

Introduction to Electronic Carnot Engine (ECE – a silent thermal engine)

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What is ECE ?

- ECE is an external combustion thermal engine with **no moving parts**.
- Through thermal cycles of free-electrons in metal or semiconductor, ECE converts thermal energy directly into electricity in high efficiency.
- An ECE consists of three key components: (1) thermal converter, (2) L/C resonant tank, and (3) controller and switch.
- Table 1 displays correlations in functional components between an ECE and a conventional (piston) engine.

Table 1: Functional Component Correlation

ECE	Conventional engine
Thermal converters	Cylinders and pistons
L/C resonant tank	Fly wheel
Controller and switch	Timing belt and ignition system

Efficiency of direct thermal energy conversion

- Conventional thermal energy conversion yields low conversion efficiency (approximately 5% to 10%) mainly due to the occurrence of **reverse bias**. Reverse bias shuts off the converter, forward bias turns on the converter.
- Take thermionic tube, a typical thermal converter, as an example (Fig. 1); current (I_e^-) flows across the load R and results in a terminal voltage ($-V_t$) in the direction opposite to the cathode emission voltage ($-V_e$), i.e., reverse bias.
- This reverse bias impedes circulation of the working medium (space charge - electrons) and therefore suppresses further generation of new current, leading to low conversion efficiency.

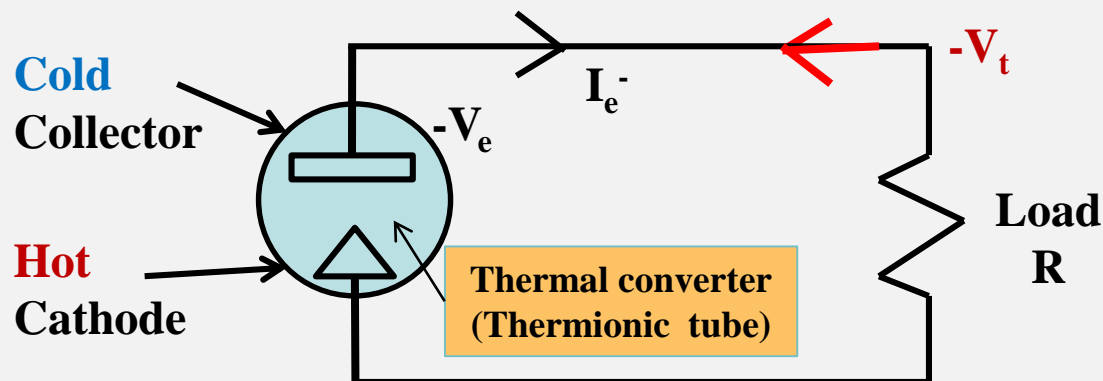


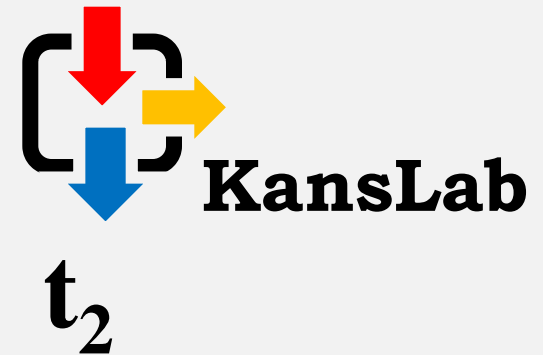
Fig. 1: A reverse bias ($-V_t$) impedes further cathode emission.

Resonant ECE Innovation

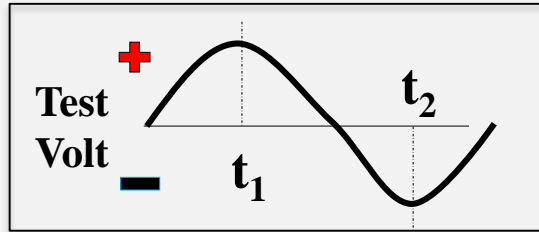
- ECE is invented with the aim at addressing the low efficiency issue resulted from direct current (DC) operation in conventional thermal energy conversion.
- In an ECE, the converter employs resonant tank and switch to generate **forward bias** to accelerate the space charge (electrons) in order to maximize current circulation to achieve higher conversion efficiency.
- An L/C energy storage tank and a switch provide needed forward bias to the converter when (1) the switch connects proper polarities with the L/C tank and with the converter respectively and (2) the switch operation **synchronizes** to the resonant frequency of the L/C tank (Fig. 2).



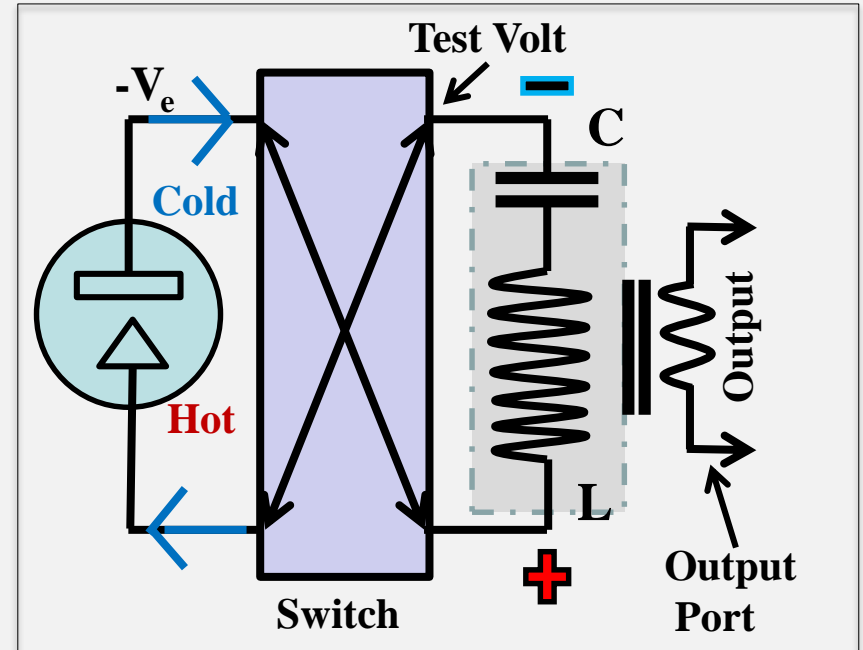
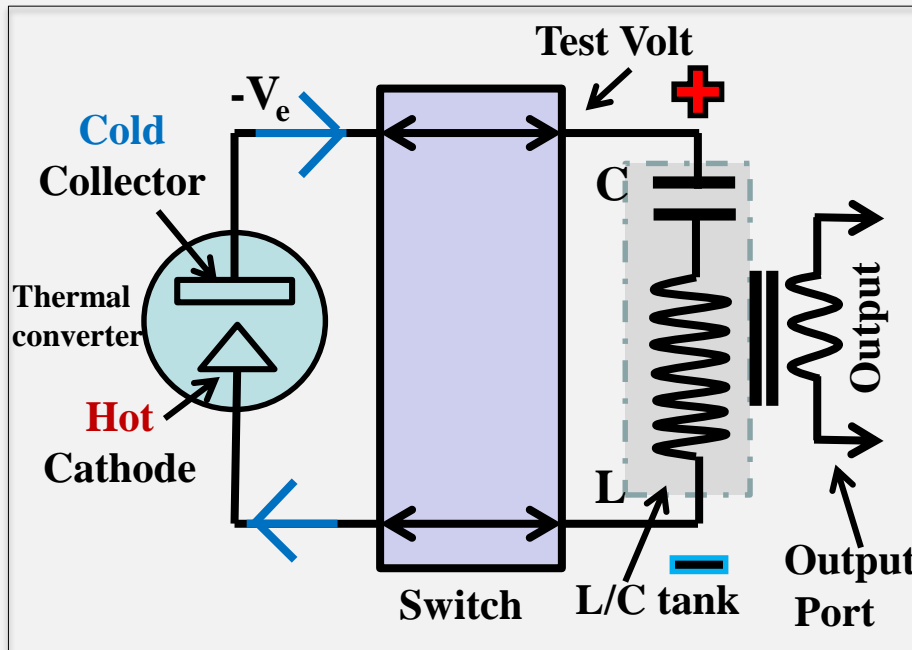
Fig. 2: How ECE Works



t_1



t_2



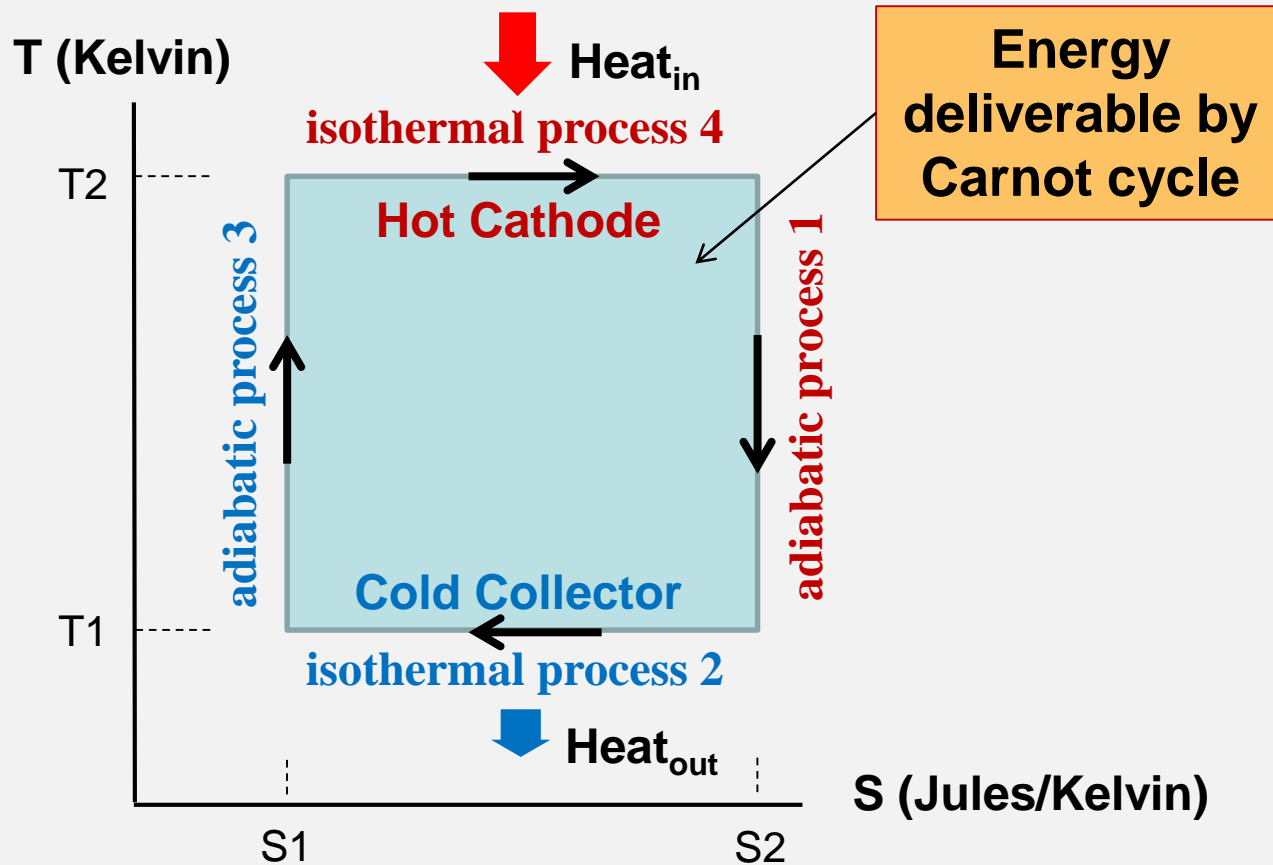
Switch is triggered by peak voltage of the L/C tank. It alternates the polarities, so the positive end of the L/C tank is always connected to the collector of the converter (**forward bias**).

ECE – Carnot Cycle

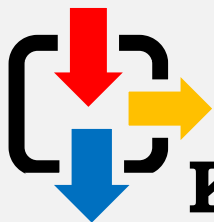
- **Massive electrons are accelerated by the forward bias across the space from hot cathode to cold collector – Adiabatic Process 1 in Carnot cycle T-S chart (Fig. 3).**
- **Hot electrons are cooled down in the collector – Isothermal Process 2.**
- **Cold electrons are then being accelerated from the collector (via. L/C tank) to hot cathode – Adiabatic Process 3.**
- **Finally electrons in cathode be heated up –Isothermal Process 4. These four processes complete a **Carnot cycle**.**
- **Fig. 3 represents an integration of $dH = T*dS$ where dH and dS are enthalpy and entropy changes at a temperature T . However, Fig. 3 doesn't tell the timing relationship between adiabatic and isothermal cycles. Depending on heat conductivity and heat capacity of electrodes material, isothermal cycle most likely takes longer time to be optimized than adiabatic cycle.**



Fig. 3: Carnot Cycle T-S Chart



T: temperature in Kelvin, S: entropy in Jules/Kelvin, Heat in Jules.



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- Assuming isothermal cycle takes four times ($N = 4$) longer than adiabatic cycle to reach to an optimal point. Fig. 4 presents a proposed push-pull circuit with $N = 4$ (N needs to be an even integer for push-pull circuits to be functional).
- Fig. 5 compares deliverable energy at each N (timing) stage. Since heat capacity is proportional to the size of the system, extend the N number beyond the optimal point doesn't increase system internal energy but wasted.

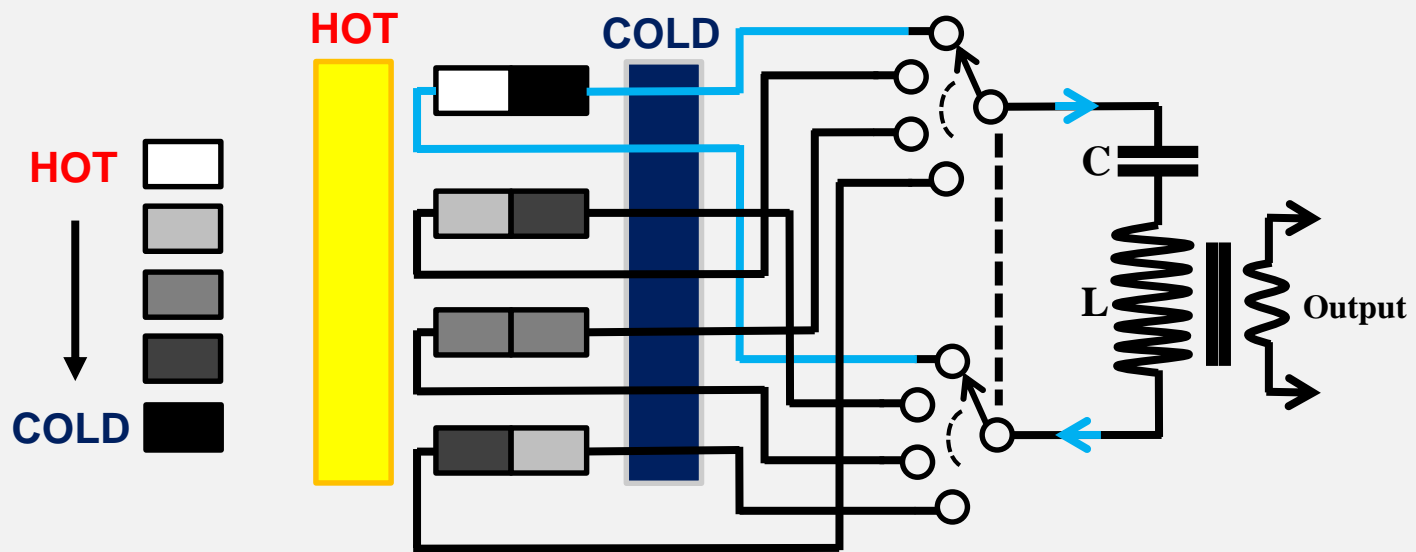
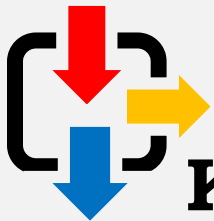
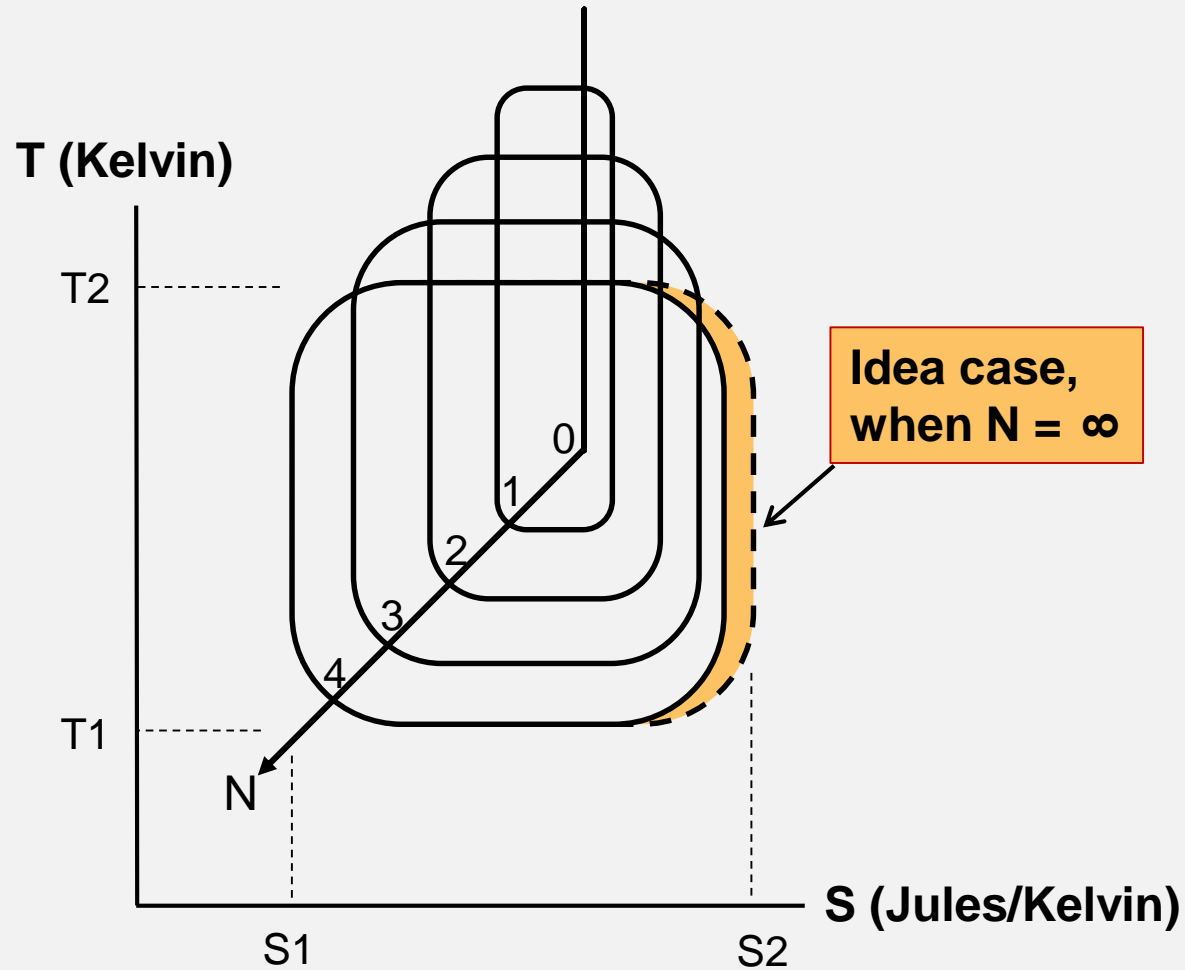


Fig. 4, Circuits for $N = \frac{\text{isothermal cycle time}}{\text{adiabatic cycle time}} = 4$

Fig. 5, Deliverable energy at each N stage.

$$N = \frac{\text{isothermal cycle time}}{\text{adiabatic cycle time}}$$



Thermal Efficiency Estimation

- Assuming an ECE operates between 100°C and 850°C, theoretically (0°C = 273°K) :

$$\begin{aligned}\text{Thermal Efficiency} &= 1 - (273 + 100) / (273 + 850) \\ &= 66.8\%\end{aligned}$$

- Net Efficiency = Thermal Efficiency × (1 – Total Efficiency Losses)
$$= 66.8\% \times (1 - 37\%^*)$$
$$= 42\%$$

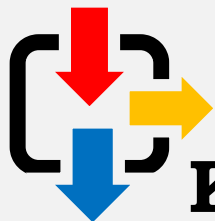
* Table 2: Estimated total Efficiency Losses = 37%



Table 2: ECE Efficiency Loss Assumptions

Combustion heat losses	~ 10%
Losses due to capacity mismatch between resonant tank and converter cells array	~ 2%
Circuits resistance losses	~ 5%
Thermal conductive losses	~ 5%
Radiation losses (for vacuum tubes)	~ 2%
Switch losses	~ 5%
Eddy current and magnetic losses (for transformer)	~ 2%
Capacitor losses	~ 1%
AC to DC converter losses	~ 5%
Total Losses	35 to 40%

Total Efficiency Losses estimated ranges from 35 to 40%. In this study Total Losses of 37% is used in Net Efficiency calculation.



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Advantages of ECE

- **High thermal efficiency.**
- **Flexibility in fuel sources to be used (external combustion).**
- **Low or zero emission (concentrated solar thermal generator).**
- **No vibration or noise.**
- **Low maintenance.**
- **Instant power.**
- **Durable and light in weight.**
- **Could be built in flexible size and power rate.**

Challenges

- **Development of initial components.**
- **More demanding in process and more stringent in material during manufacturing.**

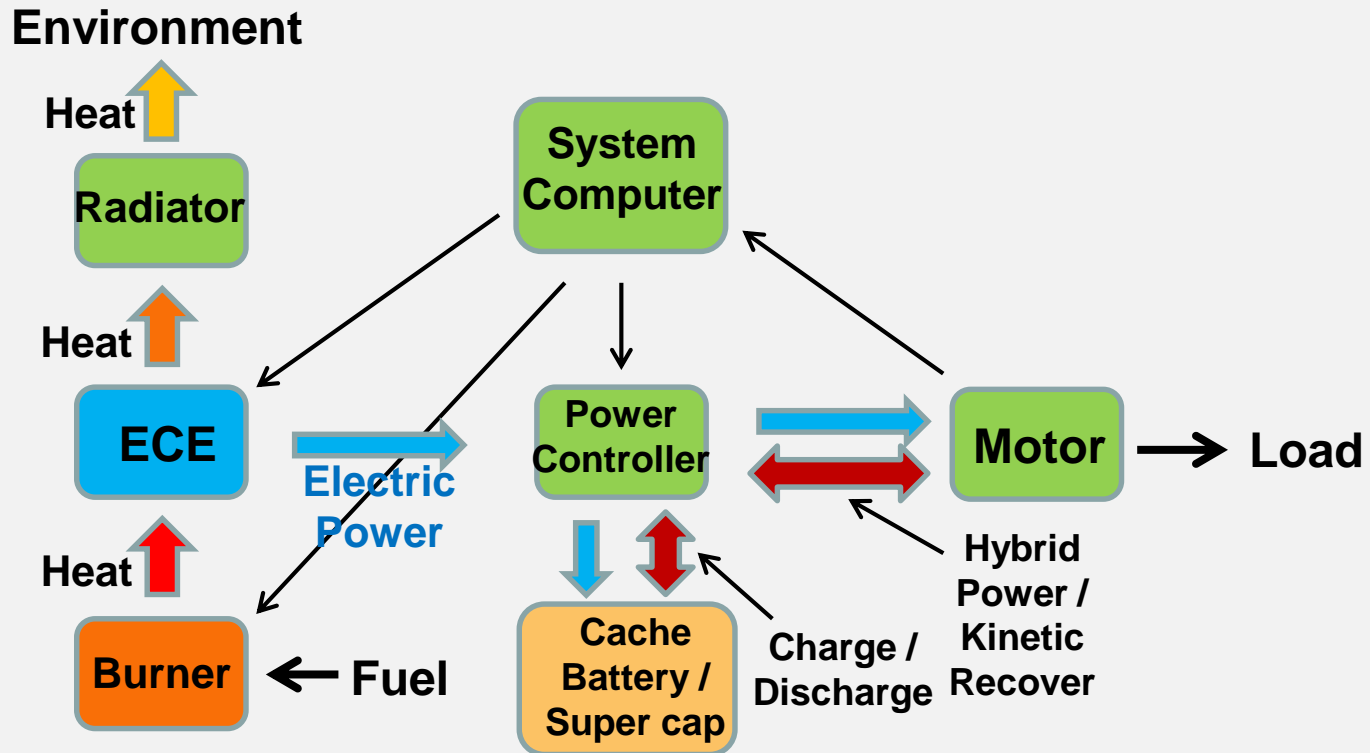


Potential Application - Samples

- Hybrid power for electric vehicles to increase performance, extend range and **reduce battery weight / cost** (Fig. 6).
- ECE implements solar thermal energy **in parallel** with solar photovoltaic energy to generate electricity (Fig. 7).
- Mini power for bicycles, gadgets or instruments.
- Portable, compact, light and silent generator to power wearable technologies or wide area network (WAN) in remote areas.
- Stirling engine replacement.
- Mobile power source for IoT/M2M, field robot or exoskeleton.
- Silent electrical air plane or vessel.
- Air independence propulsion (AIP) in space or deep water.



Fig. 6: Hybrid Power for EV



1. Motor receives hybrid power from ECE and Cache Battery / Super cap.
2. Cache battery / Super cap provides rush energy during peak load.

Fig. 7, Solar with ECE

