**Conference or Workshop Item:**

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# COMPARATIVE STUDY ON THERMAL MANAGEMENT SCHEMES WITH WASTE HEAT RECOVERY FROM ELECTRIC VEHICLE POWER TRAIN

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# Outline

- Research Motivation
- HVAC Architectures
- Electro-thermally Coupled Models for Machine and Inverter
- Powertrain Specification
- Simulation Model
- Simulation Results and Discussion
- Conclusion

# Research Motivation

**Cold weather condition (e.g. < 0° C)**

Heating power + Compressor power + Powertrain loss

⬇

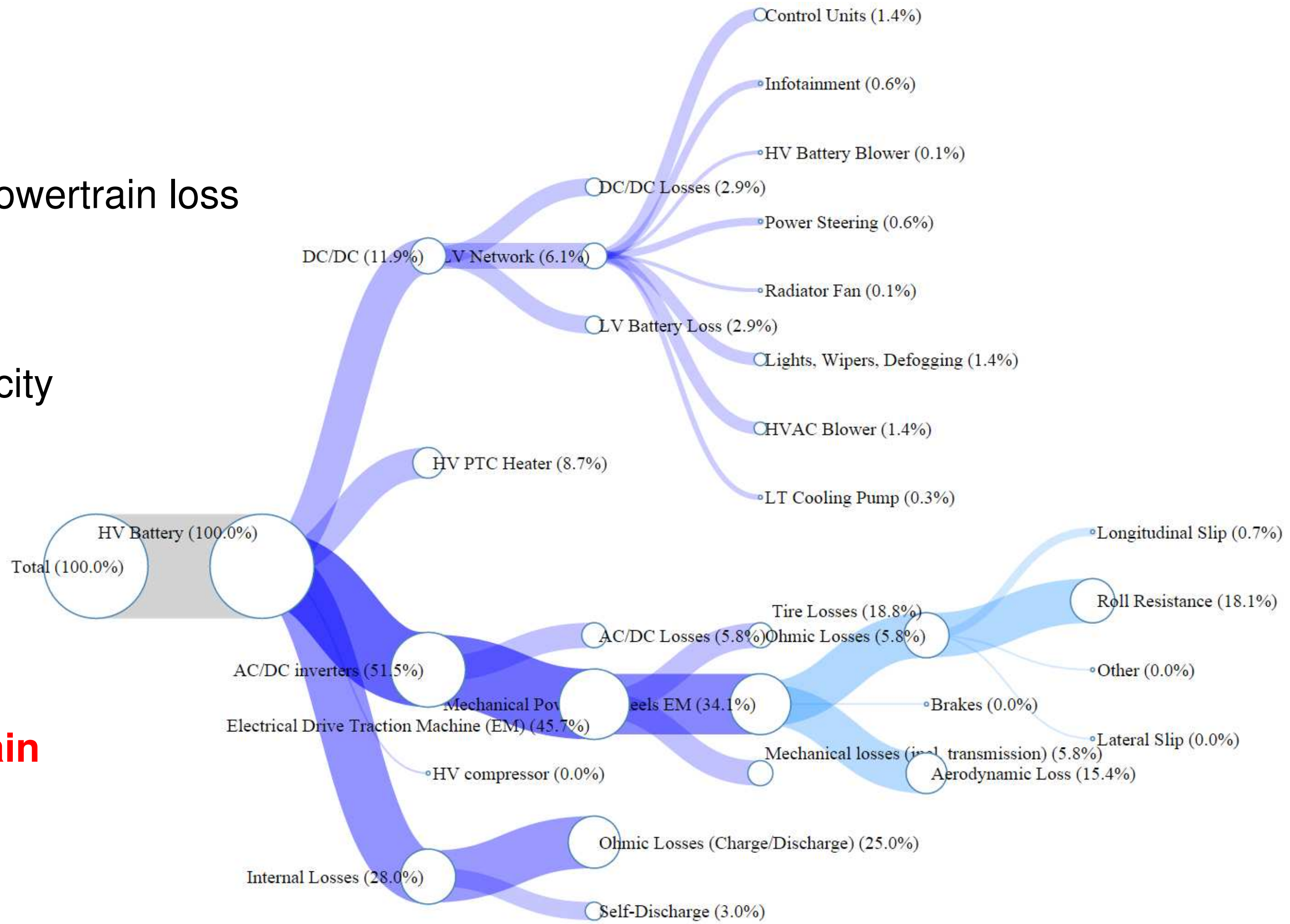
Consumes up to 50% of batteries' capacity

⬇

Mile range reduced by half

⬇

**Recover waste heat in the powertrain**



# HVAC Architectures (Heating Mode)

- **Conventional HVAC architecture**

  Evaporator, compressor, condenser, expansion valve
  
  Evaporator absorbs ambient energy, and condenser heats up cabin

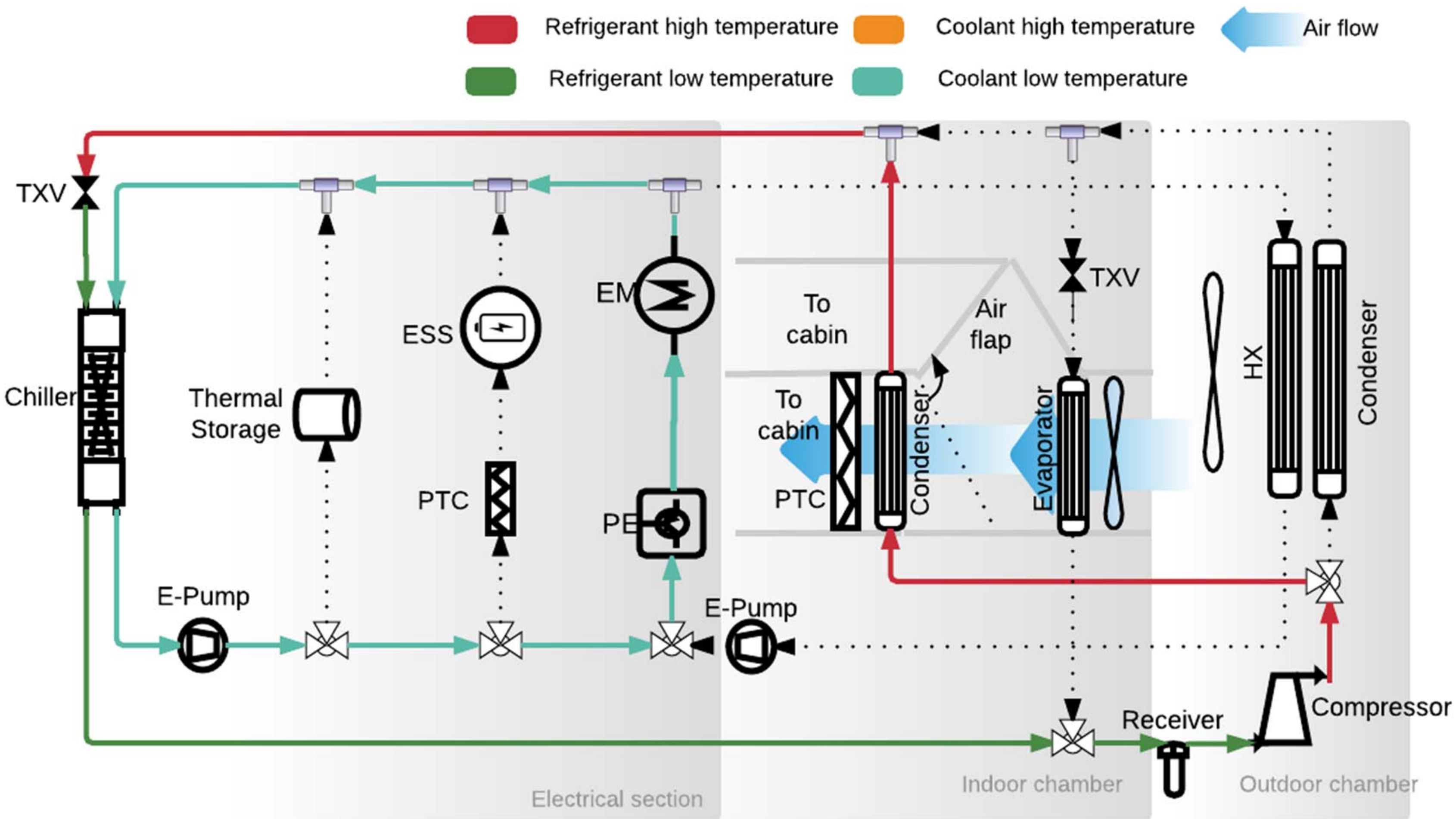
- **Waste heat-only HVAC architecture**

  Chiller (working as evaporator), compressor, condenser, expansion valve
  
  Chiller absorbs waste heat from powertrain, and condenser heats up cabin

- **Dual heat source HVAC architecture**

  Chiller (working as evaporator), evaporator, compressor, condenser, expansion valve
  
  Chiller absorbs waste heat from powertrain, Evaporator absorbs ambient energy, and condenser heats up cabin

# Waste Heat Recovery -- Waste Heat Only



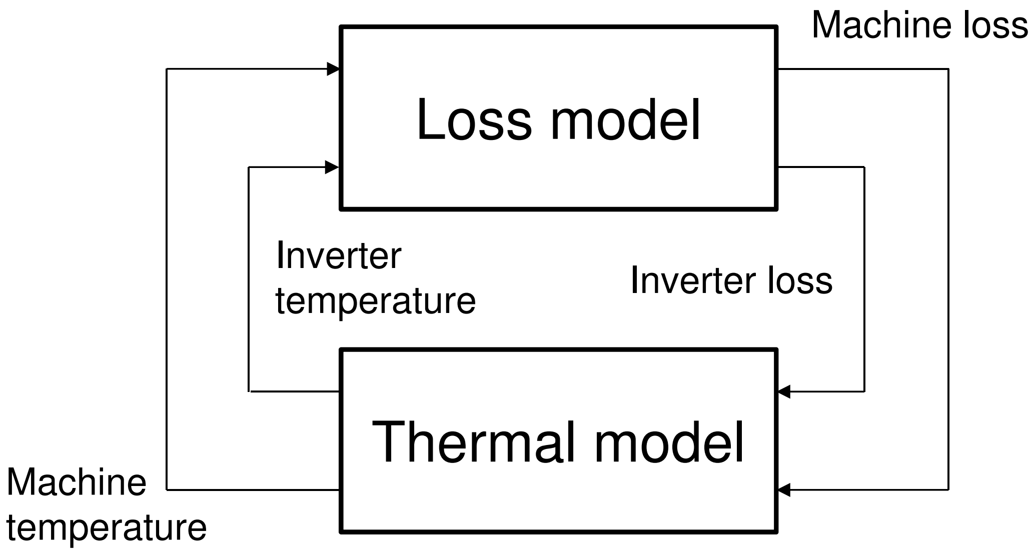
# Electro-thermally Coupled Model for Powertrain system

**Challenges:**

- **Electrical machine and inverter temperatures are subject to their losses.**
- **Machine and inverter losses are largely affected by their temperatures.**

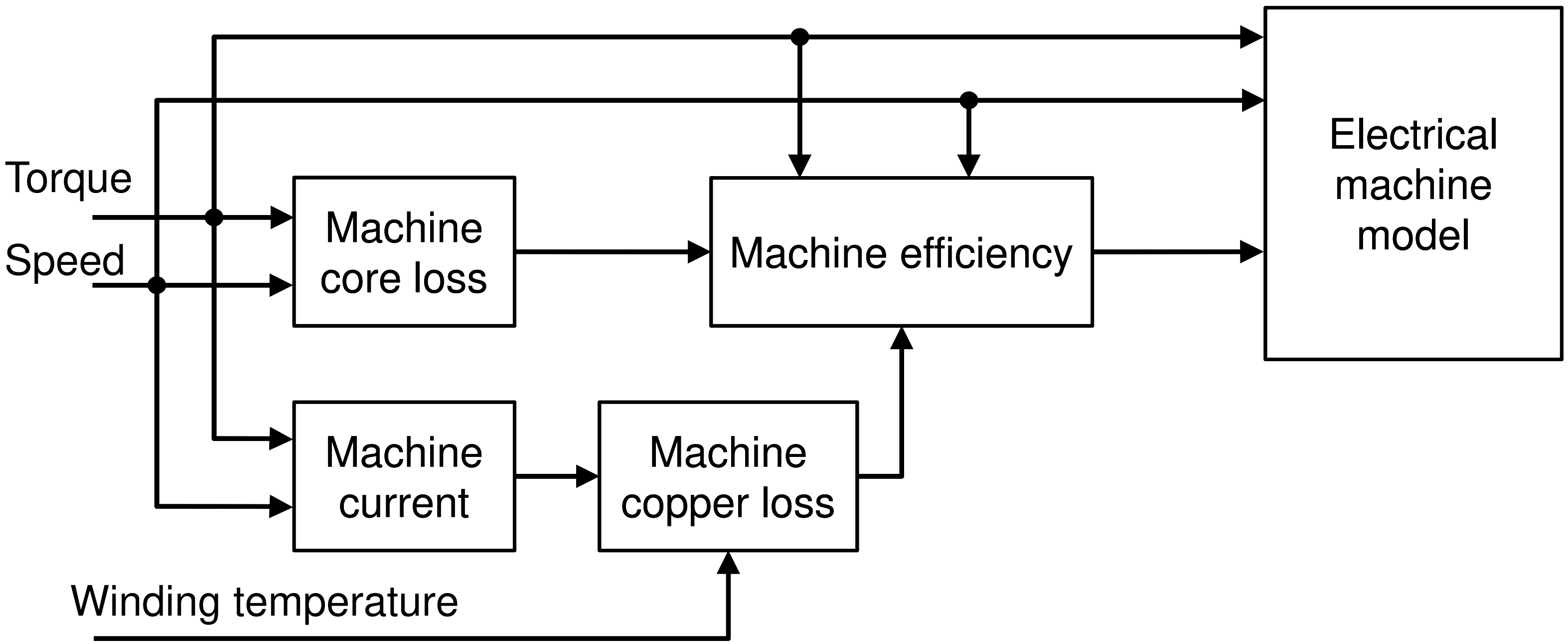
a) Machine copper loss increases by 39% for every 100°C temperature rise (assuming same current);

b) Inverter loss increases by ~20% for every 100°C temperature rise.



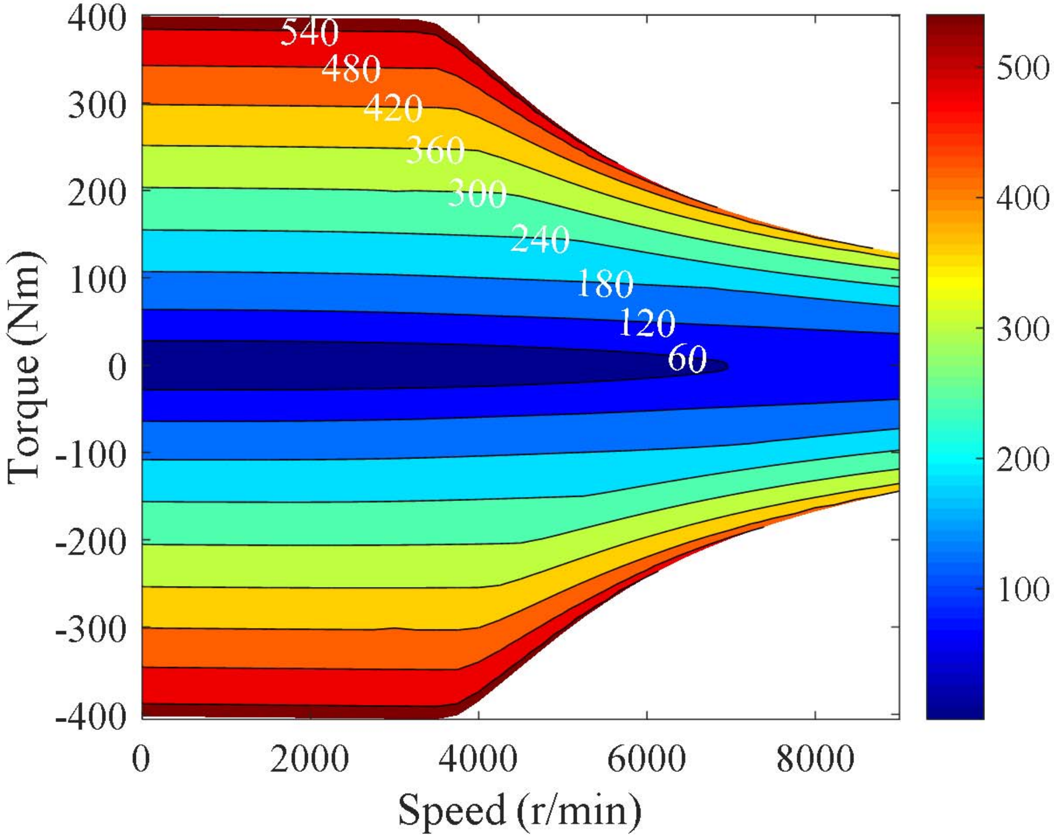
# Electro-thermally Coupled Model for Electrical Machine

## Schematic

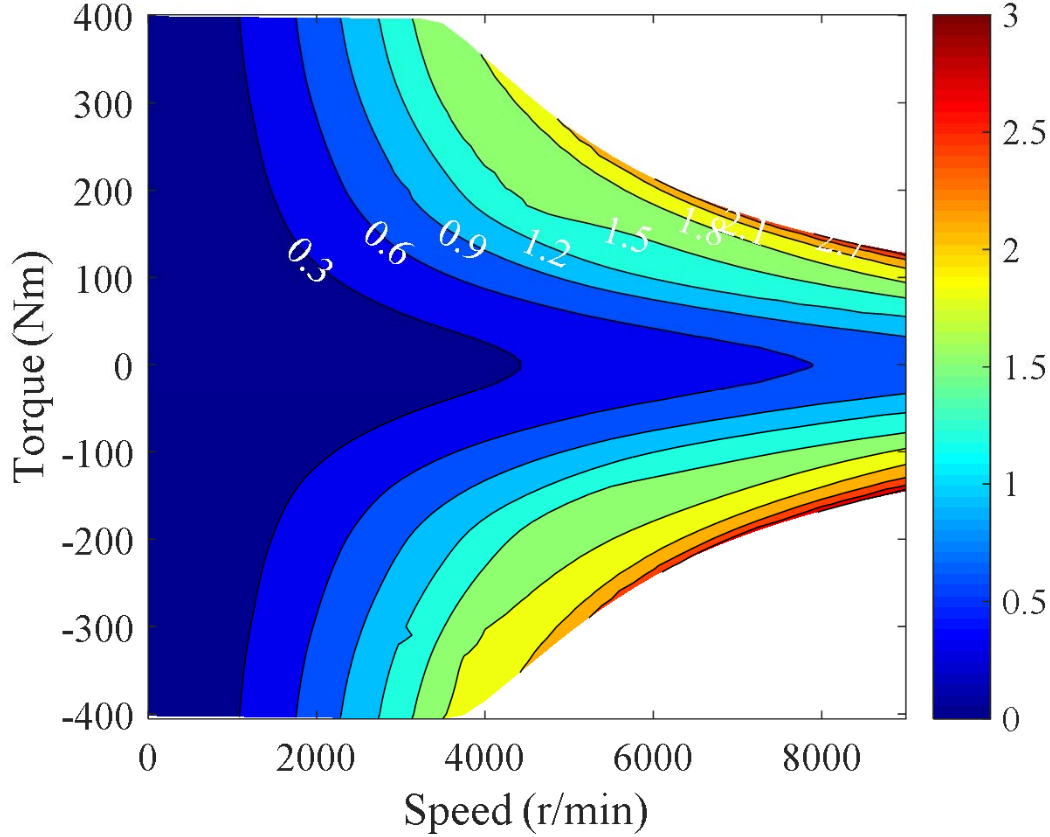


# Electro-thermally Coupled Model for Electrical Machine

Machine phase current in A (RMS)

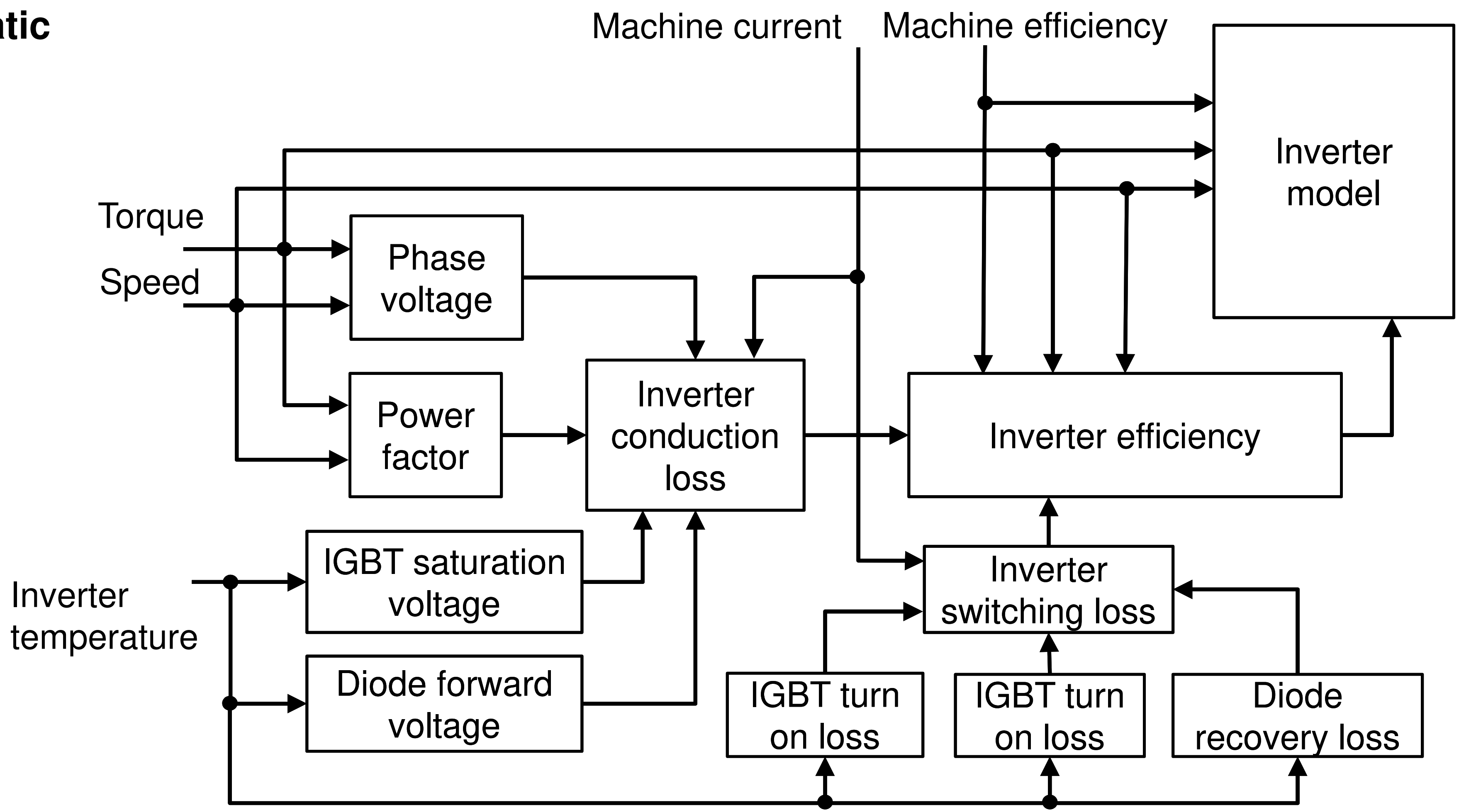



Machine core loss in kW



# Electro-thermally Coupled Model for Inverter

**Schematic**



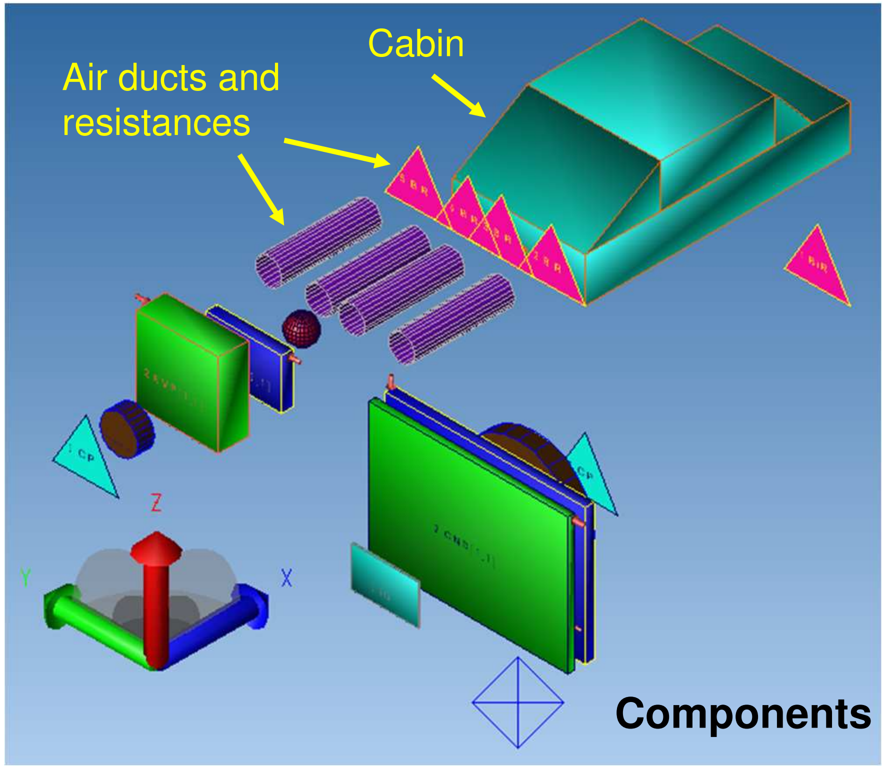
## Powertrain Specification

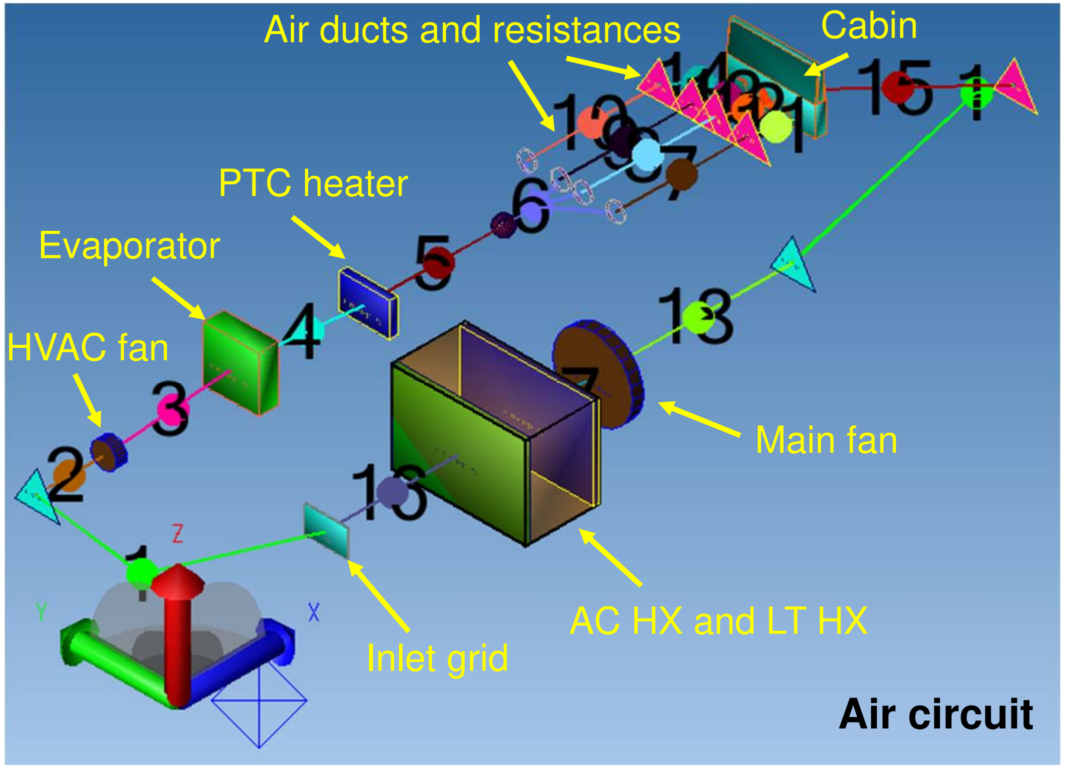
| Item | Value |
|---|---|
| Kerb weight | 1,708 kg |
| Gross weight | 2,170 kg |
| Length | 4,358 mm |
| Width | 1,812 mm |
| Height | 1,599 mm |
| Wheel base | 2,699 mm |
| Wheel size | 205/60 R16 |
| Gear ratio | 5.98 : 1 |
| Axle ratio | 1.12 : 1 |
| Aerodynamic drag coefficient | 0.28 |
| Frontal area | 2.55 $m^2$ |
| Tyre dynamic radius | 316.4 mm |
| Cabin volume | 3.5 $m^3$ |
| Window surface (for solar load) | 1.4 $m^2$ |

# Simulation Model

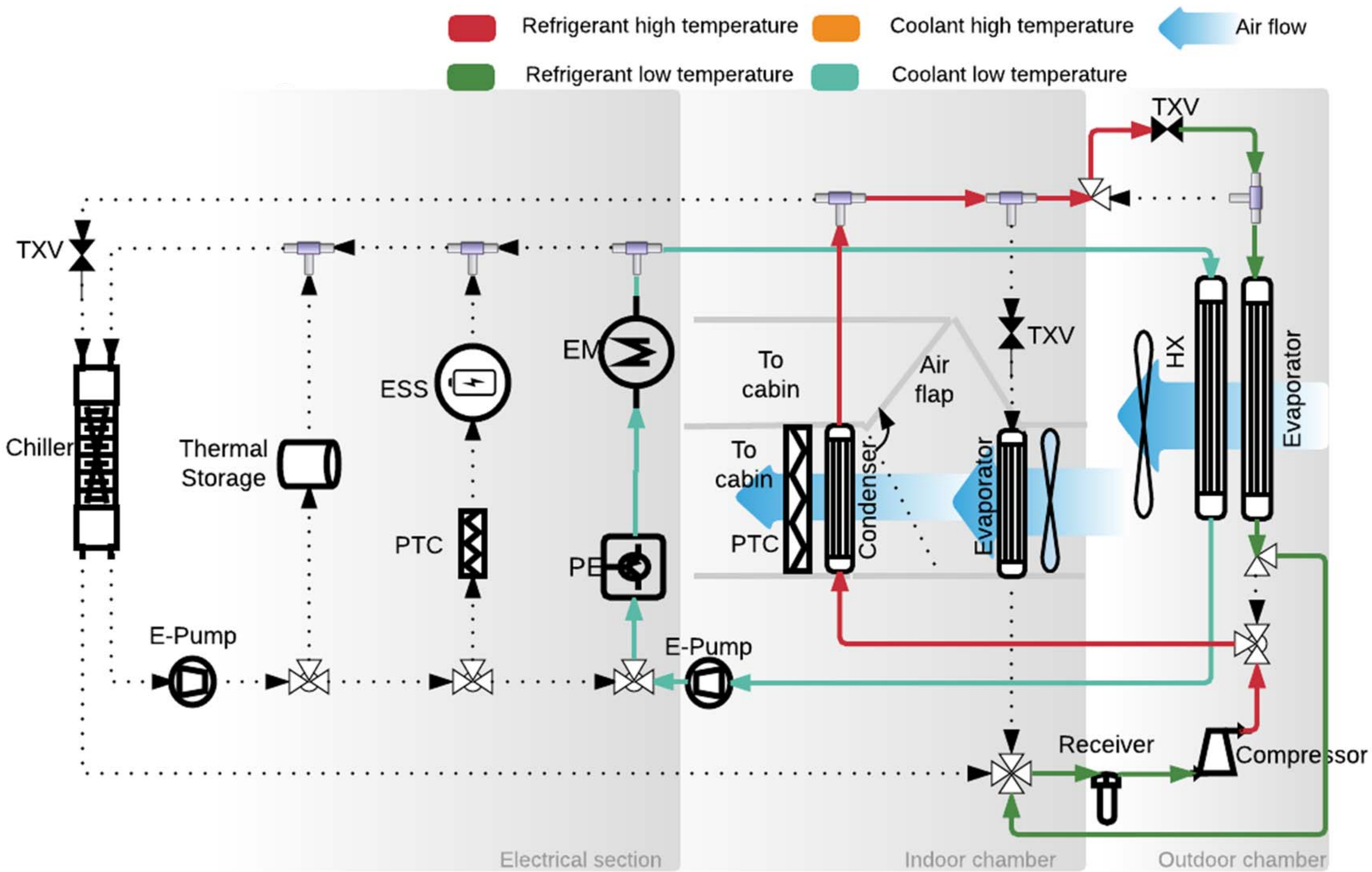
**KULI** – 1D simulation software for vehicle energy management

Components readily available: Cabin, compressor, heat exchanger, thermostatic expansion valve, blower, pump, electrical machine, inverter, battery, etc.

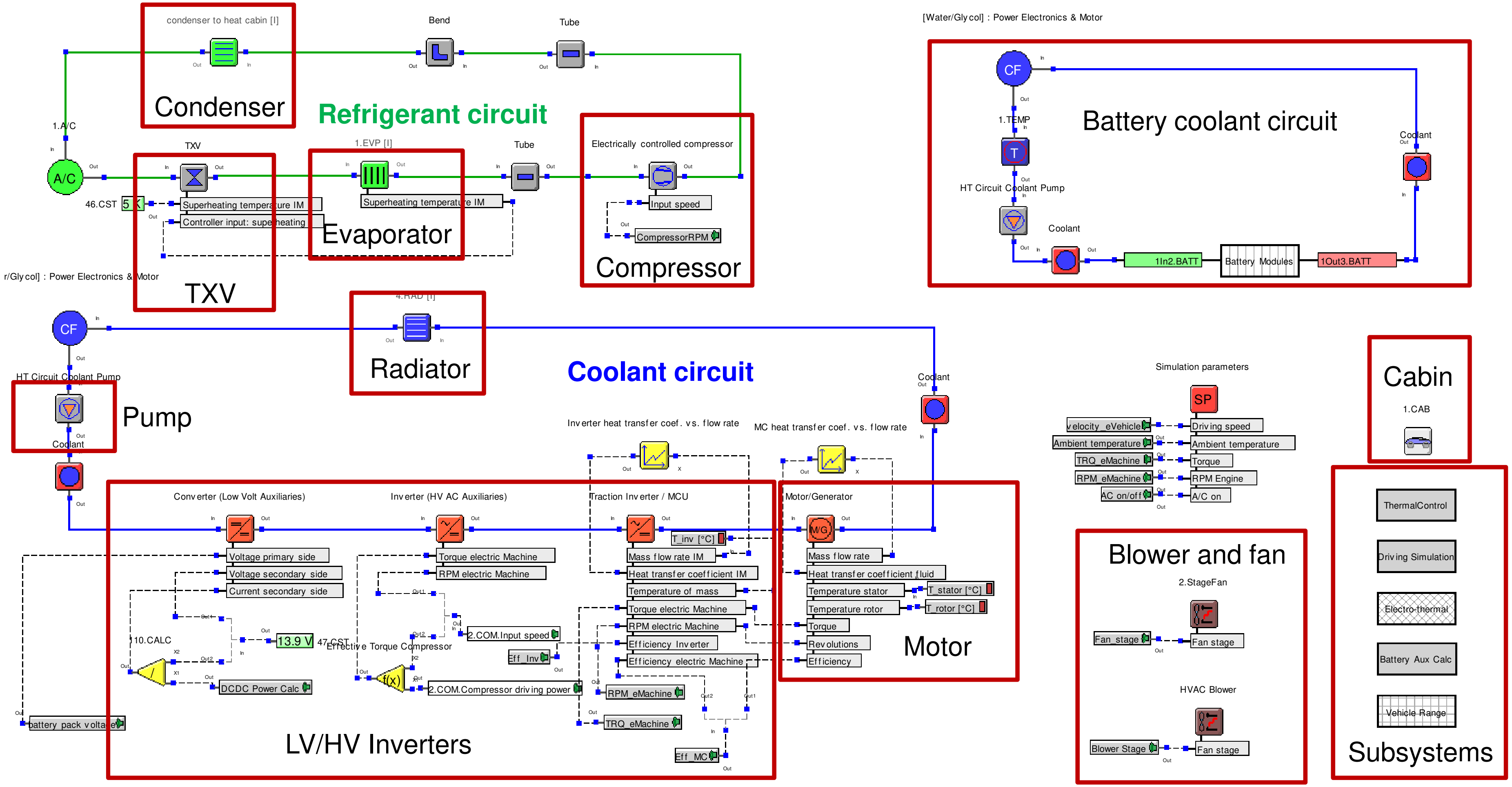


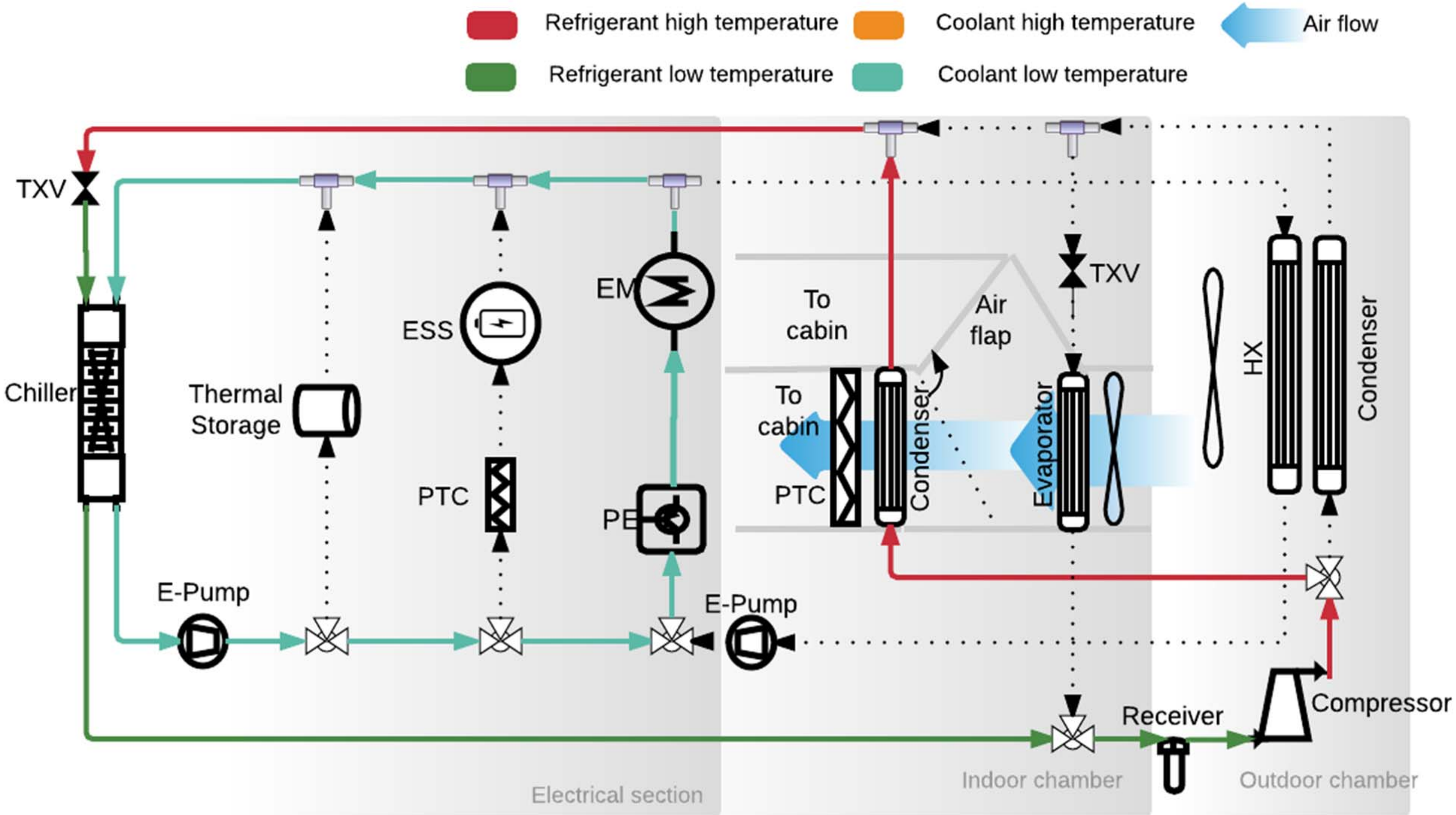
# Conventional Powertrain and HVAC system



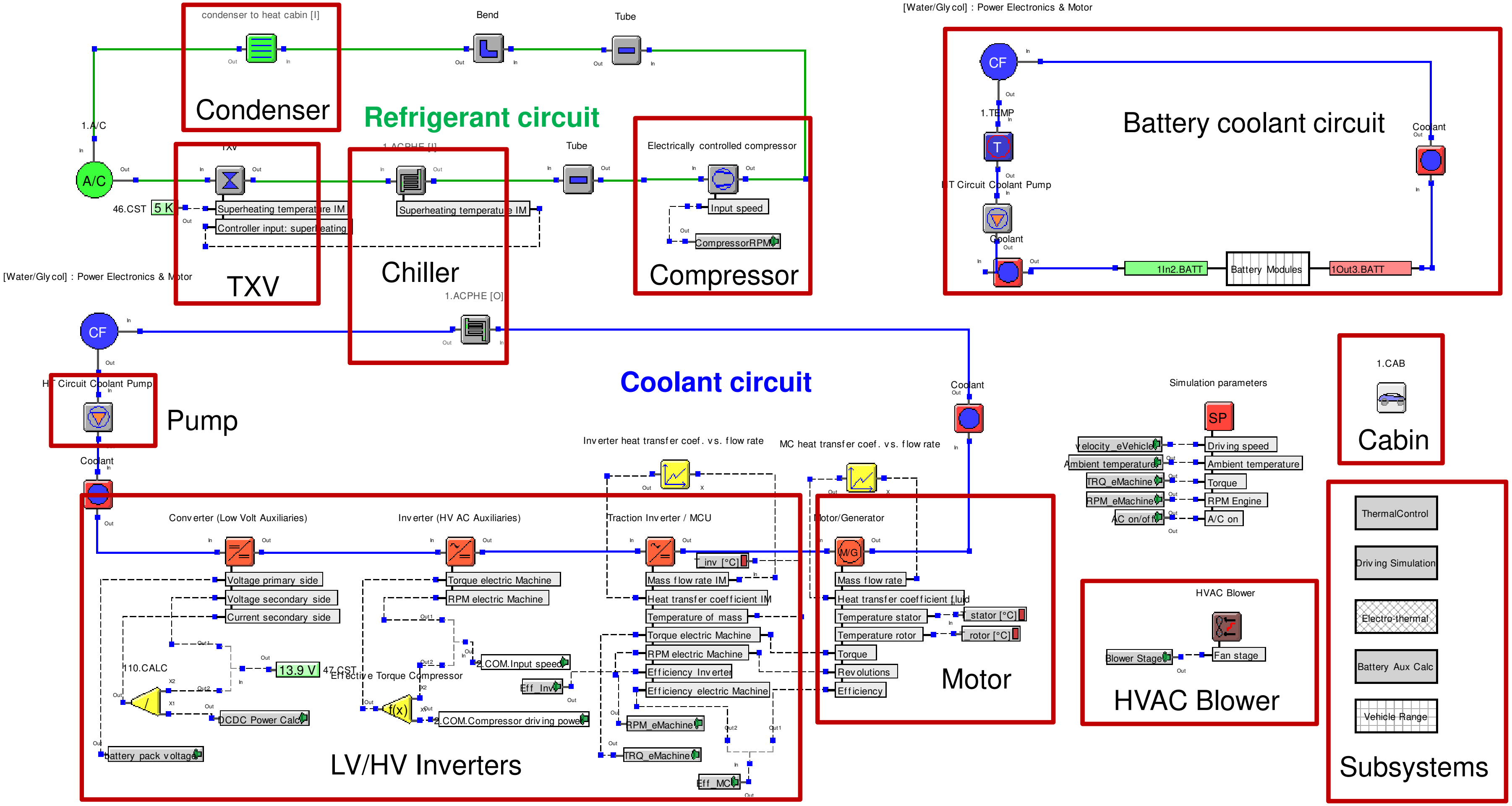
# Simulation Model – Ambient Heat Only



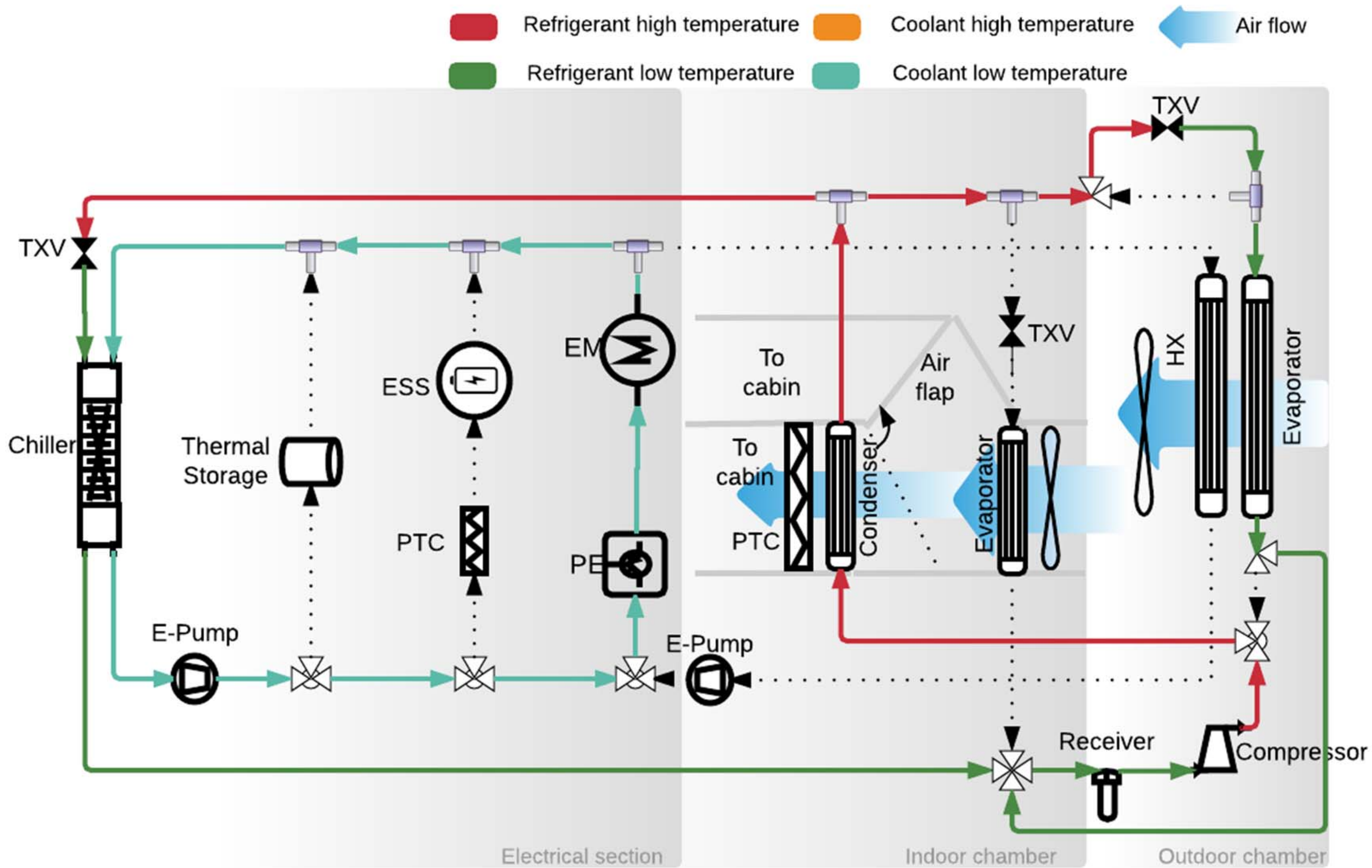
# Waste Heat Recovery -- Waste Heat Only



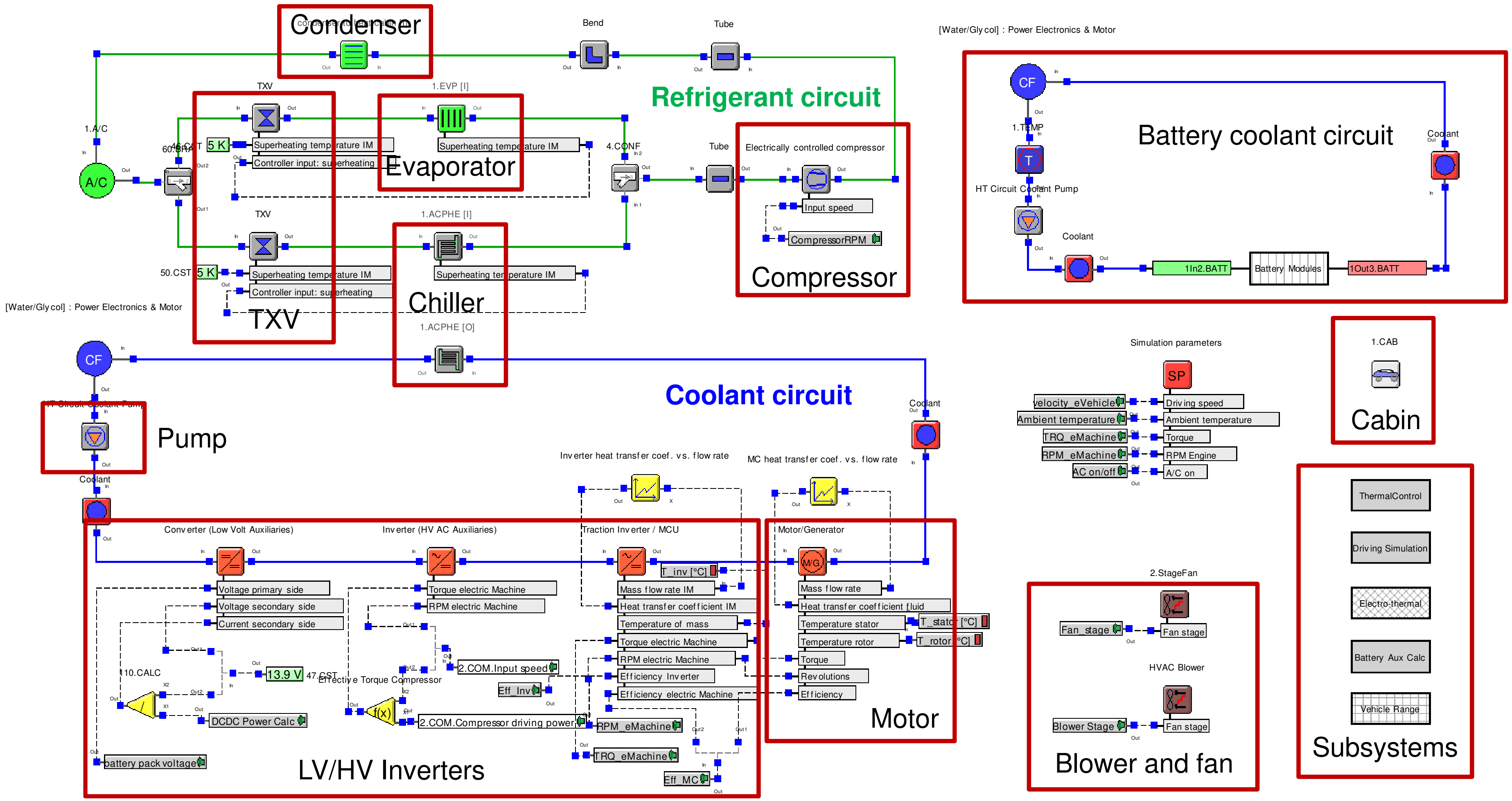
# Simulation Model – Waste Heat Only



# Waste Heat Recovery -- Dual Heat source

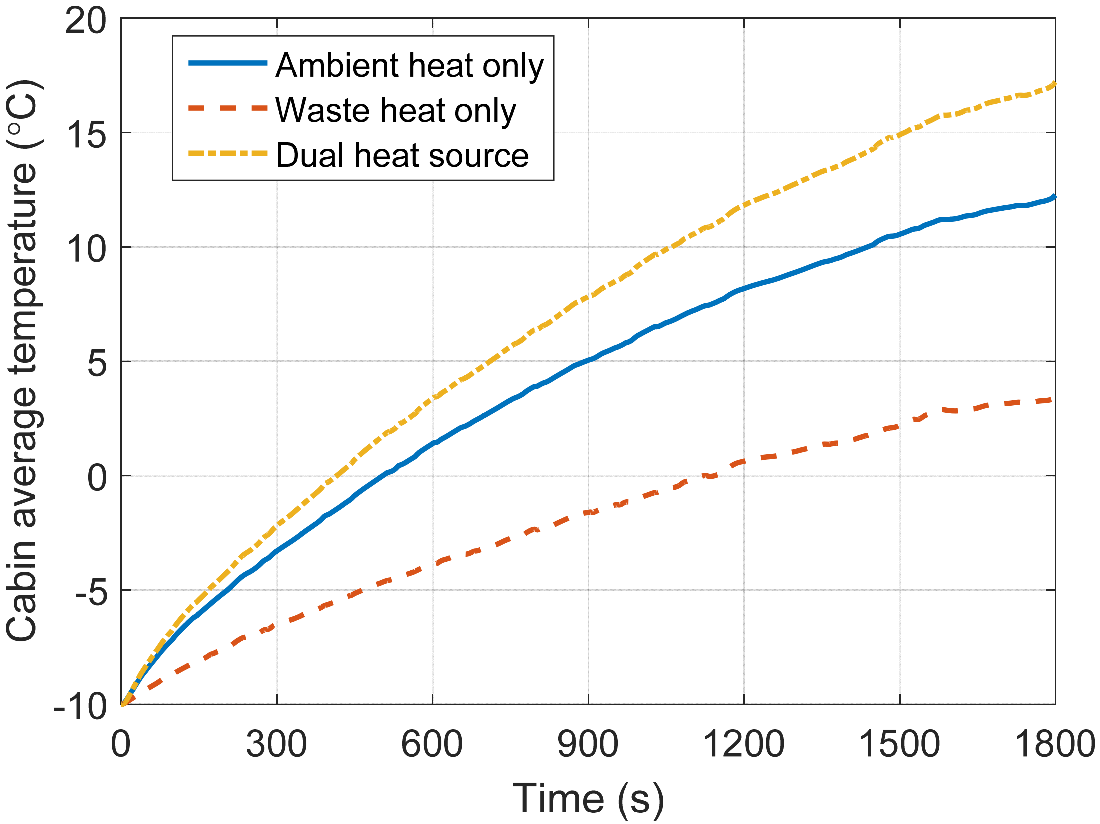


# Simulation Model – Dual Heat Source

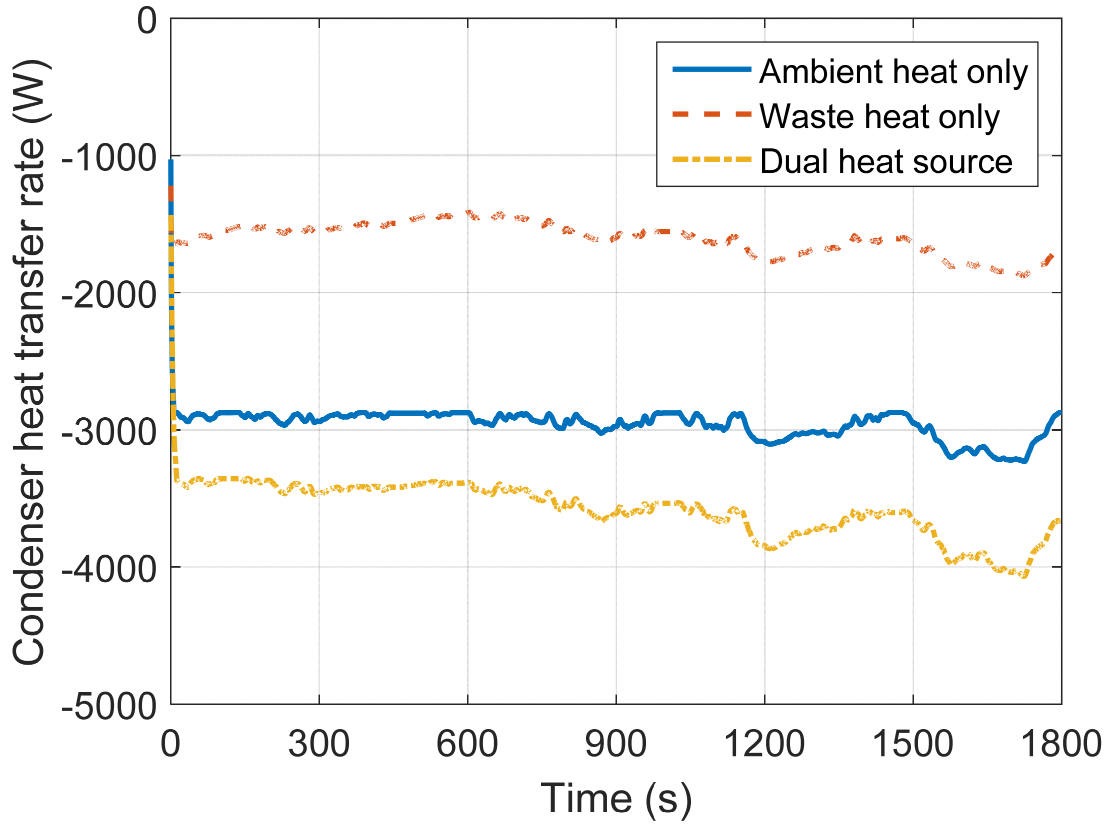


# -10° C Ambient, 1 WLTC Driving Cycle

Cabin air average temperature

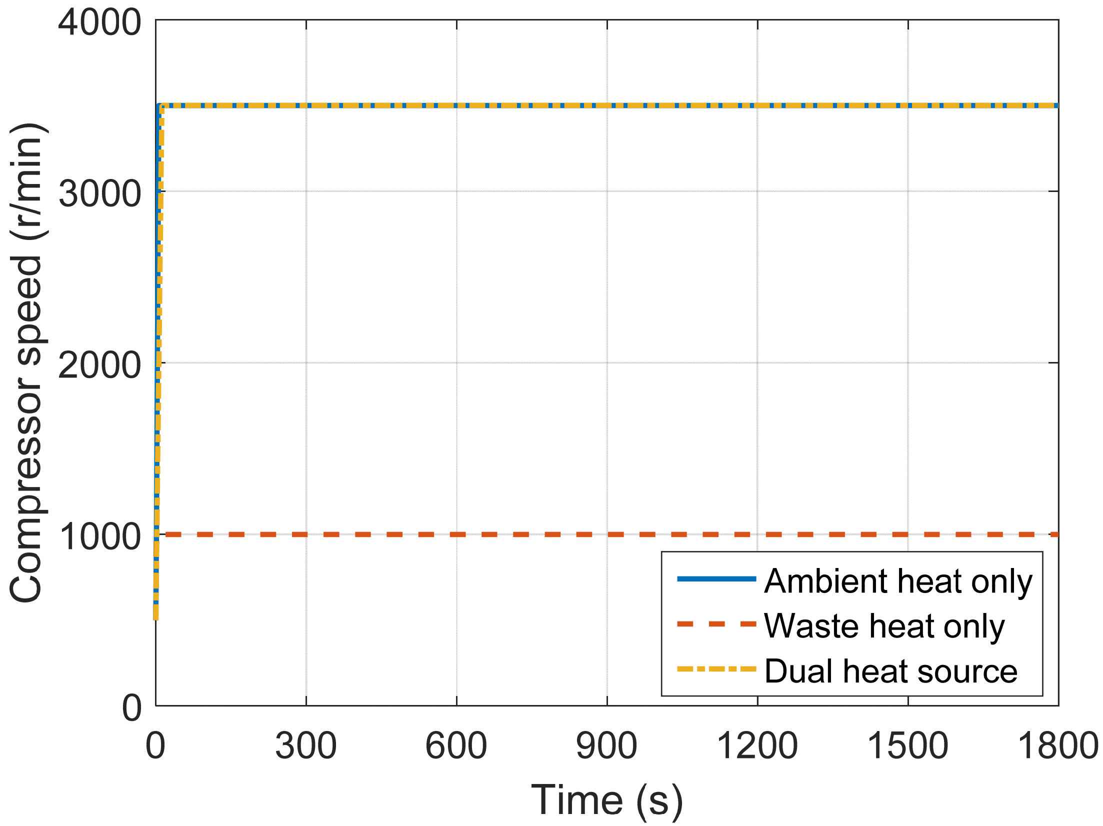



Condenser heat transfer rate

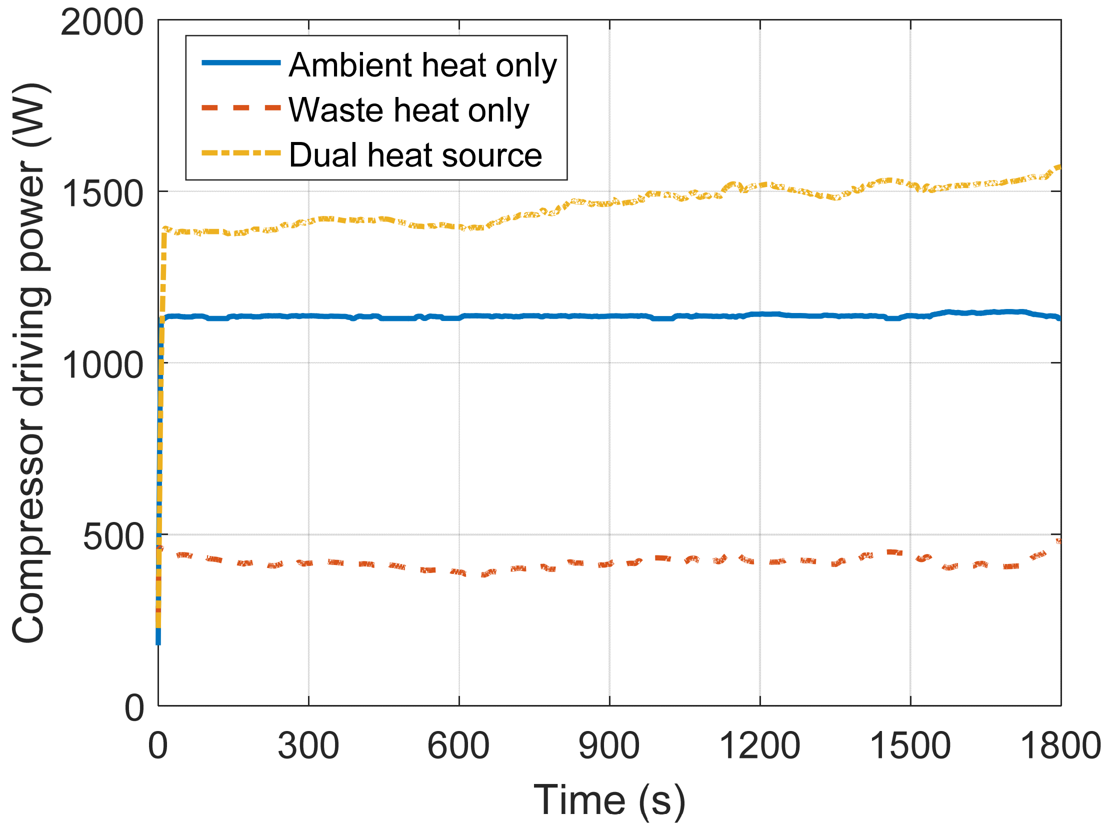


# -10° C Ambient, 1 WLTC Driving Cycle

## Compressor input speed

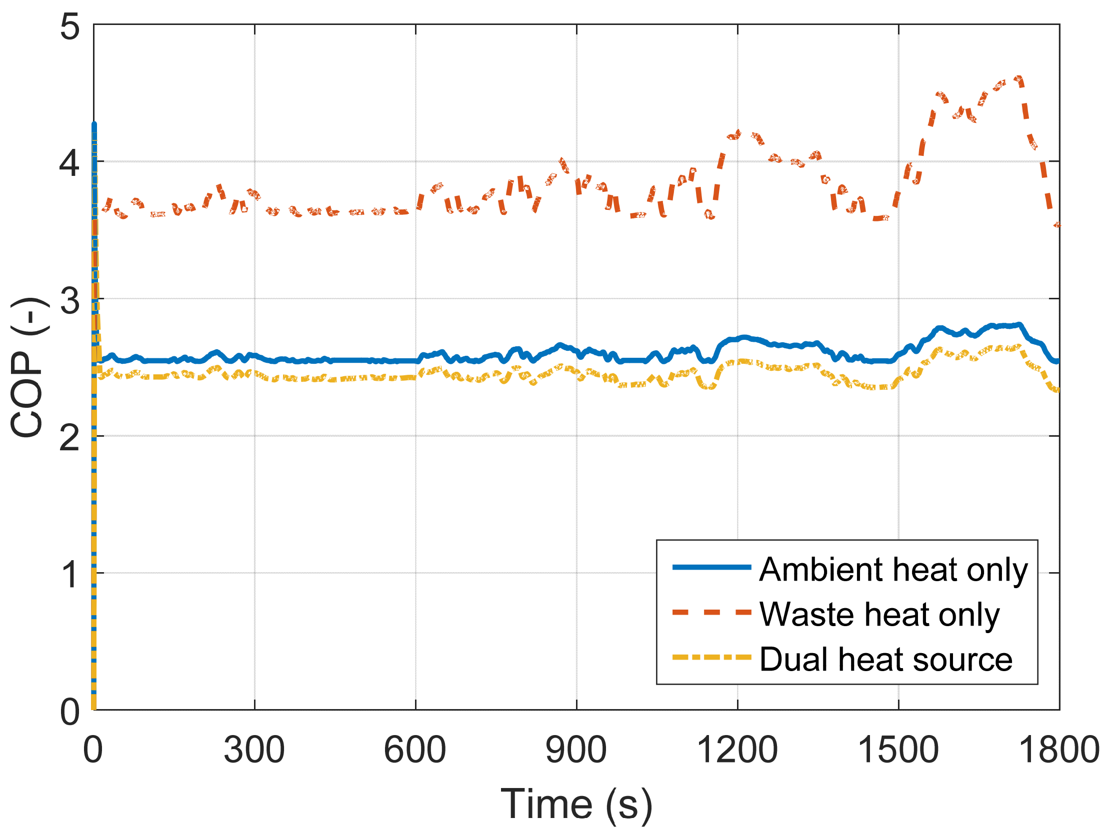



## Compressor driving power



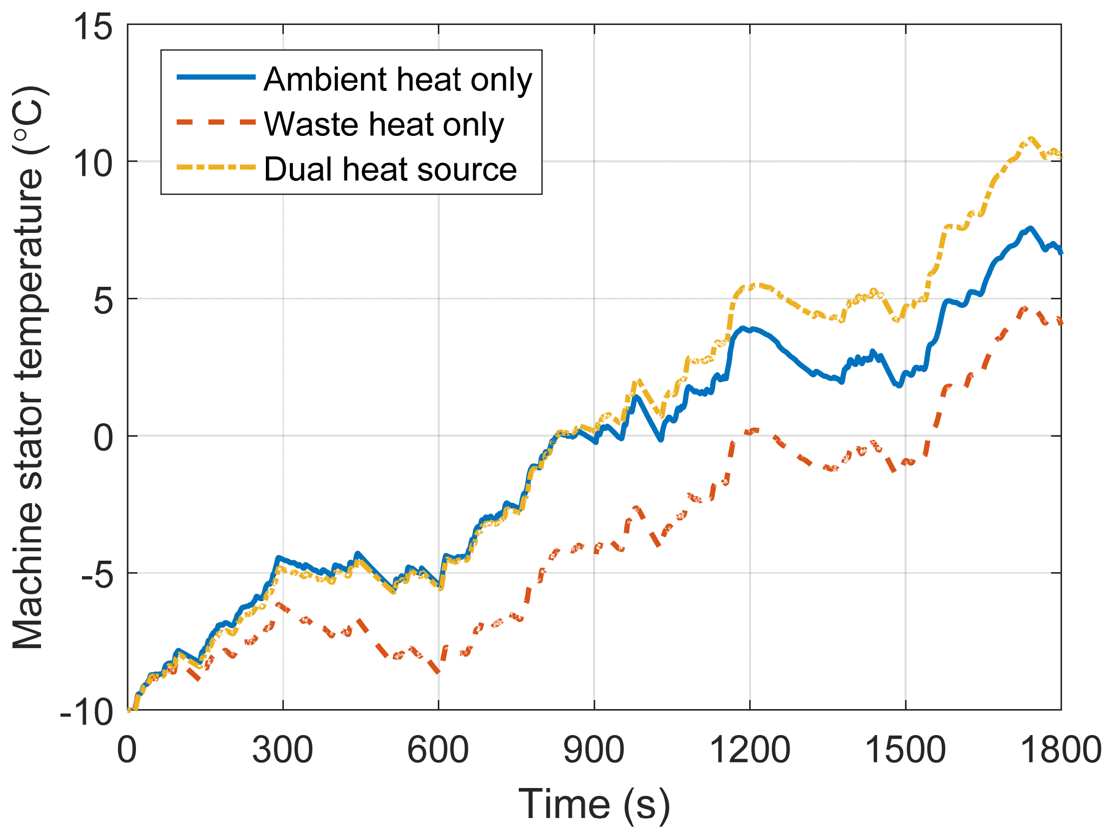
# -10° C Ambient, 1 WLTC Driving Cycle

COP

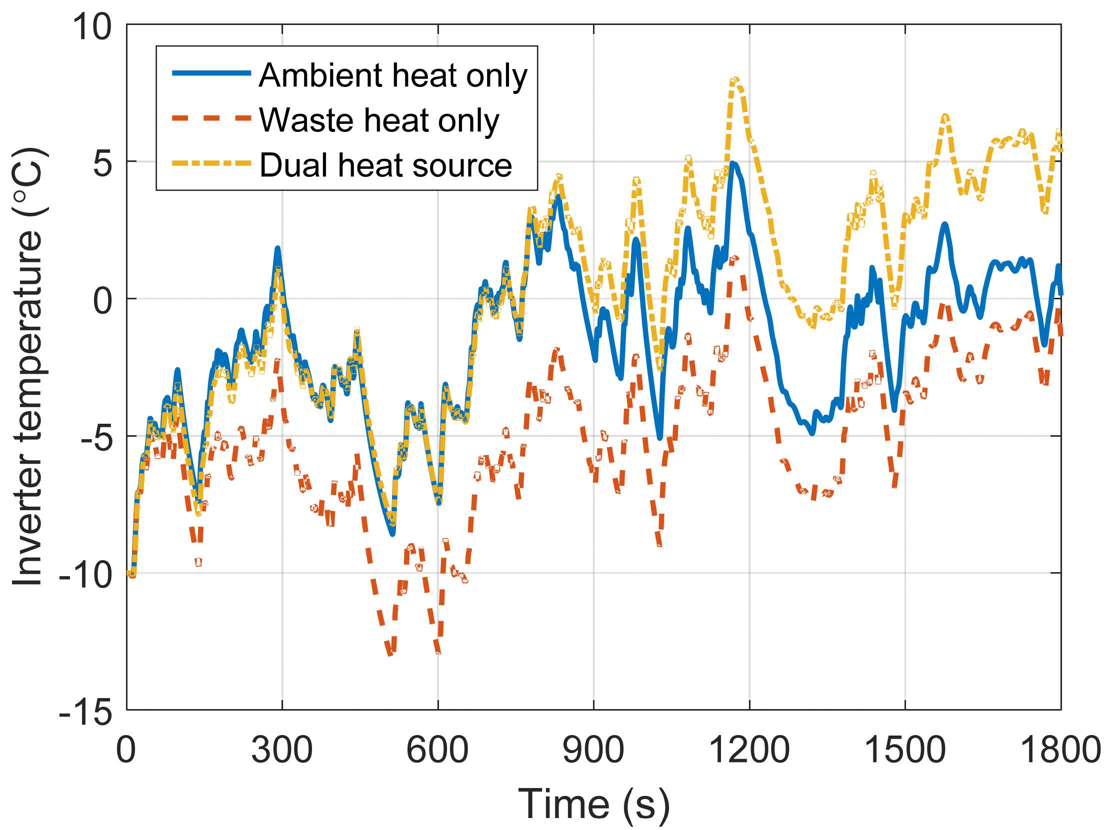


# -10° C Ambient, 1 WLTC Driving Cycle

## Machine stator temperature




## Inverter temperature



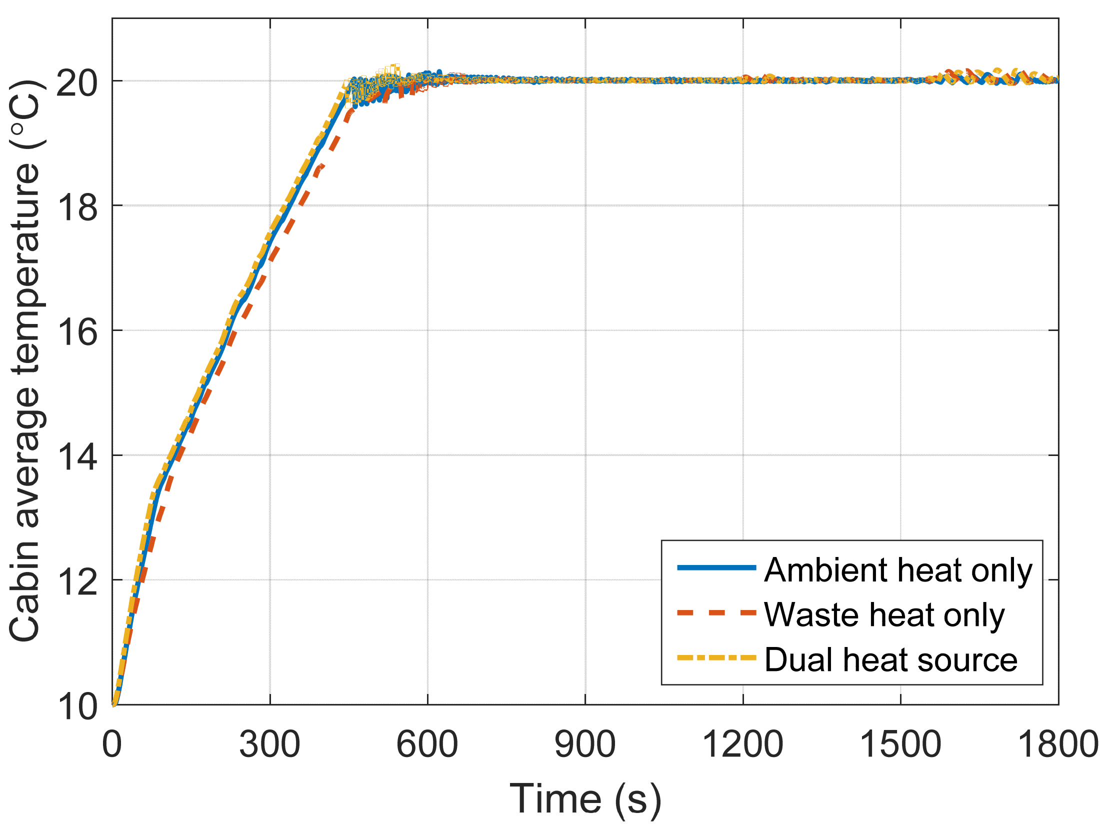
# -10° C Ambient, 1 WLTC Driving Cycle

## Net energy gain

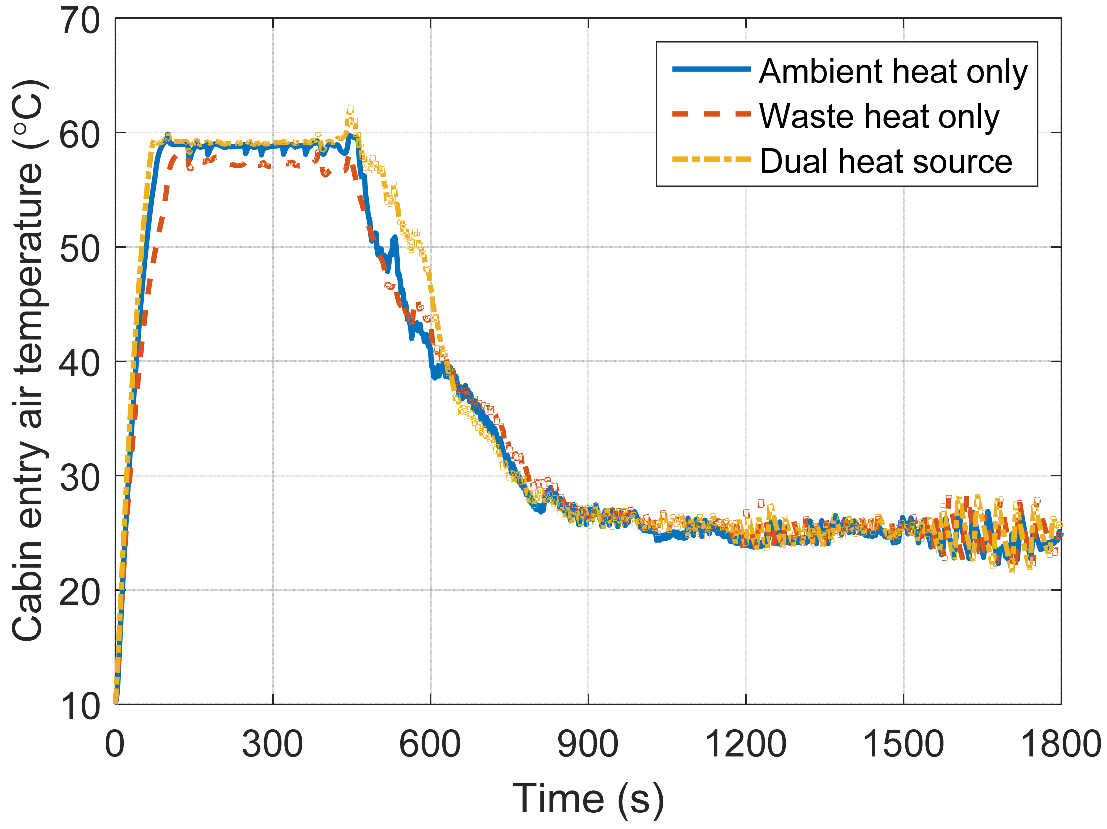
| Quantity | Unit | Ambient heat only | Waste heat only | Dual heat source |
|---|---|---|---|---|
| Compressor driving energy $W_{com}$ (including compressor loss) | MJ | 2.04 | 0.75 | 2.63 |
| Condenser energy $W_{con}$ (heat up cabin) | MJ | 5.33 | 2.88 | 6.46 |
| Evaporator energy $W_{eva}$ (waste energy recovery) | MJ | 3.79 | 2.20 | 2.26 (Ambient heat)<br>2.25 (Waste heat) |
| Net energy gain $W_{net}$ ($W_{net}=W_{con}-W_{com}$) | MJ | 3.29 | 2.13 | 3.83 |
| Total energy consumption $W_{tot}$ (Consumed battery energy) | MJ | 17.96 | 15.07 | 18.93 |
| Net energy gain ratio $R_{net}$ ($R_{net}=W_{net}/W_{tot}$*100%) | % | 18.32% | 14.13% | 20.23% |
| Average COP | - | 2.61 | 3.84 | 2.46 |

# 10° C Ambient, 1 WLTC Driving Cycle

Cabin air average temperature

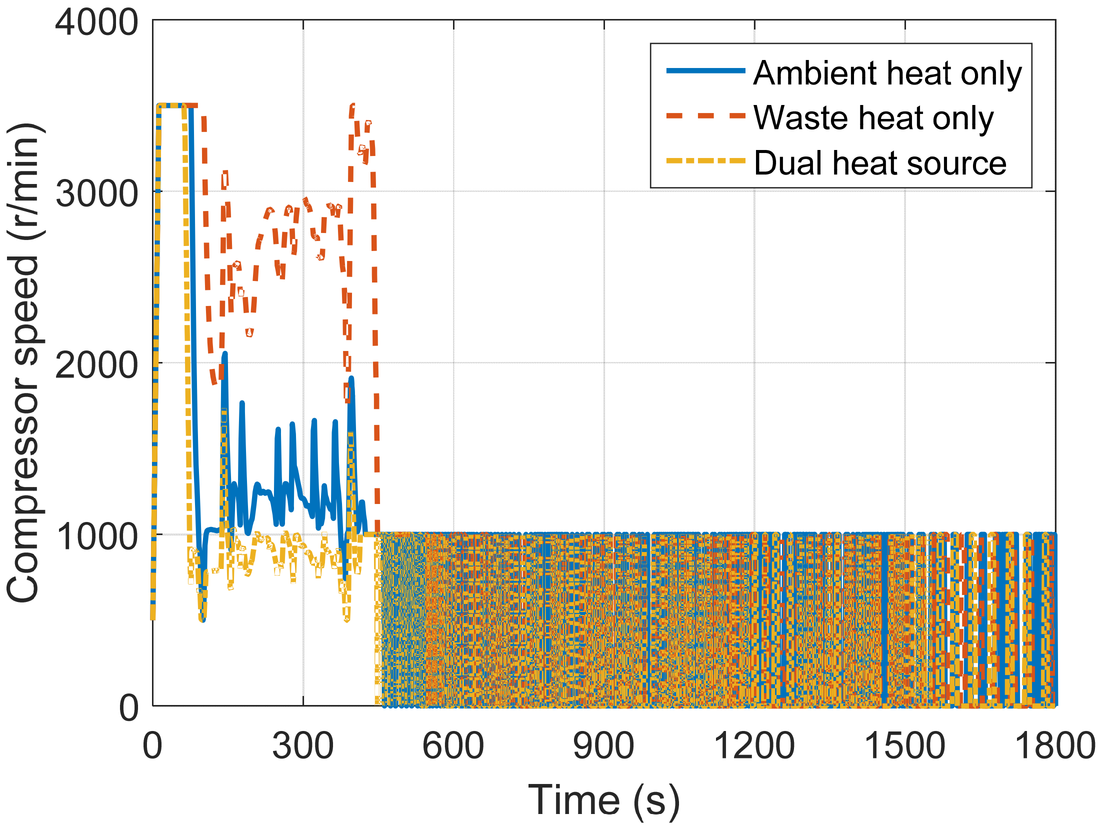



Cabin air entry temperature

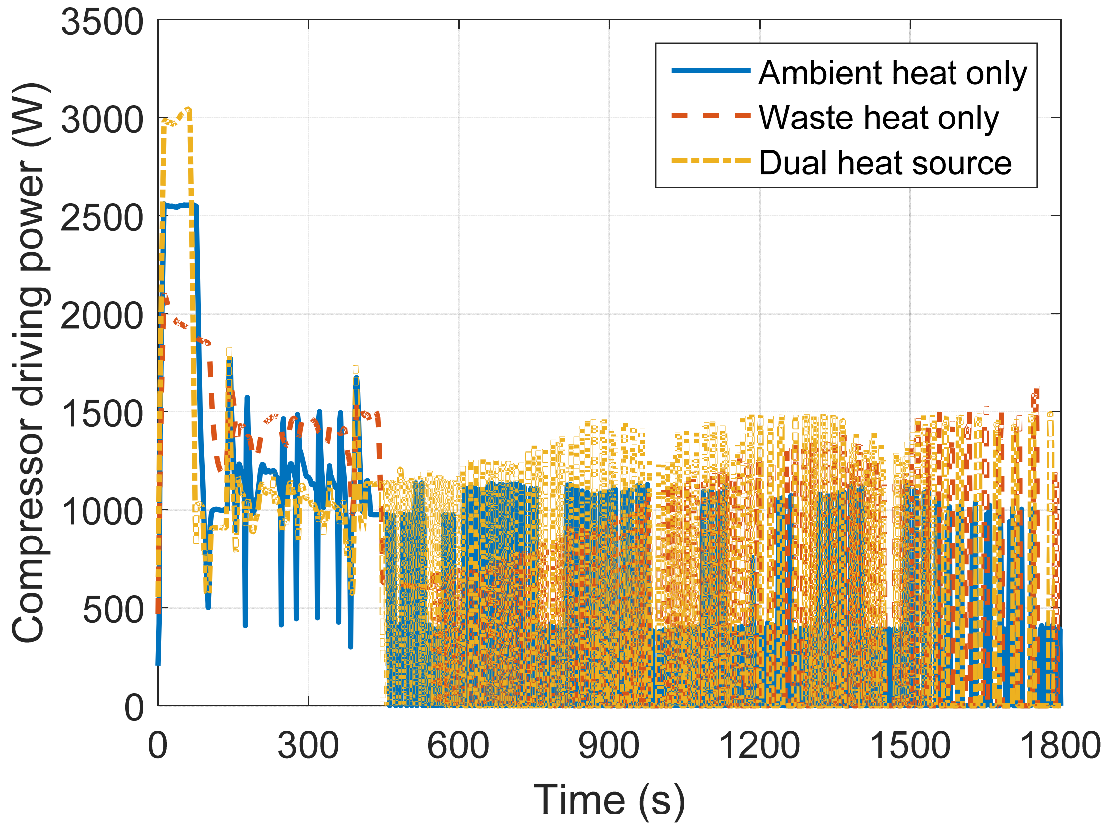


# 10° C Ambient, 1 WLTC Driving Cycle

Compressor input speed




Compressor driving power



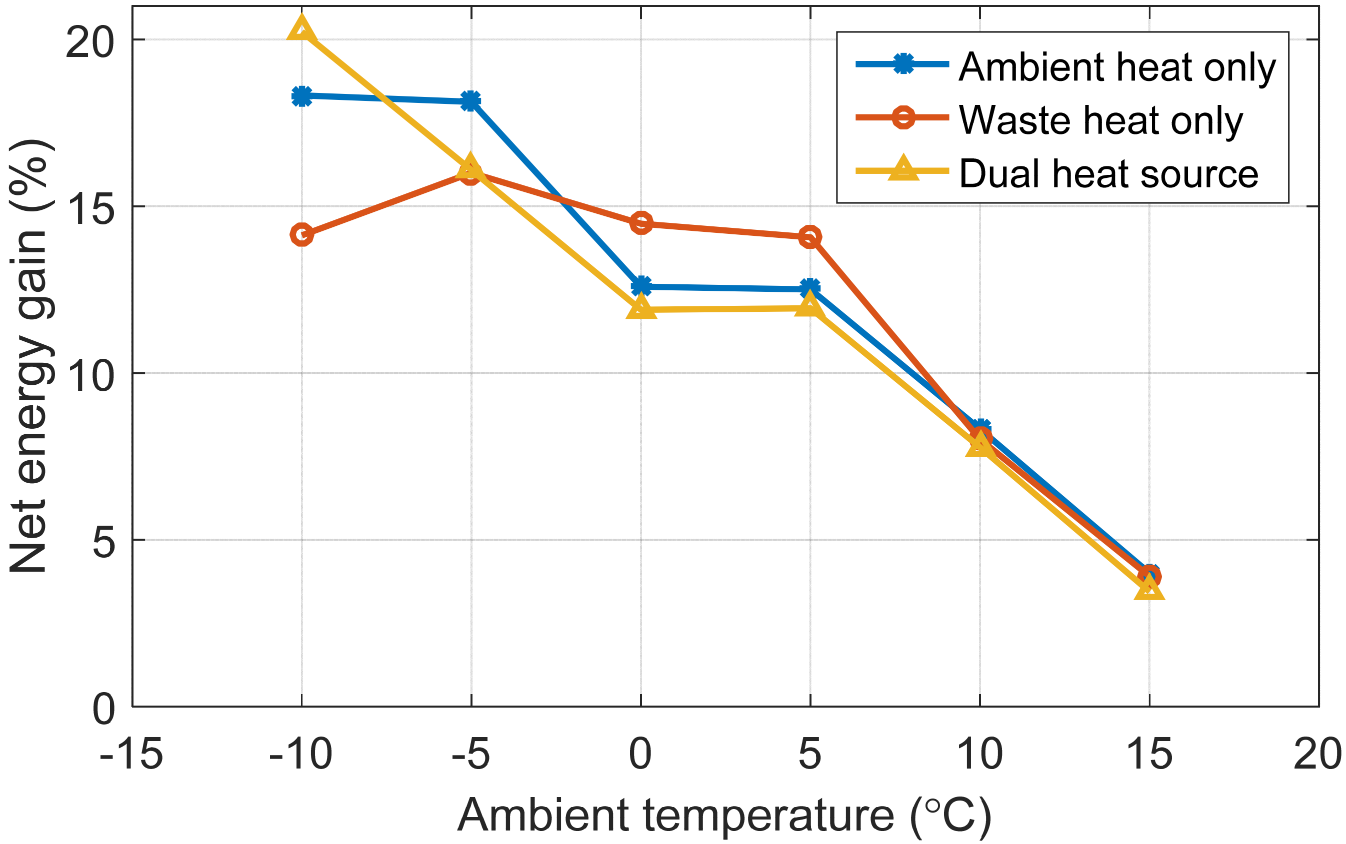
# 10° C Ambient, 1 WLTC Driving Cycle

## Net energy gain

| Quantity | Unit | Ambient heat only | Waste heat only | Dual heat source |
|---|---|---|---|---|
| Compressor driving energy $W_{com}$ (including compressor loss) | MJ | 1.01 | 1.11 | 1.04 |
| Condenser energy $W_{con}$ (heat up cabin) | MJ | 2.41 | 2.38 | 2.36 |
| Evaporator energy $W_{eva}$ (waste energy recovery) | MJ | 1.82 | 1.56 | 0.56 (Ambient heat)<br>1.10 (Waste heat) |
| Net energy gain $W_{net}$ ($W_{net}=W_{con}-W_{com}$) | MJ | 1.40 | 1.27 | 1.32 |
| Total energy consumption $W_{tot}$ (Consumed battery energy) | MJ | 16.83 | 15.85 | 16.99 |
| Net energy gain ratio $R_{net}$ ($R_{net}=W_{net}/W_{tot}$*100%) | % | 8.32% | 8.01% | 7.77% |
| Average COP | - | 2.39 | 2.14 | 2.27 |

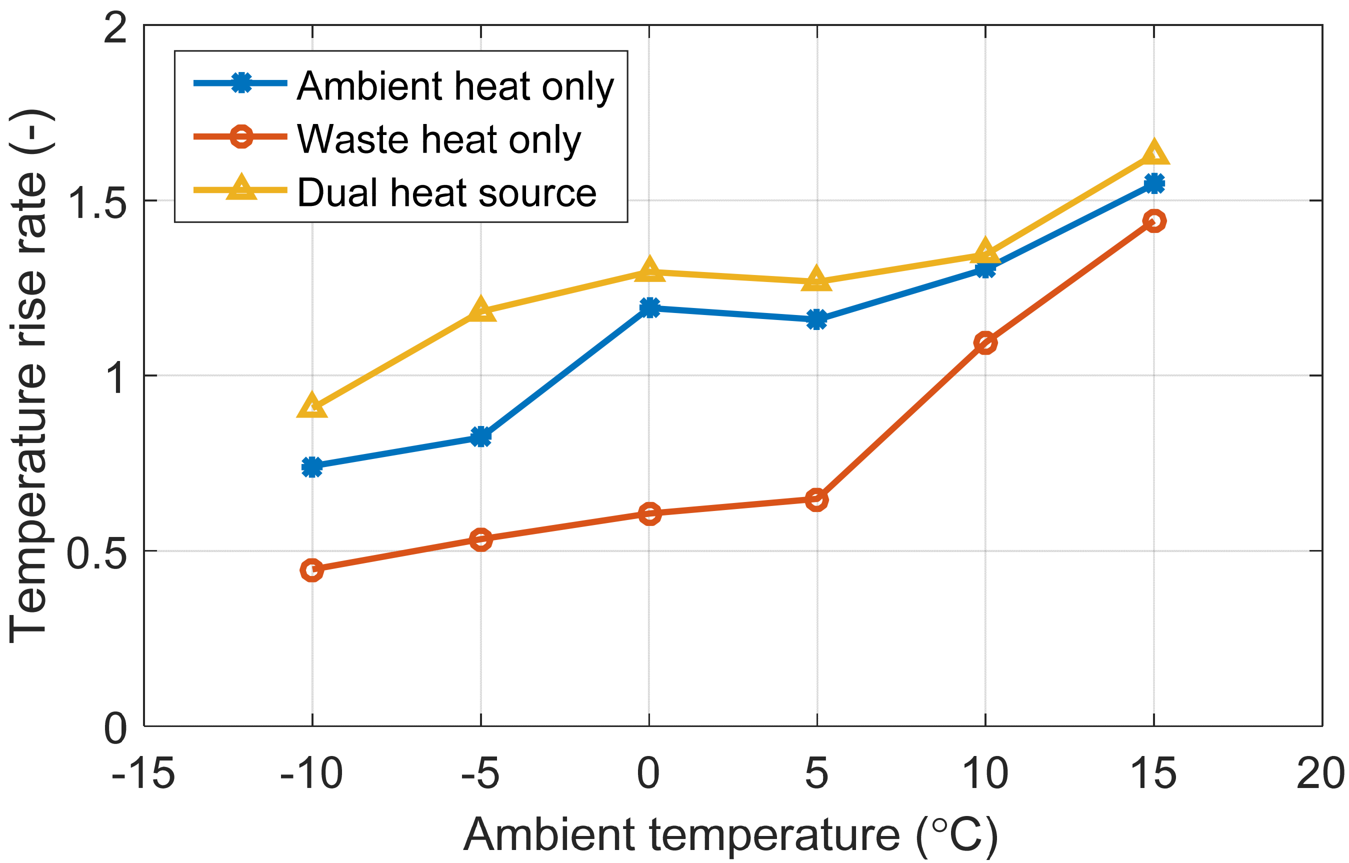
# Influence of ambient temperature

**Net energy gain vs. ambient temperature**



# Thermal Comfort Comparison

**Mean temperature rise rate before reaching 20° C target temperature**



# Conclusions and Future work

- Compared to the ambient heat only scheme, the dual heat sources scheme can work at lower temperatures, exhibits higher heating power and thus takes less time to reach thermal comfort temperature, and also has higher net energy gain.
- Compared to the waste heat only scheme, the dual heat source scheme can satisfy the thermal comfort without introducing new key components, has much higher heating power, and also higher net energy gain.
- The main trend of the net energy gain is decreasing with the increase of ambient temperature since the required energy for thermal comfort is lower at higher ambient temperature.
- The main trend of the temperature rise rate is increasing with the increase of ambient temperature because more ambient heat is available at higher ambient temperature.
- Experimental test will be performed after setting up the test rig and demo car.

# Q & A

**Thank you for your attention!**