DENSO
Crafting the Core

Smart Thermal Management

Meet & Greet met KIVI Duurzame Technologie 2024

20/03/2024

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Head of Department / Senior Manager

Mobility Energy Systems / Energy Systems R&D

Agenda

1. Introduction

2. Smart Thermal Management
    1. Prediction (Connectivity)
    2. Global coordination (Supervision)
    3. Local optimization (AI Optimisation)

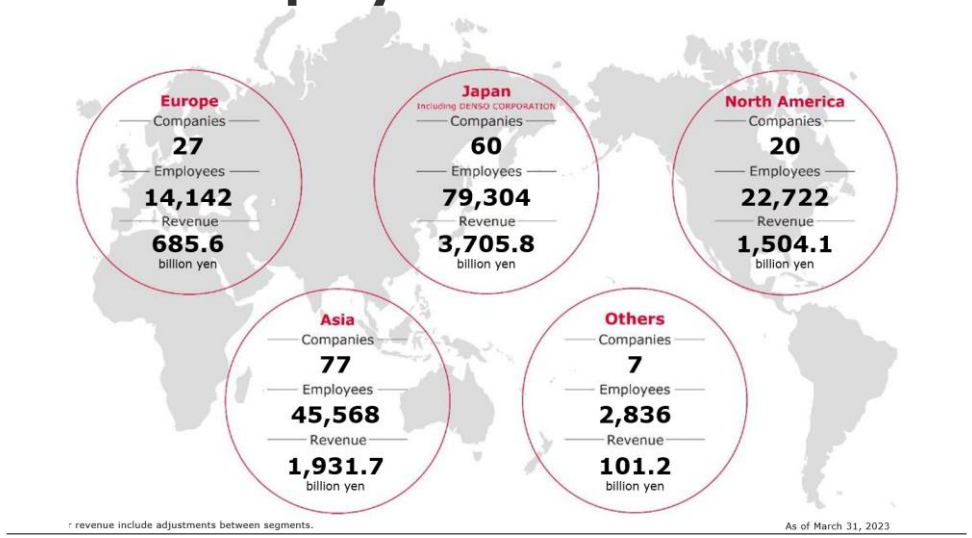
1

Introduction

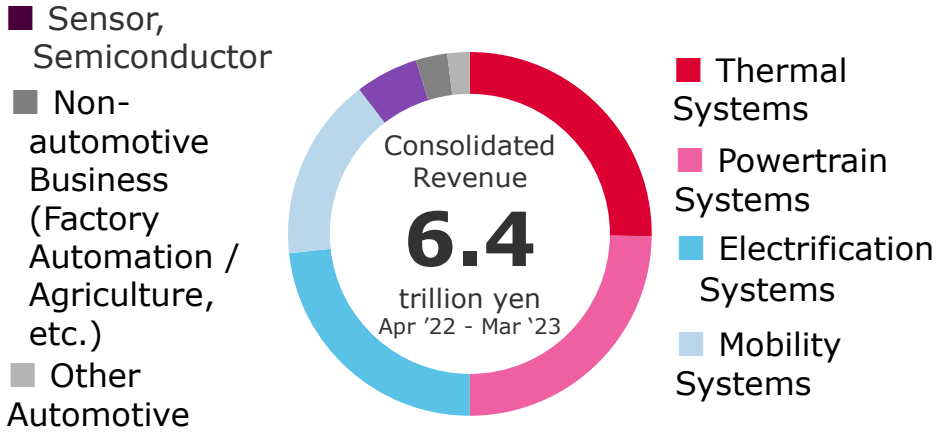
DENSO and the Battery Energy Vehicle Approach

DENSO Global Overview

Employees: ~165.000



Revenue: ~ 40 Billion Euro

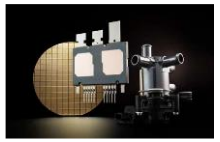


Electrification Systems: Supporting electrification in all areas of mobility to realize an enriched environment and the joy of driving

Powertrain Systems: Providing solutions that help overcome the seemingly contradictive task of balancing the joy of driving with superior environmental performance

Thermal Systems: Providing safe, comfortable systems that use the least amount of energy possible in consideration of the environment

Mobility Systems: Aiming to realize Quality of Mobility so that all people can enjoy mobility safely and comfortably



Sensor Systems & Semiconductors: Pioneering the industry through semiconductor and sensing technologies to realize an eco-friendly, comfortable, and safe mobility and society.

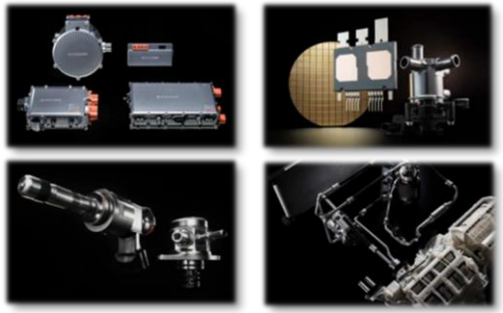
Industrial Solutions: Enhancing the productivity of the manufacturing industry and contributing to an improved quality of life with a commitment to our long-cultivated technologies

Food Value Chain: Combining technologies and ideas to contribute to an enriched society where all people can live safely and with peace of mind

DENSO European Overview

Aachen Engineering Center (AEC)

Engineering Domains



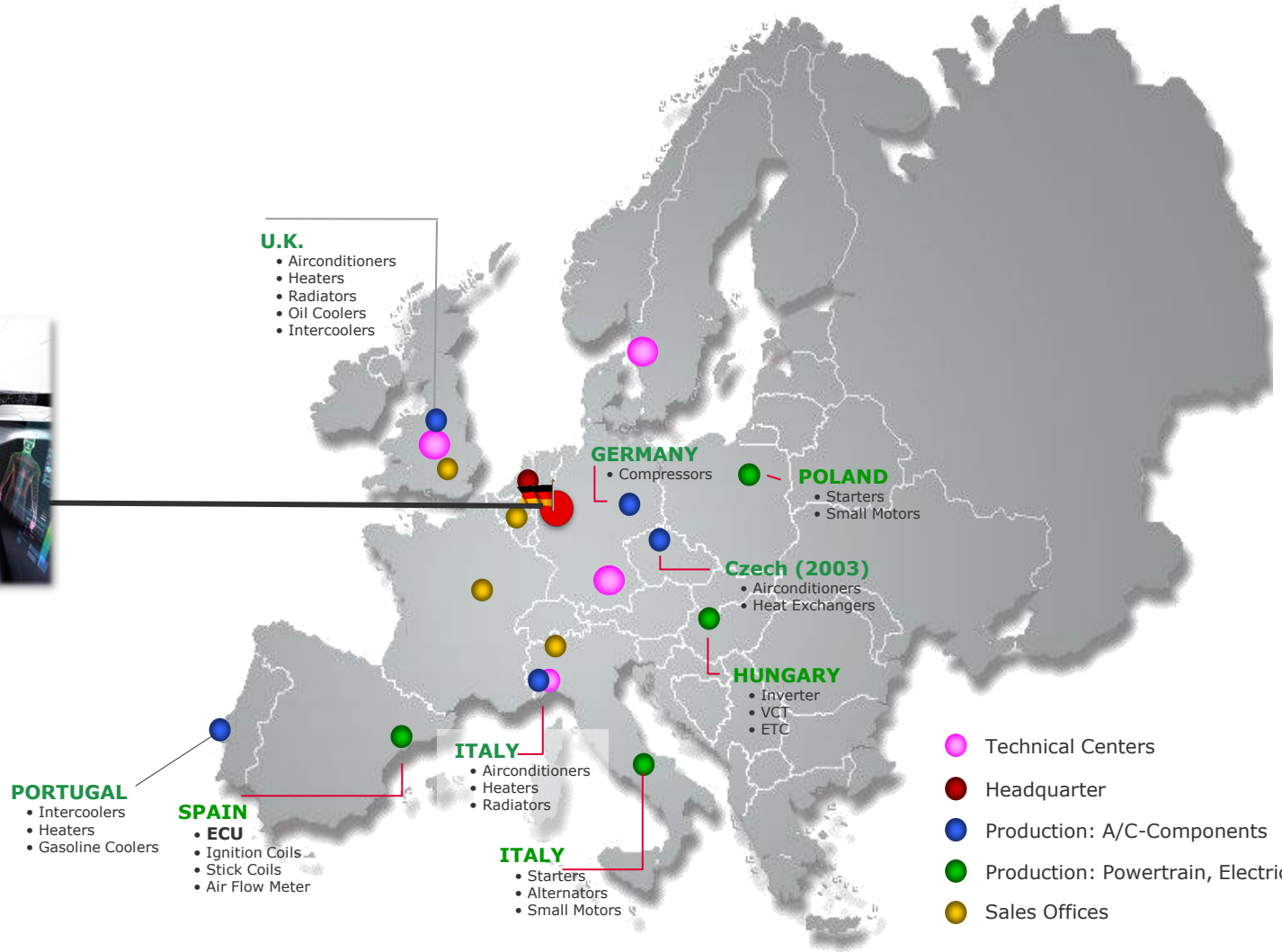
Energy Systems R&D
Powertrain Components
Exhaust Aftertreatment
Electronics
Electrification
Production Innovation

Capabilities

R&D
- *Benchmarking*
- *Concept Making*
- *Technology Research*

Advanced Engineering
- *System Engineering*
- *Demo Engine/Vehicle*

Testing
- *System Engineering*
- *Demo Engine/Vehicle*



Green

Aiming to Become Carbon Neutral by 2035

Monozukuri (Manufacturing)

Realize complete carbon neutrality at our plants

Mobility Products

Contribute to the electrification of cars to reduce CO_2 emissions to the greatest extent possible

Energy Use

Realize an energy-recycling society through the development and popularization of technologies that make effective use of renewable energy

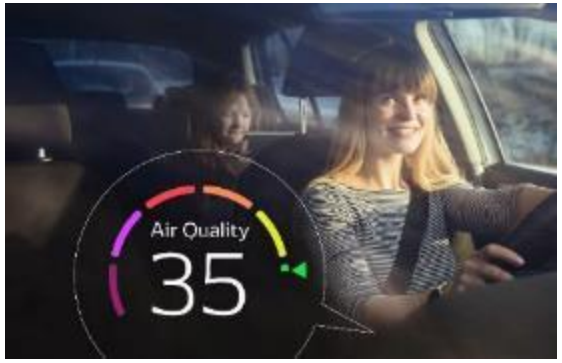
Peace of mind

Aiming to Become a Leading Company That Provides “Peace of Mind” to Society

Elimination of Fatalities from Traffic Accidents

Popularize safety products through efforts focused on “depth” and “width,” thereby realizing free mobility without fatalities from traffic accidents

Creation of Comfortable Spaces



Enhance relevant technologies for creating peaceful, comfortable spaces

Support for Working People

Draw on the technologies we have calculated in the mobility domain to establish a society where people are supported and their potential is nurtured

DENSO Vehicle Energy Management

Thermal System

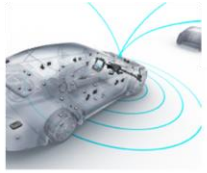
Thermal mgmt. systems & components

Powertrain Systems

Variety of Gasoline & Diesel related products.

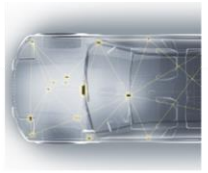
Electrification Systems

Electrification systems & components for BEV & (P)HEVS



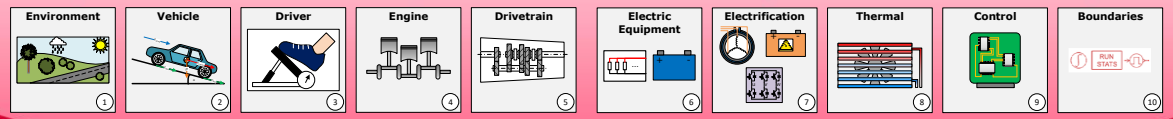
Mobility Systems

AD & ADAS products as well as Connected & Cockpit products



Electronic Systems

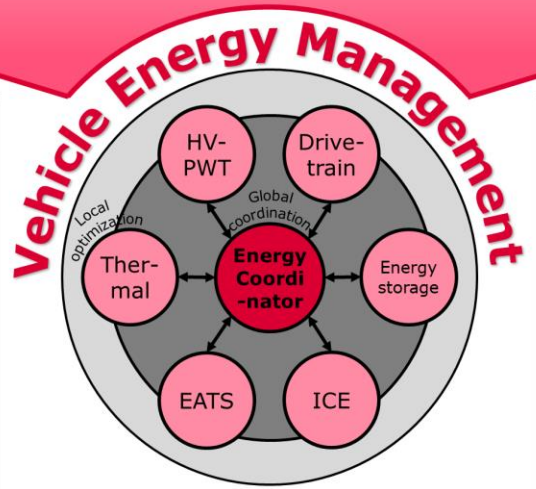
Microelectronic devices plus electronics products

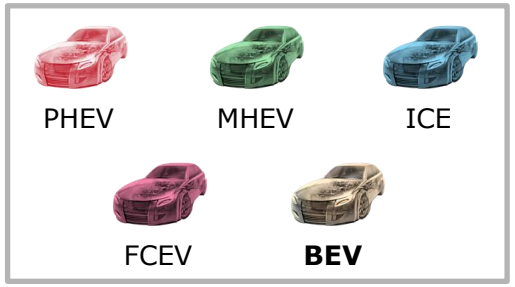


Cross Divisional Development Efforts

Tunable energy trade-off/ Customer Input :

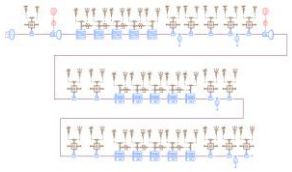
Fun-To-Drive (Performance)
Comfort (Cabin)
Convenience (Range)





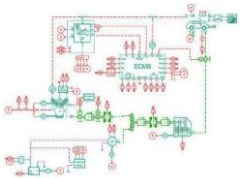
Step 1

1-3D Models for component design, functionality & optimization



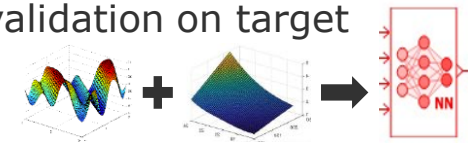
Step 2

0D Models for vehicle system evaluation on use case basis



Step 3

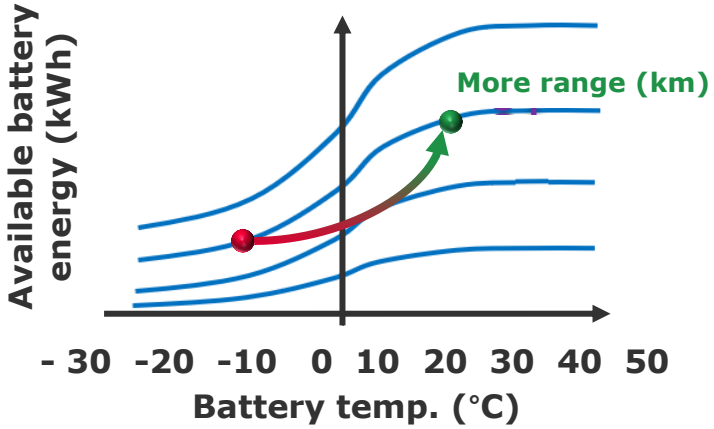
Reduced order model for MIL control development, sensitivity analyses & rapid validation on target



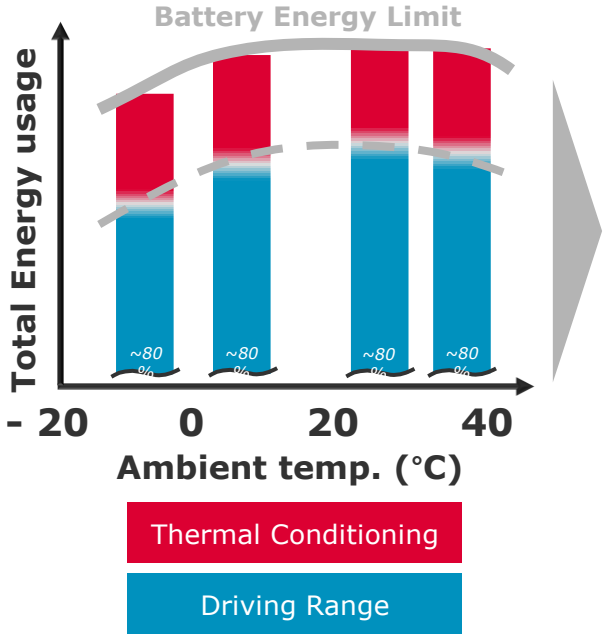
Component, System and Control modelling by cross divisional approach

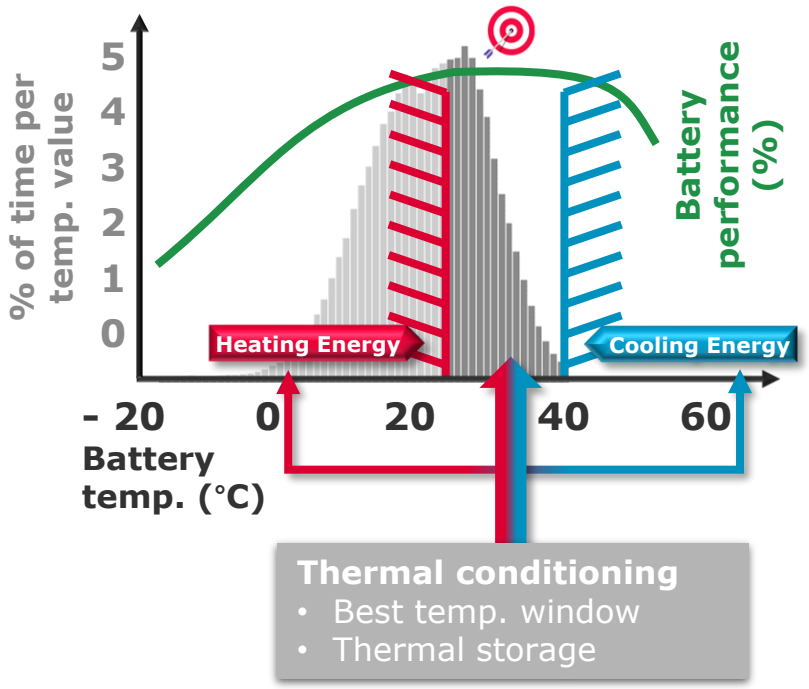
Motivation for Smart Thermal Management for BEVs

To increase the available energy of the battery, the thermal management systems (both refrigerant & coolant) **must manage the required thermal energy of the battery**



Exemplary *charge, discharge (traction), regenerative* ***powermaps***

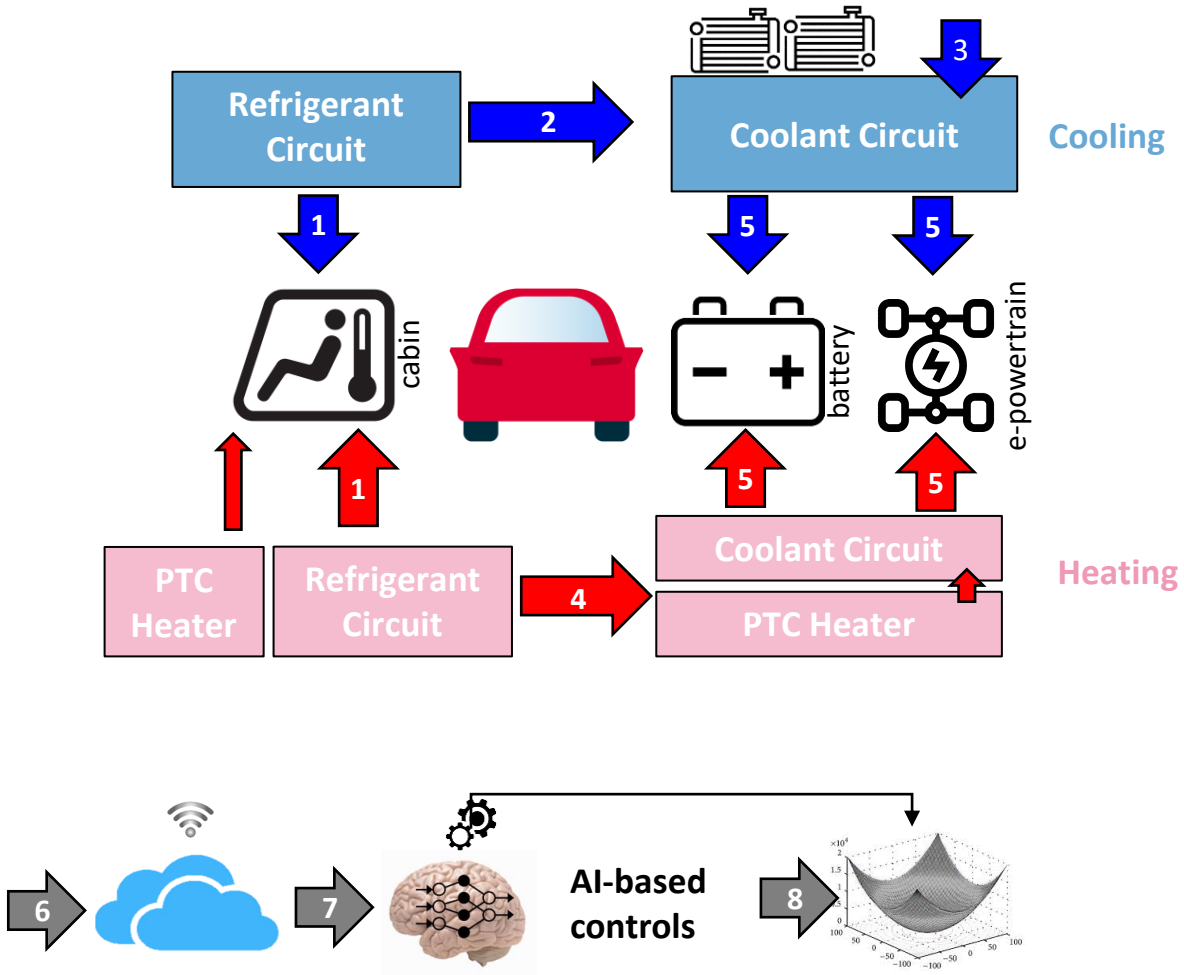




** BEV = Battery Electric Vehicle*

"Credibility of BEV technology is achieved by the customer's confidence of having always access to the same level of autonomy, charging duration and dynamic performance, anytime & anywhere"

Smart Thermal Management



Key STM Concepts	
High performance components	
1	Enhanced cabin conditioning H/P
2	Enhanced battery cooling by H/P
3	Enhanced battery cooling by radiator
4	Enhanced battery heating by H/P
5	Enhanced energy flow distribution of coolant
State-of-the-art technology	
6	Accurate prediction using connectivity
7	Global vehicle energy coordination based on MPC methods
8	AI-based thermal management using local optimization

Today's focus

Enhanced vehicle performance utilizing "Smart Thermal Management" – based on high performance components and State-of-the-Art technologies

Smart Thermal Management

Enhanced user experience

Core functionality

Layer 4

Prediction
(eHorizon and connectivity)

Out-car information

Layer 3

Global coordination
(Power distribution)

Power split

Layer 2

Local optimization
(Intelligent thermal manager)

Refrigerant | **Coolant** | **HVAC**

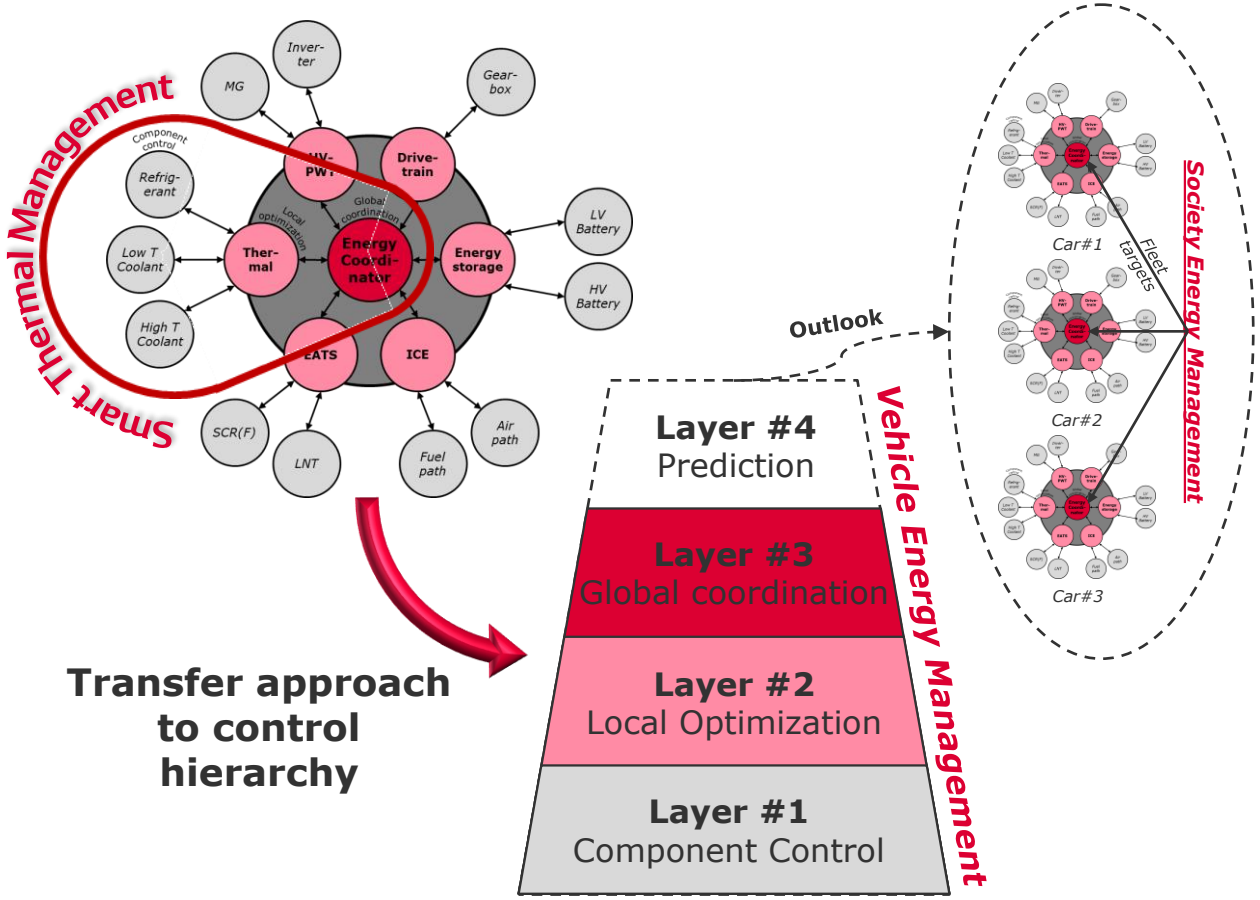
Shut valve
Battery EXV

Water pump
Valves

Blower speed
Cabin air mix

Layer 1 Component Contro

Modular control architecture



Global targets are distributed into domain specific smaller optimization problems

A distributed approach is taken in the control architecture

2

Smart Thermal Management

Smart Thermal Management - Prediction

Accurate route planning using smart connectivity

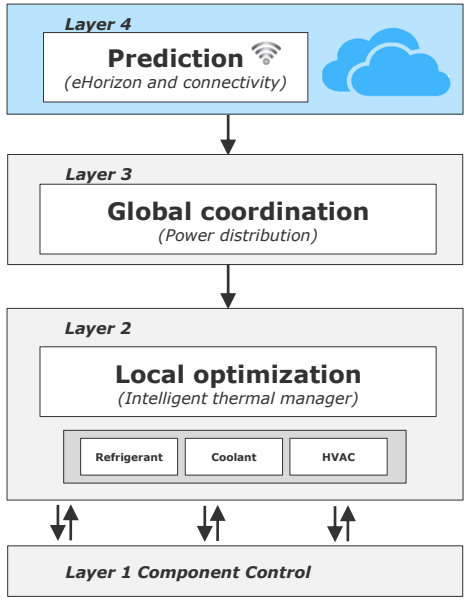
Prediction

ePowertrain Energy Request

Cabin Conditioning Energy Request

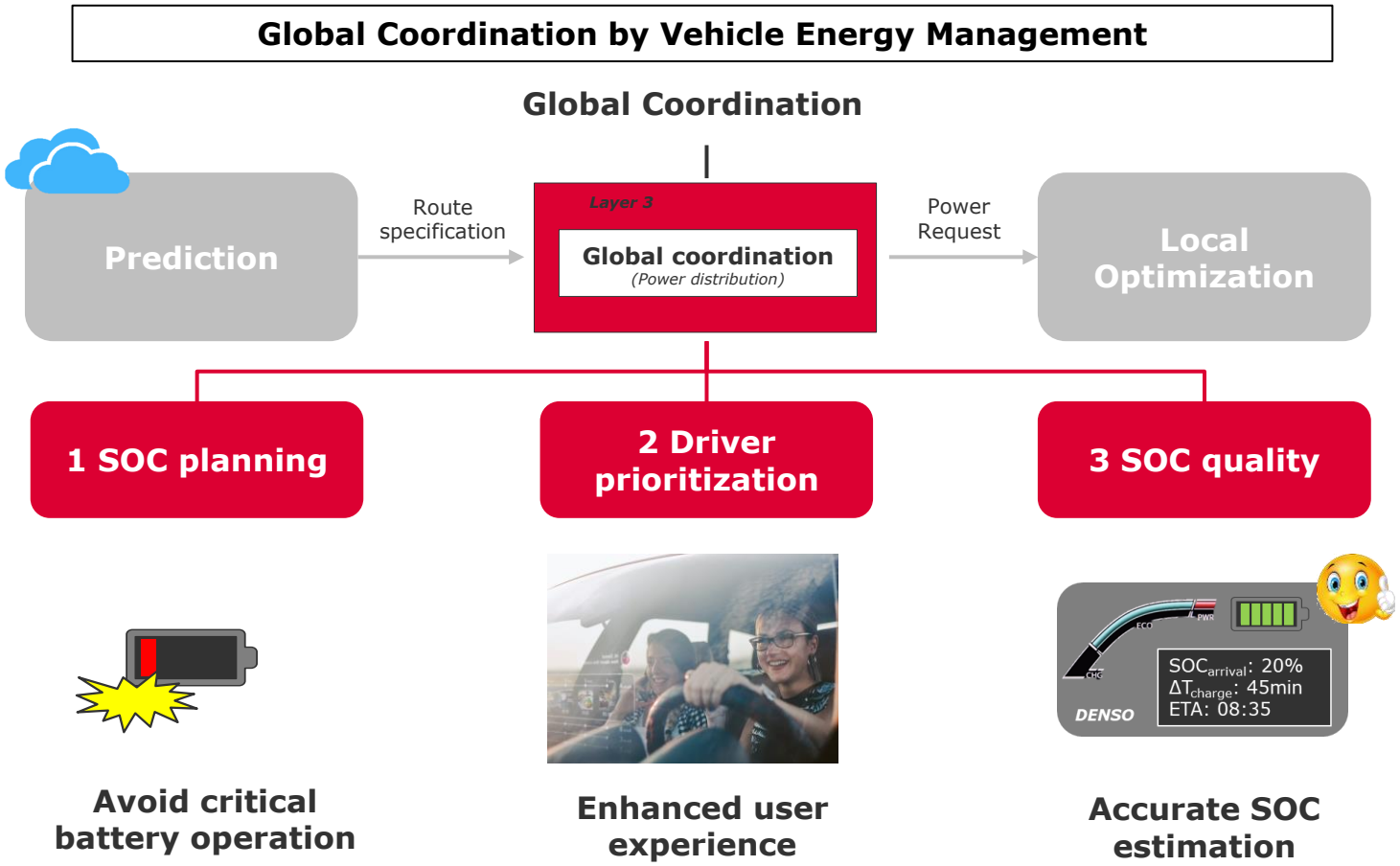
Battery Conditioning Energy Request

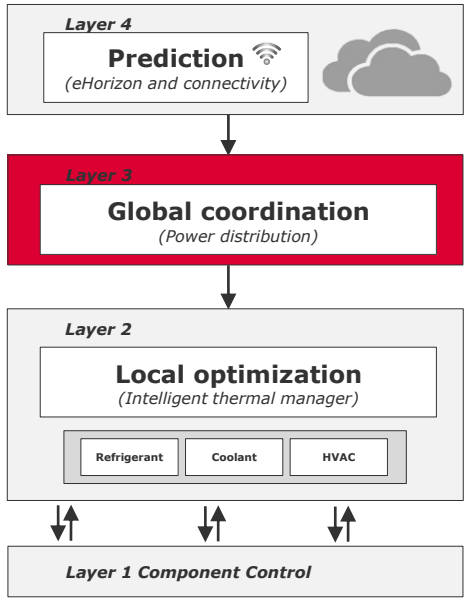
Global Coordination



Prediction information used to estimate most probable energy requests

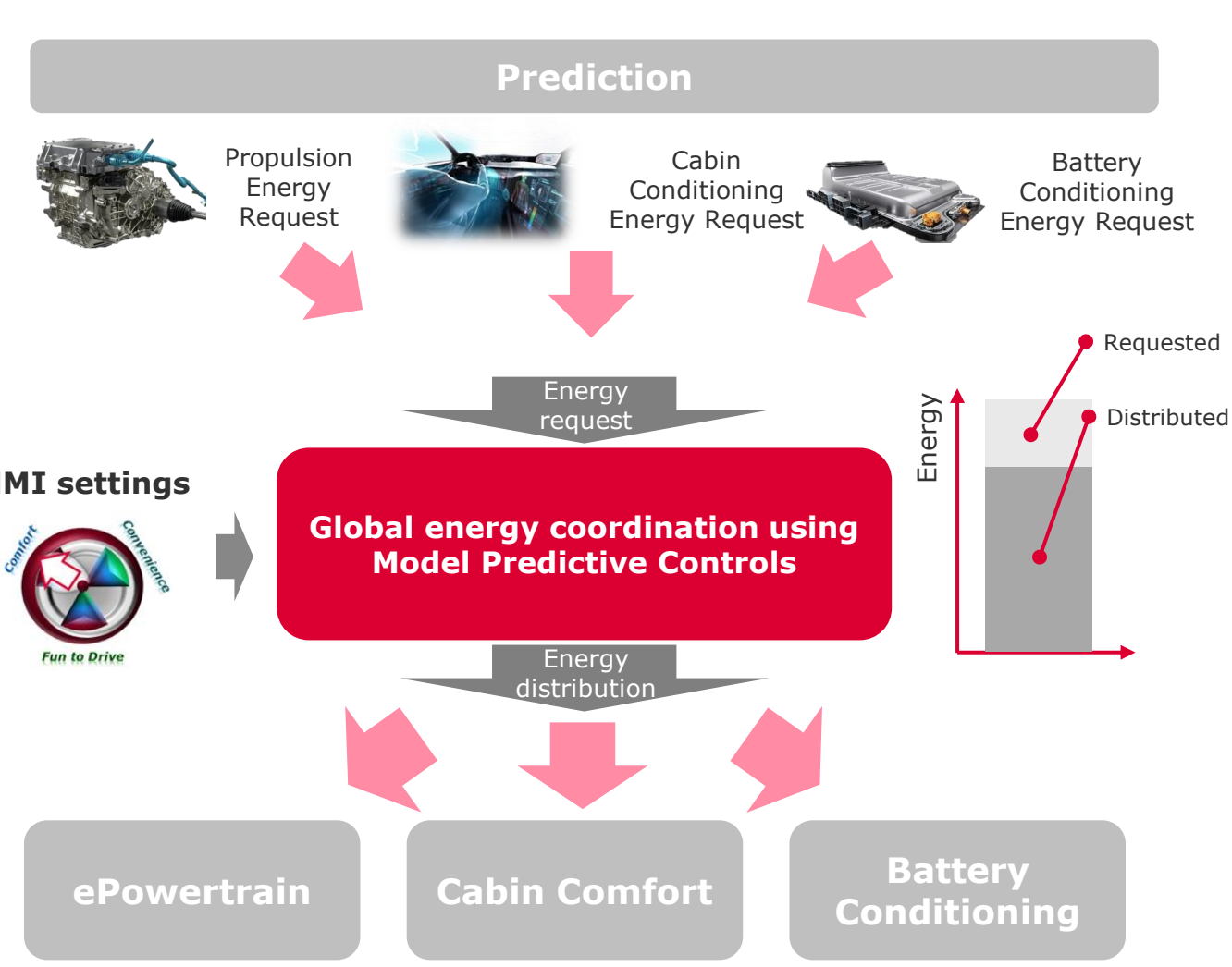
Global Coordination





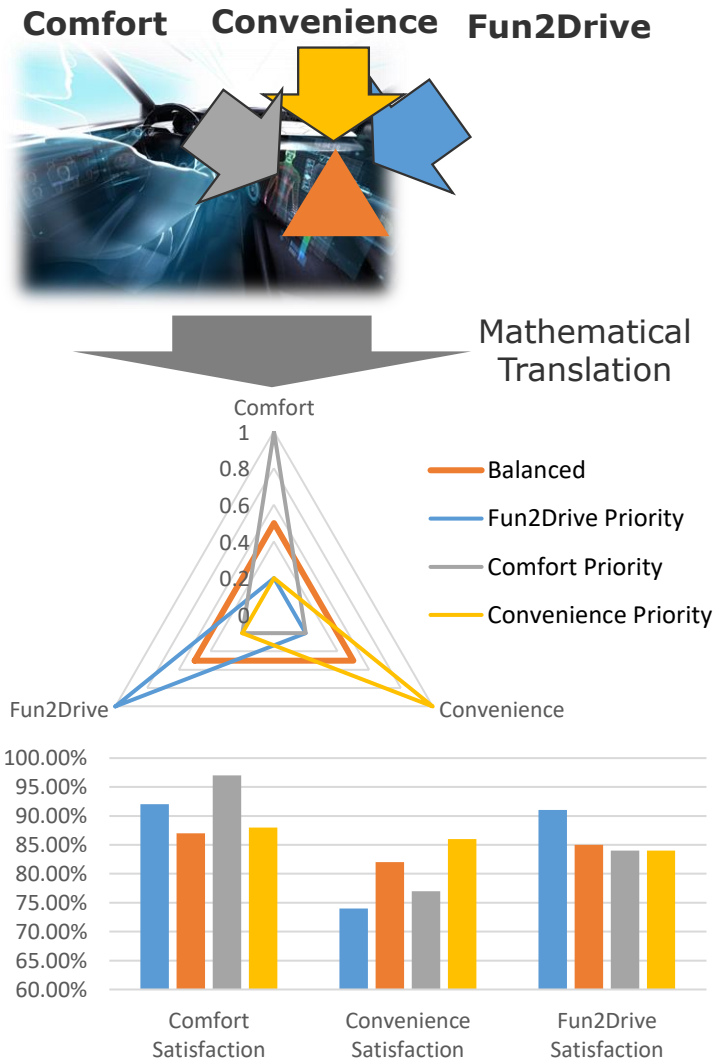
Global coordination enables power distribution to enhance the user experience

Global Coordination – Prioritization



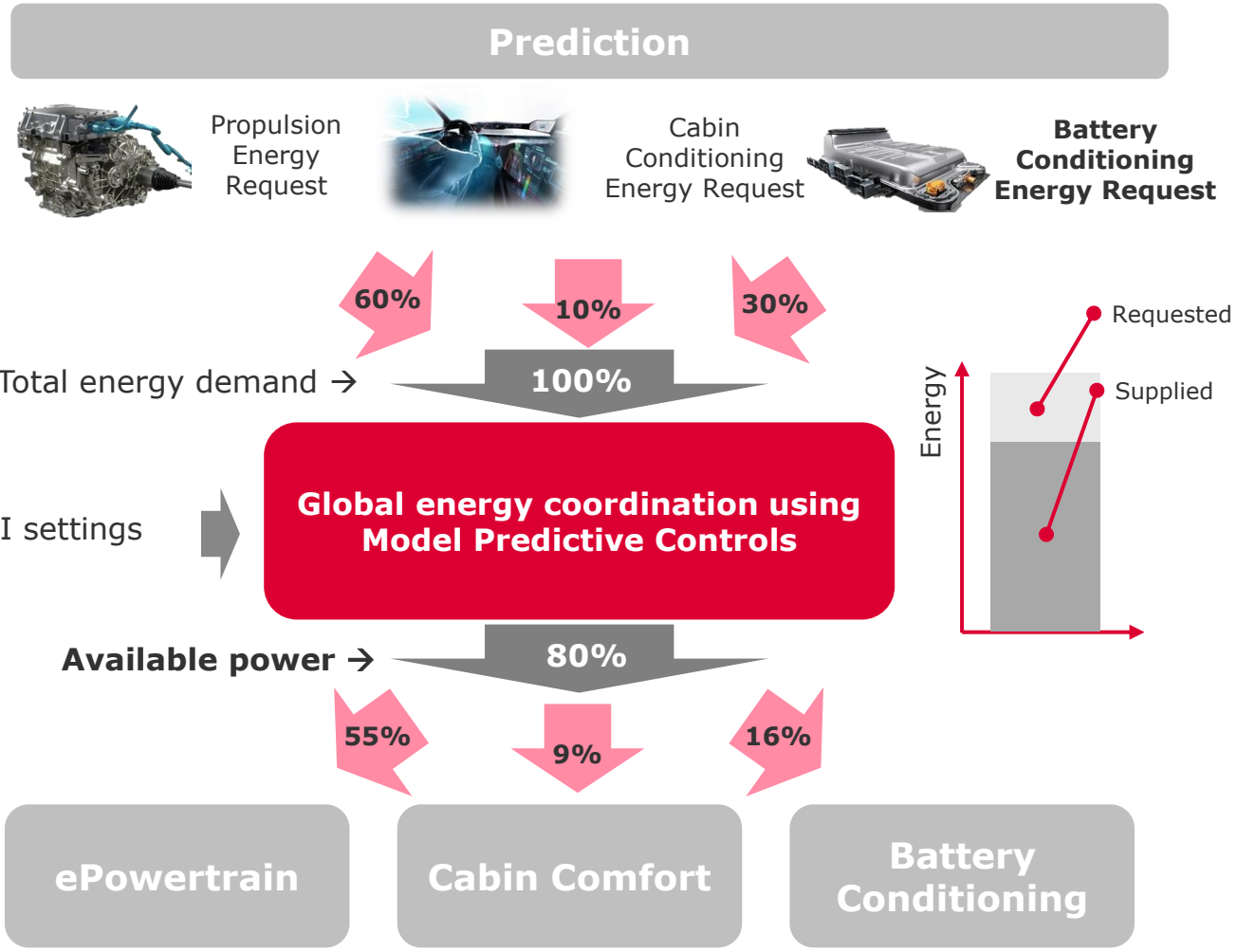
HMI Settings

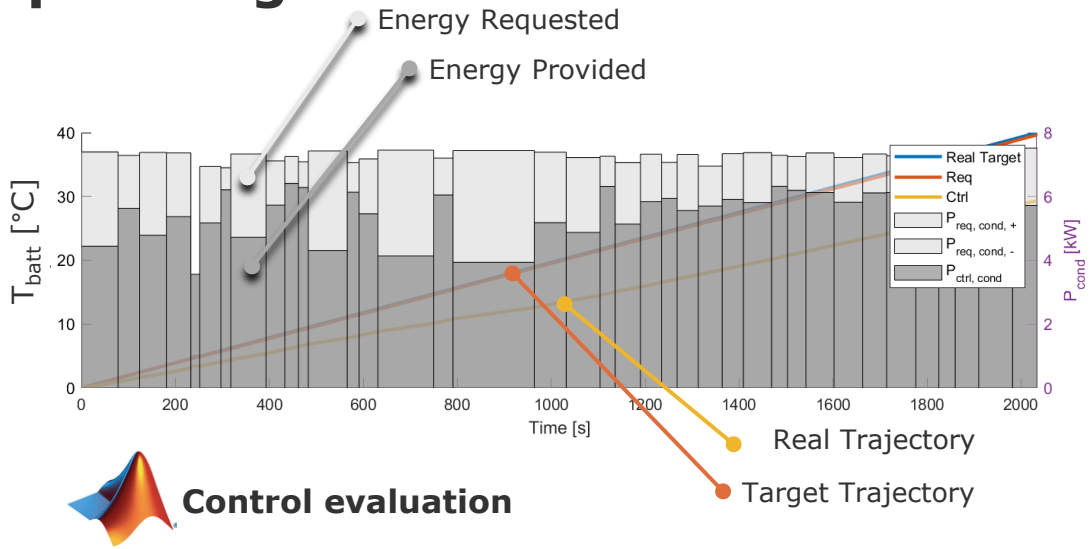
Problem Formulation



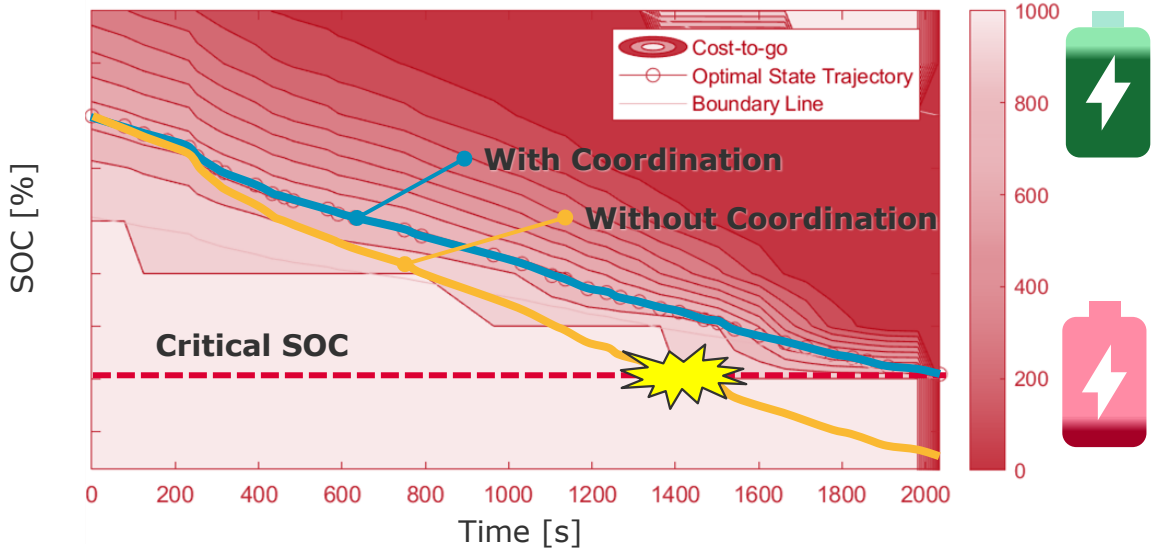
Prioritization allows driver to select preference

Global Coordination – State Of Charge (SOC) planning



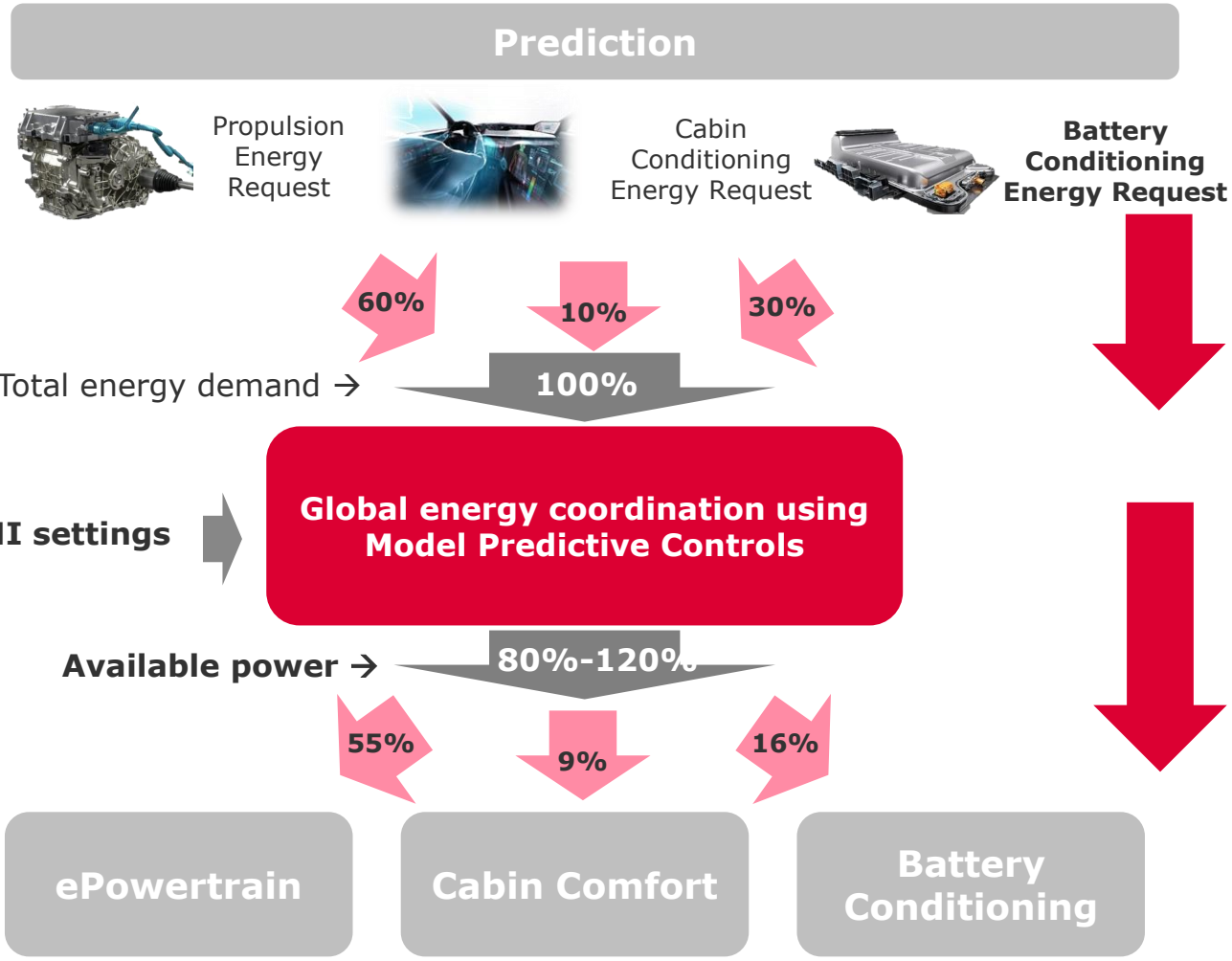


Control evaluation



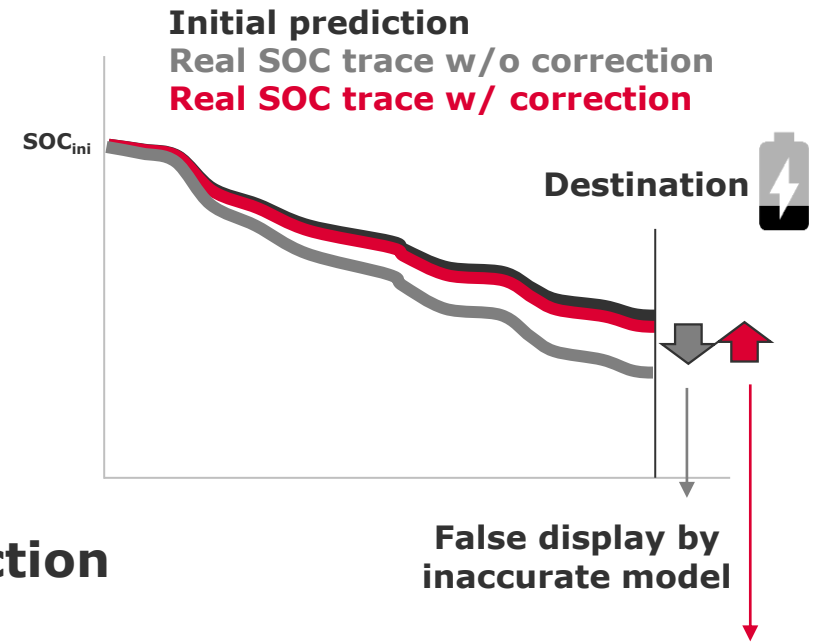
SOC planning avoids critical battery operation and optimizes towards destination

Global Coordination – State Of Charge (SOC) quality



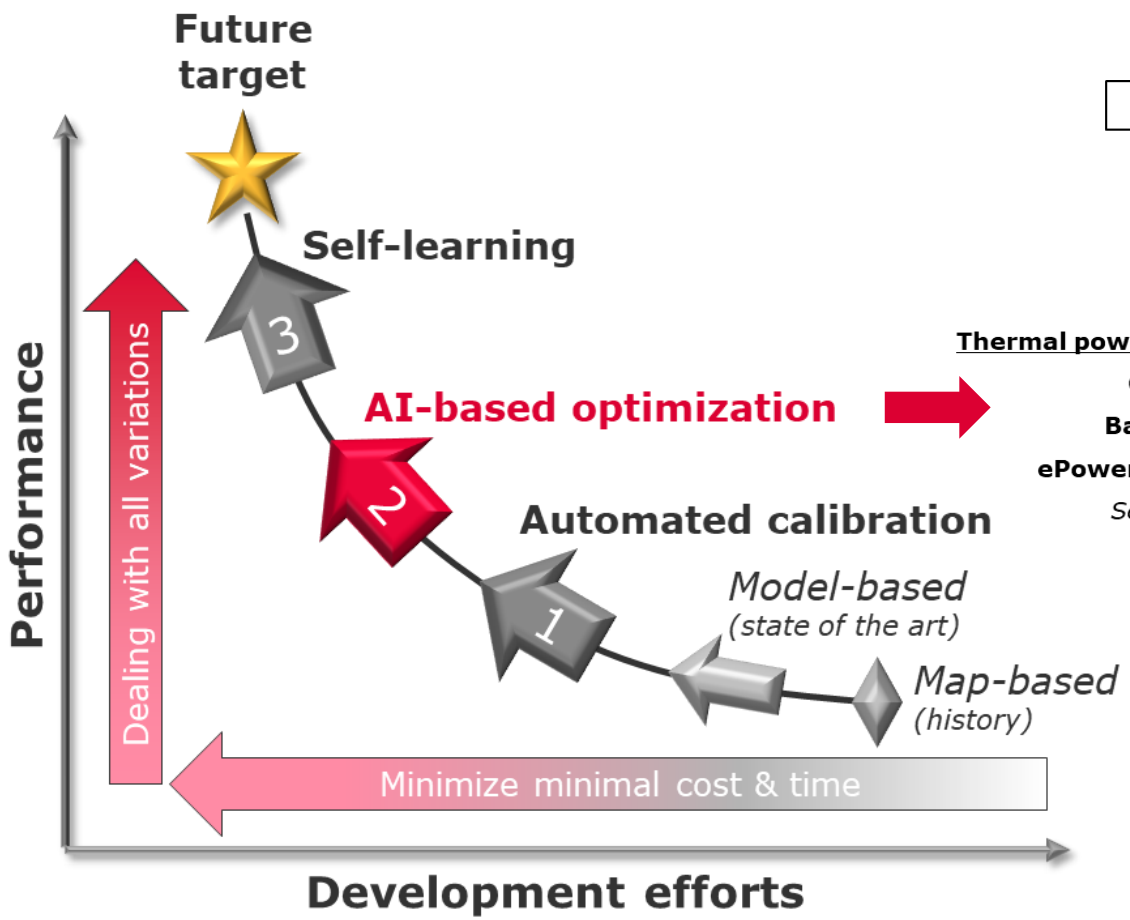
Inaccuracy

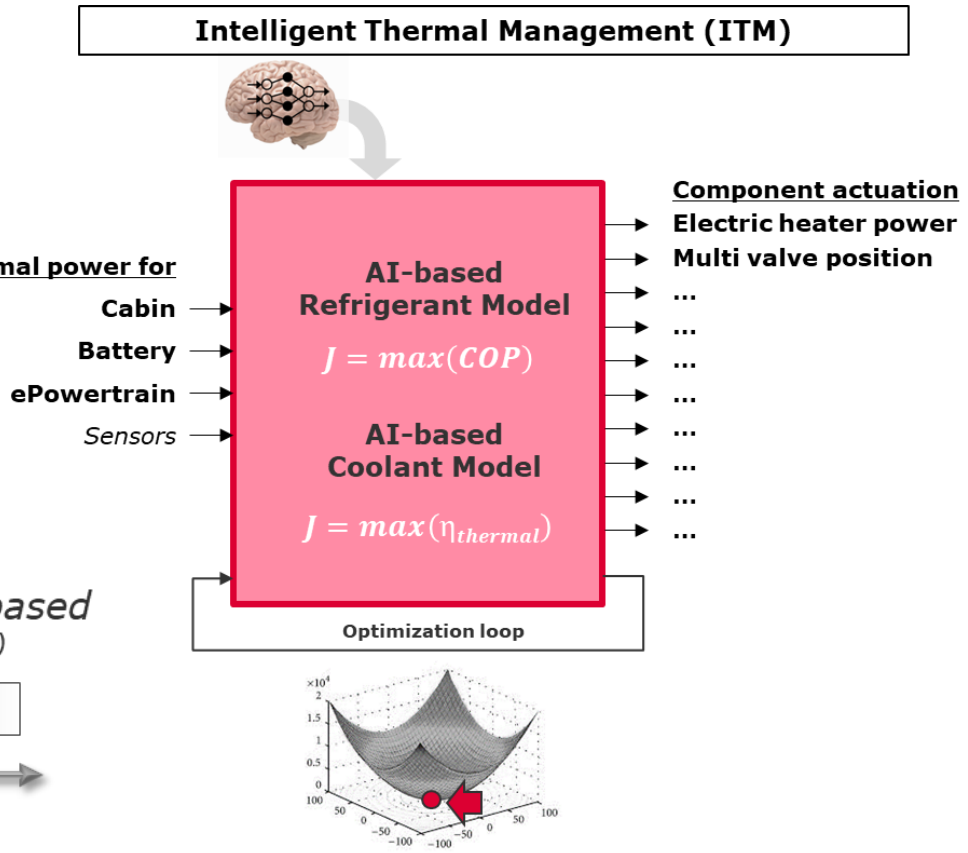
Correction

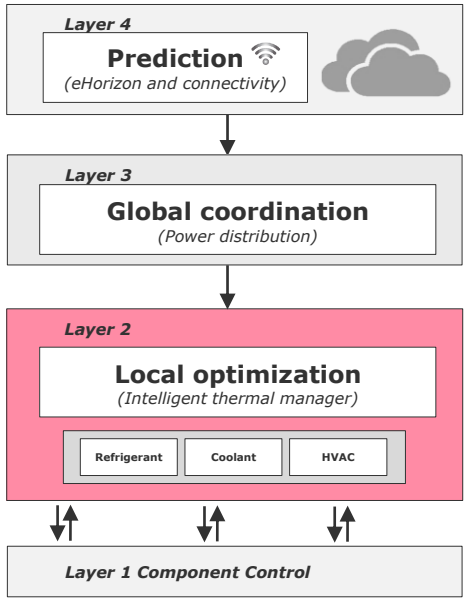


Energy coordination enhances communication to driver by energy corrections

Local optimization







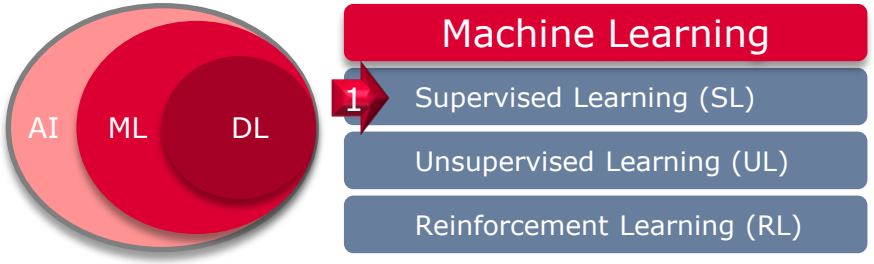
ITM realizes optimal control output for best efficiency

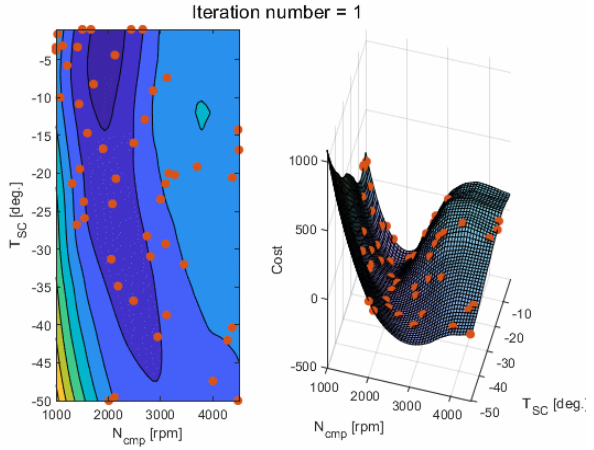
Local optimization – Machine learning by digital engineering

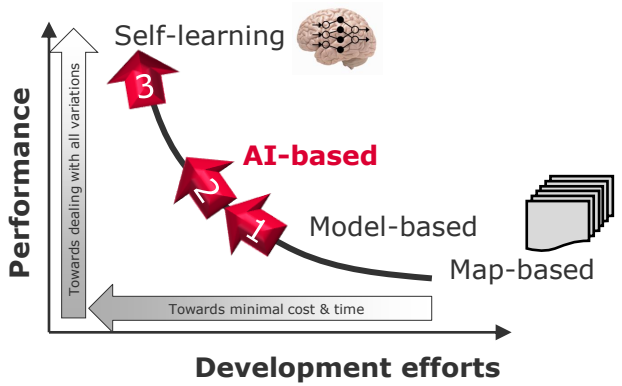
AI based optimization

Modelization of complex problem + **Real time optimization online** = **Increased performance And reduced dev. efforts**

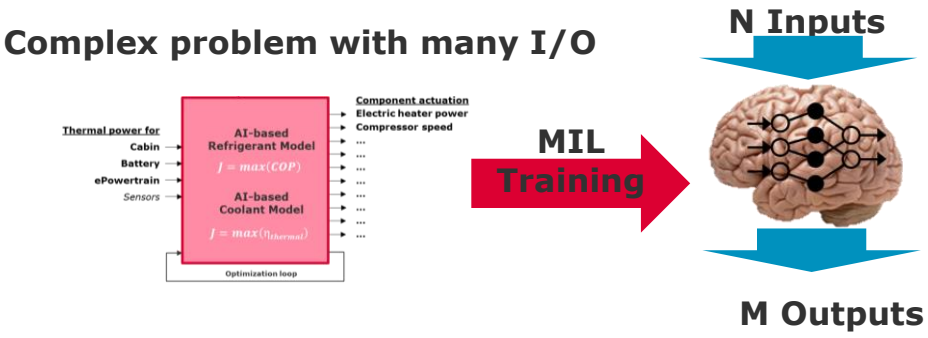
AI based optimization







Complex problem with many I/O



AI based optimization is developed to reduce development efforts and increase vehicle performance

Optimization by Artificial Intelligence – Methods

Optimization method selection

O *Good*
▲ *Medium*
X *Bad*

Algorithm	Function calls	Complexity	Parallelization	Implementability
Particle Swarm	▲	▲	O	O
Nelder Mead	X	▲	▲	▲
Powell	▲	O	O	▲
Conjugate Gradient	▲	▲	▲	X
BFGS	▲	X	O	X
Newton-CG	X	X	O	X

Particle swarm seem best suitable to find the minimum

Furthermore, the computational time is fixed for a known and defined optimization problem, which is an important criteria for real-time/ embedded applications (e.g on an ECU)

Virtual digital twin selection

Summary of supervised learning models

Model	Accuracy	Complexity	Implemen-tability	Genera-lizability
Linear regression	▲	X	O	▲
Neural Networks	O	O	O	O
Support vector machines	O	O	X	O
K-nearest neighbors	▲	▲	▲	O
Random forest	▲	O	X	O

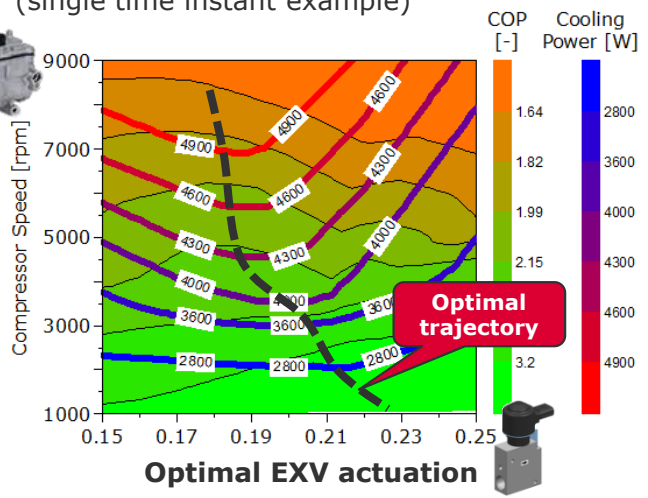
Neural network shows best modelling performance overall

Combination of Swarm Method & Neural Networks were selected as best solution

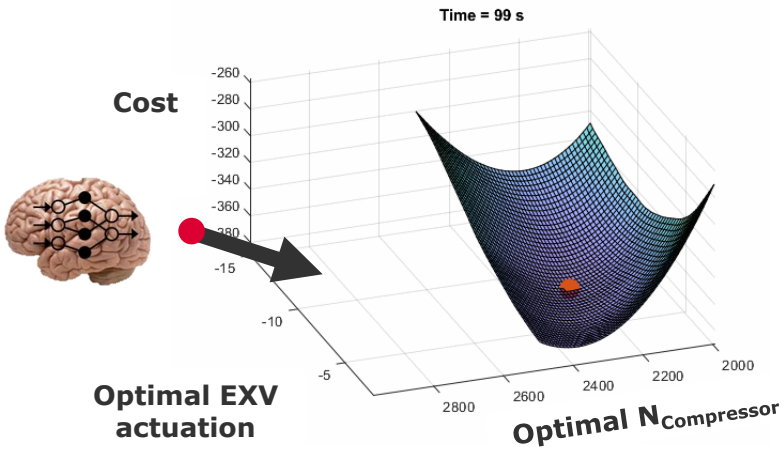
Simulation Study Heat Pump (Refrigerant) System

1. Neural Network Result

(single time instant example)



2. Demonstration real time optimization function

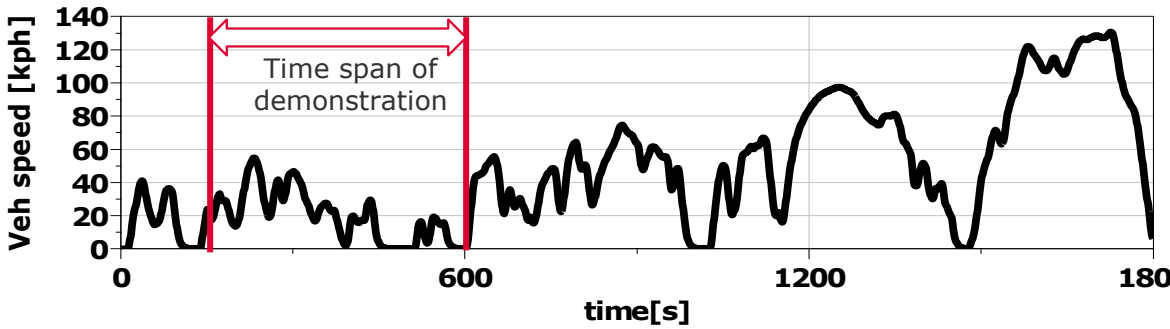


3. Benefit Quantification

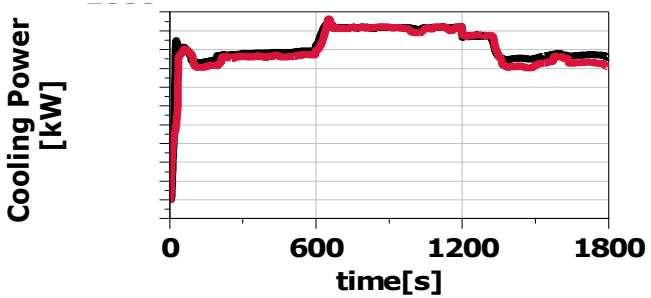
T_{amb}=35°C, Rel. humidity 60%

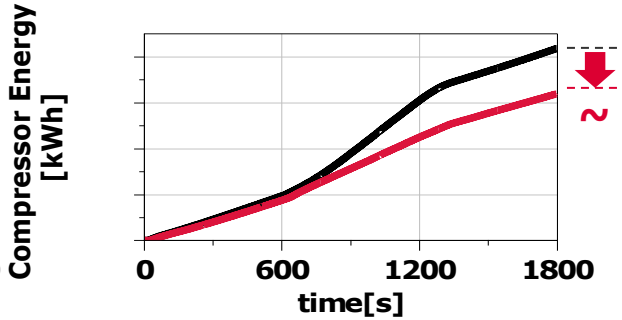
Baseline

Intelligent Thermal Management



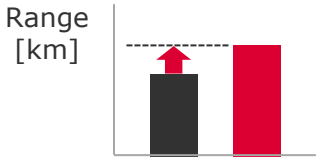
WLTC: 23km





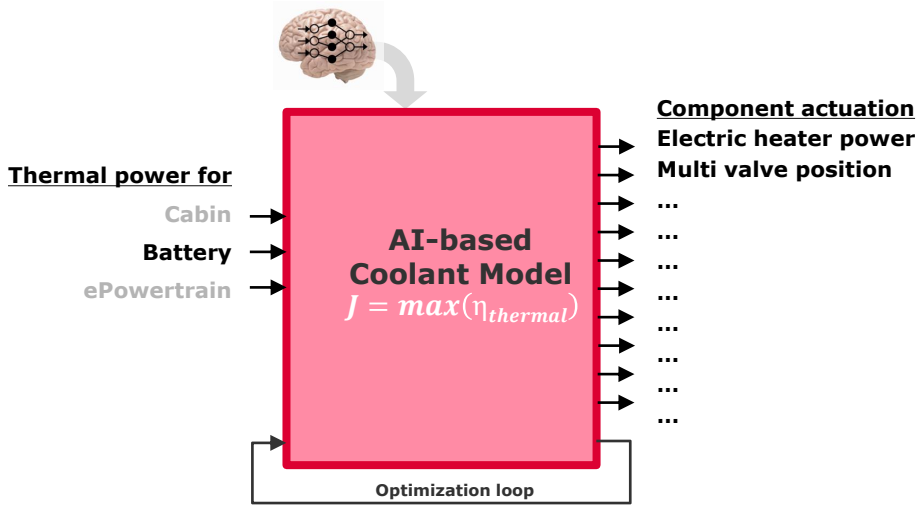
~ -25%

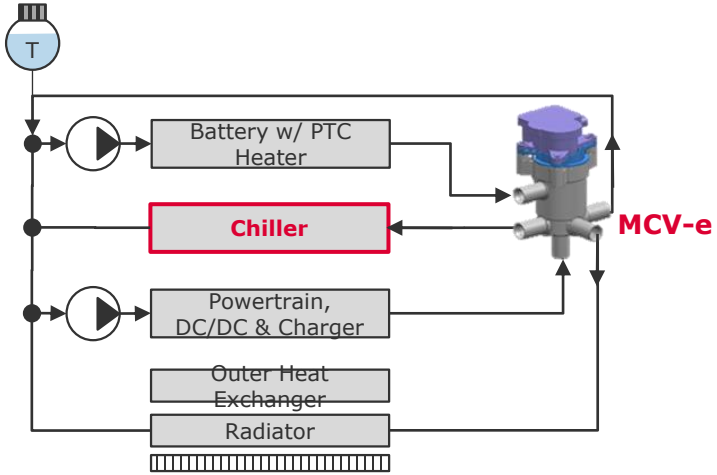
- Same cooling power
- Energy saving by smart controls

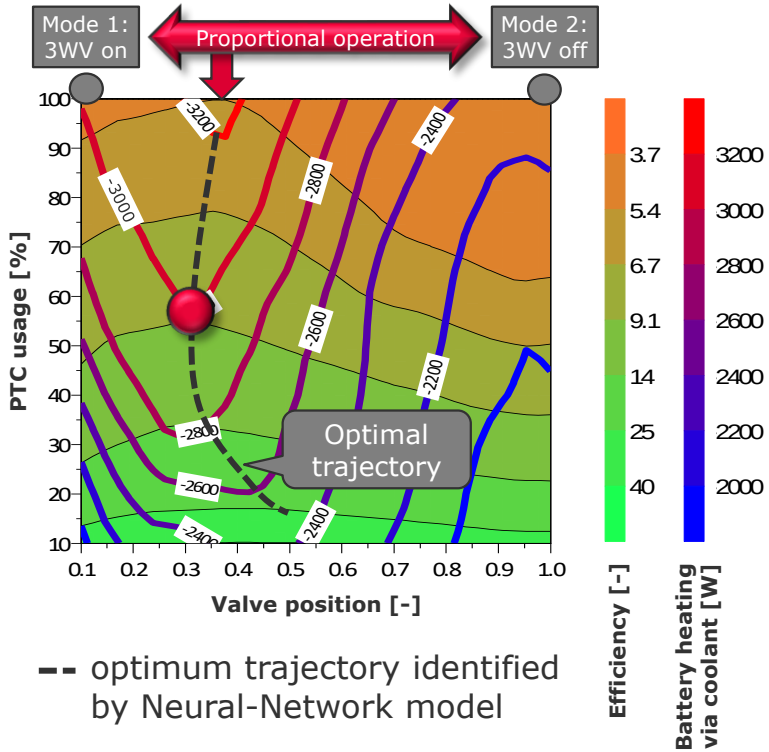


Simulation results shows range improvement by smart controls

Simulation Study Coolant System







-- optimum trajectory identified by Neural-Network model

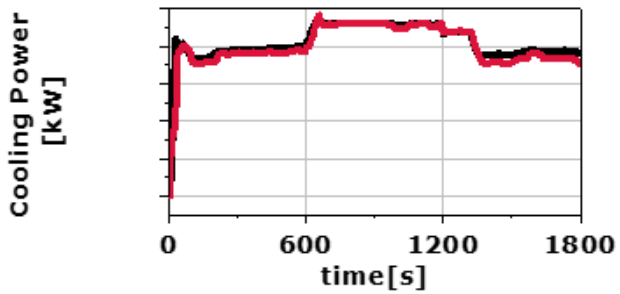
→ **Optimal efficiency found at intermediate valve position**

Optimization search is expanded to coolant system as well

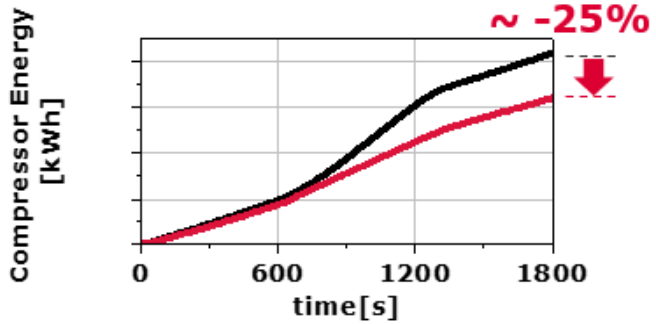
Simulation Results

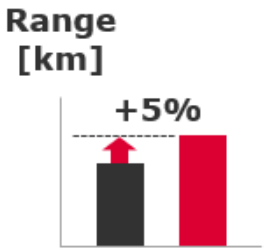
DENSO Heat Pump System

Baseline
AI-BASED REFRIGERANT CONTROLS



- WLTC 35°C
- Cabin cooling

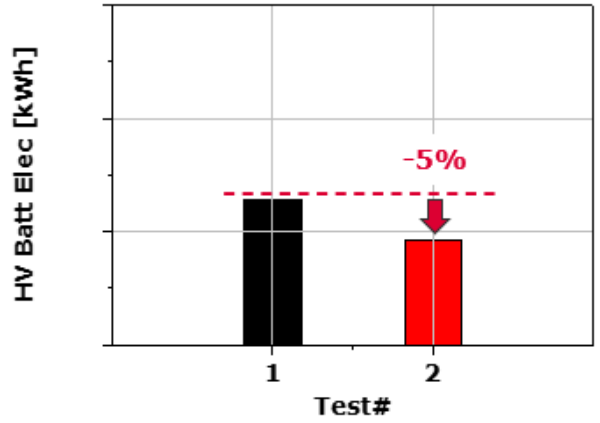




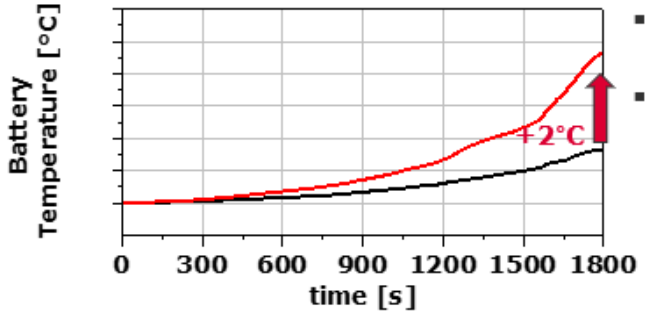
Requested energy to battery and cabin is same in both cases

DENSO Coolant System

Baseline
AI-BASED COOLANT CONTROLS



- WLTC -7°C
- Battery heating

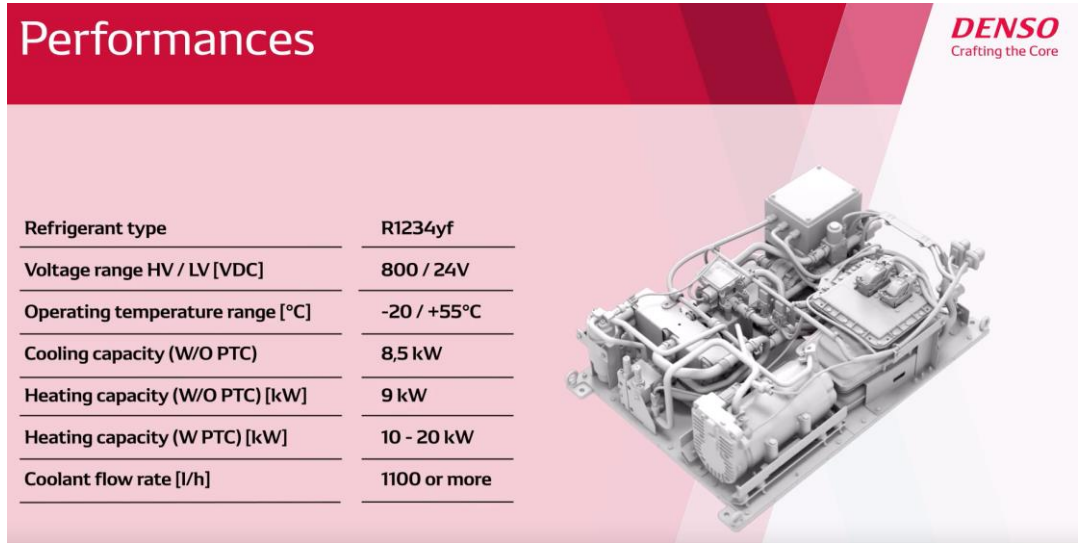


- Up to 5% range increase
- Improved battery heating

AI-based controls for Refrigerant & Coolant systems show promising driving range increasing potential in simulation

Example of Heat Pump Product in Other Domains

Battery Thermal Management System



- Stand alone device to heat and cool the battery by using heat pump system, typically used Off Road and Special Applications

Residential CO_2 Heat Pump System

- DENSO introduced CO_2 refrigerant to its Air to Water Heat Pumps in 2001, in Japan. Known as 'Eco-Cute'
- Introduced into Europe in 2009 and set a standard for compact size, light weight and low noise. It is supplied exclusively as original equipment to heat pump manufacturers.
- Our partner Vattenfall has developed a solution that incorporates a buffer system which allows the DENSO CO_2 Heat Pump to be used for space heating and domestic hot water at the same time (see Vattenfall Website)

DENSO Heat Pump Systems Towards a Sustainable Society

DENSO

Crafting the Core