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Optimized use of Energy Charged from Shore in Plug-in Hybrid Marine Vessels

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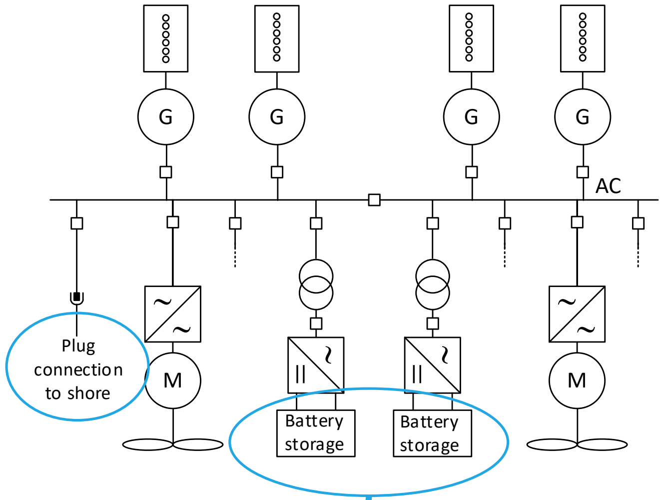
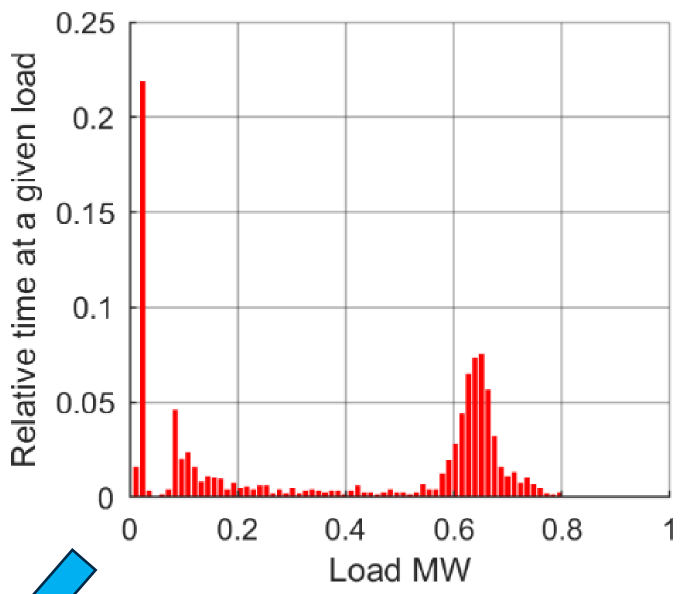
The problem to solve

Plug-in hybrid vessel with batteries and Diesel generators



Expected load distribution for next trip

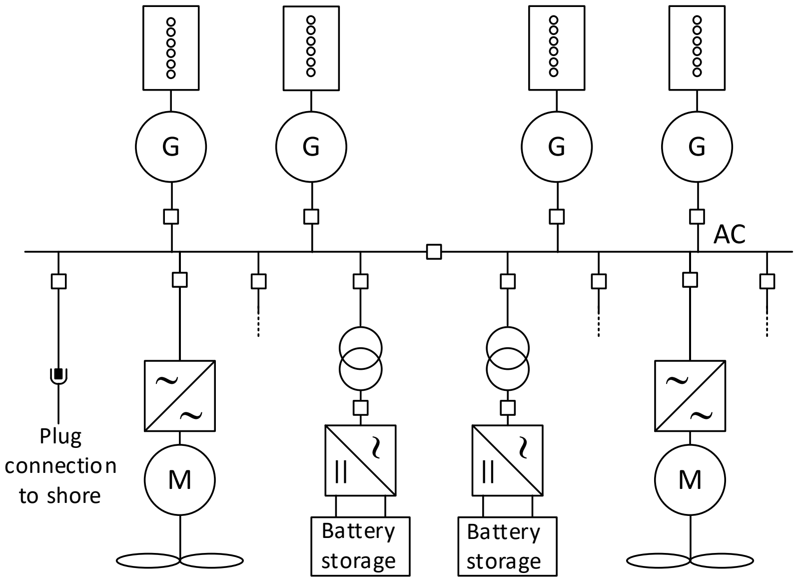


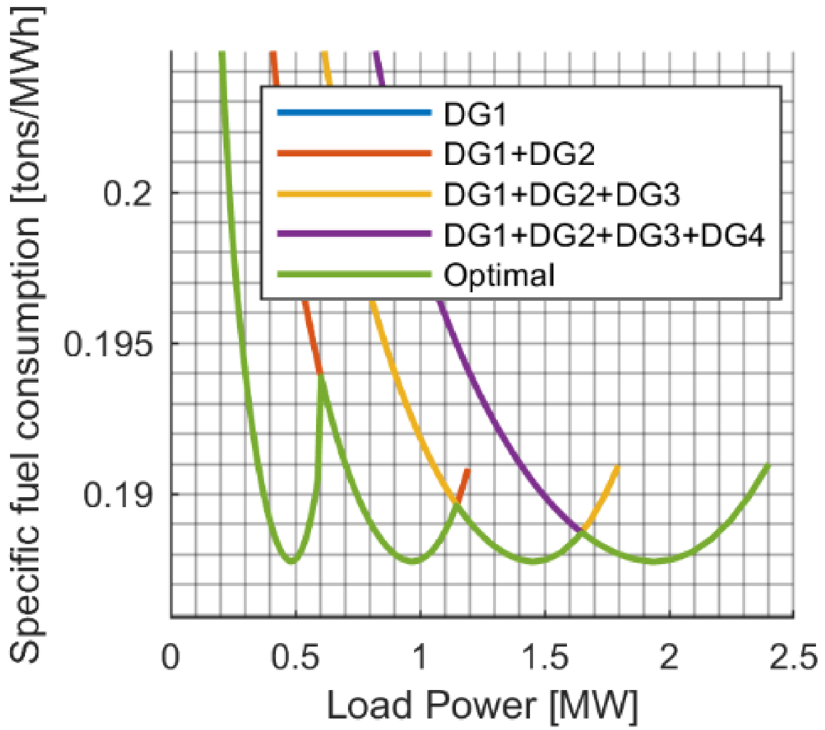
Battery with stored energy corresponding to e.g. 40 % of energy needed for next trip

How to use the stored energy such that fuel usage is minimized ?

- How many DG units to run ?
- How much power to take from the battery?

Example case





- 4x 0.6MW Diesel engines
- 0.6MW storage
- 4% storage system losses while discharging

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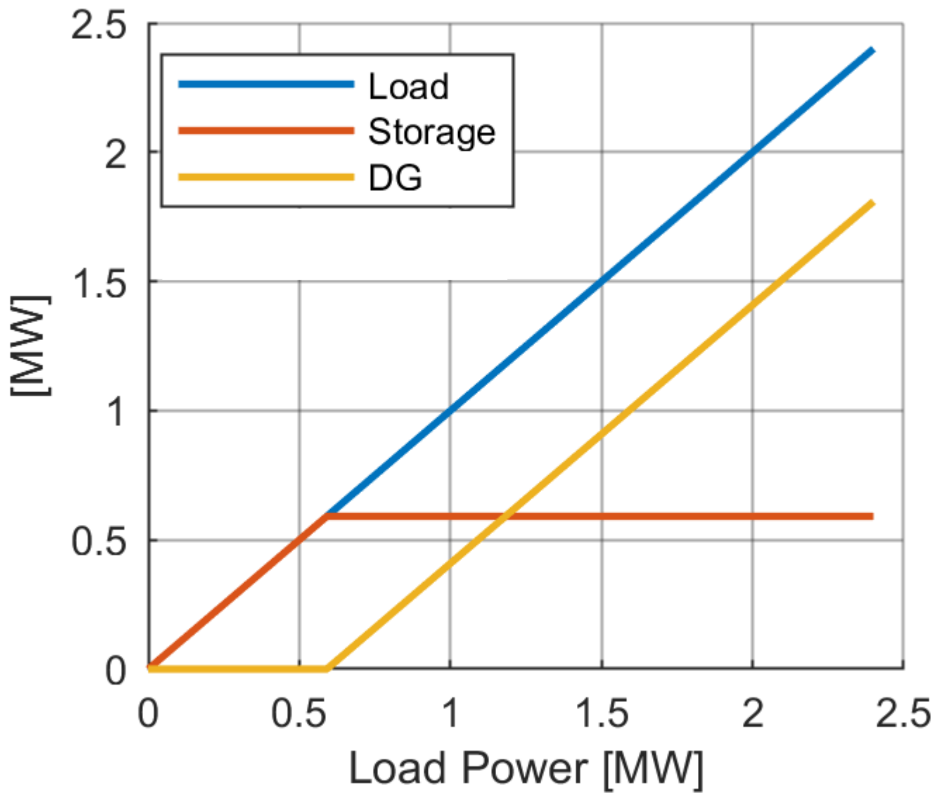
The simplest strategy:

Use the stored energy as fast as possible



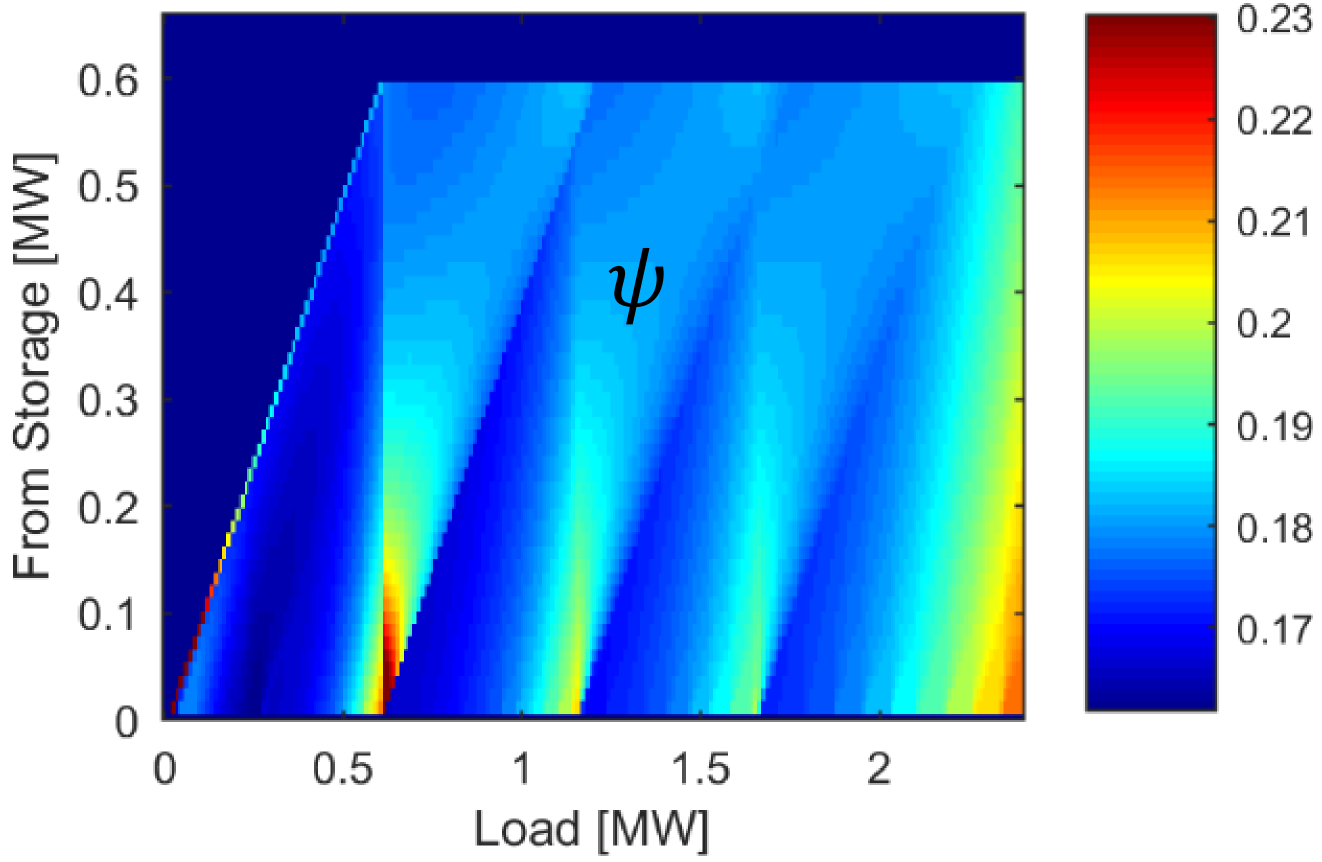
- Simple but not necessarily optimal
- Why not:
  - Storage losses increases with increased power flow
  - Diesel engines are more efficient at certain load levels

Introduces specific fuel saving psi: ψ

Fuel saving per unit of used
energy from the battery storage (tons/MWh)

ψ Specific fuel saving (tons/MWh)

... at all possible load levels (0 – 2.4MW)
... for all possible storage power flows (0 – 0.6MW)
... for the optimal number of running DG units (0 – 4 units)



Specific fuel saving: ψ

Tons of fuel saving per MWh taken from battery storage (tons/MWh)

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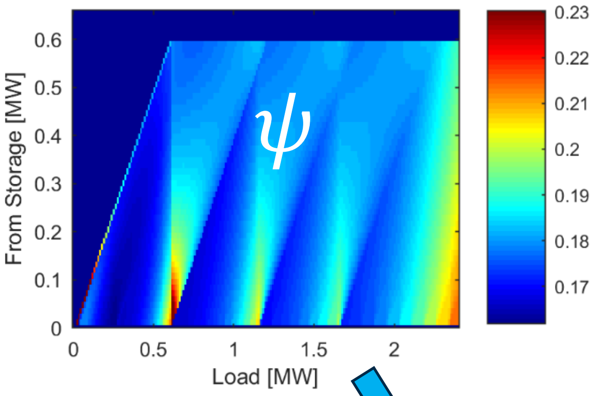
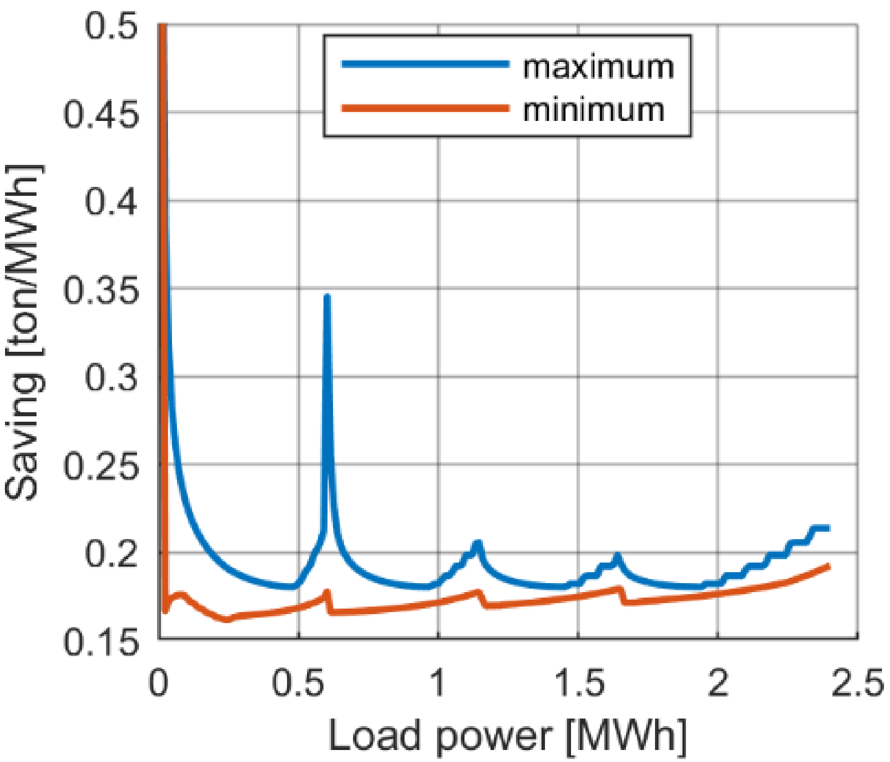
Extract minimum and maximum specific fuel saving at each load level



ψ



At each vessel load and power split there are:

- Significant fuel saving
- Significant <u>difference</u> between min. and max.

.... but how to maximize the saving for a given amount of stored MWh energy ?

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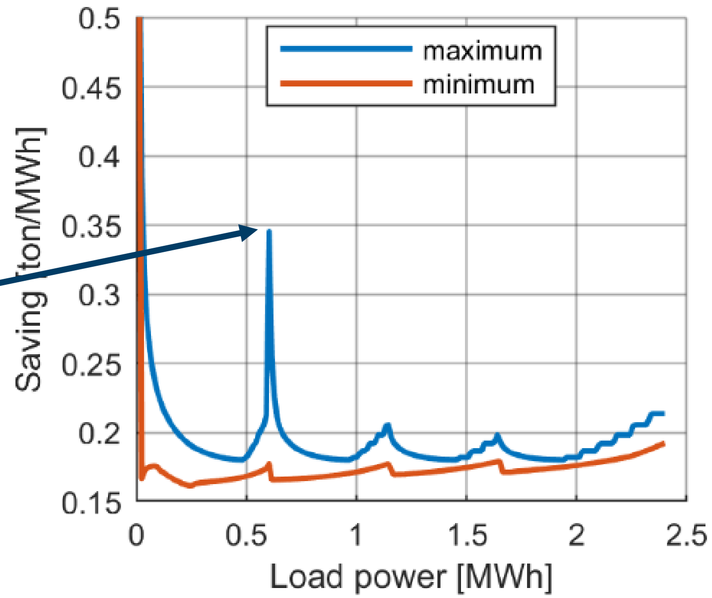
Optimization idea 1 :

- Only use the stored energy where it gives the maximum fuel saving
  (the highest peak on the blue line)



- Disadvantage/risk:
  Load will typically be at the right level for only very short time on each trip
  => Almost no use of stored energy

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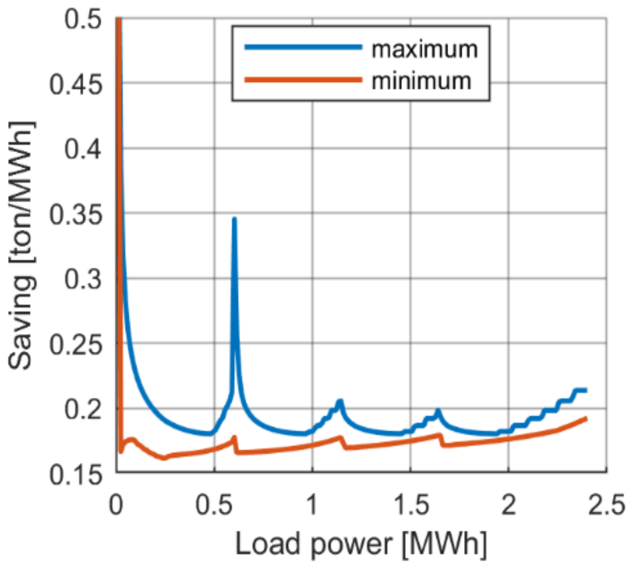
Optimization idea 2 :

- Always use the power split that maximizes the specific fuel saving (stay on the blue line)



Disadvantage/risk:
You may end up using all your stored energy in one of the "valleys" of the blue line and then having no energy left when load shifts to a operation point where saving potential is higher.

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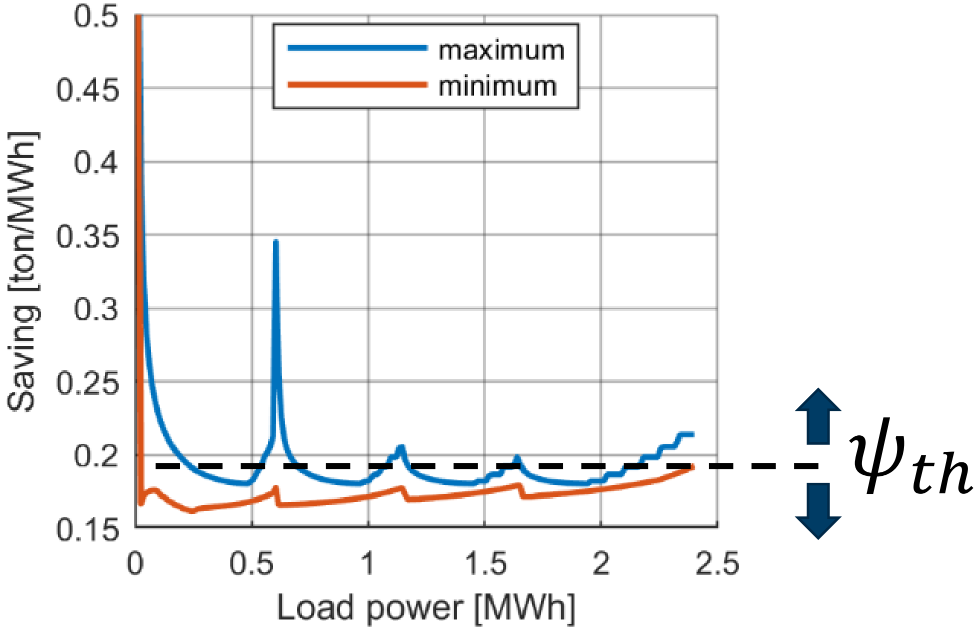
Optimization idea 3 :

- Use as much stored energy as possible as long as it gives a specific fuel saving above a defined threshold ψ_{th}

- Advantage: The threshold can be used to adapt the use of stored energy in an optimal way for a given trip
  - Increase threshold = > Less use of storage (but increased fuel saving per unit of used energy)
  - Decrease threshold => More intensive use (but less fuel saving per unit of used energy)



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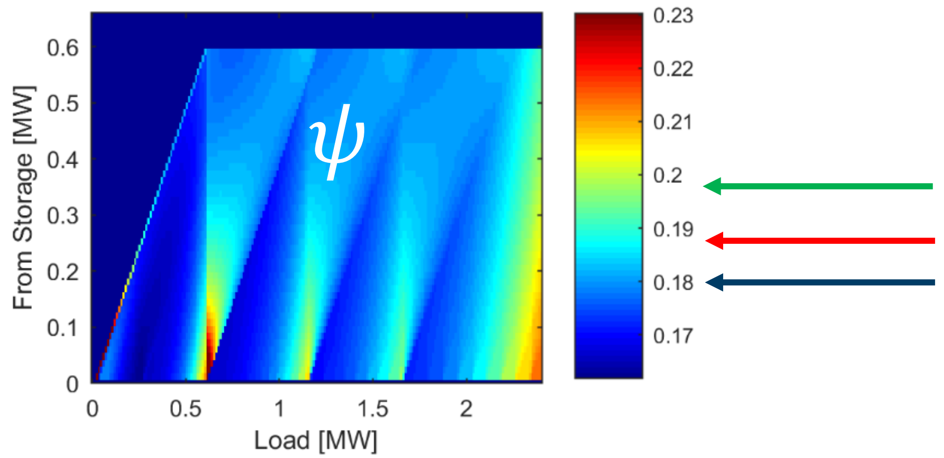
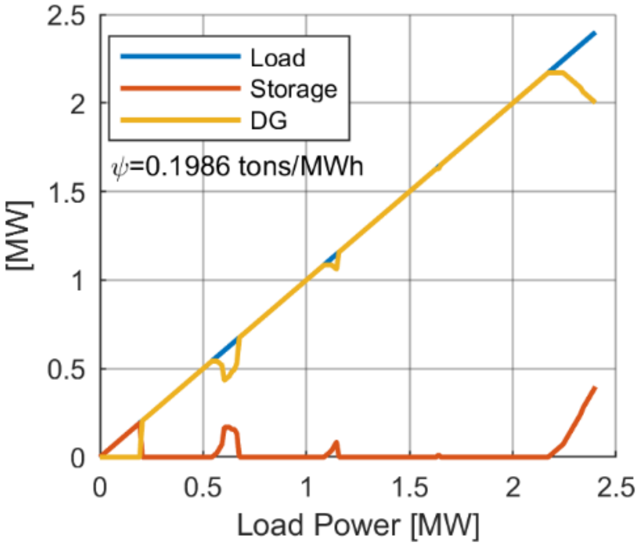
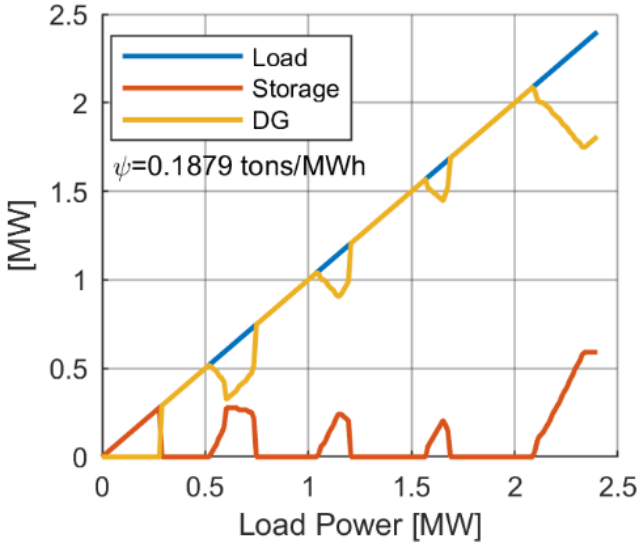
Power management strategies for different specific fuel saving thresholds



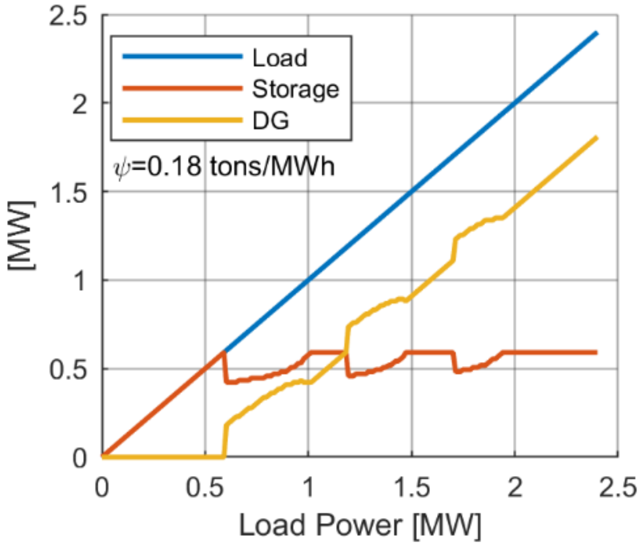
$\boldsymbol{\psi_{th} = 0.1986}$



$\boldsymbol{\psi_{th} = 0.1879}$



$\boldsymbol{\psi_{th} = 0.18}$

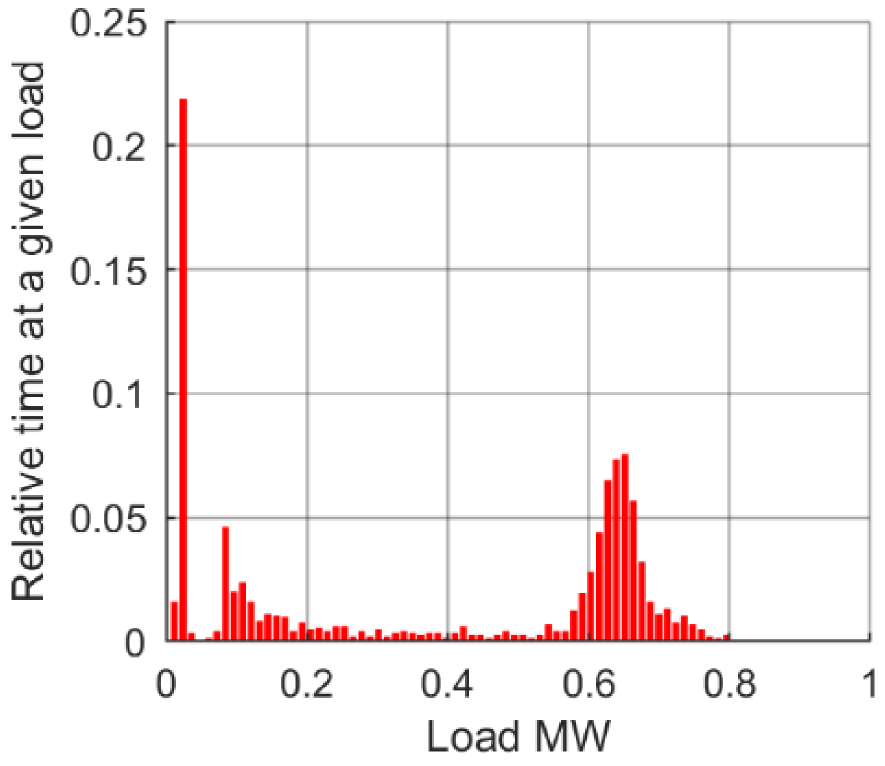


What is then the optimal threshold ?

$$\boldsymbol{\psi_{opt}}$$

Optimization against a load distribution

- The optimization for a trip requires some information about the expected load
- Uses the time distribution of load (not time series)
- Advantages compared to time series
  - Assumed to be easer to provide estimates of the time distribution than to provide representative time series of the load
  - The time distribution can be generated based on the average of many trips
  - Optimization becomes much simpler and faster compared to optimization against time series



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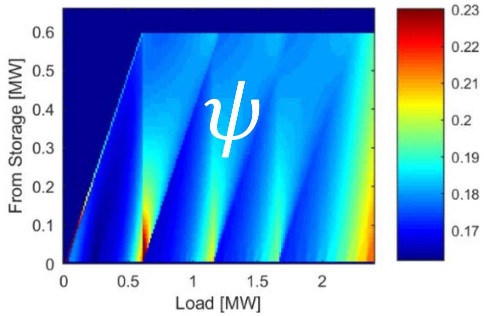
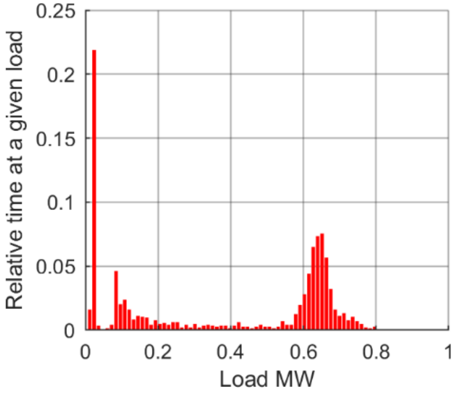
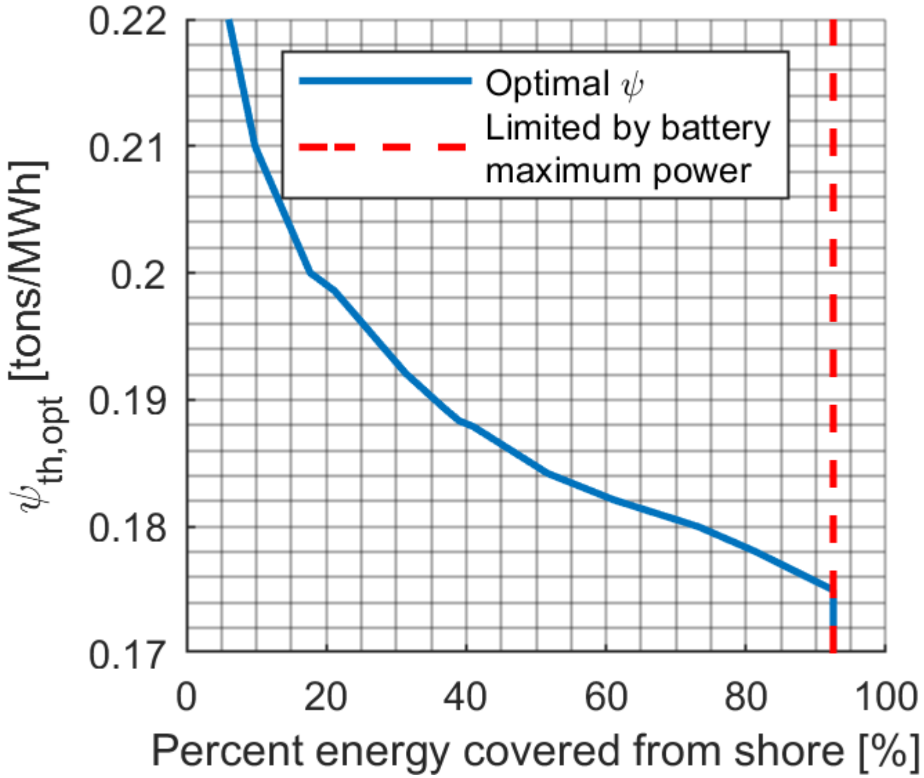
Possible to derive the relationship between:

Specific fuel saving threshold $\boldsymbol{\psi}$ ⇔ Total energy that will be discharged during trip **W**





$\boldsymbol{\psi}$



W

Note: Figure only valid for the given load distribution

The real-time strategies

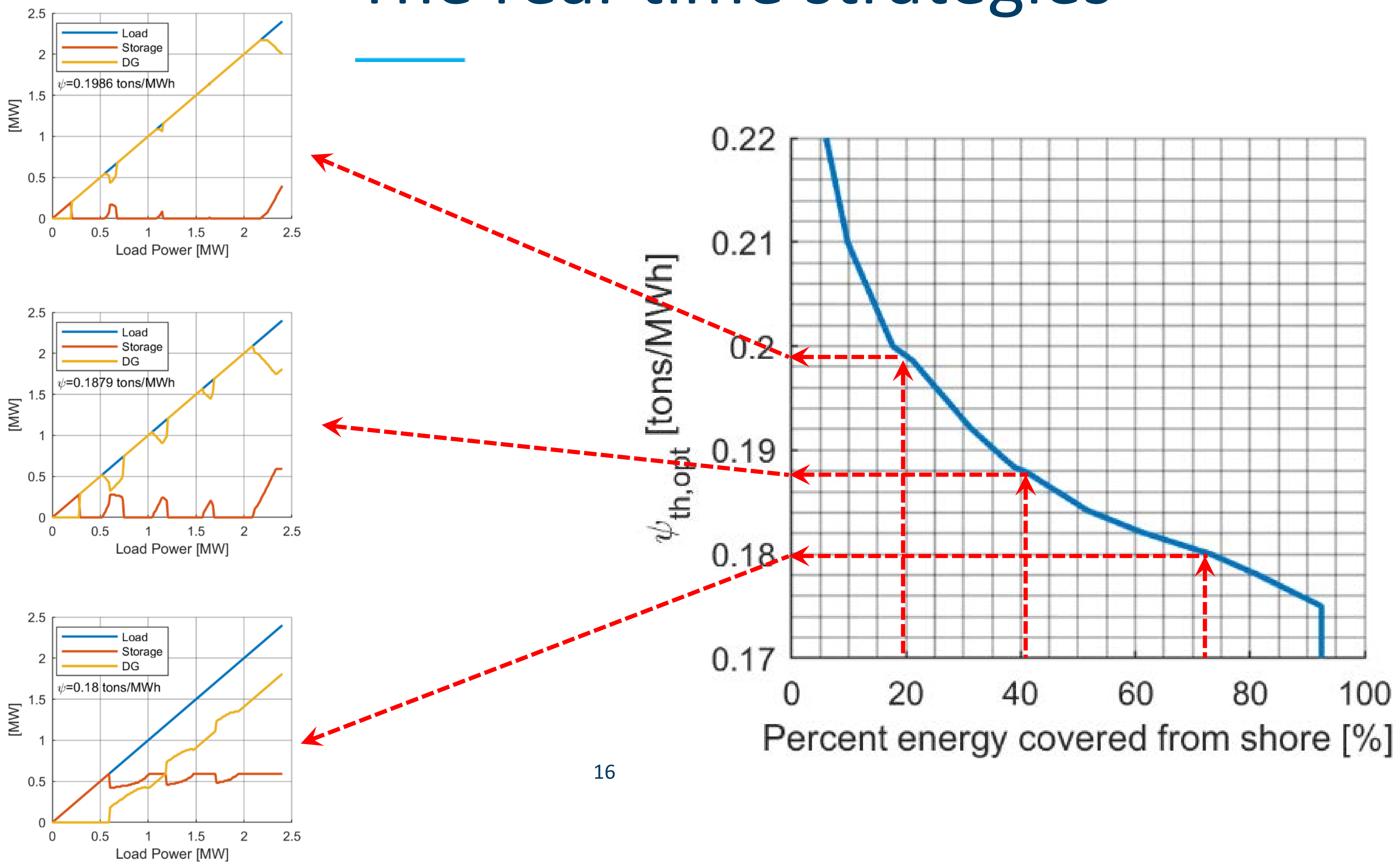


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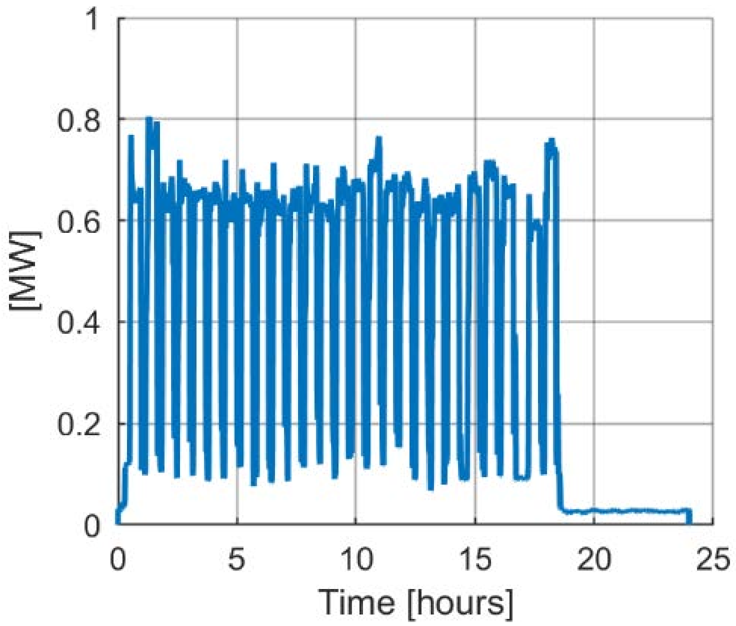
Illustration in time domain



Example time domain load variation
(ferry-type load profile)

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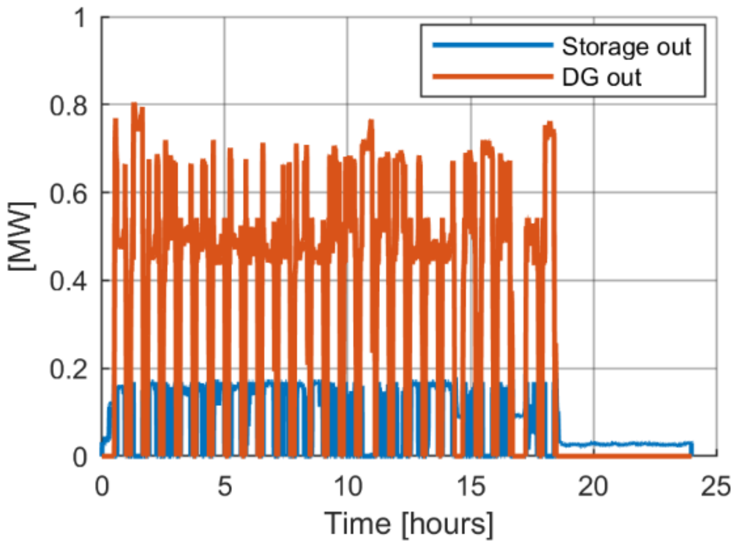
Effect of different thresholds

$\psi_{th} = \psi_{th,opt} = 0.199$

Maximum saving $\stackrel{\text{def}}{=}$ 100%

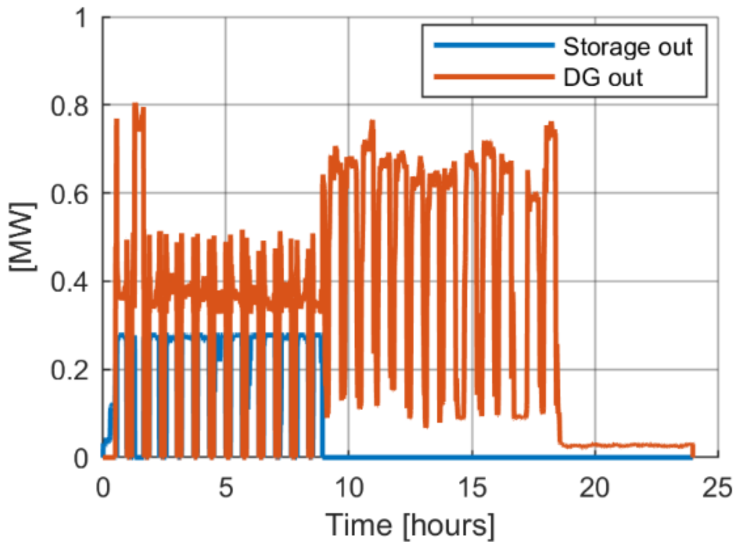
Optimal threshold



$\psi_{th} = 0.188$

90% saving

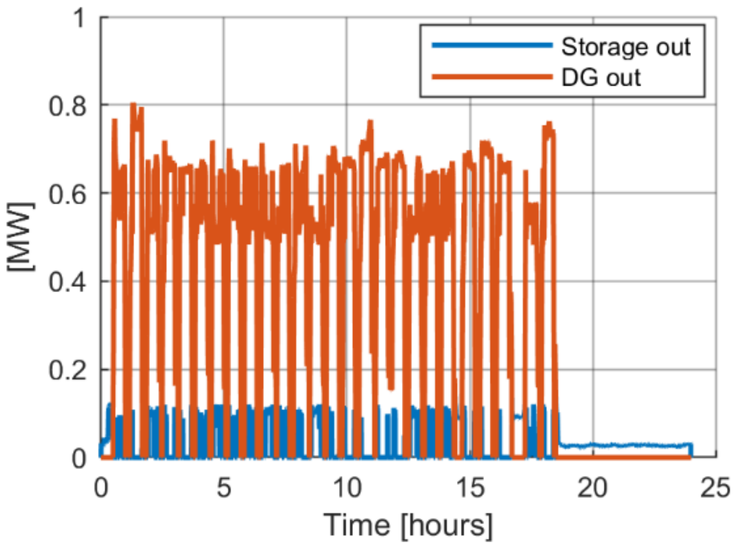
Threshold too low
=> Storage became empty too early to maximize fuel saving



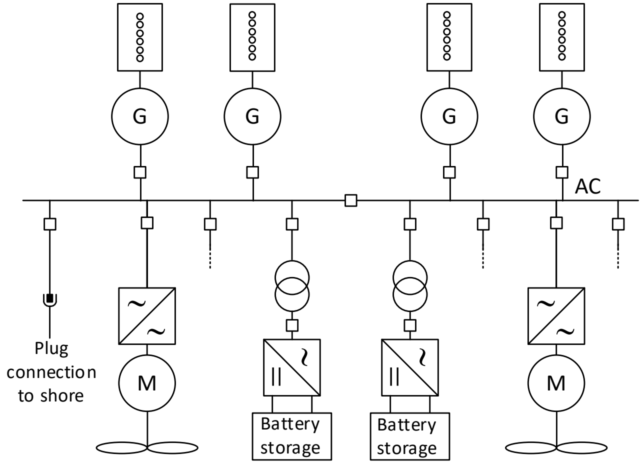
$\psi_{th} = 0.209$

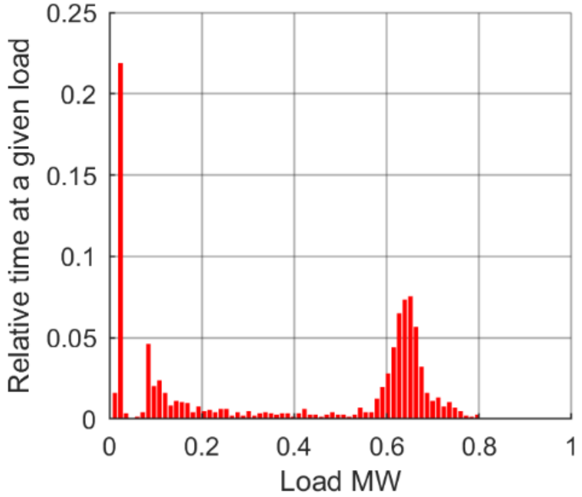
55 % saving

Threshold too high
=> Did not use all stored energy



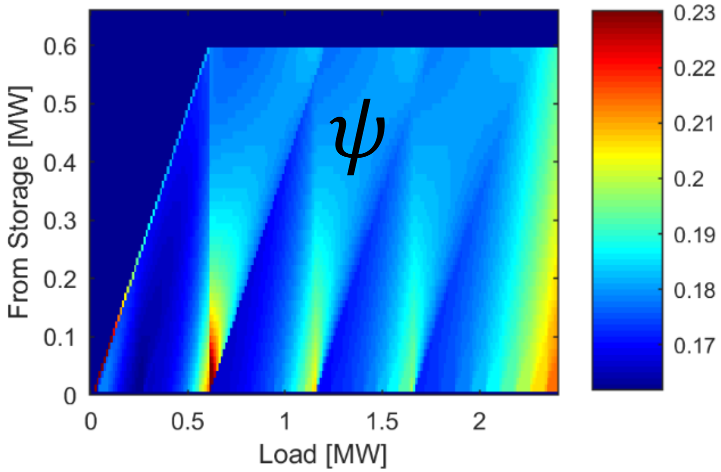
In summary



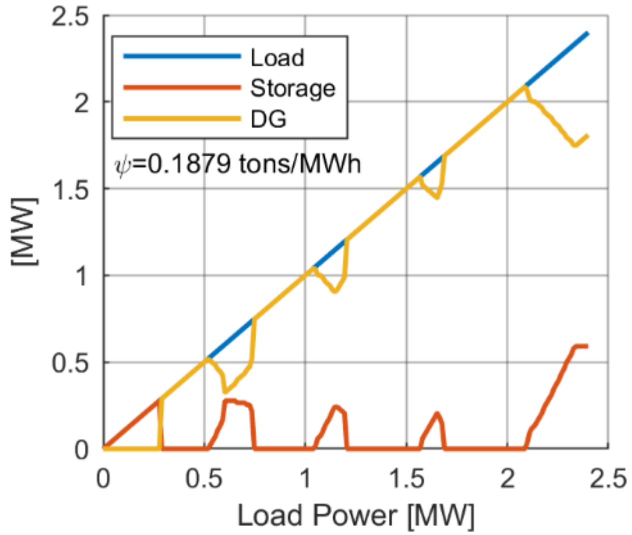


40 % energy from shore

Fuel saving tons/MWh



Optimal ower management strategy



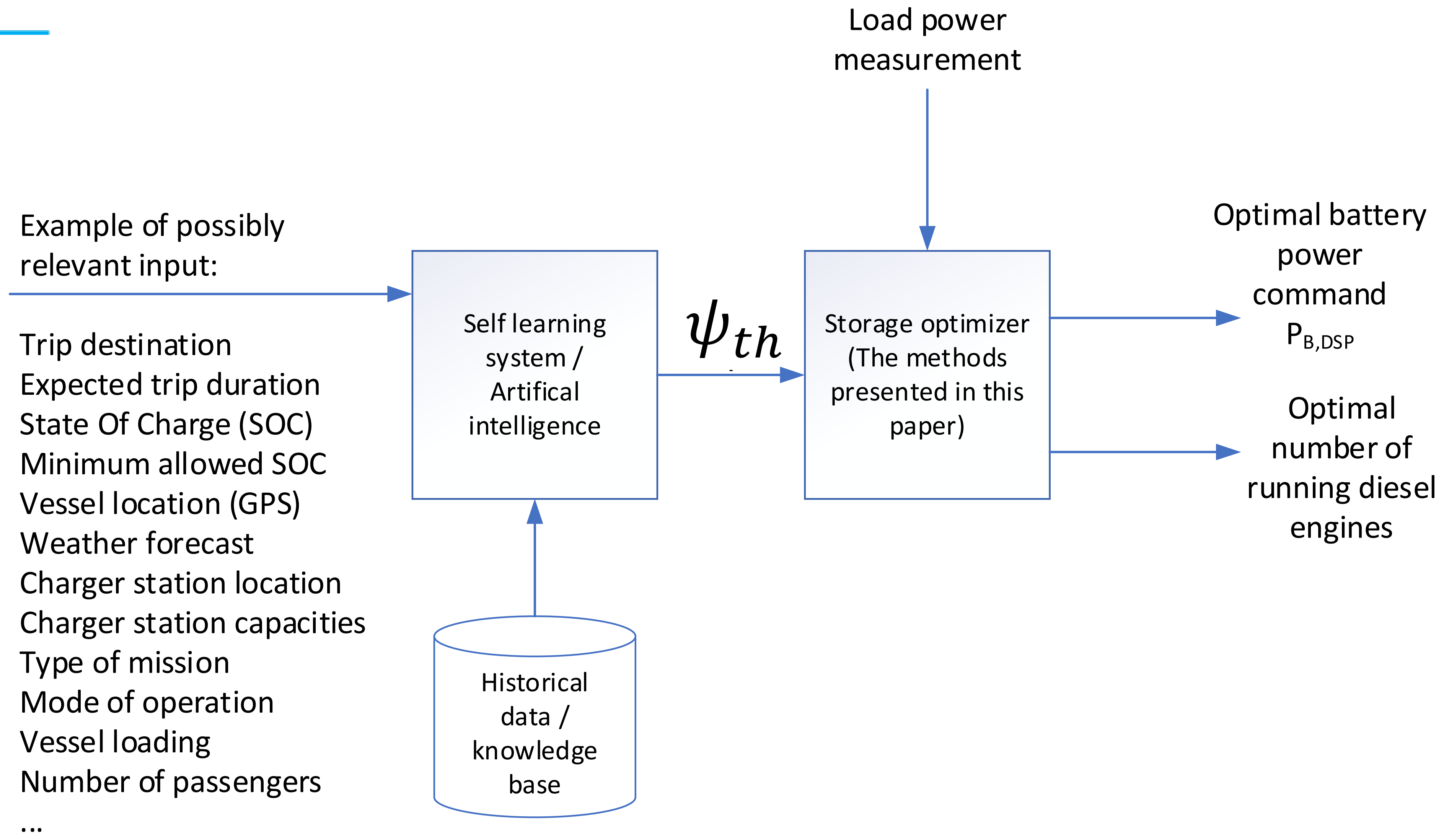
Concluding remarks

- The added value of proposed optimization depends on
  - Shape of specific fuel consumption curves for DG
  - Characteristics of the storage discharge losses
  - Load distribution for the next trip
  - Amount of stored energy ahead of the trip

- The added value of proposed optimization will typically be largest when the energy from shore covers a smaller share of the total energy

Possible extension:

Dynamic update of saving threshold during the trip



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