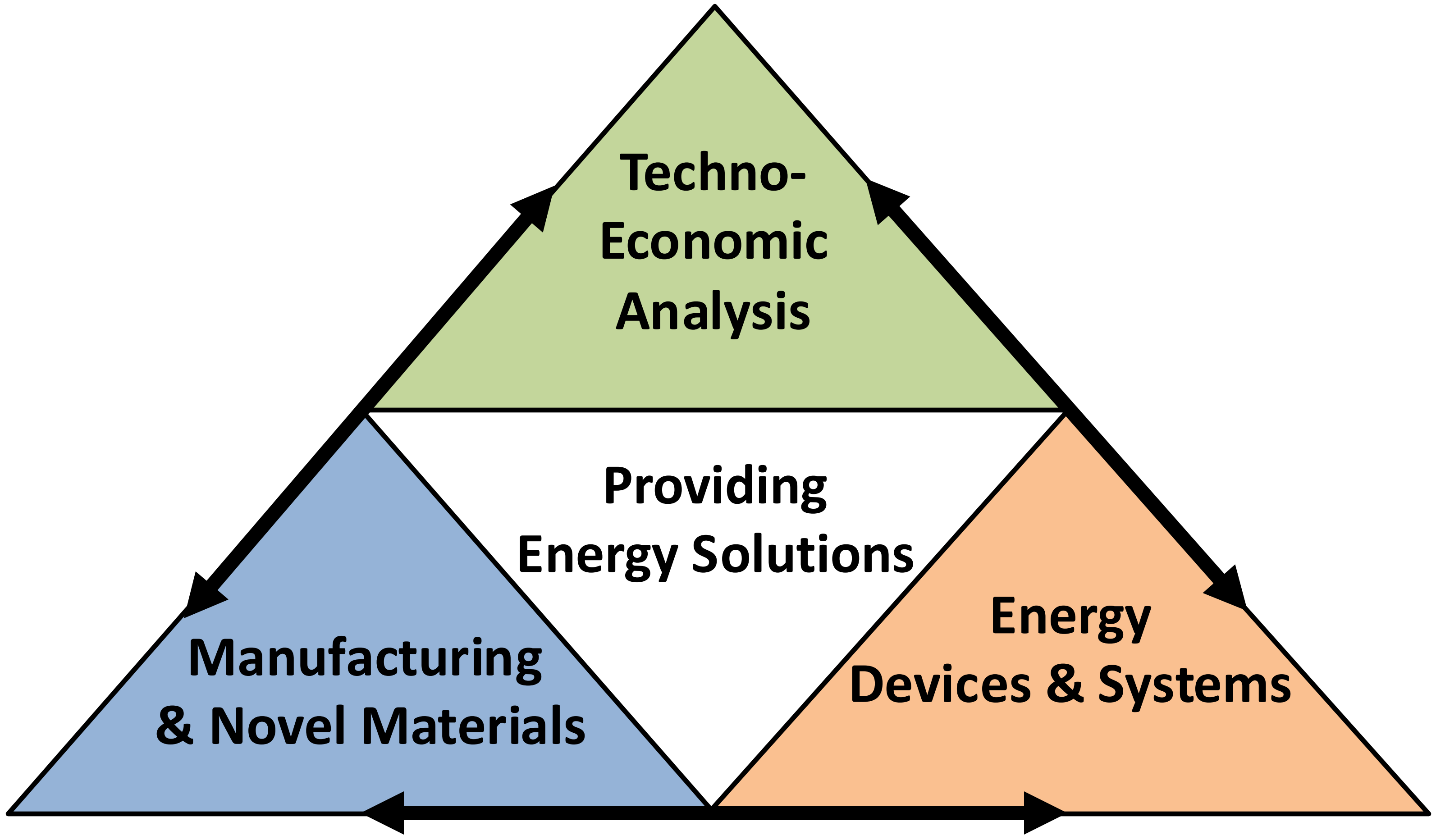


Example Output for Energy Storage



LeBlanc Lab: Materials to Systems

We create energy solutions using advanced materials and manufacturing techniques.



It takes a village…

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Industry Partners

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