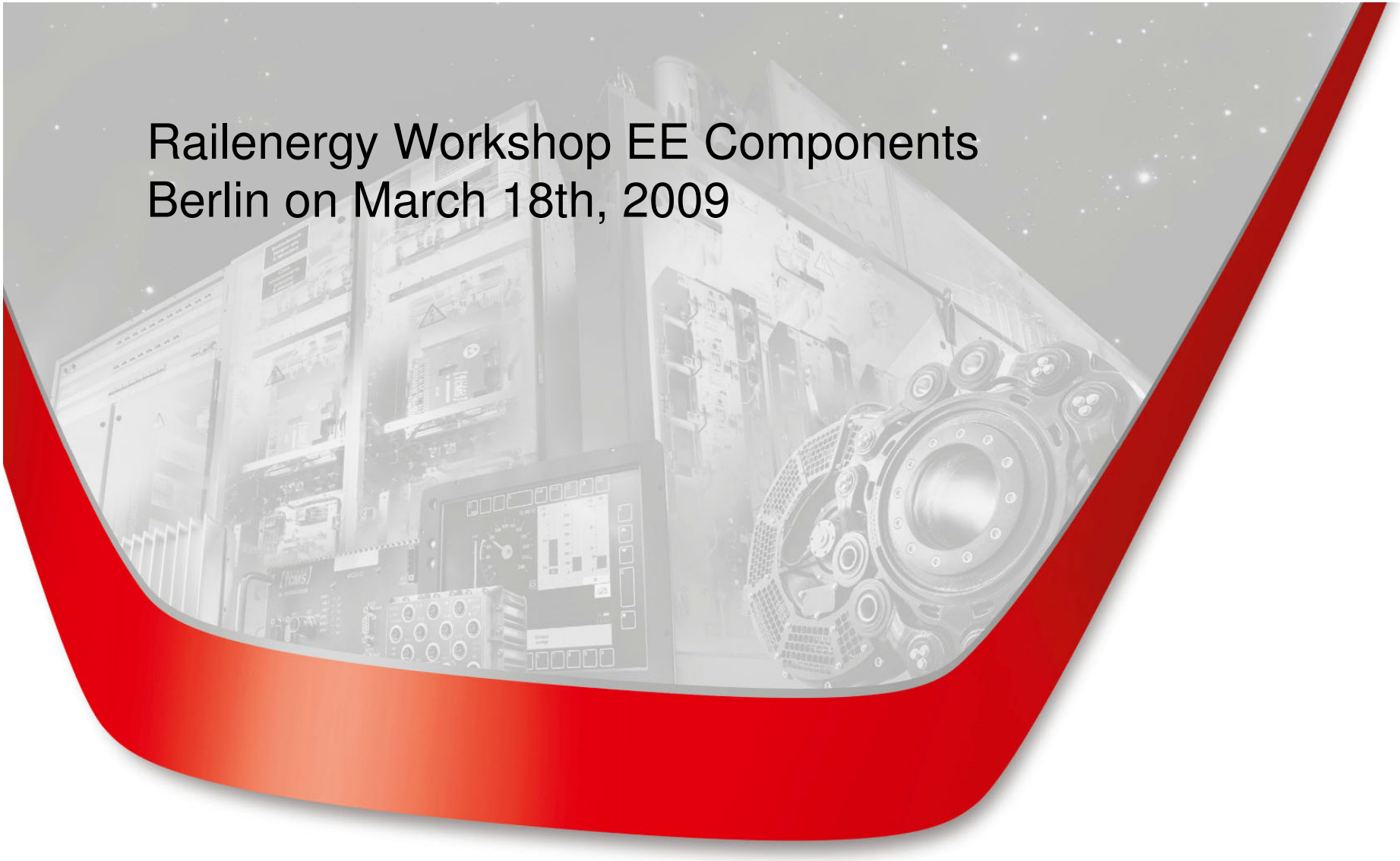
Railenergy Workshop EE Components
Berlin on March 18th, 2009



NRG 4.1 Onboard innovative components

Dr.-Ing. Markus Klohr

Railenergy

BOMBARDIER

Overview

Introduction

Bombardier Experience

Railenergy - Focus of work package NRG 4.1

Operation modes

Energy storage sizing

Onboard energy Storage technologies

Summary

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Introduction
Why do we need to think about Energy Saving ?

- **Energy becomes a scarce resource**
  - Increasing demand, caused e.g. by higher mobility and comfort level
  - Supply of raw material for energy production is affected by fluctuating world economics, politics and stock exchanges
  - Future of nuclear energy production is unclear (at least) in many countries
- **Energy prices are rising**
  - Demand is increasing stronger than supply
  - Price increases reflect higher input prices
  - Emission of CO2 gases is becoming expensive – no more free emissions
  - No more “subsidized” power supply for operators – need to buy at market prices
  - Prices for renewable energies will be above market prices due to politically guaranteed mark-ups
- **Reduction in Energy Consumption is the goal – not increasing supply**
  - Higher efficiency is cheaper solution compared to increasing supply – at least in the mid and long run
  - Supply is limited
- **Energy saving and “environmental sustainable solutions” are a “hot trend”**
  - Worldwide “green movement”
  - Higher concerns about environmental impact among consumers (our end customers) and politicians

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Bombardier Experience in energy storage
Introduction

- **Environment-friendly use of resources**
  - Existing resources must be used effectively and environmental friendly

- **Public and private operators under cost pressure**
  - Energy costs per Light Rail Vehicle about 30‘000 €/year
  - Energy costs of a Diesel Multiple Unit about 180‘000 €/year
    (@ 0,95 €/liter, 150‘000 km/year, 1,5 liter/km)

- **We are continuously investing in improving the energy use of our vehicles**
- **Our short- and middle-term solution is Storage of Brake-Energy**
- **1999 started as research topic “alternative energy supply”**
  - Investigations on storage technologies
  - Evaluation of possible applications
  - Evaluation of possible savings
  - Determining of influencing factors

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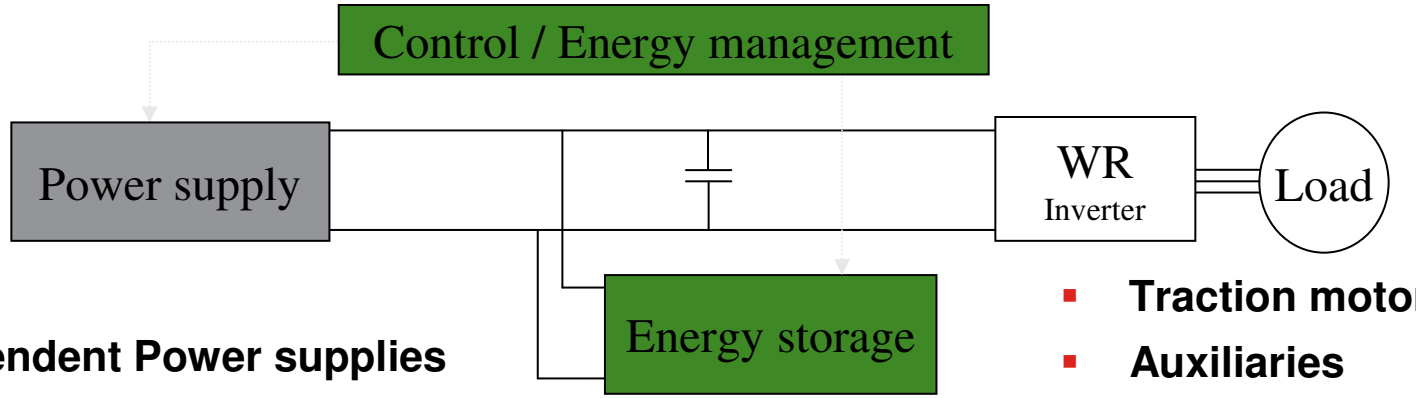
Bombardier Experience in energy storage

Applications of Energy storage



- **Traction motor**
- **Auxiliaries**

- **Application dependent Power supplies**

A) „Catenary“
el. Energy Supply

B) „Diesel Motor“

Diesel Motor
Generator, Rectifier

C) „Fuel cell“

Fuel Cell

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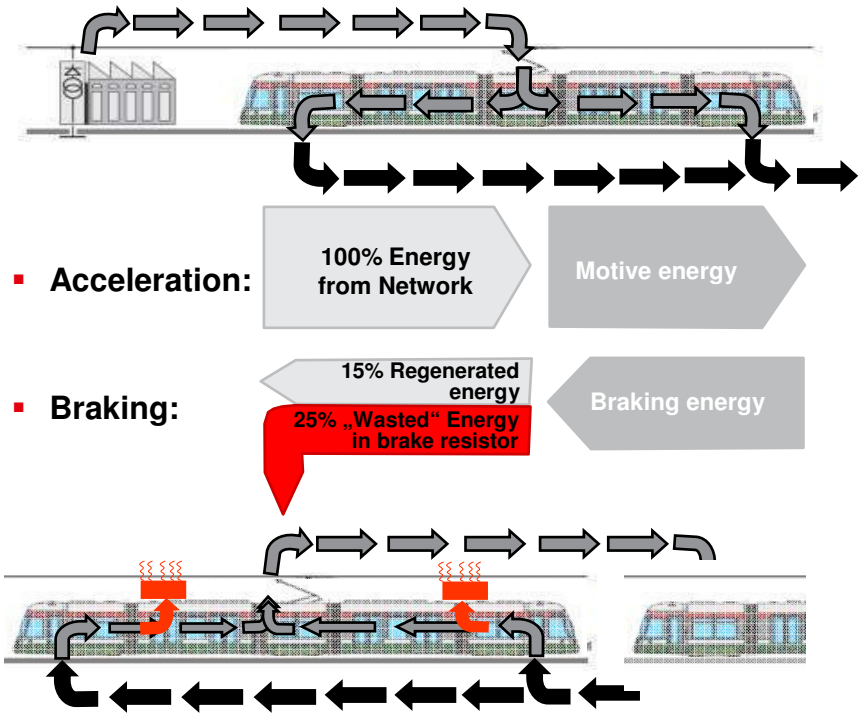
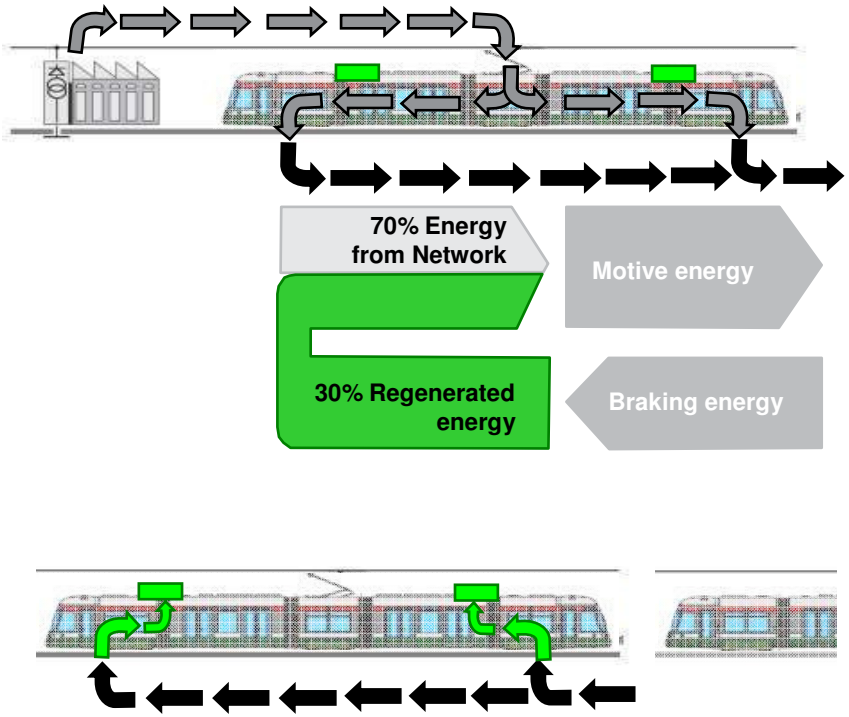
Bombardier Experience

Onboard energy storage, the Principle

- **Conventional vehicle recuperate braking energy into network**
  - Only around 15% of total input energy is recuperated in braking mode
  - Around 25% of input energy is burned in brake resistors
- **Vehicles equipped with Mitrac Energy Saver store the whole braking energy**
  - Around 70% of input energy is recuperated in braking mode and fed back to the energy storage
  - stored energy is being used for next start up





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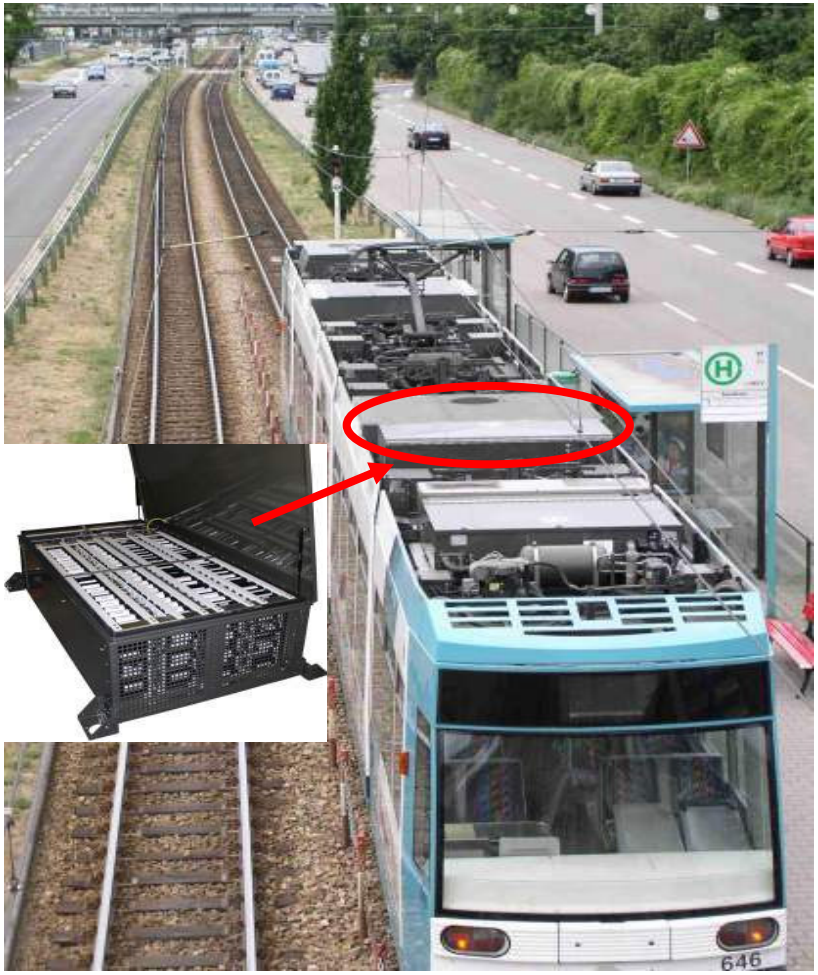
Bombardier Experience

The Energy Saving LRV – In operation from 09/03 to 12/07

- One vehicle of the Mannheim public transport operator was equipped with one additional Energy Saver for one motor bogie

- Vehicle was revenue service
  - from September 2003 to November 2007 (4 years)
  - covering a travelling distance over 125.000 km

- 2007, the RNV public transport network, decided to equip 19 new vehicles with the latest generation of *MITRAC* Energy Saver



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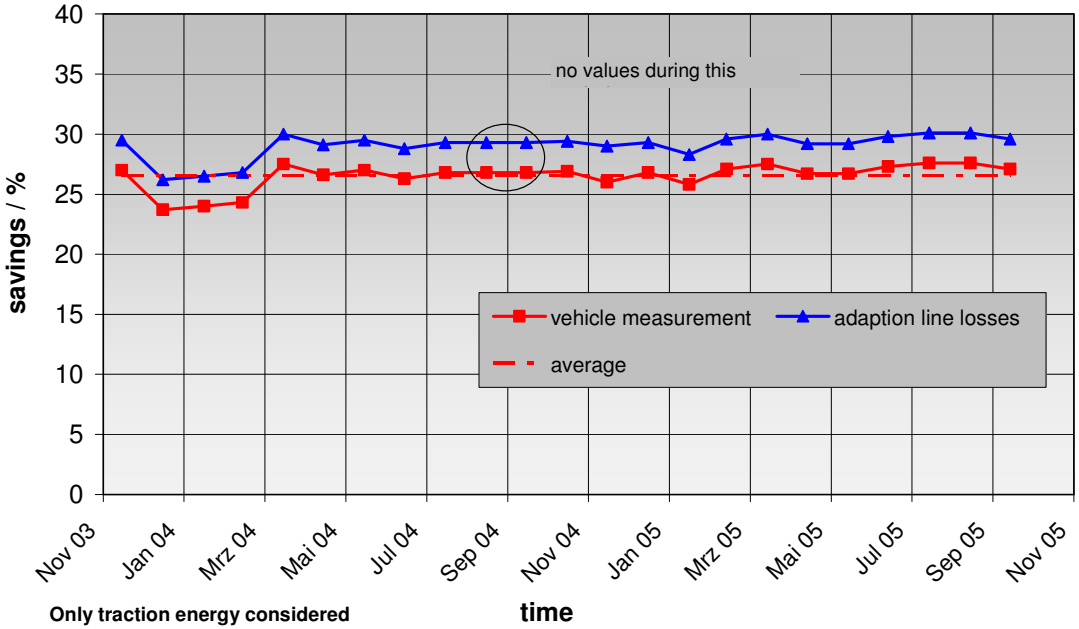
Bombardier Experience

The Energy Saving LRV – In operation from 09/03 to 12/07

- Results in Mannheim showed substantial savings
- Up to 30% energy saving
  - Re-use of recuperated “self-produced” energy which is stored during braking before taking energy out of the overhead catenary wire
- Up to 50% reduction in peak power to be supplied by network
  - Real savings in the expensive „Peak-Power Tariff“



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Railenergy - Focus of work package NRG 4.1

Aim of this work package

- **Evaluate the potential energy savings generated by an onboard energy storage system concept**
  - Verify benefits (e.g. environmental, economic), targets in fuel and emission savings
  - evaluate system benefits (CO2 reduction, fuel savings, …)
  - check safety issues of such on-board energy storage technology for railway applications
- **Screen actual technologies for onboard energy storage systems**
- **Select the most suitable application for onboard energy storage**
  - Considering Railenergy content
- **Define and specify requirements an storage systems**
- **Evaluate saving potentials**
  - On possible applications, considering Operation modes
- **Select and describe the most suitable storage technology for the desired application**

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Railenergy - Focus of work package NRG 4.1

Focus on most suitable application

- **Collection of application data**
  - High speed, Regional, Suburban
- **Taking into account most influencing parameters**
  - Saving potential, space & weight restrictions, ….
- **Aim was to focus on one application inside Railenergy**

vehicle type	energy saving potential	demonstration scenario	space and weight available for	power needed	energy needed	posibility of regeneration	operating mode
DMU-regional	++	3	good *)	medium	medium	no	many stops
DMU-ICT	+	2	fair - poor	high	very high	no	few stops
EMU-DC-regional	+	3	fair	medium	high	limited	many stops
Loco-Diesel-passenger-regional	++	3	very poor	high	high	no	many stops
Loco-Diesel-passenger-long.dist.	+	2	very poor	very high	very high	no	few stops
Loco-DC-passenger-regional	+	3	poor	high	high	limited	many stops

demonstration scenario:
1) passenger (AC)
2) mixed traffic, int.
3) passenger transport regional
*) downsizing of existing equipment

- **Most promising application is DEMU regional/ICT**
- **Followed by EMU in regional**

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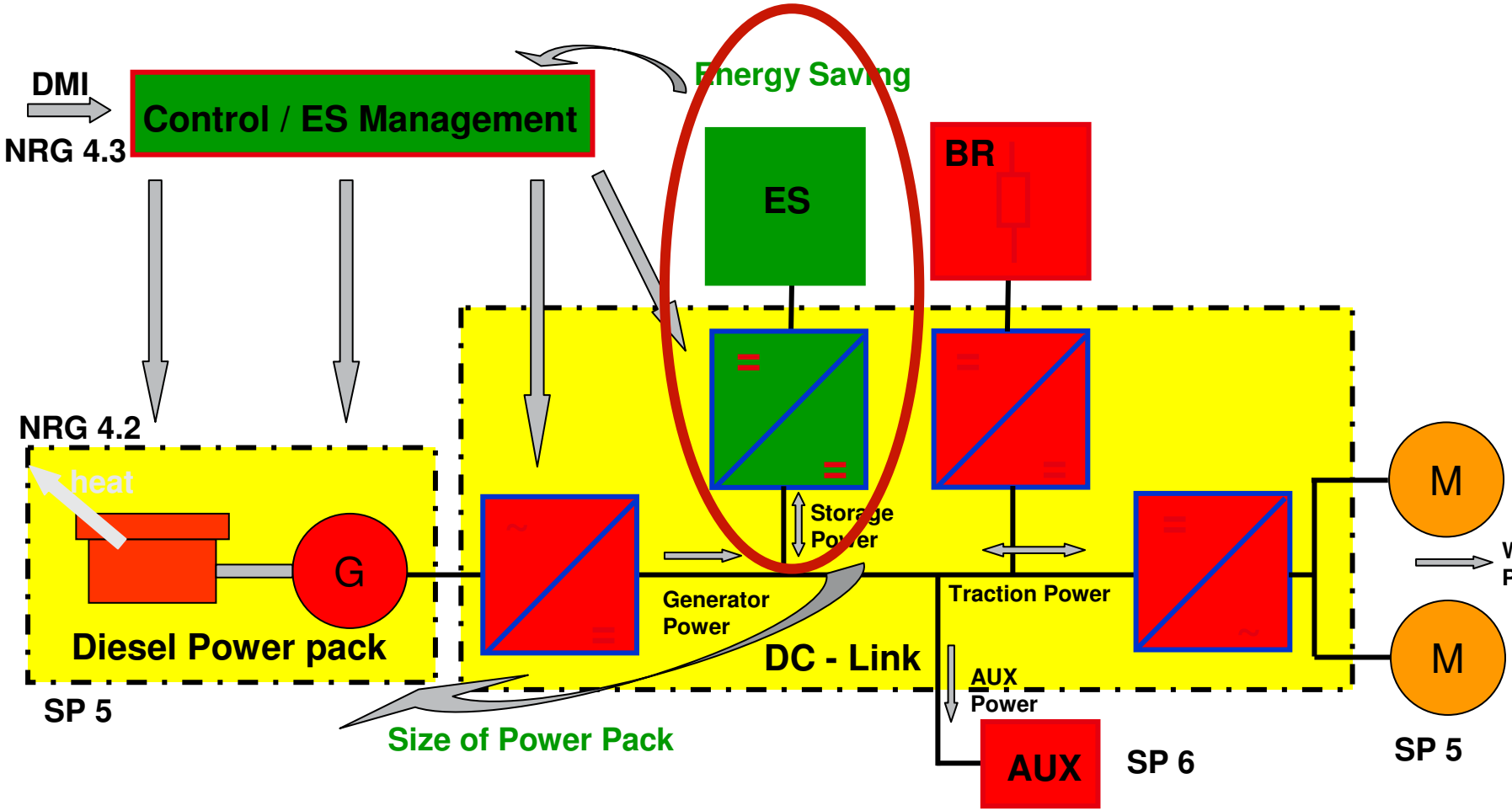
Vehicle system overview DMU with ES



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Onboard energy Storage technologies
Selection criteria's

- **Different Criteria's have to be taken into account to compare the technologies**
- **The most important which have been identified so far**
  - Energy and Power density
  - Weight and Volume
  - Cost
  - Lifetime in considered application
  - System complexity
    - Scalability / Modularity
    - Supervision system
  - Experience
  - Risks/Concerns

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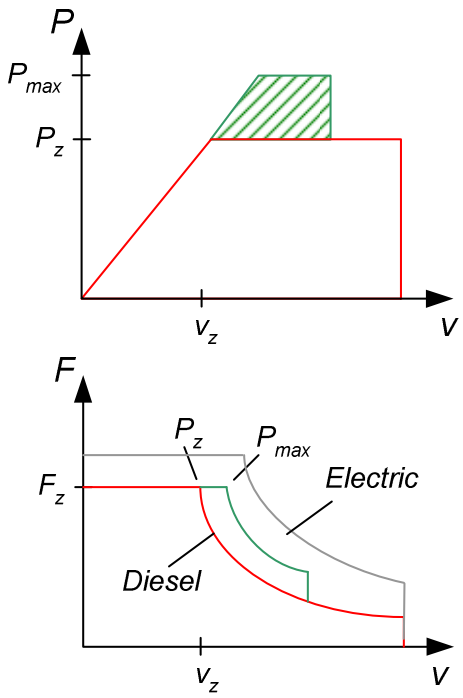
Operation modes
Boosting and coasting

- **Typically diesel power supply is less powerful then traction equipment**
- **This leads to typically less acceleration**
- **Onboard energy storage delivers additional power for acceleration**
  - Compensate for time delays
  - Apply coasting in case of time reserve
- **High savings up to 32% possible**
- **Flexible operation**
- **Timetable optimization**
- **Coasting time needs to be known**



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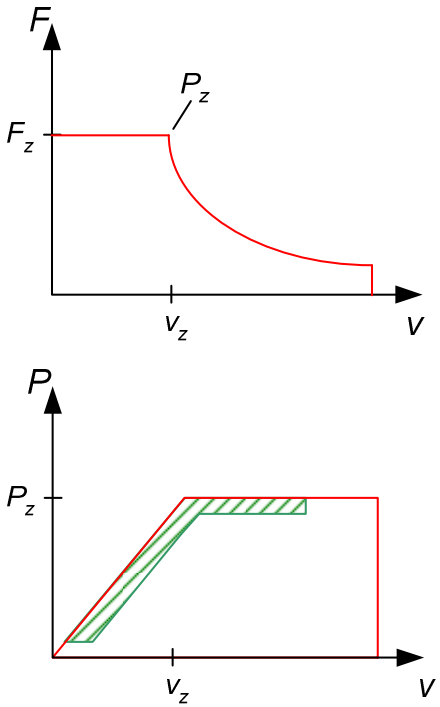
Operation modes
Energy saving

- **In case if diesel power supply and traction equipment have the same power range**
- **Operation of diesel in the optimum operation mode**
- **Onboard energy storage delivers power to compensate the power gap**
  - Compensate for time delays
  - Apply coasting in case of time reserve
- **Savings up to 7% possible**
- **Limited to the energy storable in the storage**
- **Not linked to Timetable optimization**



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Operation modes
Other control strategies

- **Both control strategies could be combined and mixed**
- **In addition other control strategies could be applied**
  - Accelerate with power from the energy storage in the station
    - noise reduction
    - Station pollution
  - Traction rescue mode
    - travel to the station in case of diesel failure
  - Boosting in certain unusual conditions
    - e.g. to recover timetable

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Energy storage sizing

Onboard energy Storage technologies

Summary

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Energy storage sizing
Influencing factors

- **Energy saving on vehicle is linked to several parameters**
- **Energy storage**
  - Storage size
  - Storage weight
  - Storage power capability
  - Control concept (Charge/discharge Power)
- **Vehicle**
  - AUX Power demand
  - Diesel Power pack Size and control (if DMU)
  - Propulsion system energy loss
  - Vehicle data
- **Track**
  - Driving behaviour (timetable)
  - Track profile

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Energy storage sizing
Consider vehicle data

- **Collection of vehicle data**
- **Taking into account most actual suppliers for DEMU**
- **Generation of typical values for power density (7 to 10 kW/t)**
- **→ Synthetic vehicles with typical values**

								2-car	3-car ES	3-car Boo
train										
mass empty	121	146	84,3	122	57 t	146 t	64 t			
mass normal load	136	166	101	138	83	160	79	85	120	115
axle arrangement	Bo-2-2-Bo'	Bo-2--2--2-Bo	Bo-2--2-Bo	Bo'2'+2'2'+2'Bo'	2'Bo'2'	A'1'A'A'A'A'1'A'	Bo'2'2'Bo'	Bo-...-Bo	Bo-...-Bo	Bo-...-Bo
max axle load	17 t	17 t	15.3	17 t		21 t	11 t	17	17	17
no of conv	2	2	2	2	2	2	4	2	2	2
no of motors	4	4	4	4	2	6	4	4	4	4
power per motor	325 kW	325 kW	315 kW	225 kW / 325 kW	2	190 kW continuous	150 kW cont.	225 / 325	325	325
no of powerpacks	2	2	2	2	2	4	2	2	2	2
engine power	662	662	505	500	390	338	375	375	500	375
engine speed	2100	2100	1800	1900 / min	1900 / min	1900 rpm	2000 rpm	2000	1900	2000
wheel diameter (half worn)	805	805	820	815 mm	830 mm	740 mm	620 mm	810	810	810
max speed	160 km/h	160 km/h	120 km/h	160 km/h	140 km/h	160 kph	100 kph	140	140	140
starting acc	0.87	0.72	1	0,62 (85 kN)	0,96 (80 kN)	0,8 m/s²	1,1 m/s²	0.95	0.8	0.8
electric brake dec	-0.62	-0.51	-1	0,51 (70 kN)		0,7 m/s²	1,1 m/s²	0.95	0.8	0.8
aux power	160	160	54	130 kW	100 kW	240 kW max.	100 kW max.	100	130	130
extras						2 x 200 kW flywheel	750 V DC supply			
Power density [kW/t]	9.74	7.98	10.00	7.25	9.40	8.45	9.49	8.82	8.33	6.52
nom. DC-Link voltage	1500	1500	750	750	750	1500	750	750	750	750
comment								Booster	Energy Saving	Booster
DC-link voltage	t.b.updated	t.b.updated	400-850	400-850	t.b.updated	700-1800	t.b.updated	WP 5.4	WP 5.4	WP 5.4
Adhesion coefficient in braking								0.15	0.15	0.15

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Energy storage sizing
Overview of simulations

- **For basic calculations all out mode is used**
  - Acceleration to maximum speed
  - Deceleration with nominal braking force
- **Simulations to select the storage size**
  - 2 car vehicle w/wo storage (ES) → boost and coast
  - 2 car vehicle w/wo storage (Boost) → boost
    - High power AUX
    - Low power AUX
  - 3 car vehicle w/wo storage (ES) → boost and coast
  - 3 car vehicle w/wo storage (Boost) → boost
    - High power AUX
    - Low power AUX

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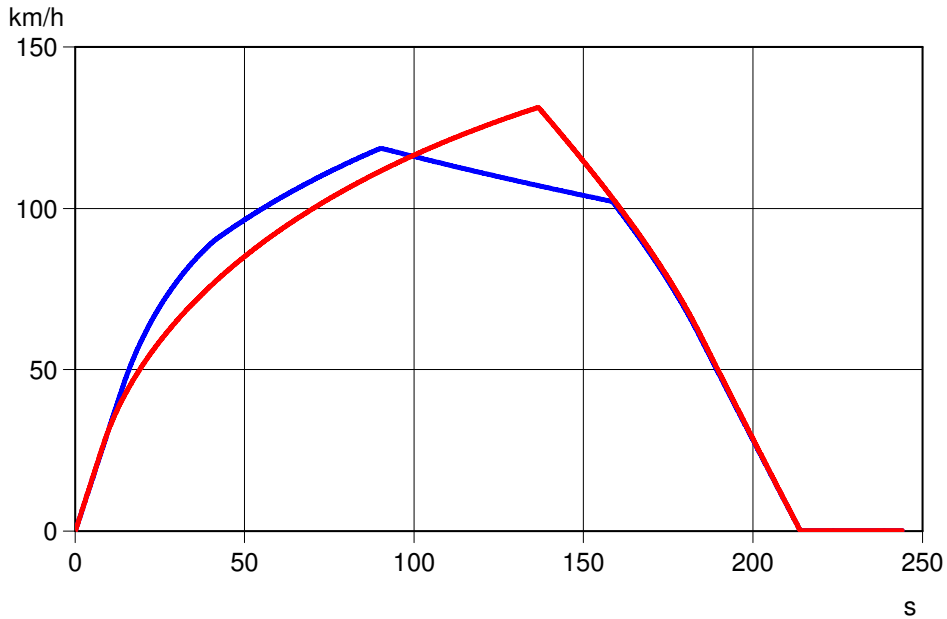
Energy storage sizing

2 car vehicle ES – speed over time example ES

- **30 kW Aux**
- **2 x 375 kW diesel**
- **Same travelling time as vehicle without ES**
- **Keep acceleration for as long as possible**
- **Apply coasting**



2-car vehicle, track: 5 km, gradient: 0%, Aux = 30kW

– 2 x 375kW-Diesel no ES
– 2 x 375kW-Diesel 2,8 kWh-ES

		2 car ES
Power pack	**kW**	**2 x 375**
Aux Power	**kW**	**30**
Storage Size	**kWh**	**2,8**
Power charging	**kW**	**310**
Power discharging	**kW**	**197**
Energy saving	**%**	**31,4**
time saving	**%**	**0**

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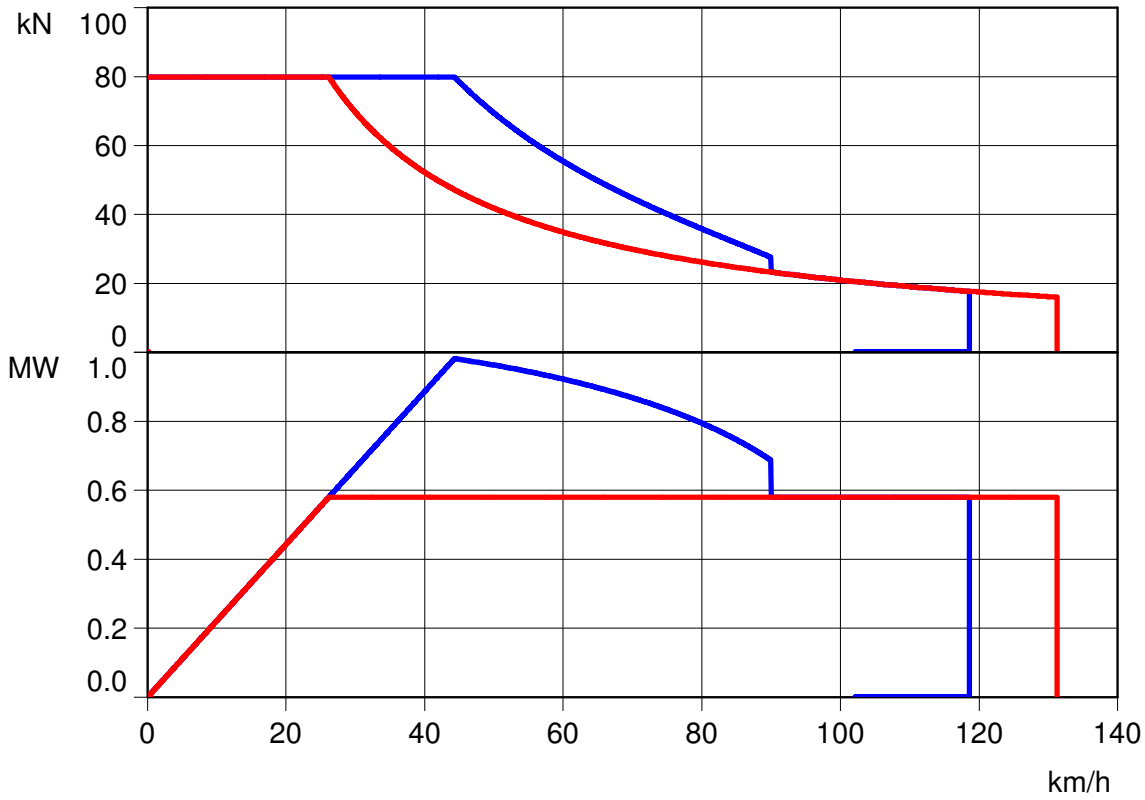
Energy storage sizing

2 car vehicle ES – tractive effort, Wheel Power

- 2 x 375kW-Diesel no ES
- 2 x 375kW-Diesel 2,8 kWh-ES



2-car vehicle, track: 5 km, gradient: 0%, Aux = 30kW

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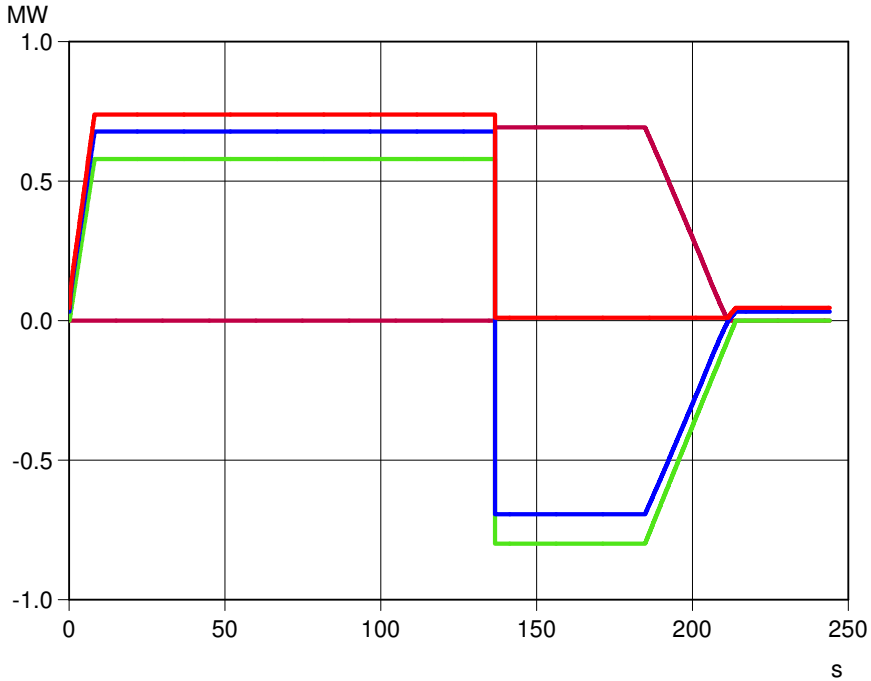
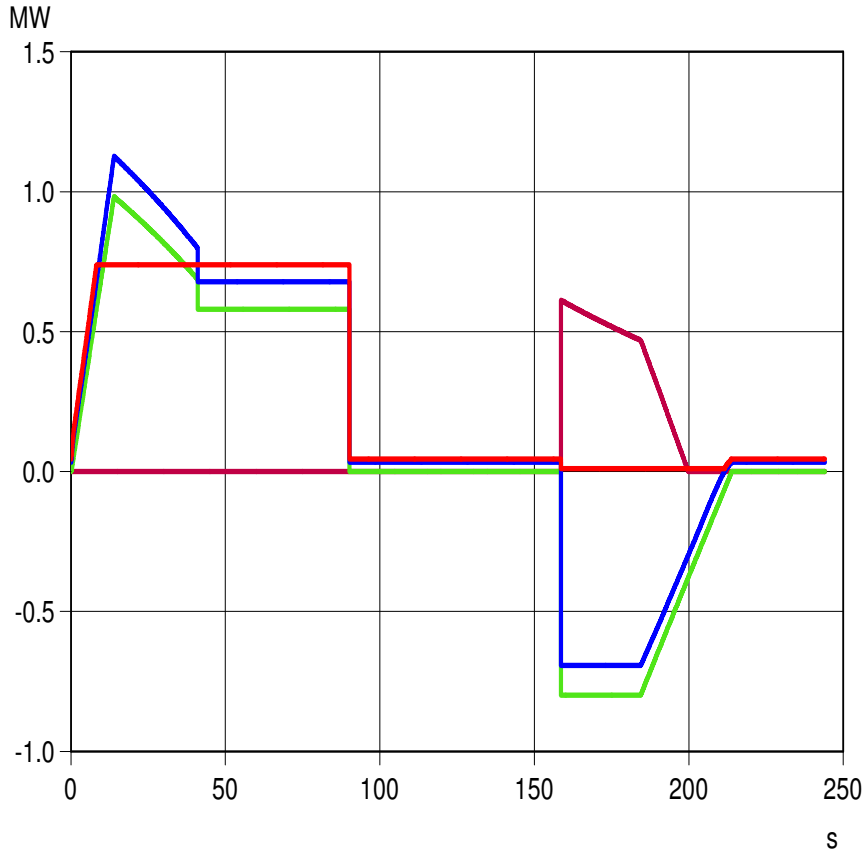
Energy storage sizing
2 car vehicle ES – Power flow

- Diesel Power
- DC – link Power
- Wheel Power
- Brake resistor Power





2-car vehicle, track: 5 km, gradient: 0%, Aux = 30kW

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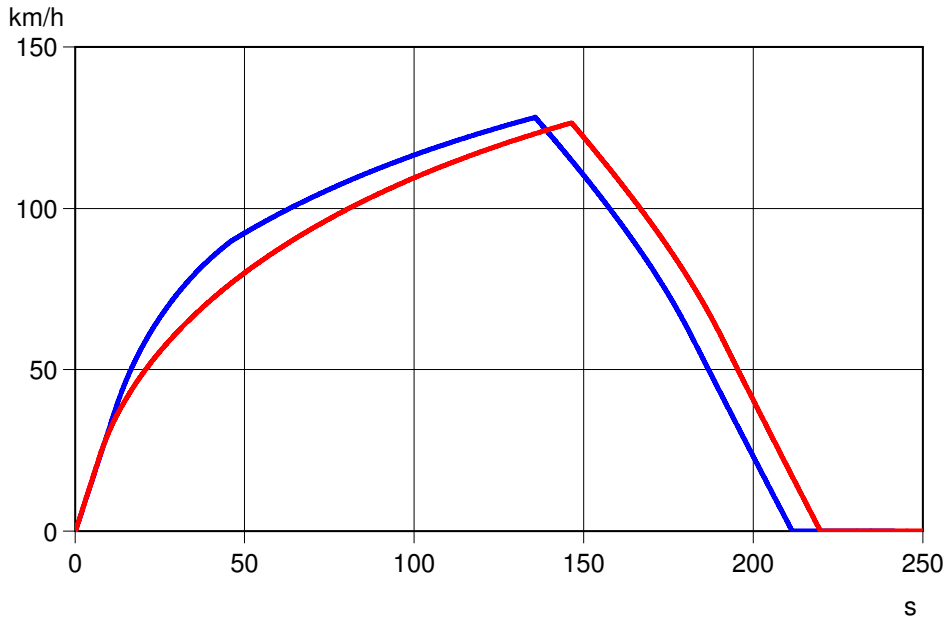
Energy storage sizing
2 car vehicle Boost – speed over time

- **100 kW Aux**
- **2 x 375 kW diesel**
- **Shorter travelling time as vehicle without ES**
- **Keep acceleration for as long as possible**
- **Apply no coasting**



2-car vehicle, track: 5 km, gradient: 0%, Aux = 100kW

– 2 x 375kW-Diesel no ES
– 2 x 375kW-Diesel 2,8 kWh-ES

		2 car Boost
Power pack	**kW**	**2 x 375**
Aux Power	**kW**	**100**
Storage Size	**kWh**	**2,8**
Power charging	**kW**	**250**
Power discharging	**kW**	**140**
Energy saving	**%**	**7,1**
time saving	**%**	**7,8**

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Energy storage sizing
Power and energy requirements

- **Required performance data**
  - Goal: Achieve energy savings to be delivered to RAILENERGY
  - Apply selected control strategies

		2 car ES	2 car boost	2 car boost	3 car ES	3 car boost	3 car boost
Power pack	kW	2 x 375	2 x 375	2 x 375	2 x 500	2 x375	2 x 375
Aux Power	kW	30	30	100	40	40	130
Storage Size	kWh	2.8	2.8	2.8	4.2	4.2	4.2
Charging							
Average Power	kW	185	125	135	225	175	195
Peak Power	*kW*	*295*	*195*	*215*	*365*	*275*	*315*
Discharging							
Average Power	kW	285	285	235	285	205	165
Peak Power	*kW*	*450*	*450*	*375*	*450*	*325*	*260*
Energy saving	**%**	**31.4**	**7.1**	**7.1**	**32.1**	**19.6**	**17.7**
time saving	**%**	**0**	**3.3**	**3.8**	**0**	**0.4**	**-0.68**

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Onboard energy Storage technologies
Overview

- **Considering the actual available technologies**
- **Focus on usage for brake energy storage**

The following technologies have been evaluated

- **Batteries**
  - Battery technology for traction will be discussed in Detail by Pierre Prenleloup from Saft
- **Supercaps**
- **Flywheels**
- **Hybrid storage**
  - Supercaps & Batteries

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Onboard energy Storage technologies
Evaluated battery technologies

- **NiMH batteries**
  - High energy density (→ 66 Wh/kg)
  - Low Power density (→ 0,5 kW/kg) compared to SC
  - Liquid cooled
  - Modules with different characteristic's available
  - Power type and Energy type available
- **Battery management needed**
  - On module level
  - Temperature, voltage level, current, ….
- **Battery thermal management needed**
  - Keep battery at constant temperature
  - Heating in winter, Cooling in Summer
- **DoD (Depth of Discharge) needs to be considered when dimensioning battery for lifetime**
  - Cycling capability increases with lower DoD → bigger storage

NHP Module from Saft

NHE Module from Saft

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Onboard energy Storage technologies
Evaluated battery technologies

- **Li-Ion batteries**
  - High energy density (→ 79 Wh/kg)
  - Moderate Power density (→ 0,8 kW/kg)
  - Liquid cooled
  - Increased peak power (compared to NiMH)
- **Battery management needed**
  - More precise (compared to NiMH)
  - Supervision and balancing on cell level
  - Temperature, voltage level, current, ….
- **Battery thermal management needed**
  - Depending on load cycle
  - Heating in winter, Cooling in Summer
- **DoD (Depth of discharge) needs to be considered when dimensioning battery for lifetime**
  - Cycling capability increases with lower DoD → bigger storage
  - Increased cycling capability (compared to NiMH)

Generic 6S Module from Saft

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Onboard energy Storage technologies

Evaluated battery technologies

- **Comparison of both battery technologies for rail power application**

NiMH	Li-ion
+ Proven safety record	+ 3 x higher power density
+ Cost effective high power solution today	+ 40% weight saving and 5% volume
+ Acceptable cycle life	+ Potential for longer life
- Thermal management due to heating in operation and T life dependence	+ Improved efficiency and thermal behaviour
- Limited ability to cost down due to raw material dependence	+ Potential to be more cost effective than Ni-MH in the future
- Weight compared to Li-ion	-abuse tolerance lower than Ni-MH (overcharge, T, crash) due to electrochemistry
	- Fumes and fire emission when abuse
	- Field experience limited in railways

- **Usage for brake energy storage**
  - NiMH are limited in peak power
  - Li-Ion shows high potential for usage in rail power applications
  - Cells and modules show technical stability, but several different solutions
  - But at the moment still seen as not technical mature on system level

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Onboard energy Storage technologies
Evaluated Supercap technologies

- **Double layer capacitors**
  - High power density (→ 20 kW/kg)
  - Weak energy density (→ 6 Wh/kg)
  - Air cooling
  - Due to the low cell voltage (typ. 2.7V) series connection needed
  - Modules for different applications available
- **Supervision and balancing**
  - Due to the aging behaviour and tolerances cell balancing is advisable
  - A supervision on module and system level is typically realized
- **Usage as brake energy storage**
  - High cycling capability ~ 2 Mio
  - Lifetime is influenced by temperature and voltage

Single cells and Modules from different suppliers

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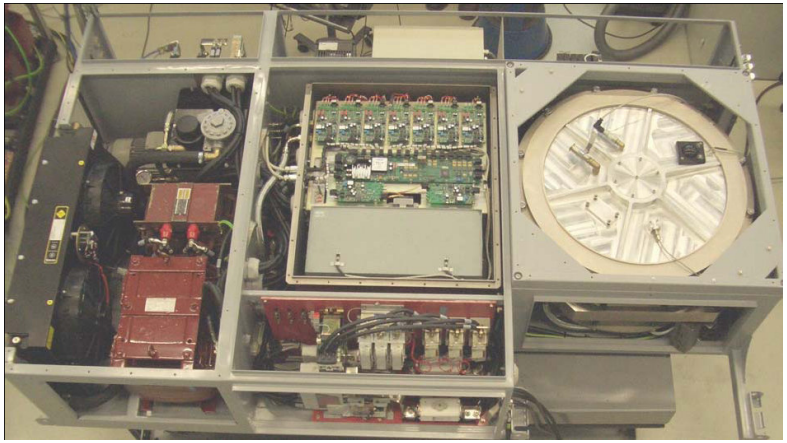
Onboard energy Storage technologies
Evaluated Flywheel technologies

- **Energy stored in rotating carbon fibre rings**
  - High Energy storage capacity
  - High power capability
- **Only few tests have been done in the past**
- **Quite complex system**
  - Flywheel
  - Converter
  - Cooling system
  - Supervision
  - Switches
  - Chopper for connection to the DC-Link
- **Usage as brake energy storage**
  - Still some topics to be solved
    - Especially the safety aspects
  - Actually no flywheel in operation in traction application



Realized flywheel system for LRV

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Onboard energy Storage technologies
Evaluated hybrid storage technologies

- **Basic idea is to combine the attributes of**
  - Batteries (low power density, but high energy density) and
  - Supercaps (low energy density, but high power density)
- **Taking into account a different load profile**
  - Including the aux power to the traction power
  - Constant power profile is covered by the battery
  - Fluctuating power (acceleration & braking) is covered by the supercaps
- **Increased saving potential expected**
  - System sizing is difficult
    - Which is the most benifitial size of both storage systems
  - Benefits have to be evaluated

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Railenergy Workshop EE Components
Overview

Introduction

Bombardier Experience

Railenergy - Focus of work package NRG 4.1

Operation modes

Energy storage sizing

Onboard energy Storage technologies

Summary

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Railenergy Workshop EE Components
Summary

- **Benefits are clear**
  - High energy savings in several applications
  - Up to 30 % energy saving due to additional power and applied coasting
  - Up to 7 % energy saving and 4 % time saving when used as booster
- **Technologies are available**
  - Batteries → promising development
  - Supercaps → allready available
  - Flywheels → still open topics
  - Hybrid Combinations → looks promising
- **Commercial and technical aspects still not fully accepted**
  - ROI, new technology, safety and reliability

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Thank you for your attention !

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