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Modelling and strategies for the assessment and **Op**timisation of **E**nergy **Us**age aspects of rail innovation

Deliverable D 6.2
Innovative technologies influence on energy usage assessment

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1. Executive Summary

As described in the task WP6.1 [1] of the OPEUS project, the Li-ion high power battery based on cylindrical VL30PFe cell was selected for the assessment of energy consumption. Four scenarios (Urban, regional, high speed and freight) will be studied according to the operating strategy for ESS mentioned in task WP3.3 [2]. Different strategies of battery utilization including the battery sizing will also discussed.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
BOL	Begin Of Life
BTMS	Battery Thermal Management System
DoD	Depth Of Discharge
EOL	End Of Life
ESS	Energy Storage System
ESU	Energy Storage Unit
EV	Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
OCV	Open Circuit Voltage
sLFP	Lithium-ion Super Phosphate (cathode chemistry)
SOC	State Of Charge

3. Background

The present document constitutes the Deliverable D6.2 “Innovative technologies influence on energy usage assessment” in the framework here under in OPEUS (Stage 02, WP06)

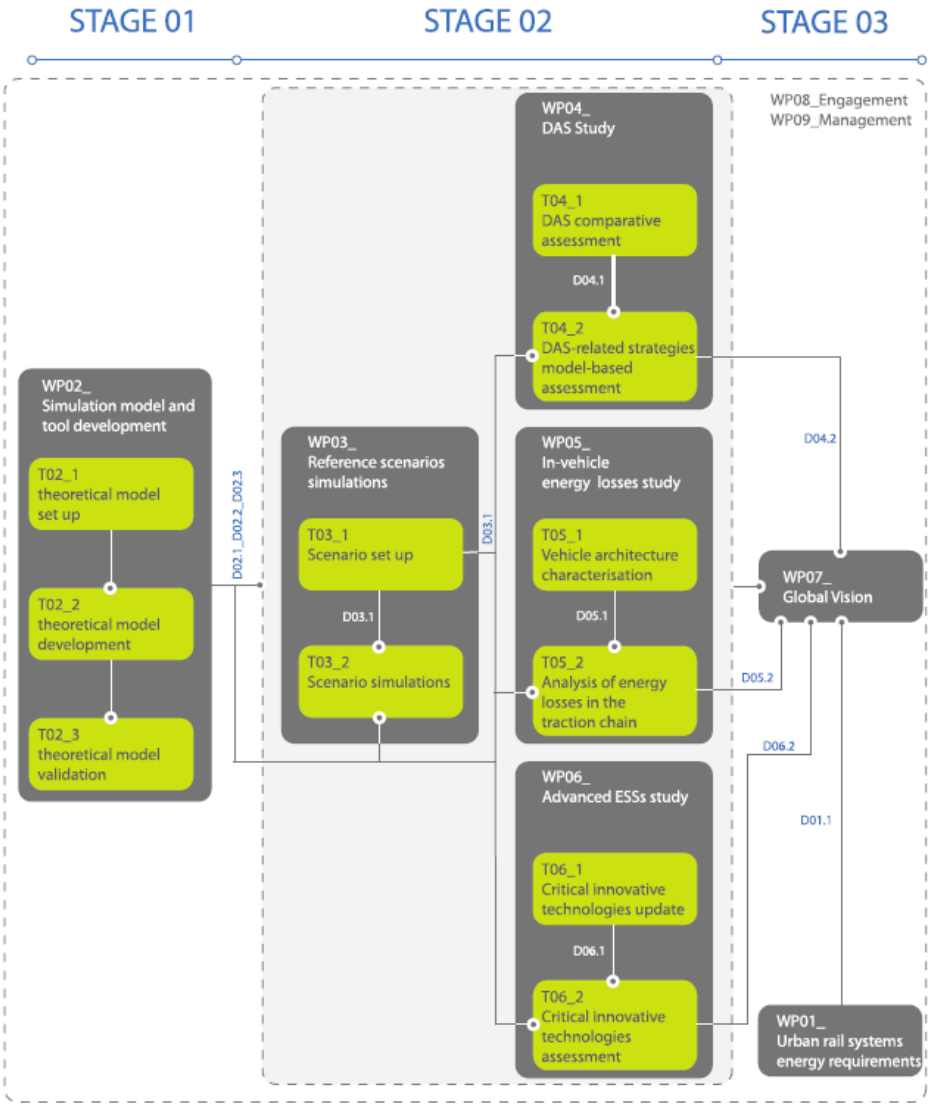

Figure 1 . Relationship between the different activities included in the OPEUS work plan

4. Objective/Aim

In the deliverable WP6.1, [1], the advantages and the drawbacks of EDLC & batteries were separately expressed in detail. The supercapacitors are utilized in applications that require a high-power capability for a short duration. Otherwise, one of the most important factors of the batteries is the maximum attainable energy density. To underline this point, it is important to compare some main characteristics of several representative batteries and supercapacitor.

ESU component	Power density (W/kg)	Energy density (Wh/kg)	Capital cost ($/kWh)	Cycle efficiency (%)	Cycle life (cycle)	Self-discharge per day
Lead-acid battery	180	30-40	74-222	70-90	500-800	0.1-0.3%
NiMH battery	250-1000	30-80	450-1000	66	500-1000	2%
NiCd battery	150	40-60	296-890	70-90	1 500	0.2-0.6%
Li-ion battery	1 800	**150-250**	**1040-1484**	80-90	1 200	**0.1-0.3%**
Supercapacitor	1000-2000	**2.5-15**	**2 000**	>93	100 000	**20-40%**

Table 1. Comparison of ESU component (batteries and supercapacitor), [3]

The supercapacitor presented in Table 1 show a very good cycle life regarding the Li-ion batteries, but their energy density is lower than the one of Li-ion batteries. Furthermore, the self-discharge of the supercapacitors is very important and has to be considered. Finally, according to the Table 1, the storage of 1kWh of energy within a supercapacitor is more expensive than the storage of 1kWh within Li-ion batteries.

The performance characteristics make the Li-ion batteries attractive for traction applications such as railway, electric vehicles, hybrid electric vehicle and plug-in hybrid electric vehicles. Another way to compare the supercapacitors with the batteries is to use the Ragone chart, [4]. Figure 3 shows the trade-off between specific energy and specific power for different electrochemical energy storage devices (fuel cells, capacitors and batteries).

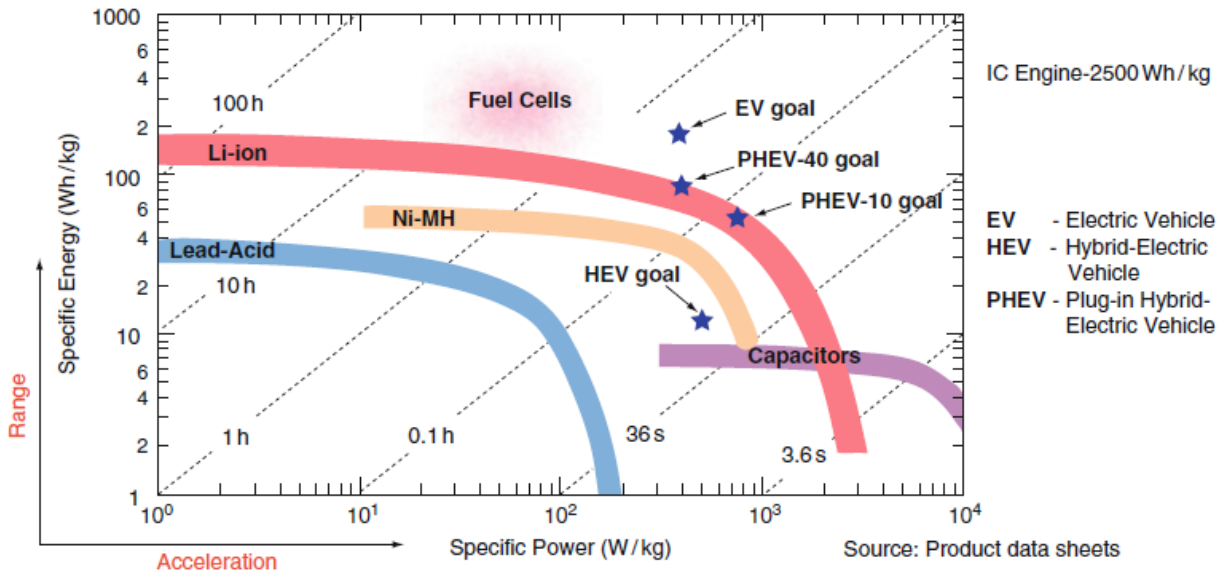

Figure 2. Ragone plot of specific energy versus specific power for different electrochemical energy storage devices.

The Ragone plot shows that the capacitors are dedicated to the short time and very high specific power. The Li-ion batteries fit better to the EV or PHEV applications.
According to the chemistry of the Li-ion batteries cathode, the energy and power density could be varied, [1]. The high-power VL30PFe cylindrical cell from SAFT was selected to integrate the ESU battery model into the vehicle model under Matlab/Simulink. This sLFP technology offers a very high safety level regarding the other chemistries and the goods cycle and calendar life.

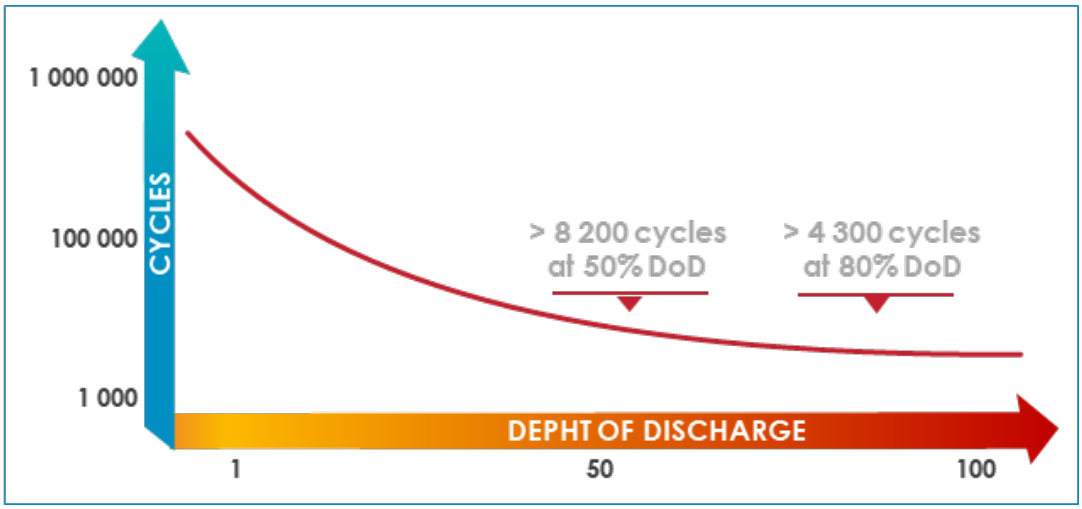

Figure 3. Life cycle of SAFT high-power batteries over the depth of discharge

Figure 3 depicts the life cycles of the high-power batteries in dependency of the depth of discharge (DoD). For the short pulse at high C-rates (few dozen seconds) of charge/discharge in railway

application, which demands a lower depth of discharge, the cycle life of the battery can achieve at least 1 million cycles. For other rail applications that request a longer charge and discharge like 80% DoD, the minimum of end of life is about 4300 cycles.

In the current task WP6.2, different scenarios with various services categories with the dedicated application profiles are considered as the input for the VL30PFe cell-based battery simulation. Some main electrical characteristics of the battery are reminded here-under, [1]:

Chemistry technology	Nominal voltage per cell	Standard voltage	Number of cells per module	Number of modules per box	Box nominal voltage
sLFP	3.3V	750V	12	20	792V

Table 2. Configuration of one branch of sLFP Li-ion batteries (Source: SAFT).

To assess the energy consumption and due to the numerous simulations performed with the OPEUS-tool, in the task WP6.2, the recuperated energy at the catenary and the traction energy at the catenary will be elaborated in the report for each vehicle category and each scenario. Every data concerning the battery was obtained at the end of life with 40% of capacity loss and 100% of internal resistance growth, [1].

In this work, the reference simulation for every scenario is the case without the ESU battery. Otherwise, several approaches with the battery will be carried out for the following scenarios:

- SOC balancing is performed at the end of the course. The aim is to balance the SOC between the initial state (is considered at maximum value of SoC = 90%) and the end state of the trajectory. This one is applied for the all service categories.
- SOC balancing is adopted at the end of the course and the battery could be recharge at stop by respecting the time table. This scenario is performed for the service categories where the vehicle has several times at stop along the course.

When the vehicle operates several times in cruising mode, the following scenario, which were discussed with SNCF [5], could be carried out:

- Geometric approach: SOC balancing at the end of the course and partial electrification (4 zones) where the train speed is constant.
- Peak shaving approach: SOC balancing at the end of the course with a partial traction power request could be fulfilled by the ESU battery. In other words, the discharge power of the battery will be limited.

In the next chapter, it is important to recall the operating strategy for energy storage systems described in the deliverable WP3.3 performed by UROS, [6].

5. General operating strategy for energy storage systems

This chapter is a part of the work done by UROS, [6]. The main objective of this chapter is the description of an operational strategy for an energy storage system. The basic approach of the ESS operating strategy is shown in Figure 4.

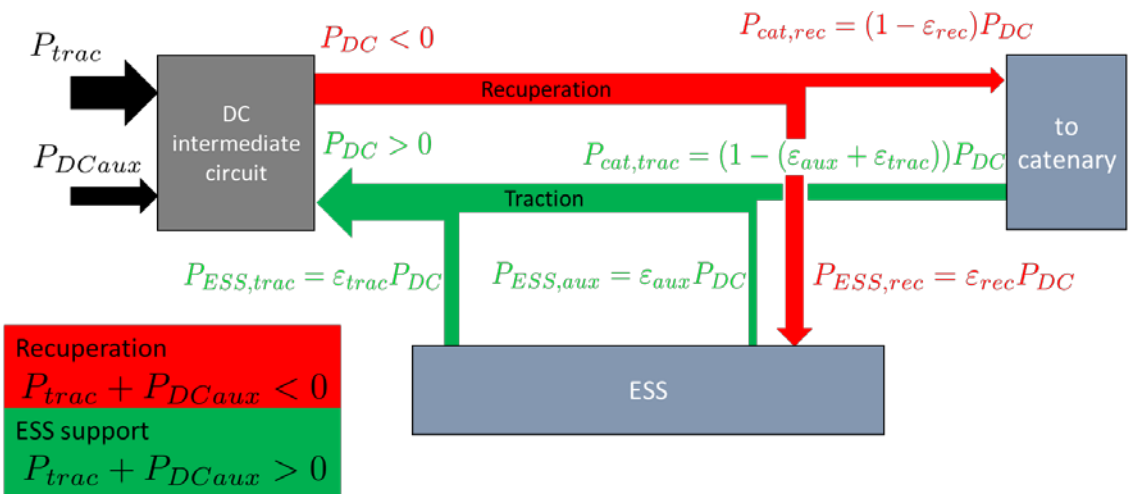

Figure 4: Basic approach for operating strategy for ESS, [6].

The algorithm used for the power flow between the catenary, the DC intermediate circuit and the ESS solicit the case of hybrid locomotive in which the conventional combustion motor is coupled to the electric one. The electric power requirement from the auxiliaries (DC links, or on-board ESS) should be provided in case of diesel engine shutdown by the ESS.

In OPEUS project, only electric traction is considered for all service categories. The fact of permanent connection to the infrastructure (except the several specific non-electrified zones, see the following chapters) ensures the feed of auxiliary power from the catenary. The battery will only solicit the power demand in case of acceleration or cruising modes to lighten the very high peaks of the traction requirement and to reduce the energy consumption at the catenary.

When the train is in operation, the braking phase (to recharge the battery) is defined by the following conditions:

- The acceleration of the train is negative and the SOC of the battery is below its initial value.
- The sum of the power request at the DC intermediate circuit - the traction power P_{DC_trac} (in braking), the auxiliary power P_{DC_aux}, the power of the on-board battery P_{obb} as well as the dynamic cooling power for the battery $P_{ESS,cooling}$ - is negative:

$$P_{DC,sum} = P_{DC\_trac} + P_{DC\_aux} + P_{ESS,cooling} < 0. \quad (5.1)$$

- The power needed to recharge the battery $P_{ESS,rec}$, (is conventionally considered negative, as per IEC62928), is directly calculated by the total power request $P_{DC,sum}$ and the recuperation factor ε_{rec}:

$$P_{ESS,rec} = \varepsilon_{rec}\, P_{DC,sum}. \tag{5.2}$$

During acceleration the battery will fully support the traction power (with traction factor ε_{trac} =1) and doesn't feed the auxiliary and the cooling power of the battery except some specific study cases (geometric approach for non-electrified zones):

$$P_{ESS}=\min\,(\varepsilon_{trac}*P_{DC\_trac},\ P_{ESS\_max\_dch}) \tag{5.3}$$

In which $P_{ESS\_max\_dch}$ is the maximum discharge power authorized by the battery.

In case of geometric approach in cruising mode (constant speed), there are several zones without electric network to feed the vehicle, the on-board battery will be fully used to support the power demands from the traction, the auxiliaries and the battery cooling power:

$$P_{ESS\_max\_dch} \geq P_{DC\_trac} + P_{DC\_aux} + P_{ESS,cooling} \tag{5.4}$$

During the zones without network connection, the battery needs to ensure all electric power requirements so that the size of the battery has to be adjusted. According to the category service (e.g. Reg160, HS300, …), the minimum battery size will be estimated.

6. Energy optimized operating strategy

The main objective of this section is the application of the presented ESS operating strategy in order to determine an energy optimal solution. The optimization problem is defined in subsection 6.1 as some possible optimization algorithms are summarized in subsection 6.2. The simulation results for this operating approach are presented in detail in [6]. Nevertheless, a selection of simulation results is also presented in the following sections.

6.1. Definition of the optimization problem

The optimization problem that is to be solved for the energy optimal operating strategy is minimizing the cost function $J_{ESS}(E_{net}, SOC)$. This cost function is defined with

$$J_{ESS} = E_{net} + \alpha_{\mathrm{soC}}(SOC(t_0) - SOC(t_f))^2. \tag{6.1}$$

Here, E_{net} represents the total net energy at the end of the course. This energy value is determined by evaluating the total traction chain model, included in the OPEUS-tool. Additionally, the cost function includes a penalty term considering the final deviation of the SOC. The SOC at the beginning is denoted with $SOC(t_0)$ as $SOC(t_{end})$ describes the SOC at the end of the course. This SOC-penalty term avoids an additional recharge or discharge at the terminal station.
The operating parameters $\varepsilon_{trac}, \varepsilon_{aux}$ and ε_{rec}, determining the power split (see section 5), are summarized in the parameter vector $\underline{\varepsilon}$. Thus, the parameters $\underline{\varepsilon}^*$ represents the solution of the optimization problem and are determined by minimizing the cost function

$$\underline{\varepsilon}^* = arg(min\{J_{ESS}(\underline{\varepsilon})\}). \quad (6.2)$$

As no gradient information can be derived for the stated cost function, the optimization problem has to be solved with a gradient-free optimizer. The implemented optimization algorithms are summarizing briefly in the sequel.

6.2. Overview of implemented optimization algorithms

The implemented optimization approaches for the energy optimal ESS strategy are based on evolutionary algorithms. Especially, this report presents a summary of the following three algorithms:

- PSO – default Particle Swarm Optimization,
- GWO – Grey Wolf Optimizer,
- CMA-ES – Covariance Matrix Adaption – Evolution Strategy.

The PSO as well as the GWO are inspired by the swarm/pack behavior of animals in real nature, whereas the CMA-ES is based on a stochastic observation.
The presented evolution algorithms are based on the population of randomly determined solution candidates. These possible solution candidates are stated as the particle. Every particle is characterized by a position within the parameter space $x_{i,k}$ and a corresponding cost value $J_{i,k}(x_{i,k})$. Here, i states the current iteration of the algorithm as k denotes the k-th particle.
The movement/evaluation of the particle specifies the characteristic of the single algorithm.

The particle movement of the PSO algorithm is based on the position of the best position of the total swarm – the global best position g_i^{best} – as well as on the best position of the individual particle – the personal best position $p_{i,k}^{best}$. The current particle movement is now given with $v_{i,k} = w_k v_{i,k-1} + r_{1,k}(p_{i,k}^{best} - x_{i,k-1}) + r_{2,k}(g_k^{best} - x_{i,k-1})$. (6.3)

Here, w_k describes a decreasing weight function for the movement of the particle itself, as $r_{1,k}$ and $r_{2,k}$ are randomly determined weighting factors (default PSO setting: $r_{1,k}, r_{2,k} \in [0,2]$).
The total position update $x_{i,k} = x_{i,k-1} + v_{i,k}$ is presented in Figure 5.

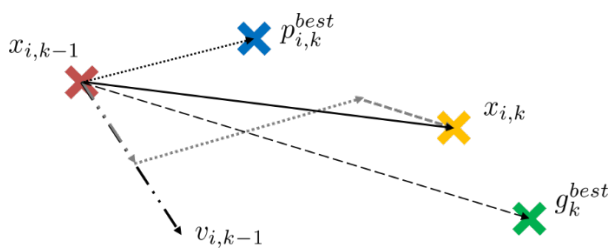

Figure 5. Particle movement for the PSO

For a more detailed description of the PSO algorithm, refer to [7].

In analogy to the PSO algorithm, the GWO is a swarm algorithm as well. As the name denotes, the particle movement of this algorithm is inspired by the hunting behaviour of grey wolves in nature. Here, the particles are denoted as the wolves, as the total swarm is called the pack.
In contrast to the default PSO, the particle movement of the GWO is based on the position of the three leading wolves (called alpha-, beta- and delta-wolves). The total position update for the GWO algorithm is presented in Figure 6. Within this figure, $A_{1,2,3}$ represent the spaces for possible positions of the three leading wolves, $C_{1,2,3}$ defines the possible space for the position update for the k-th wolf and $d_{\alpha,\beta,\delta}$ representing the observed distances to the three leading wolves.

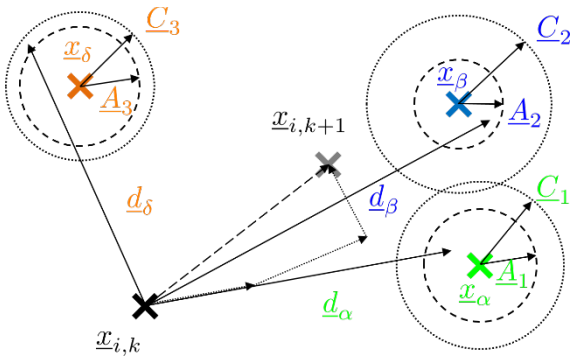

Figure 6. Particle movement for the GWO

For more a more detailed description of the GWO algorithm, refer to [8]. A detailed example of a GWO application for an ESS management of an electric railway vehicle is presented in [9].

The third presented optimization algorithm is based on the stochastic determination of the particle. For the CMA-ES algorithm, the distribution of the particle is characterized by the covariance matrix.

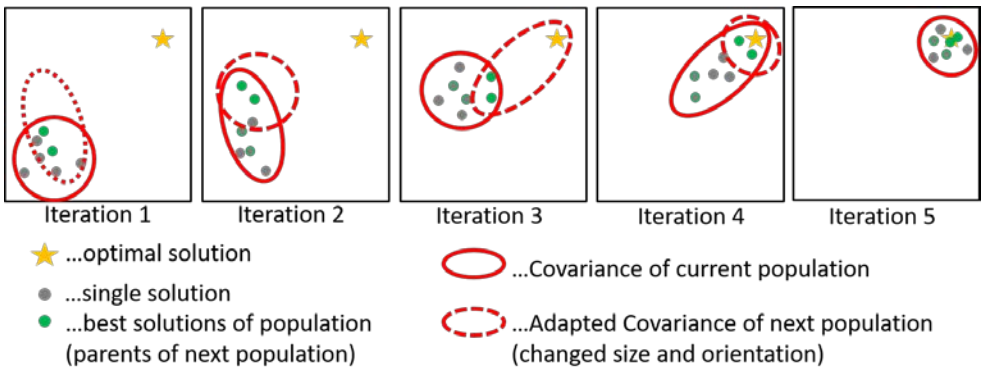

Figure 7. Particle movement for the CMA-ES

According to Figure 7, the form of the covariance matrix is adapted according to the position of the best individual particles of the current iteration. For evolutionary optimization approaches these particles are denoted as the parents of the population and determining the form of the covariance matrix of the next iteration. The position update for the next iteration than determined

by the adapted covariance matrix.
For more information regarding the CMA-ES algorithm can be found in [10].

The detailed simulation results for the energy optimized operating strategy are presented and discussed in the OPEUS deliverable "D3.3 – S2R innovation (state01) simulation result and periodic assessment – Part 2". Therefore, the presented results in section 7 – section 10 are included for the sake of completeness and to complete the overview of the evaluated simulation scenarios.

7. Urban scenario

7.1. Tram service category

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: Tram
  - Track profile: Tram
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T03 (DC power supply)

- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: No double layer capacitor presence.
  - ESS-battery: 1 ESU-battery integrated and a BTMS for cooling system of the battery.
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite.
  - Initial state of charge: $SoC(t_0 = 0) = 90\%$.
  - A single branch of battery consists of 240 VL30PFe cells in serial. The total weight of one branch including the power box (equipped a manual switch, contactor, fuses and BMS) is 541kg.
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliary power at the DC link or on-board ESS will be charged by the catenary during the course.

- The electrical cooling power of the battery (at ESS level) will be provided by the catenary. According to the dynamic power profile of the vehicle, the RMS (Root Mean Square) cooling power is calculated by:

$$P_{cooling\_battery}^{rms} = \sqrt{\frac{1}{T} * \int_0^T P_{thermal}^2(t)dt} \quad (6.1)$$

Where $P_{thermal}$ is the heat generated by Joule effect due to the internal resistance of the battery:

$$P_{thermal} = n_{par} * \left(0.75 * Ri_{EOL_{branch}}\right) * I_{branch}^2 \quad (6.2)$$

In which:

- n_{par} is the number of branches in parallel,
- Ri_{EOL_branch}(in Ω) ist the internal resistance of each branch at EOL. The thermal power is estimated from 50% growth of BOL internal resistance.
- I_{branch} (in A) denotes the electric current per branch.

The presented scenarios for the Tram simulation results in the sequel are summarized within Table 3.

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 3 branches - SOC balancing at the end of the course	battery charge during braking phase	**3**	240 VL30PFe cells in serial
III	with battery of 3 branches - charging at every 4th stop and SOC balancing at the end *-proposed in OPEUS progress meeting [11].	battery charge during braking phase and at intermediate stops	**3**	
IV	with battery of 1 branch- SOC balancing at the end *-proposed in OPEUS progress meeting [11].	battery charge during braking phase and every 4 stops. The size of the battery can be reduced according to the maximum profit of SOC range	**1**	
V	With battery of 1 branch – energy optimal strategy according to section 6	Energy optimal operating strategy, SOC balancing during the process of the course	**1**	

Table 3: Considered scenarios with the presence of ESU-battery, Tram service category

7.1.1. Reference scenario – Scenario I

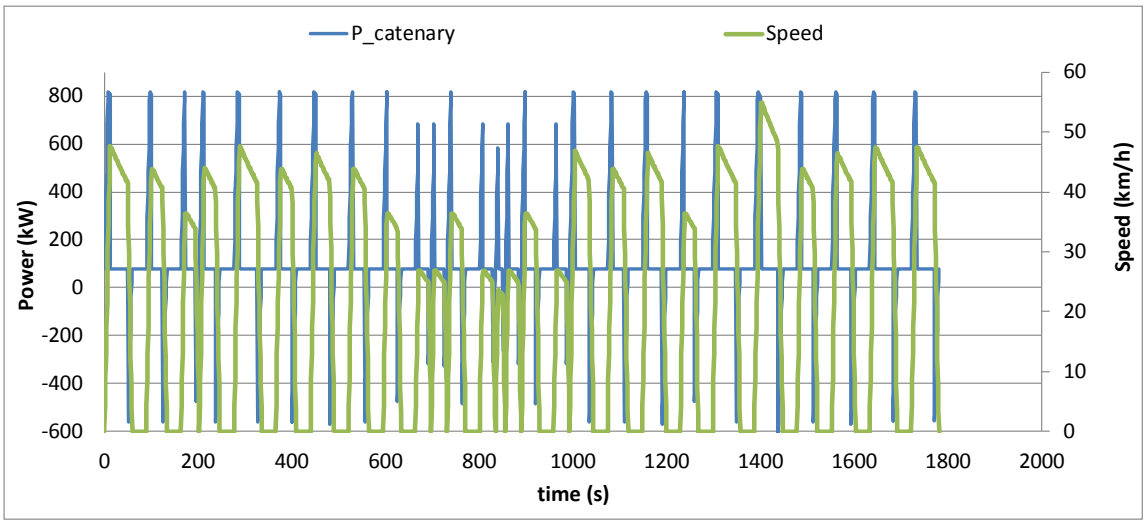

Figure 8. Simulation result without battery - Reference scenario. Tram service, Scenario I

In case without an ESS battery, the maximum peak power taken from the catenary to support the acceleration phase of the tram is about 819kW. Furthermore, the speed profile has many stops where the battery can be quickly recharged in case with ESS (see following sub-chapter).

7.1.2. SOC balancing at the end with 3 branches – Scenario II

With the aim of re-using the battery for the next course and optimizing the life cycle time of the ESU, the battery needs to be recharged at the end. Figure 9 and Figure 10 show the evolution of the SOC of the battery in dependency of the time. The course theoretically lasts 1780s (1198s of travelling and 582s at stop). At the end of the course (1780s), the SOC of the battery drops to 63%. With the configuration of 3 branches in parallel, the battery needs about 3.6 minutes to reach its initial SOC. This strategy applied at the end of the trajectory is considered as the conventional approach when using the on-board ESS battery.

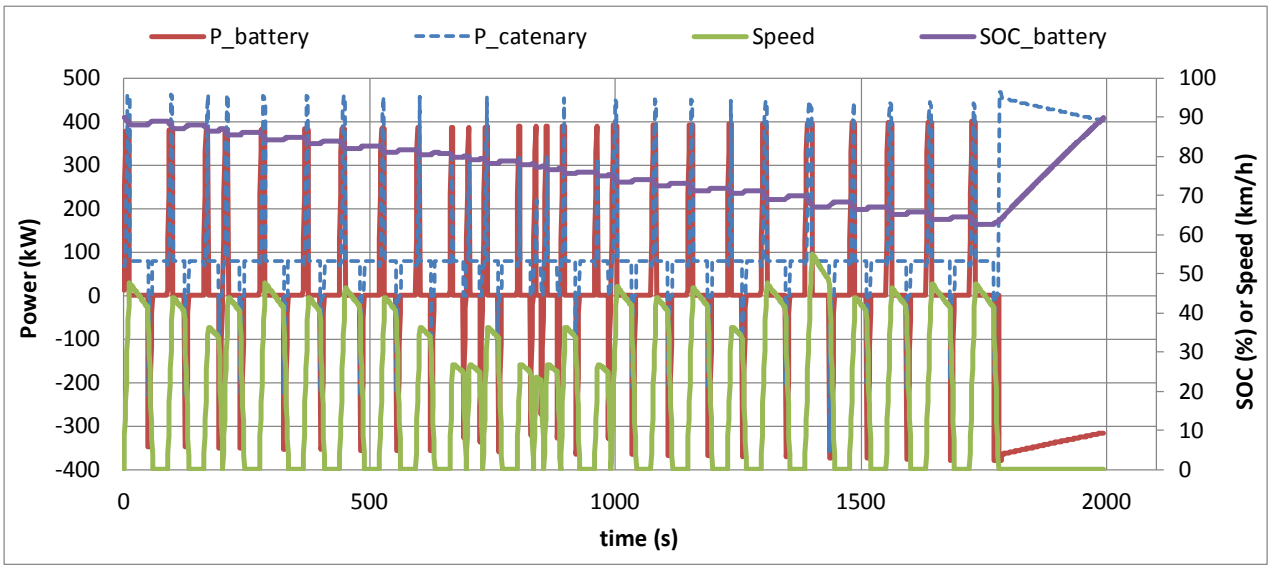

Figure 9. Simulation result with SOC balancing at the end of the course. Battery of 3 branches in parallel. Tram service category. Scenario II

Regarding scenario I without ESS battery, the maximum peak power from the catenary serving to the acceleration of the tram is 470kW, which represents 57% of the maximum power peak of the catenary in reference scenario without ESS. The battery plays an important role to lighten the load peaks at the catenary. The required power for the cooling system with the battery of 3 branches in parallel is estimated with 7kW of electric power. The following figure allows verifying the battery only supporting the power request for the acceleration of the vehicle.

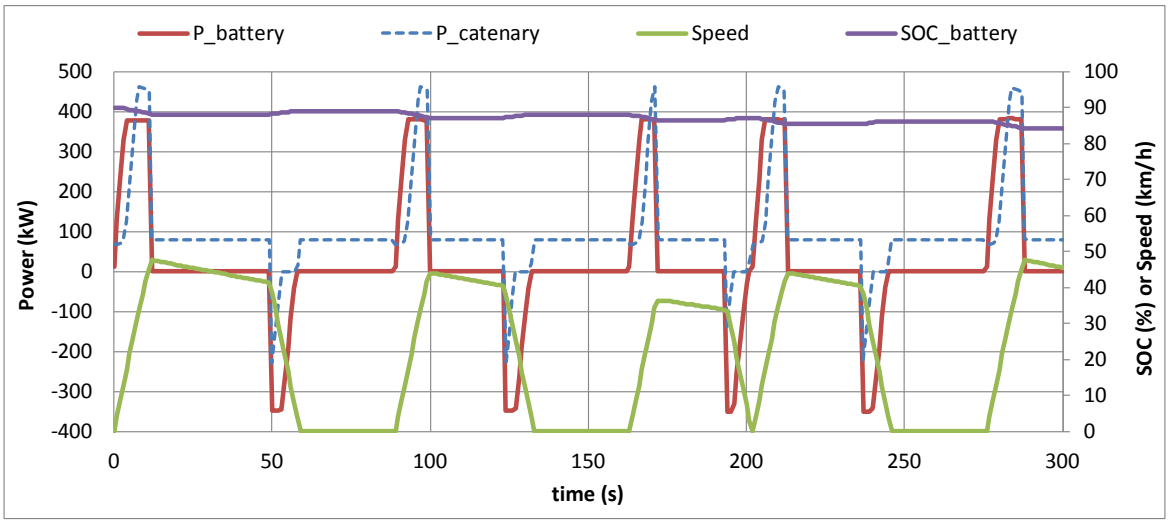

Figure 10. Simulation result with SOC balancing at the end of the course. Battery of 3 branches in parallel. Tram service category. Scenario II. Zoom 0-300s.

The energy consumption as well as the recuperated energy will be detailed and compared with other scenarios to enable a global overview.

7.1.3. Charge at every 4 stops and SOC balancing at the end with 3 branches– Scenario III

For the TRAM service category, another approach is taking profit of the intermediate stop for a very quick recharge. The current high-power Li-ion battery can easily response to this recharge requirement. Based on the condition when the vehicle speed is zero (see vehicle speed profile in the Figure 8 green curve), the battery charges with its maximum allowed power.

In the Figure 11, the SOC of the battery with 3 branches does vary about 6%DoD (purple curve). That's why the battery needs a very short time (0.7min) to recharge at the end.

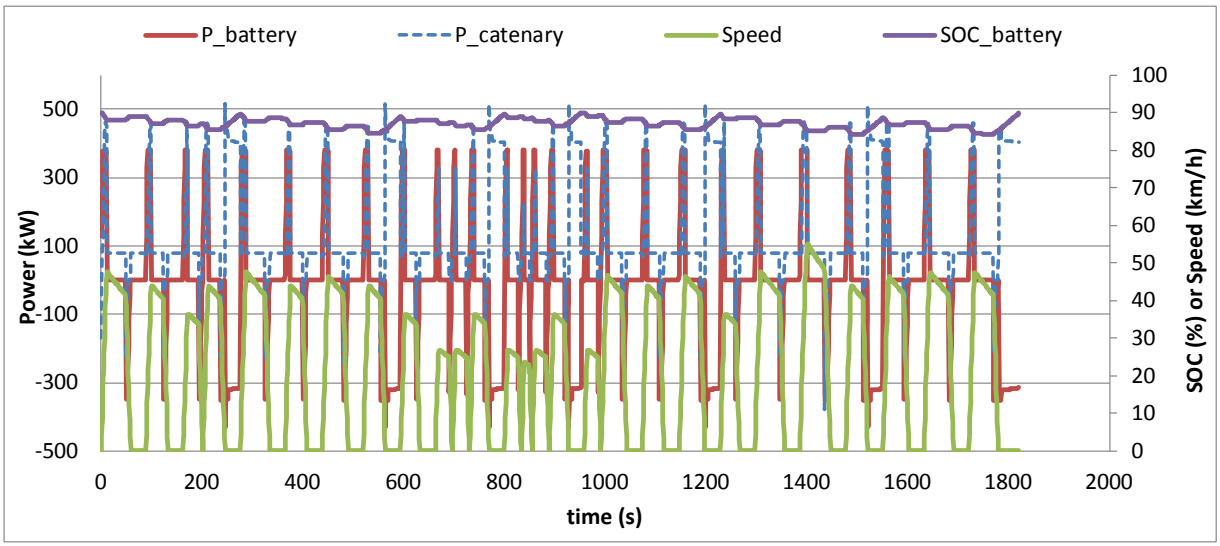

Figure 11. Power of battery (red curve), power at catenary (blue curve) and tram speed (green curve) over time for Tram category with SOC balancing at the end of the course and at every 4th stop. *Case of 3 branches in parallel*. Tram service category. Scenario III

The maximum peak power from the catenary serving to the acceleration of the tram doesn't change (470kW) regarding the one in case without out charging at the stops. The required power for the cooling system with the battery of 3 branches in parallel is estimated with 7kW of electric power.

7.1.4. SOC balancing at the end with 1 branch – Scenario IV

With 3 branches in parallel, the scenario II shows a DoD of 27%. If the battery size downs to 1 branch, the discharge power of the battery will be reduced so that the maximum power peak from

the catenary, when the vehicle accelerates, is higher (86% of total electric power requirement) compared to scenario II.

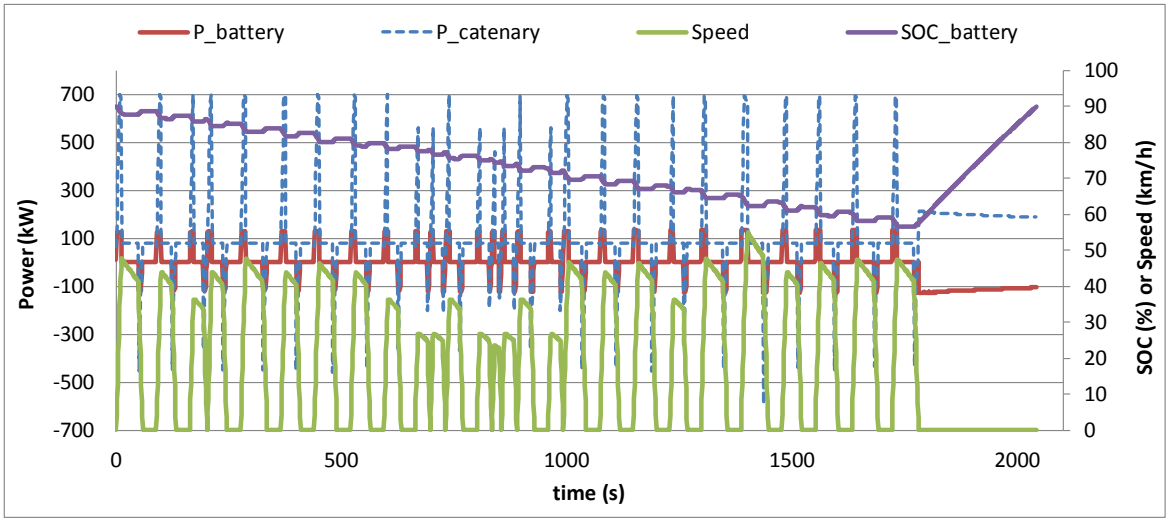

Figure 12. Simulation result with SOC balancing at the end of the course. Battery of 1 branch. Tram service category. Scenario III

The required power for the cooling system with the battery of 3 branches in parallel is estimated with 3kW of electric power.

7.1.5. Energy optimized operating strategy – Scenario V

For the presented scenario V for the tram service category, the ESS covers 5% of the traction power ($\varepsilon_{trac} = 0.05$) and 11% of the auxiliary ($\varepsilon_{aux} = 0.11$) as 100% of the braking power is recuperated ($\varepsilon_{rec} = 1$).

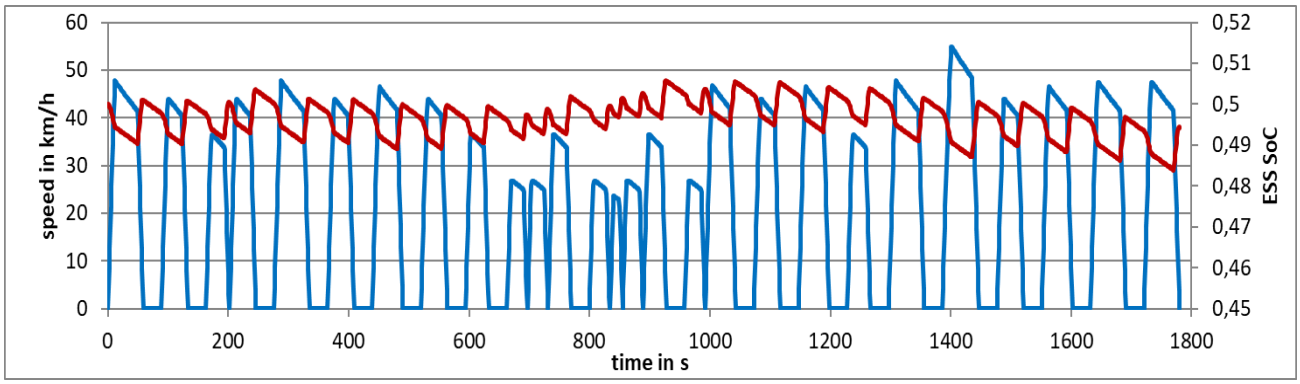

Figure 13. Simulation result with SOC balancing during the course. Battery of 1 branch. Tram service category. Scenario V

7.1.6. Comparison between Tram scenarios

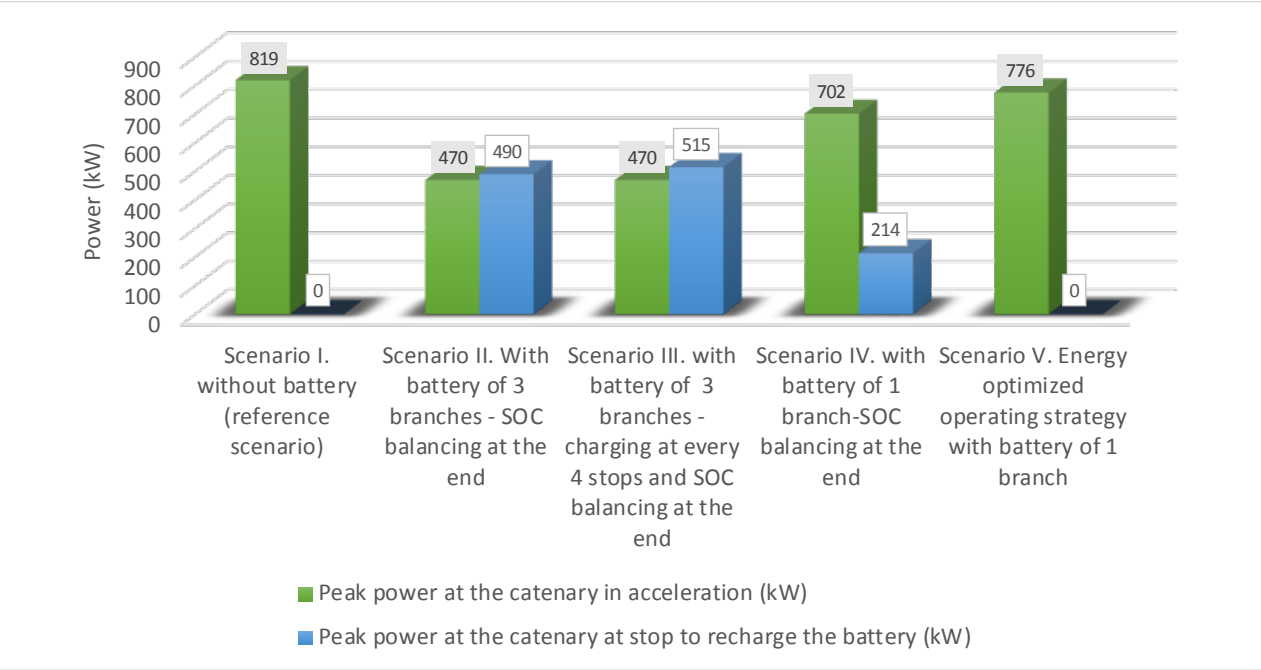

Figure 14: Peak power (in kW) for different scenarios. Tram service category

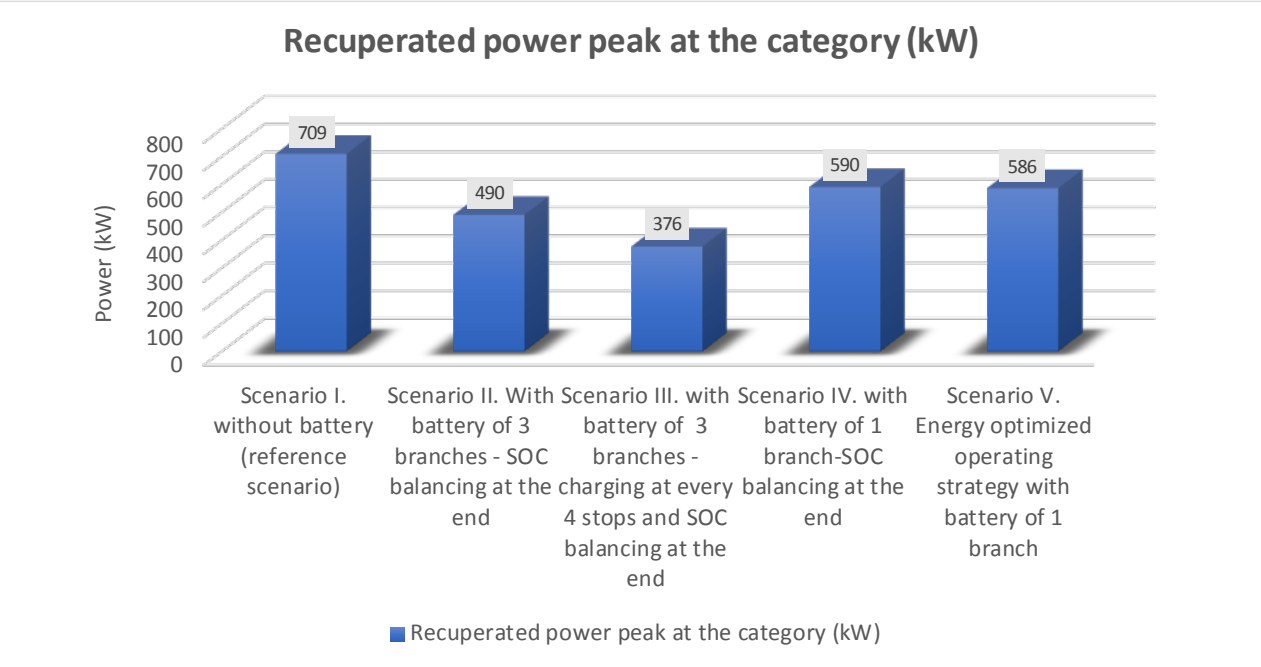

Figure 15: Recuperated peak power (in kW) for different scenarios. Tram service category

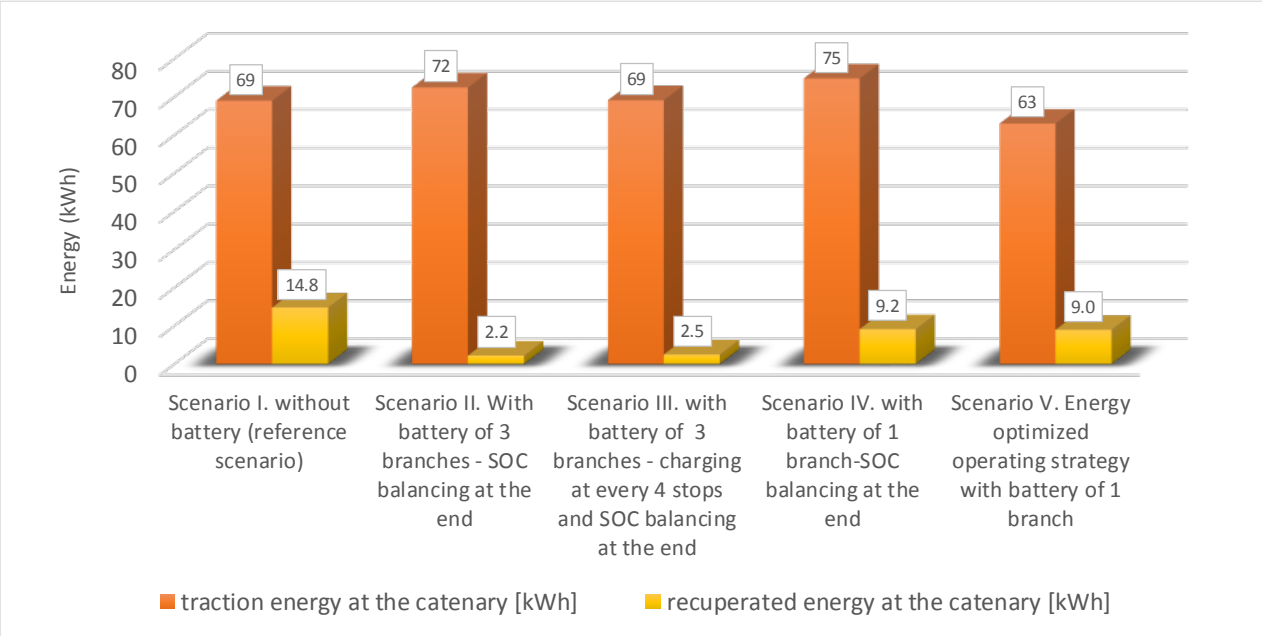

Figure 16: Traction and recuperated energy (in kWh) at the catenary. Tram service category

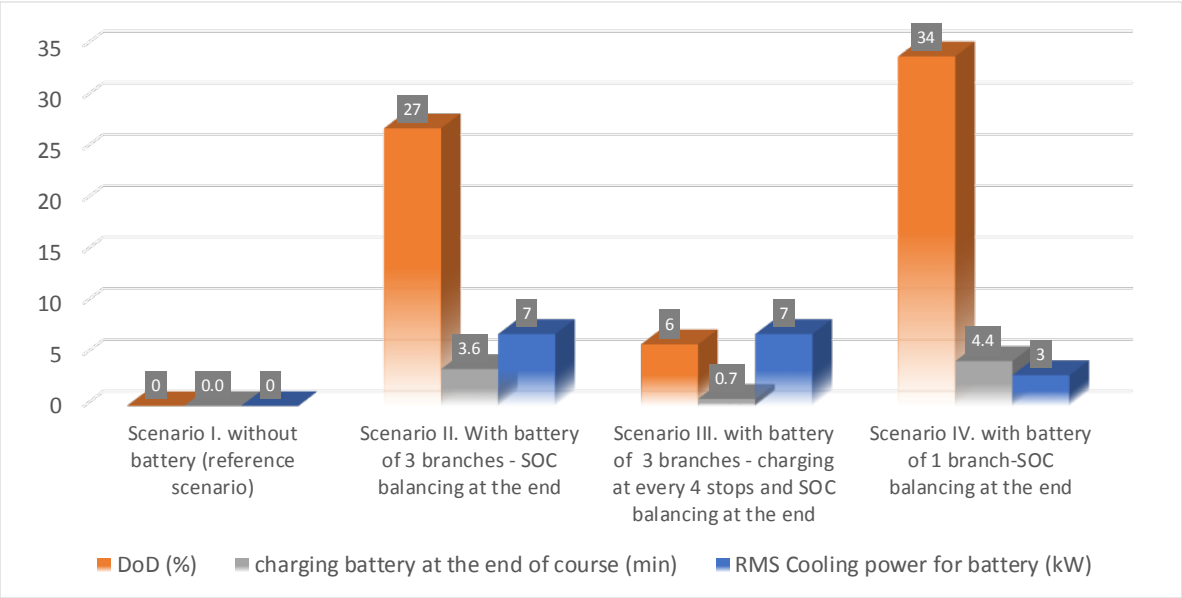

Figure 17: DoD, charging time and RMS cooling power of the battery. Tram service category

The scenario III does allow for a reduction of almost the half of peak power and consumes less traction energy (-12%) at the catenary regarding the reference scenario. Additionally, a short time (0.7 min) is required to recharge the battery at the end of the course. This scenario is performed

with a small Depth of Discharge (DoD = 6%). This could ensure a very high lifetime of the battery in cycling. In this case, it will be possible to double the tramways circulation without increasing the power at catenary. The scenario V shows the lowest traction energy at the category regarding the others scenarios and the baseline.

7.2. Metro service category

The main initial conditions for the below simulation results (general inputs) are:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: Metro
  - Track profile: Metro
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T03 (DC power supply)

- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: No double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated and a BTMS for cooling system of the battery
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: $SoC(t_0 = 0) = 90\%$
  - A single branch of battery consists of 240 VL30PFe cells in serial. The total weight of one branch including the power box (equipped a manual switch, contactor, fuses and BMS) is 541kg
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.

The presented scenarios for the Metro simulation results in the sequel are summarized within Table 4.

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	Battery with 16 branches - SOC balancing at the end of the course	battery charge during braking phase	**16**	240 VL30PFe cells in serial
III	Battery with 16 branches -	battery charge during braking phase	**16**	

	charging at every 4th stop and SOC balancing at the end *-proposed in OPEUS progress meeting [11].	and at intermediate stops		
IV	Battery with 12 branches - SOC balancing at the end	battery charge during braking phase. the size of the battery can be reduced according to the maximum profit of SOC range	**12**	
V	With battery of 1 branch – energy optimal strategy according to section 6	Energy optimal operating strategy, SOC balancing during the process of the course	**1**	

Table 4: Considered scenarios with the presence of ESU-battery, Metro service category

7.2.1. Reference scenario – Scenario I

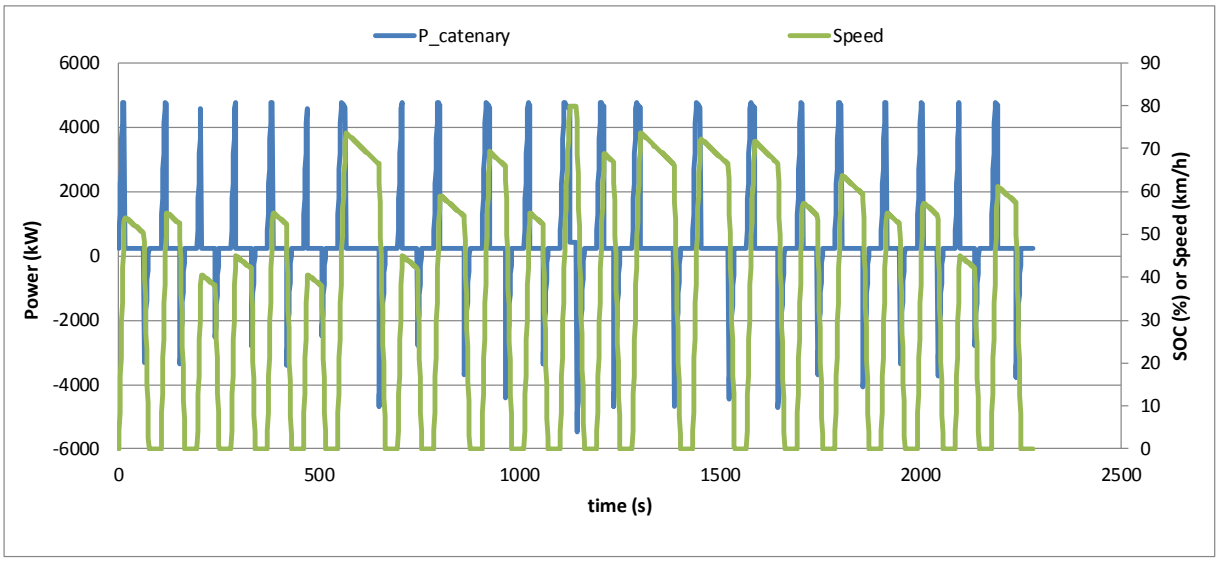

Figure 18. Result without battery (Reference scenario). Metro service category, Scenario I

In case without ESS battery, the maximum peak power taken from the catenary to support the acceleration phase of the Metro is about 4727kW. Furthermore, the speed profile has many stops where the battery can be quickly recharged in case with ESS (see following sub-chapter).

7.2.2. SOC balancing at the end with 16 branches – Scenario II

With the aim of re-using the battery for the next course and optimizing the life cycle time of the ESU, the battery needs to be recharged at the end. Figure 19 shows the evolution of the SOC of the battery in dependency of time. The course theoretically lasts 2280s (1625s of travelling and 655s at stop). At the end of the course (2280s), the SOC of the battery drops to

58%. With the configuration of 16 branches in parallel, the battery needs about 4 minutes to reach its initial SOC. This strategy applied at the end of the trajectory is considered as the conventional approach when using the on-board ESS battery.

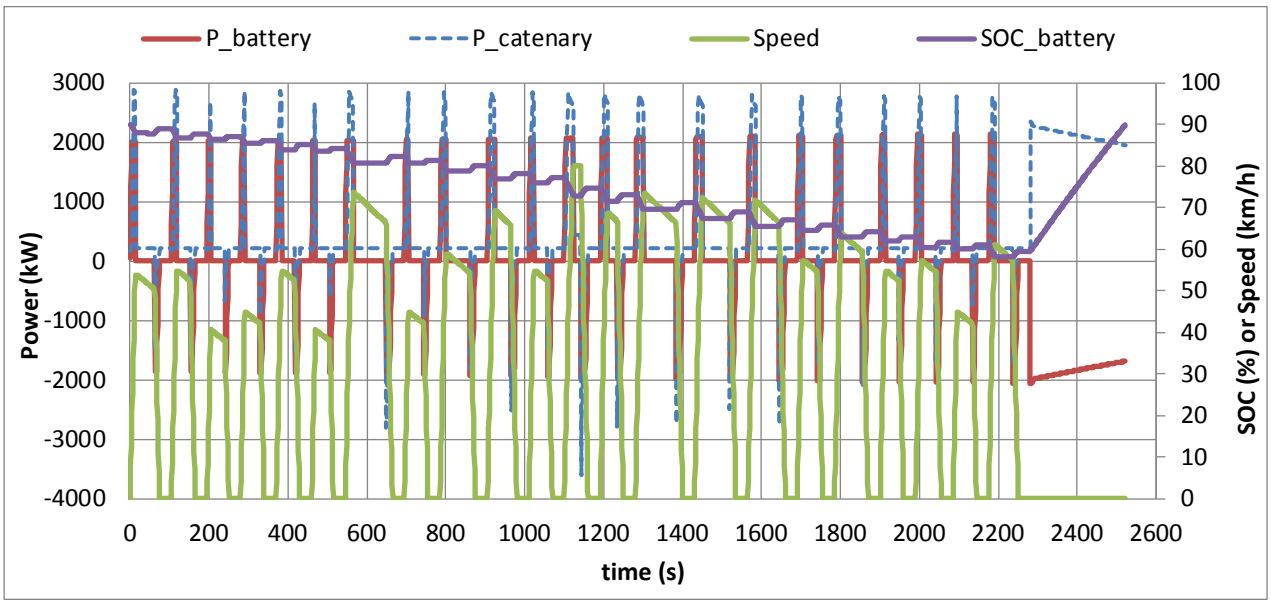

Figure 19. Result with SOC balancing at the end of the course. Battery of 16 branches in parallel. Tram service category. Scenario II

Regarding scenario I without ESS battery, the maximum peak power from the catenary serving to the acceleration of the metro is 2909kW, which represents 62% of the maximum power peak at the catenary in the reference scenario (without ESS). The battery plays an important role to lighten the very high peak power at the catenary. The required power for the cooling system with the battery of 16 branches in parallel is estimated with 39kW of electric power.

7.2.3. Charge at every 4th stop and SOC balancing at the end with 16 branches – Scenario III

For the Metro service category, another approach is taking profit of the intermediate stops for a quick recharge. Based on the condition when the vehicle speed is zero (see vehicle speed profile in the Figure 18 green curve), the battery charge with its maximum allowed power if needed.

In the Figure 20, the SOC of the battery with 16 branches does vary about 14% DoD (purple curve). Thus, the battery needs a short time (1.6min) to recharge at the end.

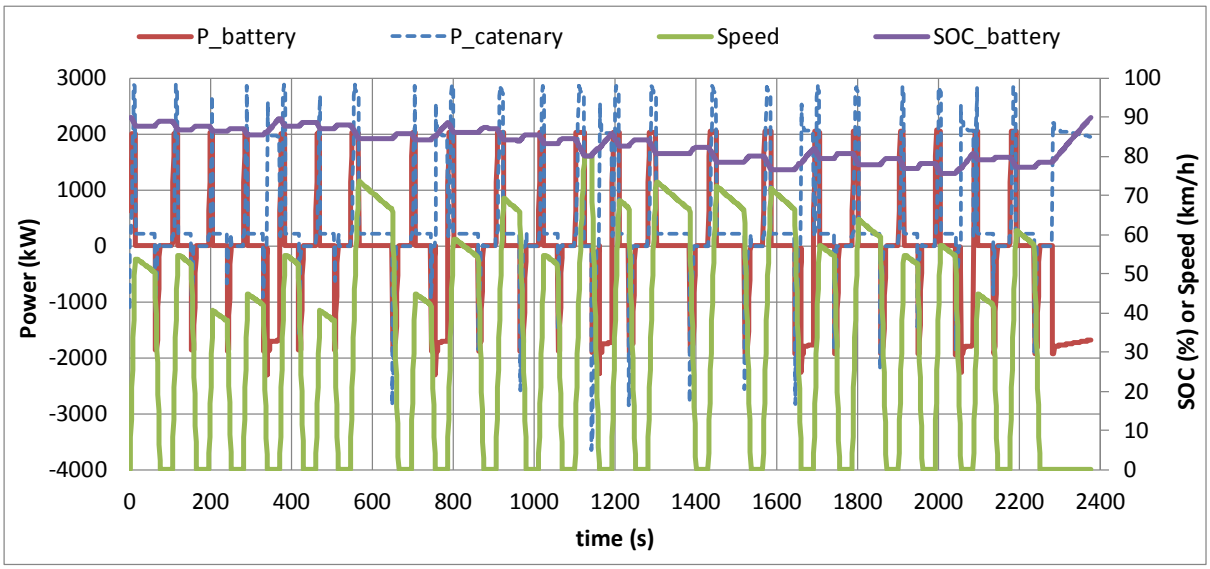

Figure 20. Power of battery (red curve), power at catenary (blue curve) and speed (green curve) over time with SOC balancing at the end of the course and at every 4th stop. *Case of 16 branches in parallel*. Metro service category. Scenario III

7.2.4. SOC balancing at the end with 12 branches – Scenario IV

With 16 branches in parallel, the scenario II shows a DoD of 32%. If the battery size decreases to 12 branches, the discharge power of the battery will be reduced so that the maximum power peak at the catenary (during acceleration) is higher (71% of total electric power requirement) compared to scenario II.

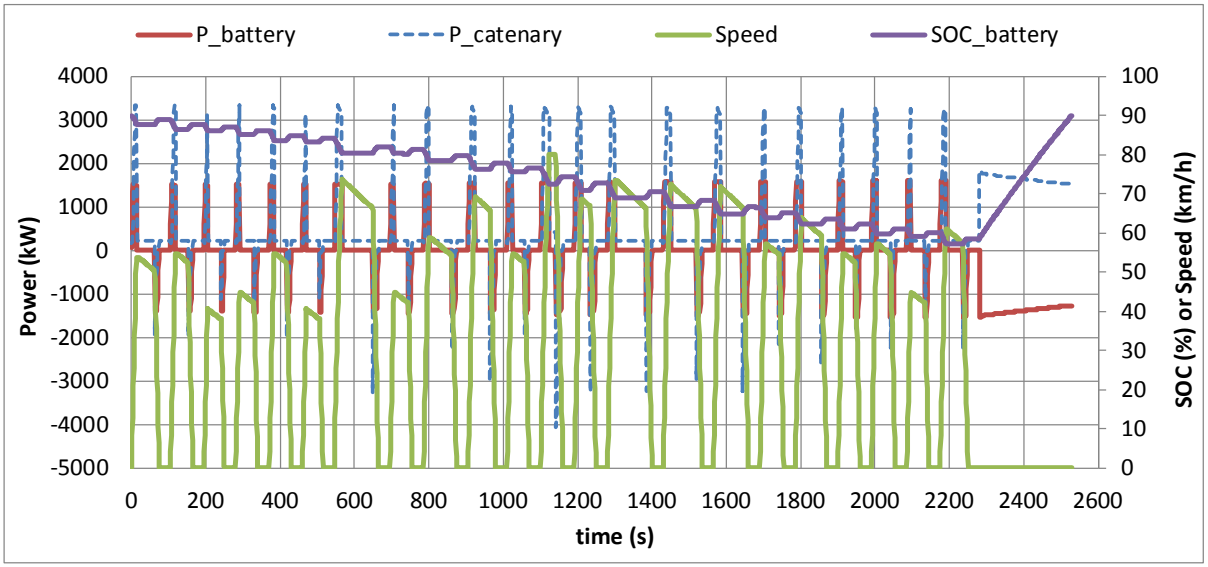

Figure 21. Simulation result with SOC balancing at the end of the course. Battery of 12 branches. Metro service category. Scenario IV

With the reduction of the battery size (4 branches less), the SOC operation range of the battery doesn't widen very much regarding the scenario II (+1%). Furthermore, the catenary must support 71% of the electric power demand which is higher than the 61% power demand in case of the scenario II.

7.2.5. Energy optimized operating strategy – Scenario V

For the presented scenario V for the Metro service category, the ESS covers 3.5% of the traction power ($\varepsilon_{trac} = 0.035$) and 28% of the auxiliary ($\varepsilon_{aux} = 0.28$) as 100% of the braking power is recuperated ($\varepsilon_{rec} = 1$).

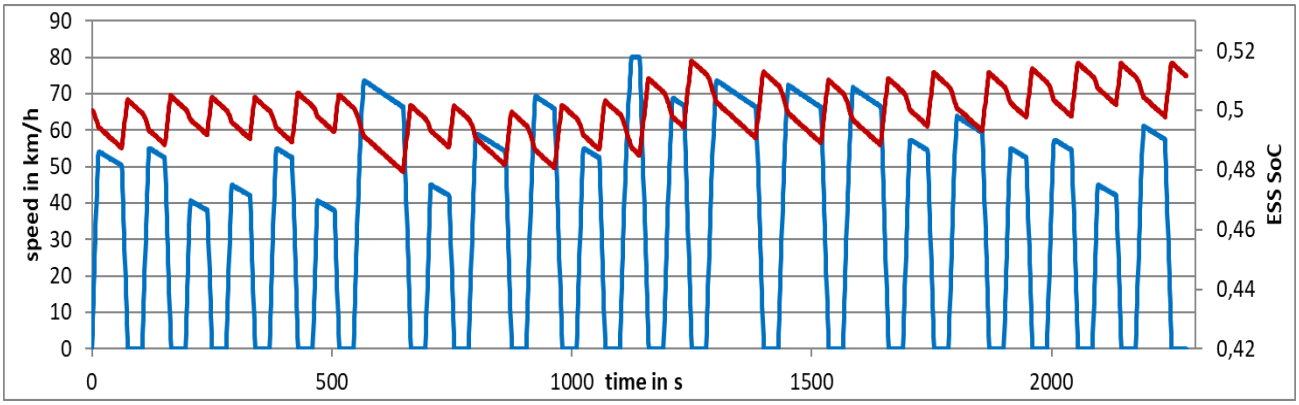

Figure 22. Simulation result with SOC balancing during the course. Battery of 1 branch. Metro service category. Scenario V

7.2.6. Comparison between scenarios

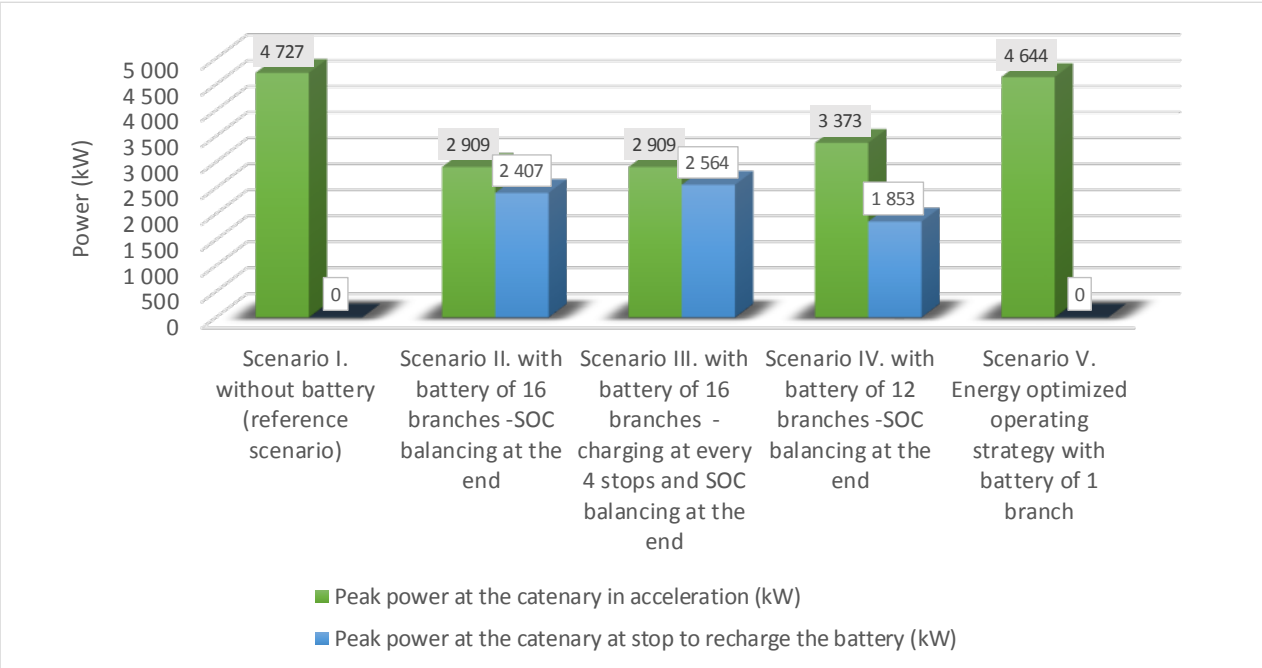

Figure 23: Peak power (in kW) for different scenarios. Metro service category

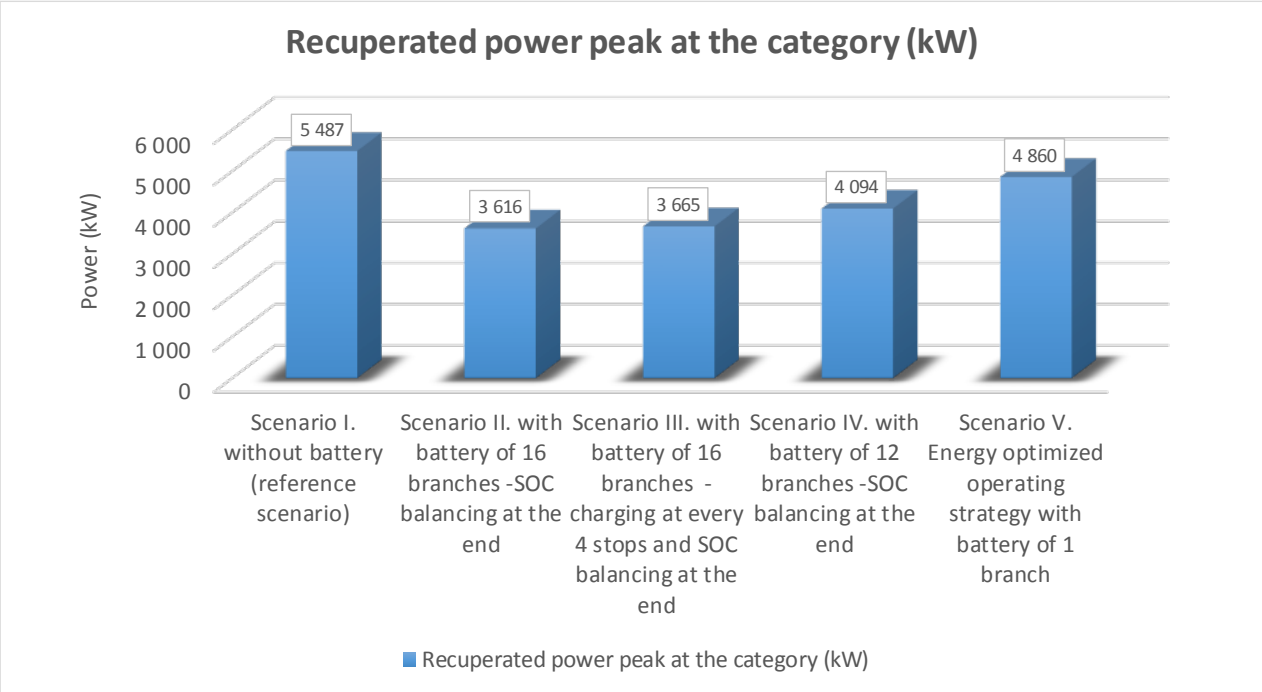

Figure 24: Recuperated peak power (in kW) for different scenarios. Metro service category

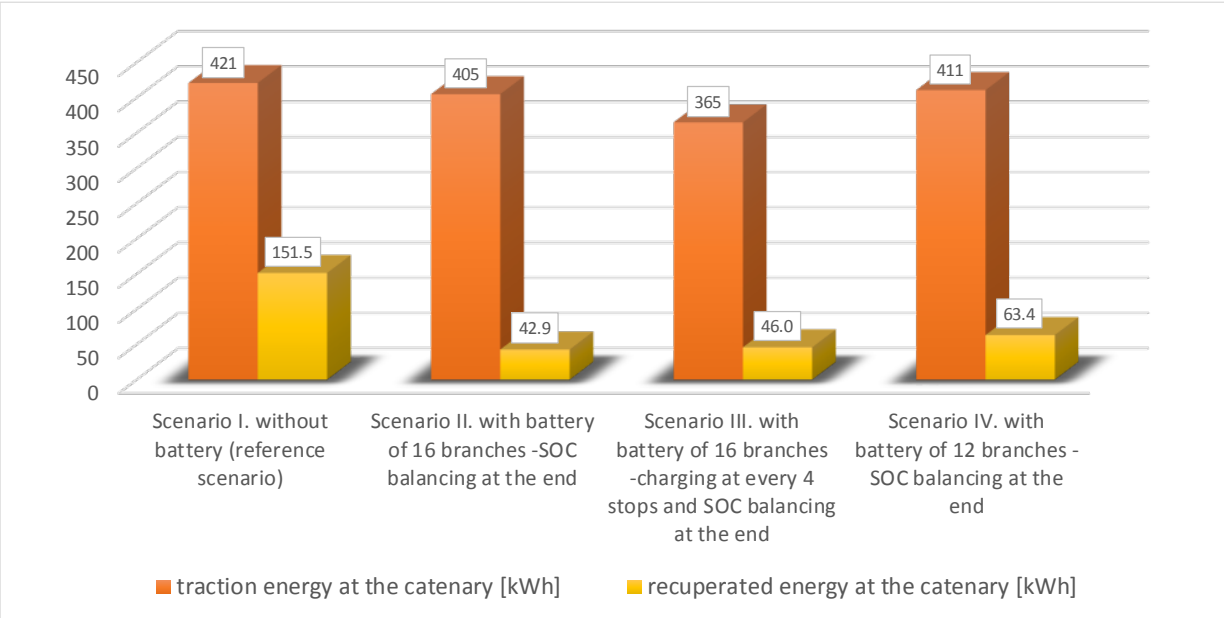

Figure 25: Traction and recuperated energy (in kWh) at the catenary. Metro service category

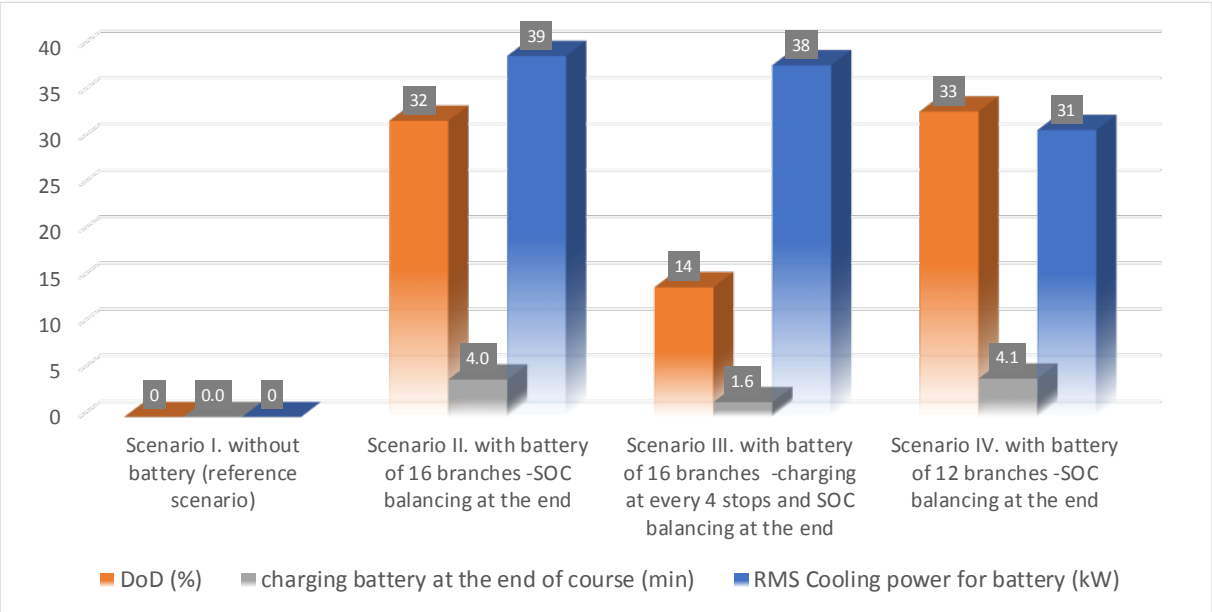

Figure 26: DoD, charging time and RMS cooling power of the battery. Metro service category

scenario III allows for a reduction of almost the half of peak power and consume less traction energy (-13%) at the catenary regarding the one of the reference scenario. Additionally, only a short time (1.6 min) is required to recharge the battery at the end of the course. This scenario is performed with a small Depth of Discharge (14%DoD). This could ensure a very high lifetime of the battery in cycling.

8. Regional scenario

8.1. Regional 160 service category

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: Regional 160
  - Track profile: Regional 160
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T01 (DC power supply)
- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: no double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: $SOC(t_0 = 0)$ =90%
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.
  - The battery needs to ensure all electric power requirements so that the size of the battery mustn't be too small. According to the regional scenario, the minimum battery size will be estimated

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 12 branches - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**12**	240 VL30PFe cells in serial
III	With battery of 9 branches - SOC balancing at the end of the course and partial electrification (geometric approach) *-discussed with SNCF [5]	The battery discharge ensures its auxiliary requirement, fully support the DC link auxiliaries and power demand during 4 non-electrified zones and recharge at the end of the course	**9**	
IV	With battery of 12 branches - SOC balancing at the end of the course with 42% of DC traction power request from battery (peak shaving approach) *-discussed with SNCF [5]	The battery only accepts 42% of (DC traction power request and the auxiliaries at DC link & on-board ESU) in acceleration	**12**	
V	With battery of 5 branch – energy optimal strategy according to section 6	Energy optimal operating strategy, SOC balancing during the process of the course	**5**	

Table 5: Considered scenarios with the presence of ESU-battery, Reg160 service category

8.1.1. Reference scenario – Scenario I

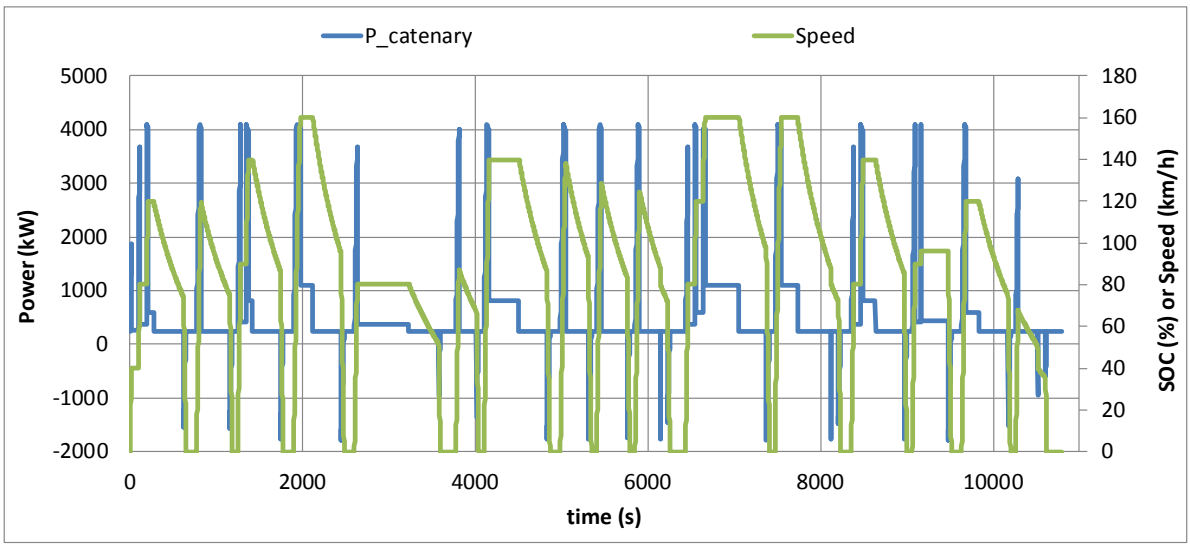

Figure 27. Result without battery (Reference scenario). Reg160 service category

According to the Reg160 speed profile, there are many phases where the train operates in cruising mode. A geometric approach for the case with several zones with no network infrastructure (scenario IV, Table 5) is developed with the cooperation of the FINE1 member SNCF.

8.1.2. SOC balancing at the end with 12 branches – Scenario II

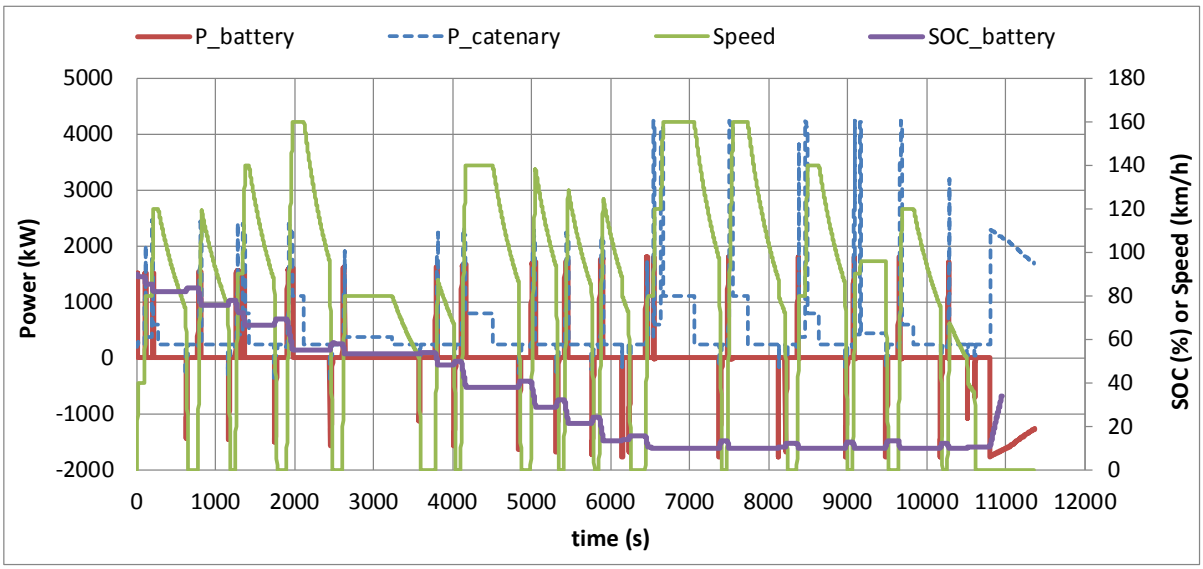

Figure 28. Simulation result with SOC balancing at the end of the course. Battery of 12 branches in parallel. Reg160 service category. Scenario II

Figure 28 shows the results of the scenario number II, Table 5. The battery recharges at the end of the course within 9.4 minutes to reach its initial value of SOC.

According to the duty cycle in term of electric power at the motor converter, the battery is fully utilized during the first half of cycle so that the SOC drops from 90% to 10% (minimum authorized for the battery).

In the Figure 29, when the SOC doesn't reach the minimum value of 10%, 2490kW is the maximum peak power of the catenary can support the acceleration. That means the battery of 12 branches lighten the electric power demand (-39%) from the catenary regarding the same peak power at the same moment in the case without battery (4100kW).

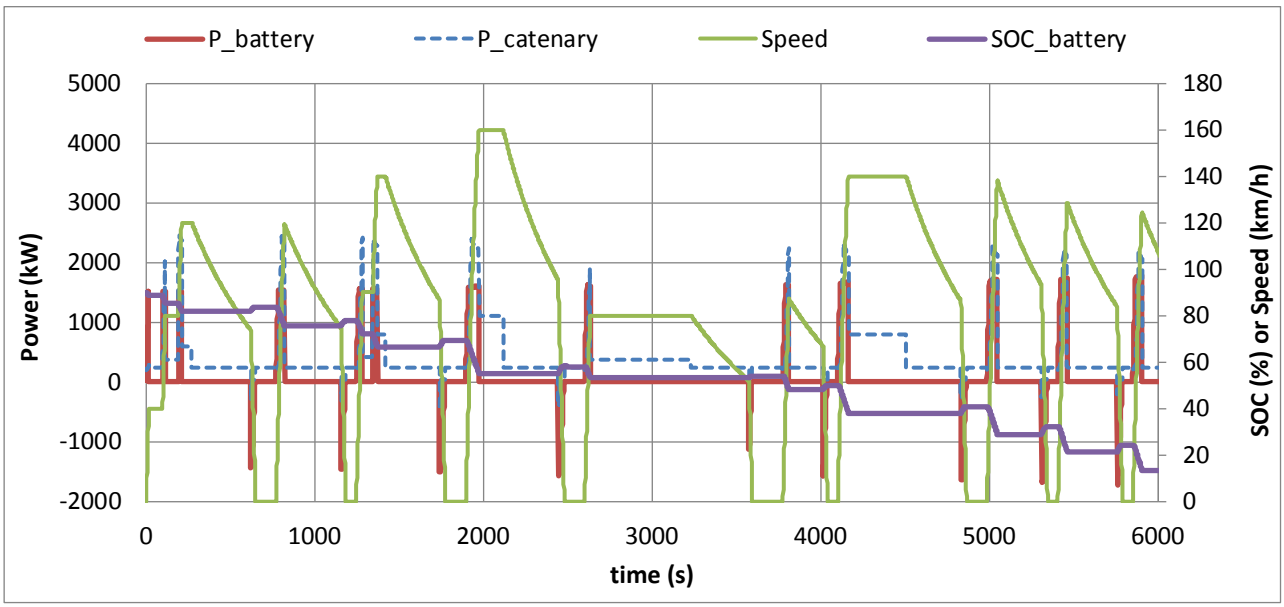

Figure 29. Simulation result with SOC balancing at the end of the course. Battery of 12 branches in parallel. Reg160 service category. Scenario II. Zoom 0s-6000s

Furthermore, the braking phases during the course after 6000s are not enough to maintain the SOC above 10% till the end of the course. It reaches 10% after 6500s. After that, the maximum peak power of the catenary attaint a higher value (4241kW) than the maximum peak in the case without battery.

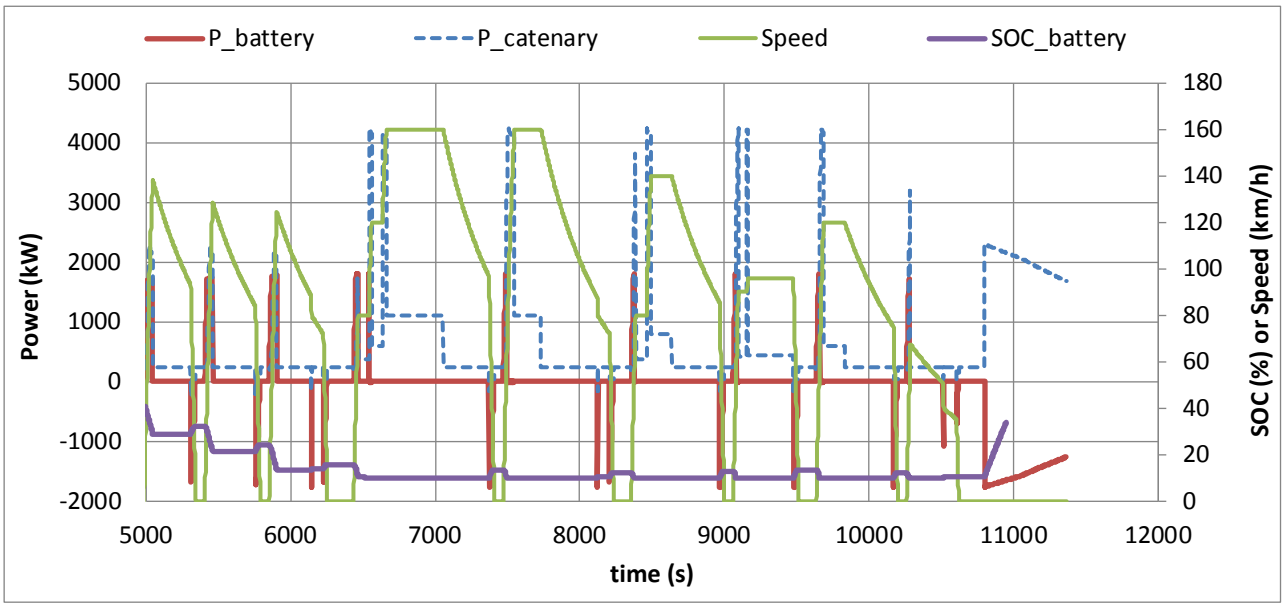

Figure 30. Result with SOC balancing at the end of the course. Battery of 12 branches in parallel. Reg160 service category. Scenario II. Zoom 5000s-12000s

This higher value can be explained by the fact that the catenary need to feed the power demand from the acceleration, the auxiliary at the DC links and the auxiliary of the battery, P_{obb}. That effect is mainly based on the increased train mass, which results from the additional components for the ESS.

8.1.3. SOC balancing at the end and partial electrification with 9 branches – Scenario III

The scenario III is adopted with the places where there is no electrical network to feed the train. Four non-electrified zones (for 2km, 3km, 4km and 5km) are defined, where the train operates in cruising mode (or when the speed is constant) as presented below.

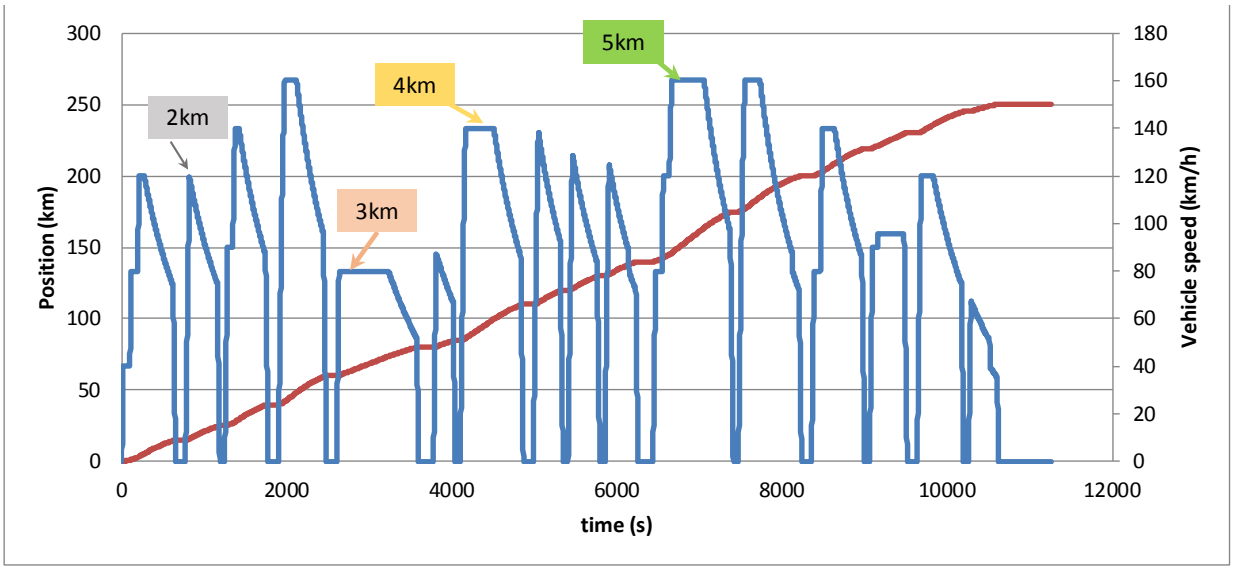

Figure 31: Definition of 4 non-electrified zones according to the speed (blue curve) and position (red curve). Reg160 service category. Scenario III.

The defined 4 non-electrified zones respectively have 2km, 3km, 4km and 5km of distance as shown in Figure 31.

The four positive peaks of the battery discharge power (corresponding to 4 important drops of SOC) represent four zones without infrastructure. In the zones, there is no energy consumption at the catenary.

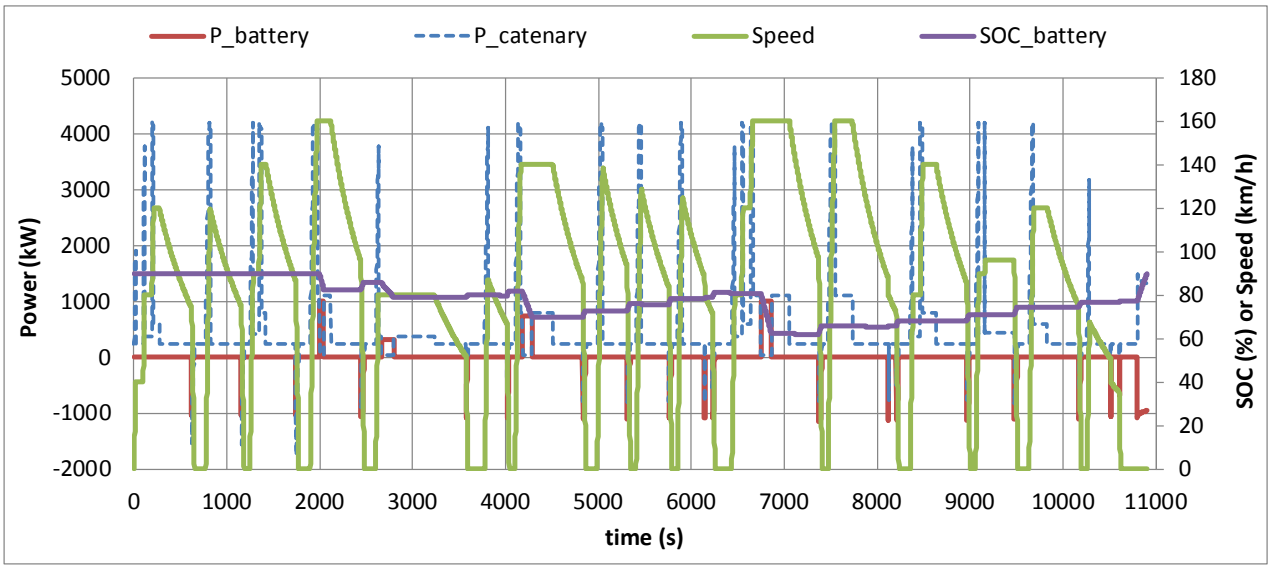

Figure 32. Simulation result with SOC balancing at the end of the course. Battery of 9 branches. Reg160 service category. Scenario III

During the non-electrified zones, the battery needs to ensure all electric power requirements so

that the size of the battery is considered 9 branches in parallel.

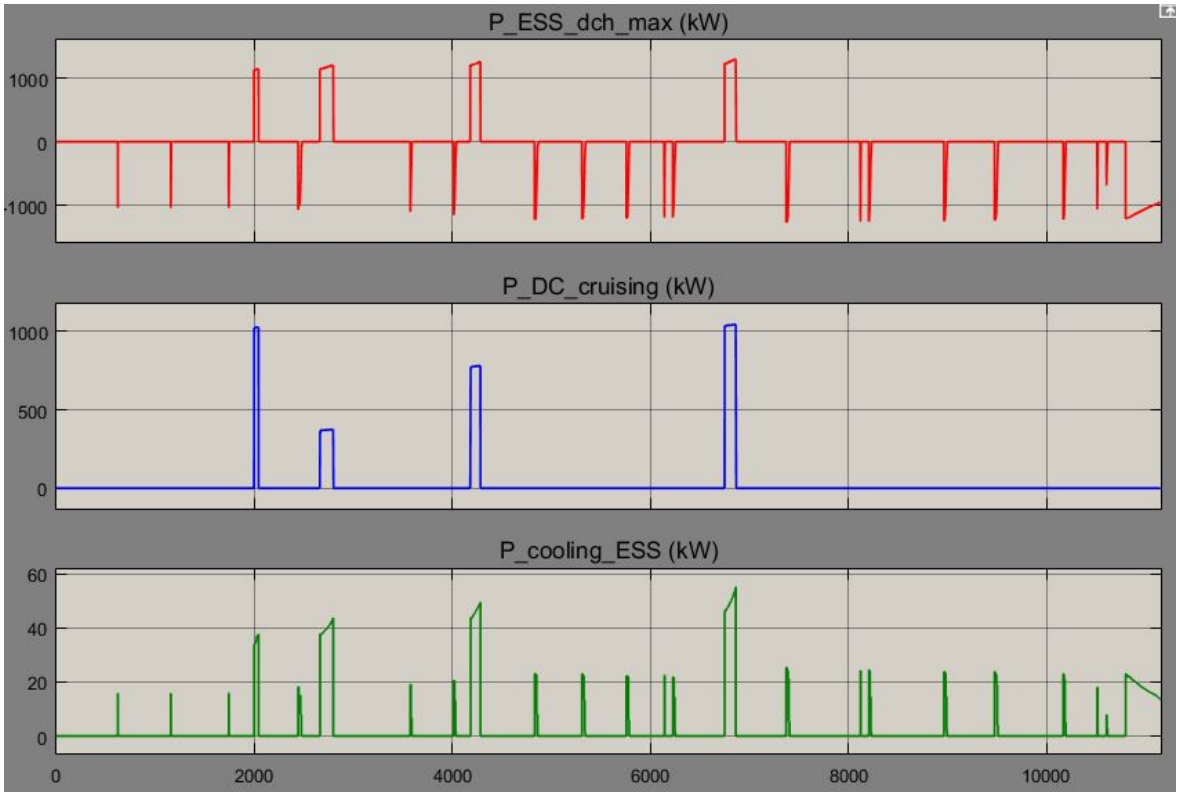

Figure 33. Max discharge power of the battery, electric demand and cooling power. Battery of 9 branches. Reg160 service category. Scenario III

In Figure 33,

$$P_{DC,cruising} = P_{DC,trac} + P_{DC,aux} + P_{ESS,cooling} \qquad (7.1)$$

is the total power demand of 4 non-electrified zones (blue curve). The maximum power in discharge of the battery (red curve) is always higher than $P_{DC,cruising}$. The cooling power of the battery is dynamically represented by the green curve with the RMS value is 7kW.

For the whole trajectory, the maximum DoD of the battery is 29%. During the two non-electrified zones 2Km (at 2000s) and 3km (at 2660s) it shows that the power coming from the catenary (dashed curve) is zero and the battery fulfil the total electric power demand (red curve). In parallel, the SOC of the battery decreases during these two zones.

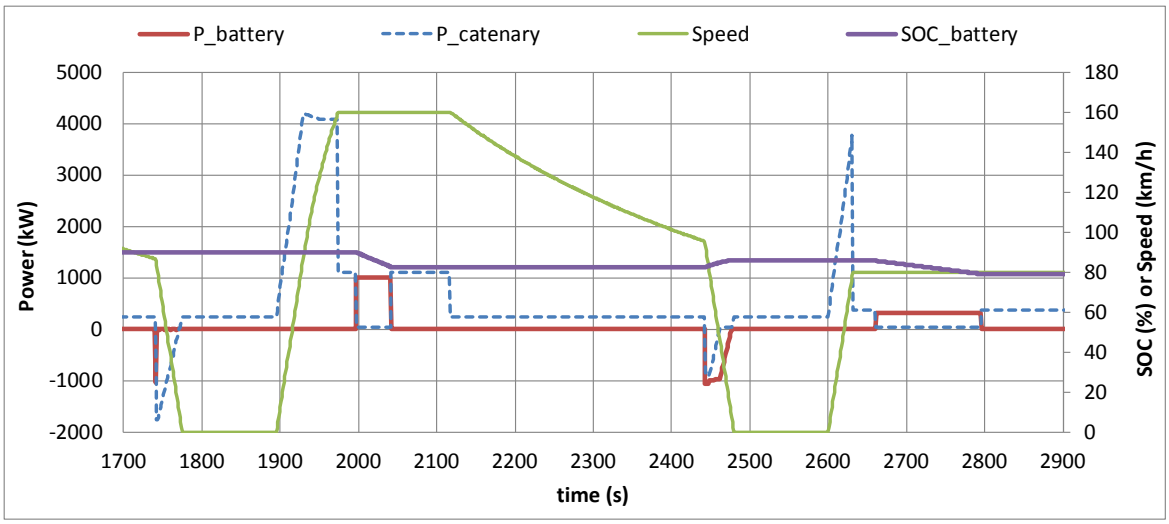

Figure 34. Simulation result with SOC balancing at the end of the course. Battery of 9 branches. Reg160 service category. Scenario III. Zoom 1700s-2900s

8.1.4. SOC balancing at the end with 12 branches – peak shaving approach – Scenario IV

The presented peak shaving approach is an operating strategy to limit the high-power peak requirement during acceleration phases, by applying the battery system. For a given battery of 12 branches in parallel 42% of DC traction power request comes from the battery. This battery size ensures the partial support of the battery to the catenary, and to maintain the SOC higher than its minimum value SoC = 10% before the end of the course.

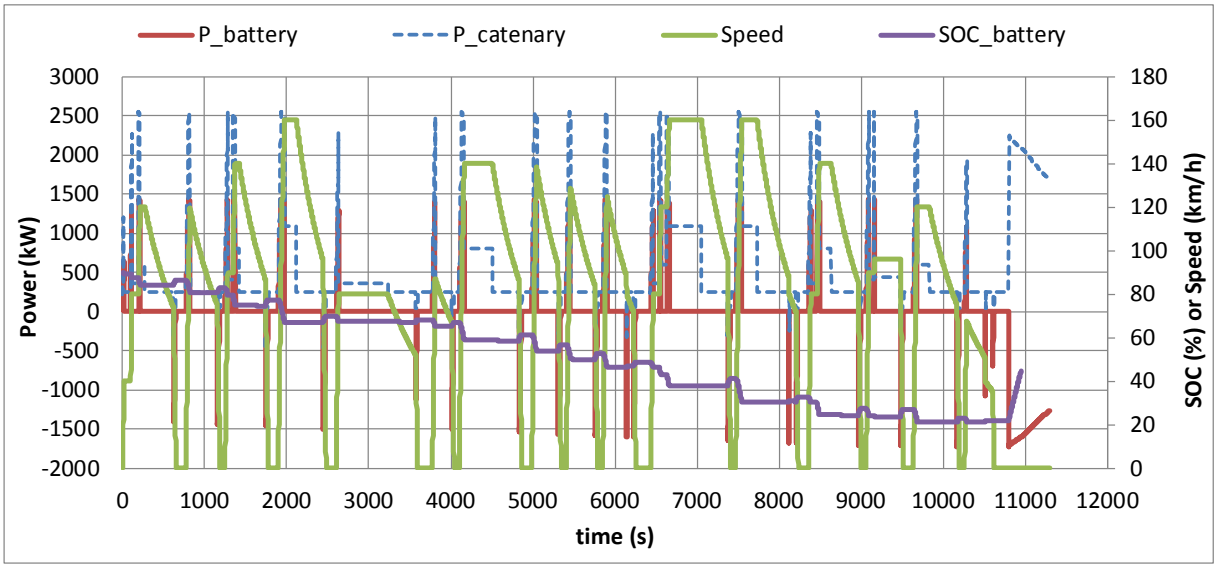

Figure 35. Simulation result with SOC balancing at the end of the course Battery of 12 branches. Reg160 service category. Scenario IV.

At the end of the course, the SOC of the battery drops to 21% and the battery needs 8mins to recharge to 90%. The maximum power peak in acceleration from the catenary is 2584kW, which represent 63% of the power peak (4100kW) in case without battery (scenario I).

8.1.5. Energy optimized operating strategy – Scenario V

For the presented scenario V for the Regional 160 service category, the ESS covers 3% of the traction power ($\varepsilon_{trac} = 0.03$ and 7% of the auxiliary ($\varepsilon_{aux} = 0.07$) as 100% of the braking power is recuperated ($\varepsilon_{rec} = 1$).

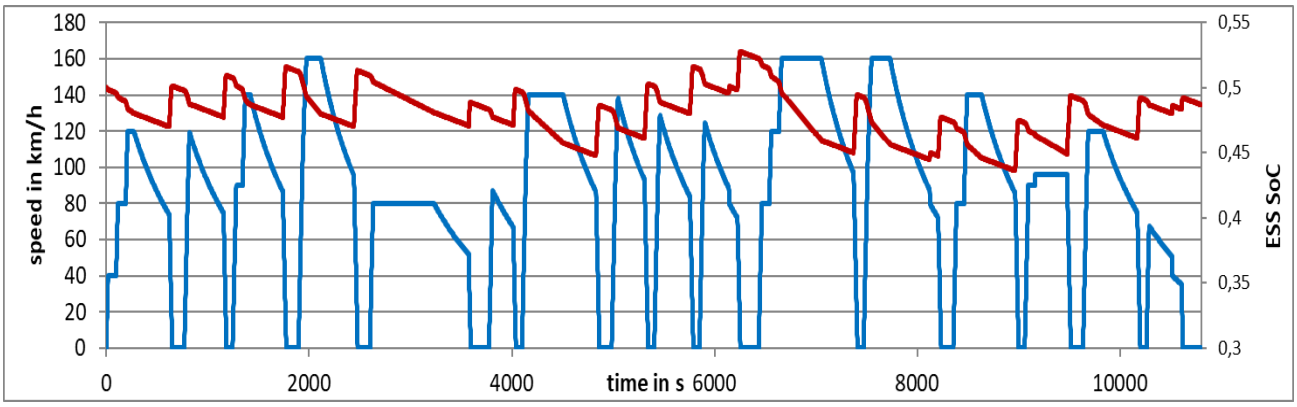

Figure 36. Simulation result with SOC balancing during the course. Battery of 5 branches. Regional 160 service category. Scenario V

8.1.6. Comparison between scenarios

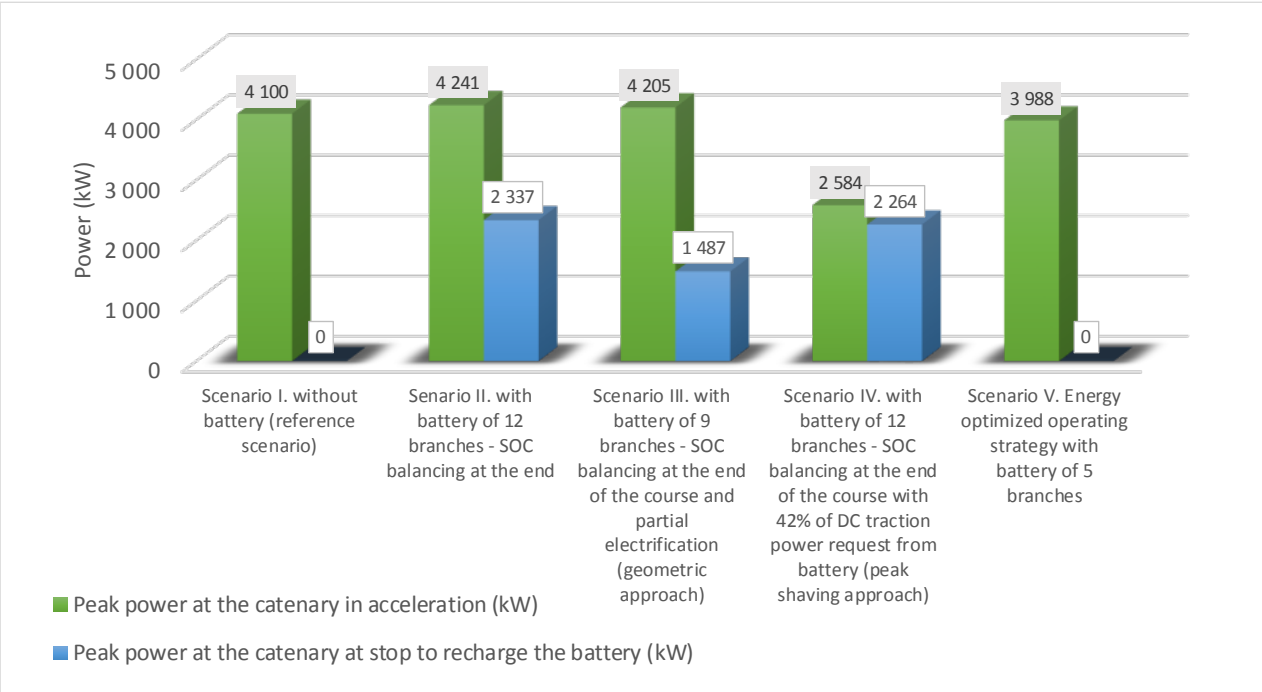

Figure 37: Peak power (in kW) for different scenarios. Reg160 service category

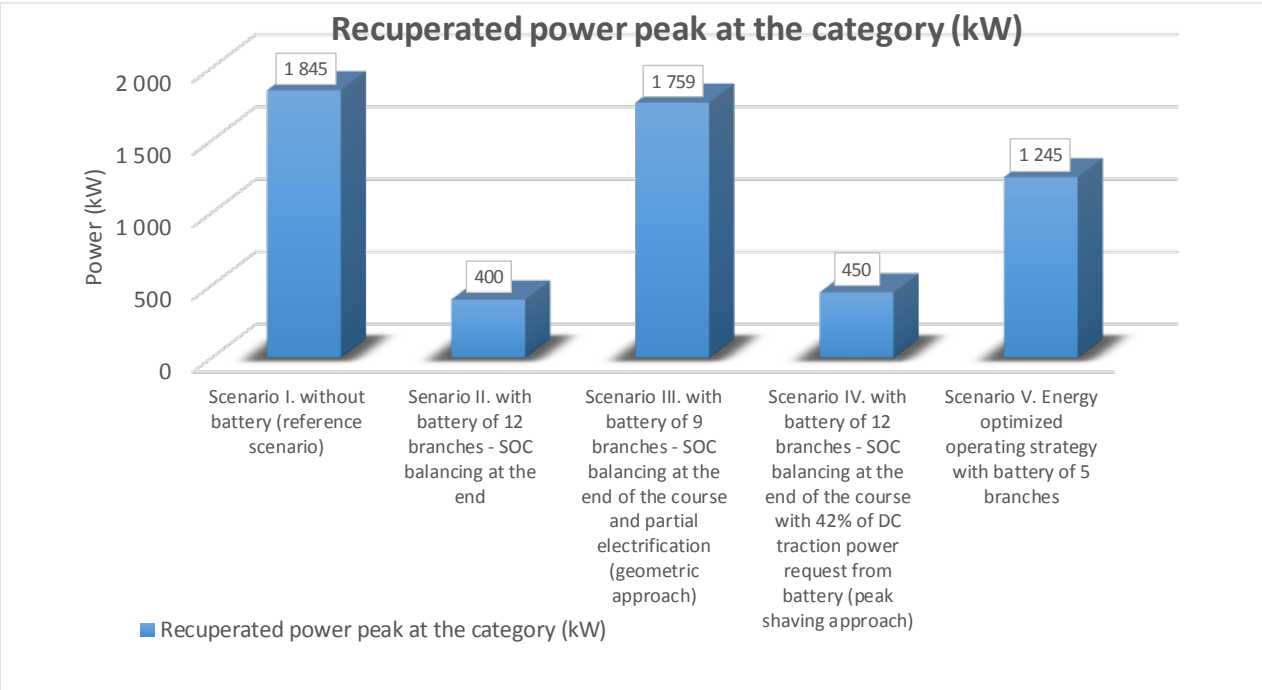

Figure 38: Recuperated peak power (in kW) for different scenarios. Reg160 service category

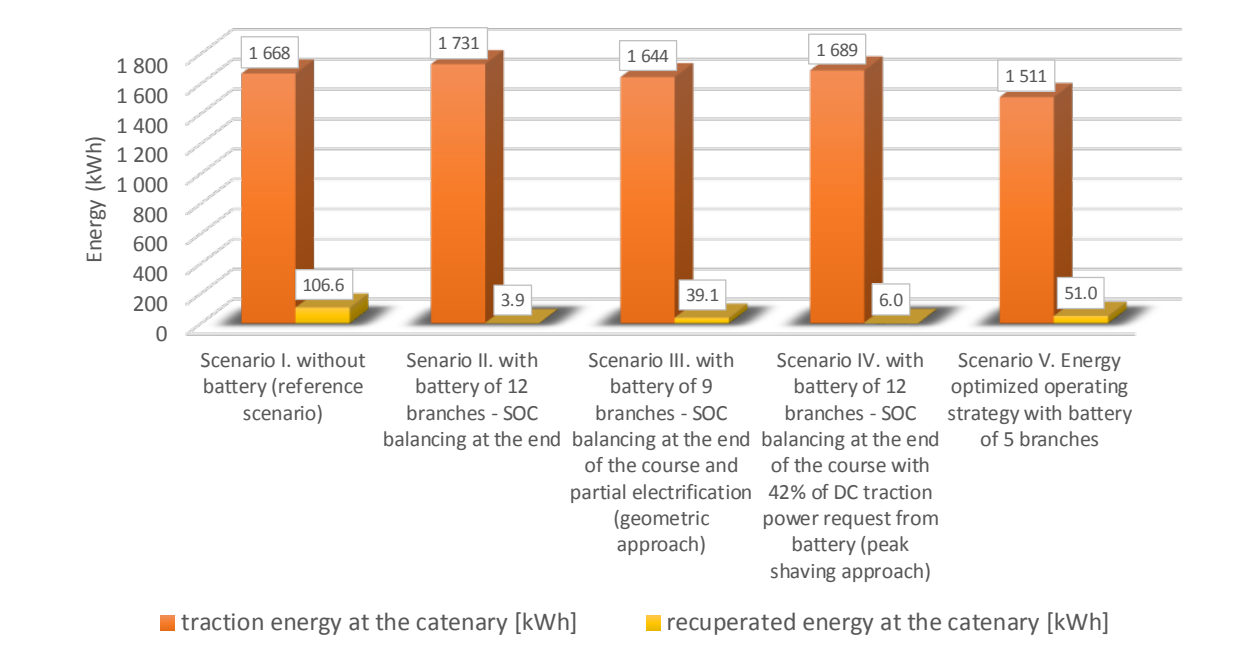

Figure 39: Traction and recuperated energy (in kWh) at the catenary. Reg160 service category

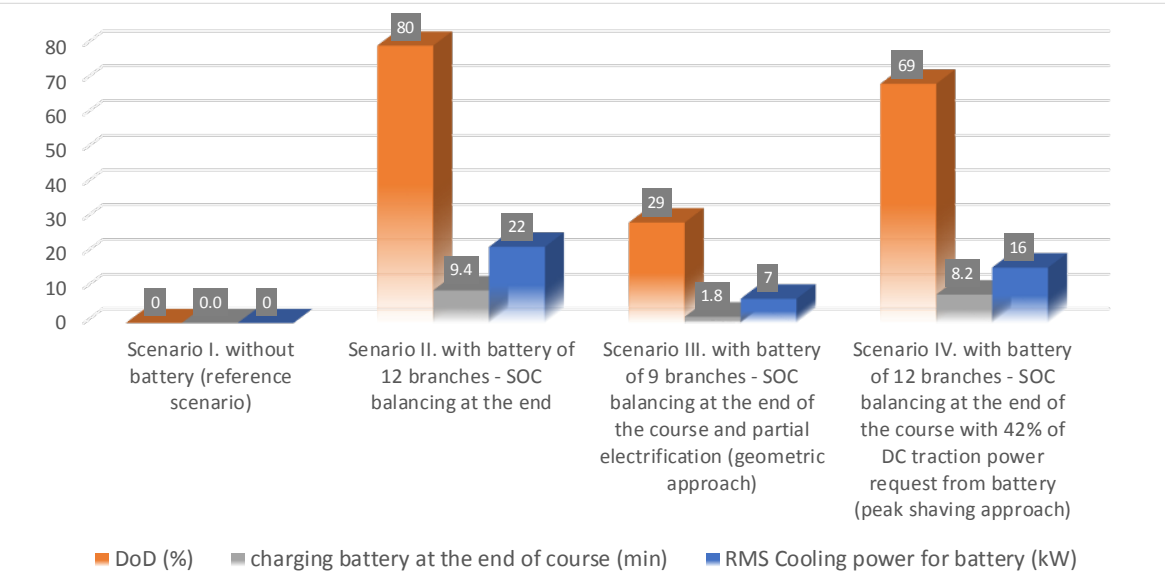

Figure 40: DoD, charging time and RMS cooling power of the battery. Reg160 service category

The scenario III allows to avoid the electrification of expensive area for infrastructure with a slight consumption of traction energy at the catenary.

Scenario IV allows fora reduction of 37% of peak power and consume without increasing significantly the traction energy consumption.

In term of energy consumption at the catenary, the last scenario V with the optimization of the

operation strategy is the optimized scenario even regarding the baseline.

8.2. Regional 140 service category

Regarding the Reg160 service category, to increase the variety of the study cases, this chapter focuses on the ALLOUT trajectory mode.

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: Regional 140
  - Track profile: Regional 140
  - Trajectory mode: **allout**
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T01 (DC power supply)
- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: no double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: 90%
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.
  - The battery needs to ensure all electric power requirements so that the size of the battery mustn't be too small. According to the regional scenario, the minimum battery size will be estimated

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 12 branches - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**12**	240 VL30PFe cells in serial
III	With battery of 1 branch - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**1**	
IV	With battery of 9 branches - SOC balancing at the end of the course and partial electrification (geometric approach) *-discussed with SNCF [5]	The battery discharge ensures its auxiliary requirement, fully support the DC link auxiliaries and power demand during 4 non-electrified zones and recharge at the end of the course	**6**	

Table 6: Considered scenarios with the presence of ESU-battery, Reg140 service category

8.2.1. Reference scenario – Scenario I

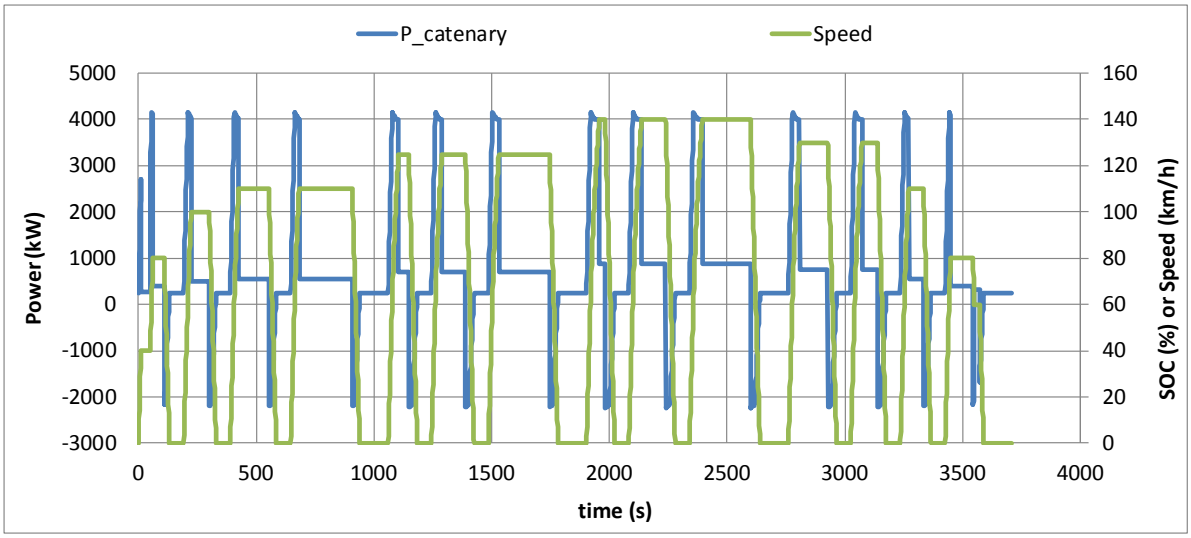

Figure 41. Simulation result without battery (Reference scenario). Reg160 service category

According to the Reg140 speed profile, there are many phases, where the train operates in cruising mode. A geometric approach for the case with several zones with no network infrastructure (scenario IV, 6) is developed with the cooperation of the FINE1 member SNCF.

8.2.2. SOC balancing at the end with 12 branches – Scenario II

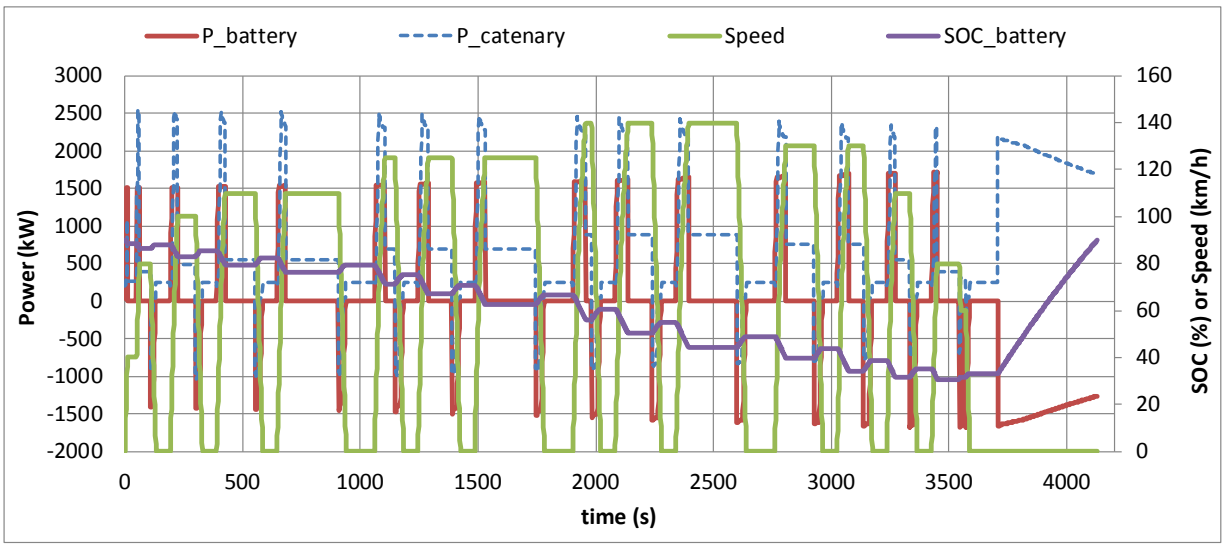

Figure 42. Result with SOC balancing at the end of the course. Battery of 12 branches in parallel. Reg160 service category. Scenario II

Figure 42 shows the results of the scenario II, Table 6. The battery recharges at the end of the course within 7 minutes to reach the initial value of the SOC. According to the duty cycle in term of electric power at the motor converter, the battery is not fully utilized during the whole cycle. Otherwise the SOC drops from 90% to 31%.

The maximum peak power of 2571kW at the catenary can support during acceleration. That means, the presence of the battery of 12 branches lighten the electric power demand (-38%) from the catenary regarding the same peak power at the same moment in the case without battery (4151kW).

A battery of 12 branches in parallel operates with 59% DoD and doesn't reach the minimum SOC at the end of course. The following part will show the results with a battery of 1 branch to see if the SOC of the battery drops to 10%.

8.2.3. SOC balancing at the end with 1 branch – Scenario III

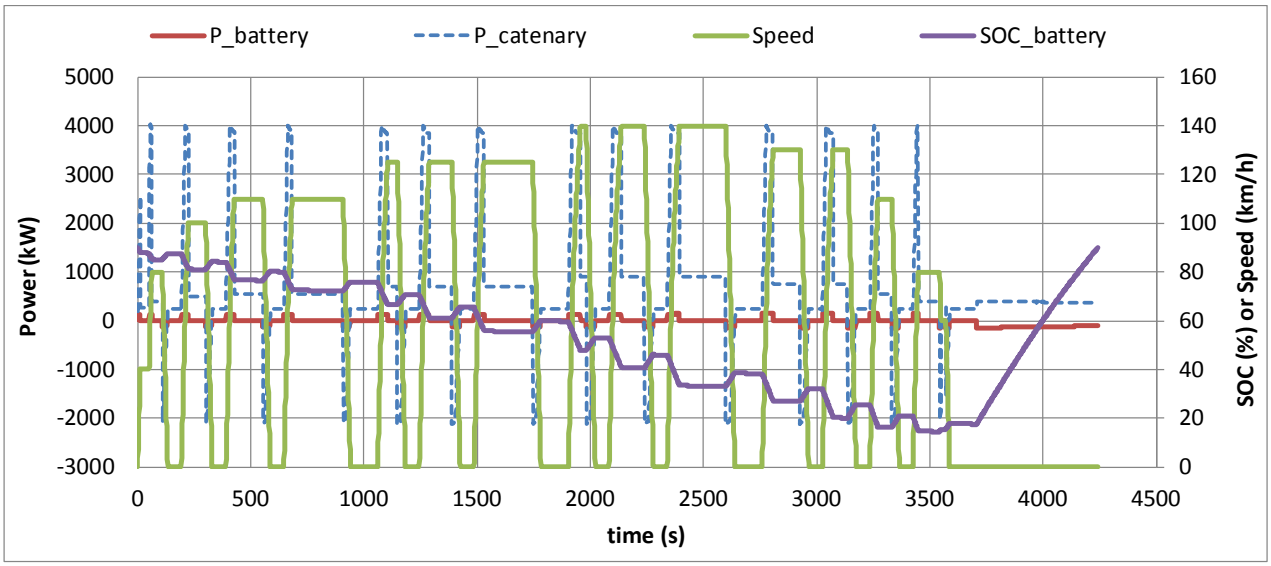

Figure 43. Simulation result with SOC balancing at the end of the course. Battery of 1 branch. Reg160 service category. Scenario III

Figure 43 shows the results of the scenario III, Table 6. The maximum peak power of 4022kW at the catenary can support during acceleration. That means the presence of the battery of 1 branch decreases the electric power demand (-3%) at the catenary regarding the same peak power at the same moment in the case without battery (4151kW).

The battery recharges at the end of the course within 8.9 minutes to reach its initial value of SOC. According to the duty cycle in term of electric power at the motor converter, the battery is not fully utilized during the whole cycle. Otherwise the SOC drops from 90% to 15%.

Even with a battery of 1 branch, there is no limitation of SOC operation of the battery. In this case, the peak shaving approach is not necessary to be studied. By choosing the allout mode, the braking

phases during the Reg140 trajectory are enough to recharge the battery and maintain the SOC above the minimum value of SOC =10%.

8.2.4. SOC balancing at the end and partial electrification with 6 branches – Scenario IV

The scenario IV is adopted with the places where there is no electrical network to feed the train. Four non-electrified zones (for 2km, 3km, 4km and 5km) are defined, where the train operates in cruising mode (constant speed) as below.

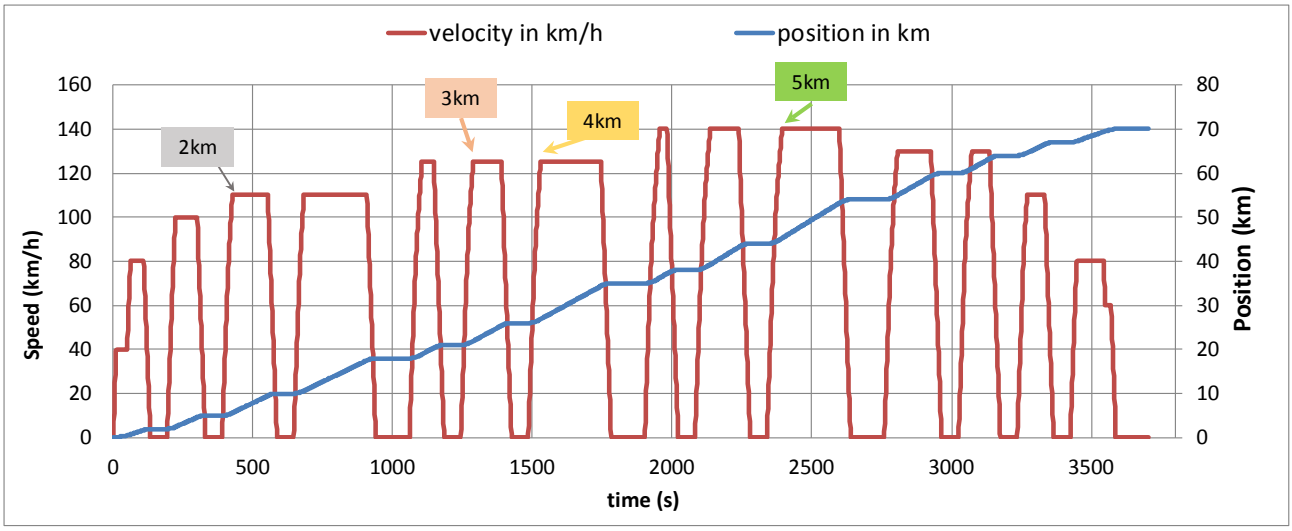

Figure 44: Definition of 4 non-electrified zones according to the speed and position. Reg140 service category. Scenario IV.

The 4 defined non-electrified zones respectively have 2km, 3km, 4km and 5km of distance and are presented in Figure 44.

The four positive peaks of the battery discharge power (corresponding to 4 important drops of SOC) represent four zones without infrastructure. Except these zones, the battery only ensures the auxiliary requirement from the on-board ESU along the trajectory. The auxiliaries from the DC link are fulfilled by the catenary.

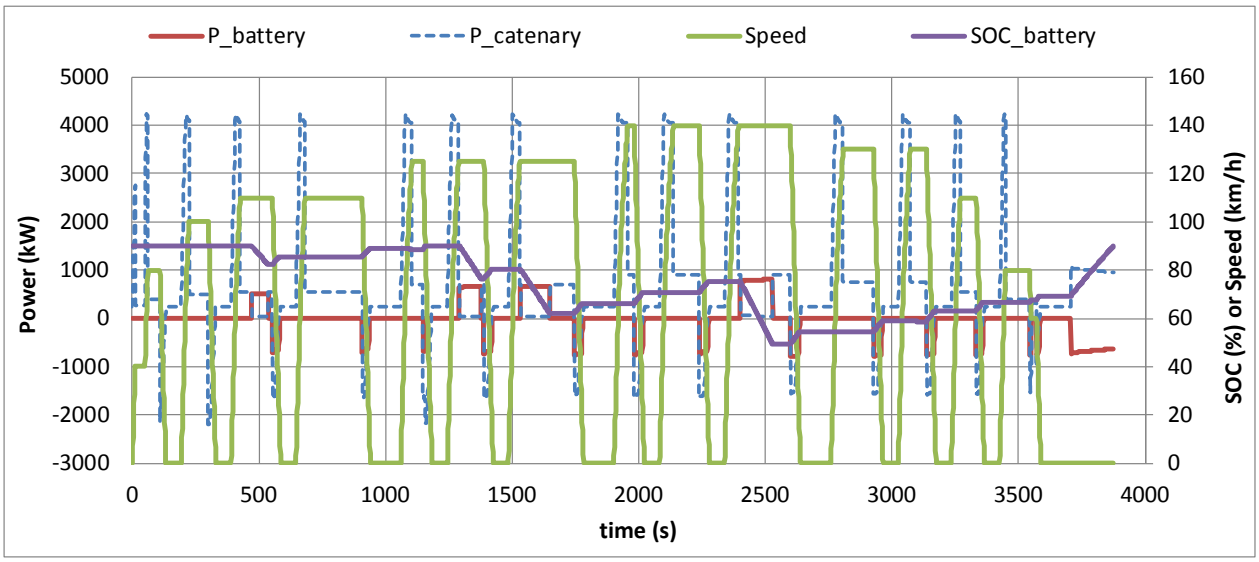

Figure 45. Simulation result with SOC balancing at the end of the course and partially electrified. Battery of 6 branches. Reg140 service category. Scenario IV

The battery needs to ensure all electric power requirements so that the size of the battery is considered at least 6 branches in parallel.

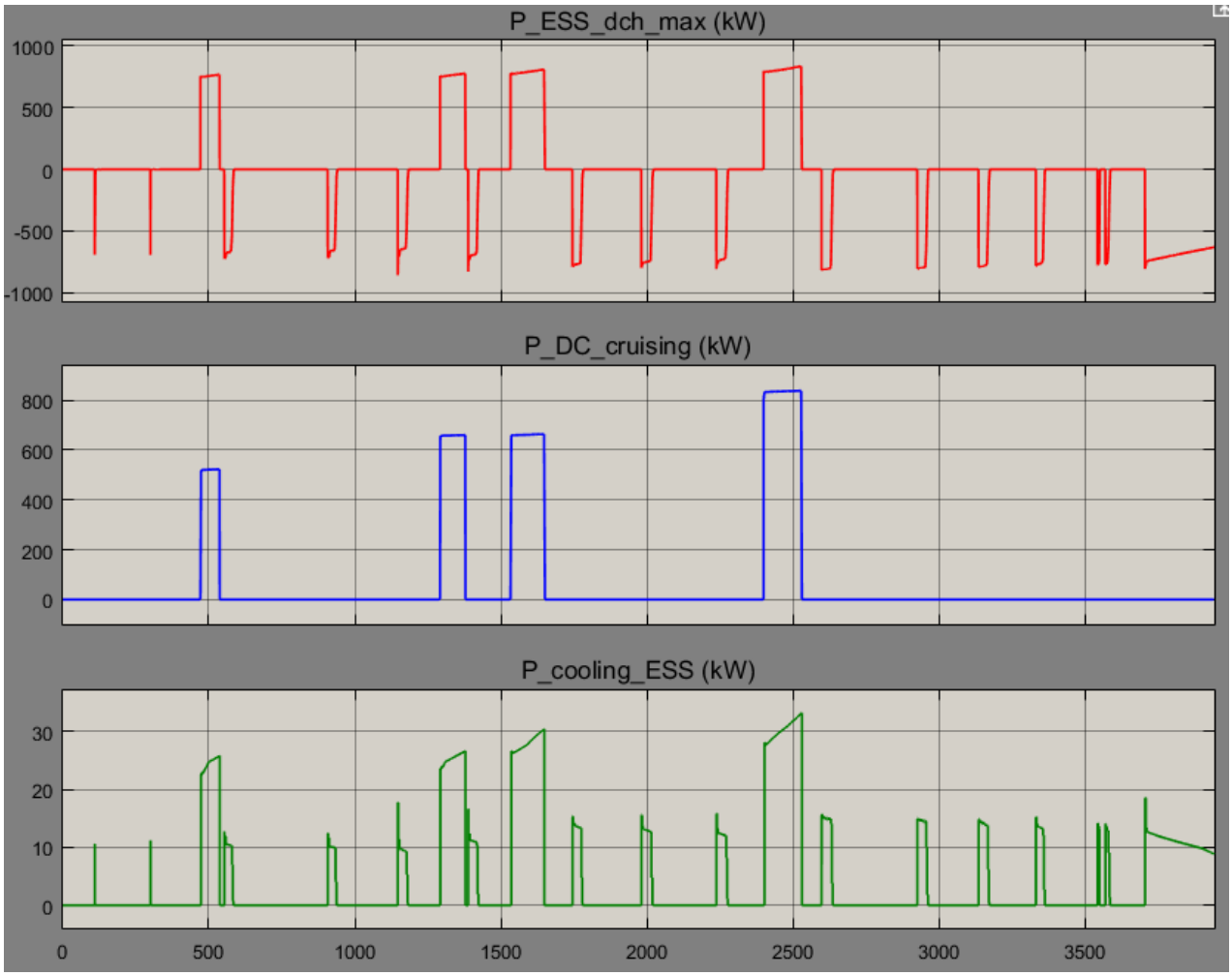

Figure 46. Max discharge power of the battery, electric demand and cooling power. Battery of 6 branches. Reg140 service category. Scenario III

In the Figure 46, $P_{DC,cruising} = P_{DC,trac} + P_{DC,aux} + P_{ESS,cooling}$ is the total power demand during the 4 non-electrified zones (blue curve). The maximum power in discharge of the battery (red curve) is always higher than $P_{DC,cruinsing}$. The cooling power of the battery is dynamically represented by the green curve with the RMS value is 8kW.

For the whole trajectory, the DoD of the battery is 41%. During the two non-electrified zones 3Km (at 1291s) and 4km (at 1533s) the power at the catenary (dashed curve) is zero and the battery fulfil the total electric demand (red curve). In parallel, the SOC of the battery decreases during these two zones.

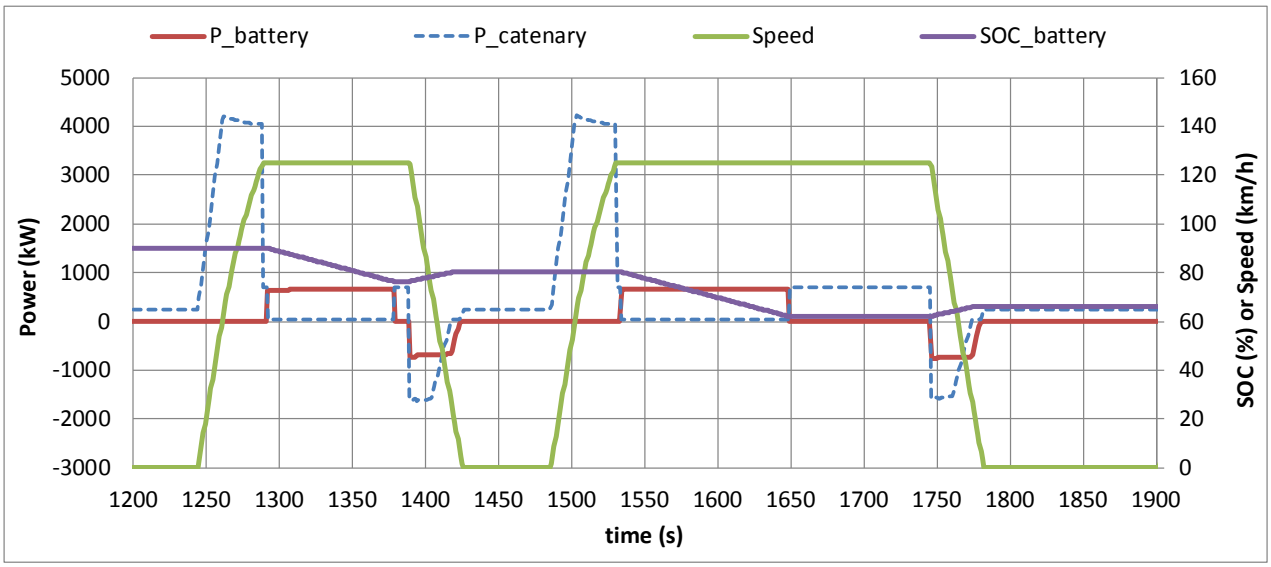

Figure 47. Simulation result with SOC balancing at the end of the course. Battery of 6 branches. Reg140 service category. Scenario IV. Zoom 1200s-1900s

8.2.5. Comparison between scenarios

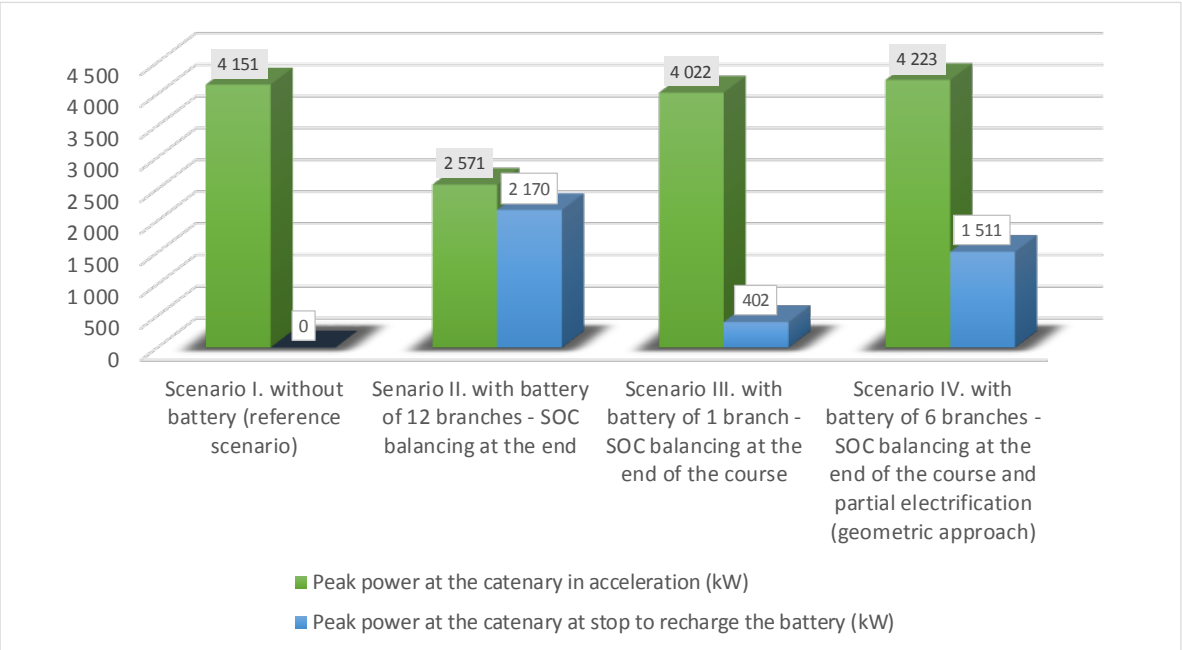

Figure 48: Peak power (in kW) for different scenarios. Reg140 service category

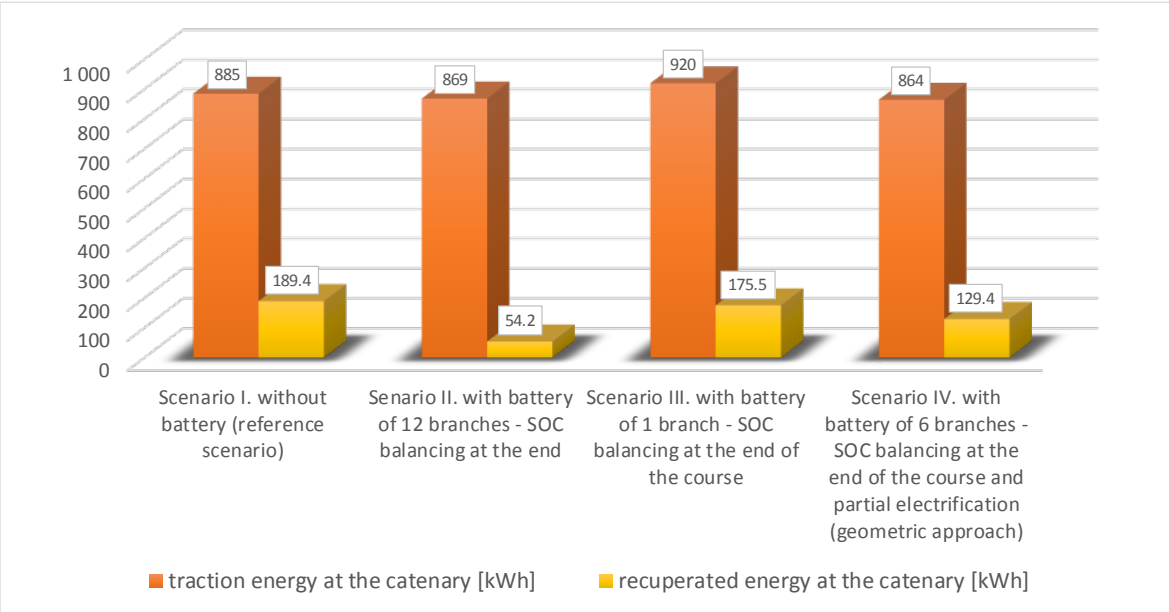

Figure 49: Traction and recuperated energy (in kWh) at the catenary. Reg140 service category

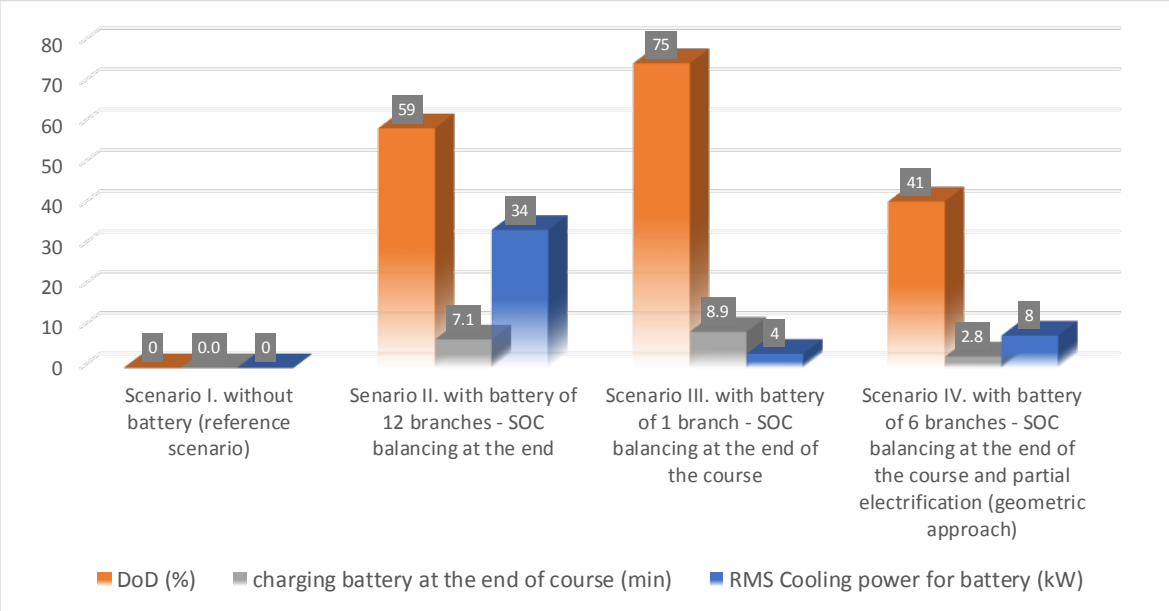

Figure 50: DoD, charging time and RMS cooling power of the battery. Reg140 service category

The scenario II shows the peak shaving advantage (-38%) of peak power in acceleration of the reference scenario by slightly reducing the consumption of traction energy at the catenary.

9. High-Speed scenario

9.1. HS300 service category

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: HS300
  - Track profile: HS300
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T01 (DC power supply)
- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: no double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: 90%
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.
  - The battery needs to ensure all electric power requirements so that the size of the battery mustn't be too small. According to the regional scenario, the minimum battery size will be estimated.

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 20 branches - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**20**	240 VL30PFe cells in serial
III	With battery of 20 branches - SOC balancing at the end of the course and partial electrification (geometric approach) *-discussed with SNCF [5]	The battery discharge ensures its auxiliary requirement, fully support the DC link auxiliaries and power demand during 4 non-electrified zones and recharge at the end of the course	**20**	
IV	With battery of 20 branches - SOC balancing at the end of the course with 27% of DC traction power request from battery (peak shaving approach) *-discussed with SNCF [5]	The battery only accepts 27% of (DC traction power request and the auxiliaries at DC link & on-board ESU) in acceleration	**20**	

Table 7: Considered scenarios with the presence of ESU-battery, HS300 service category

9.1.1. Reference scenario – Scenario I

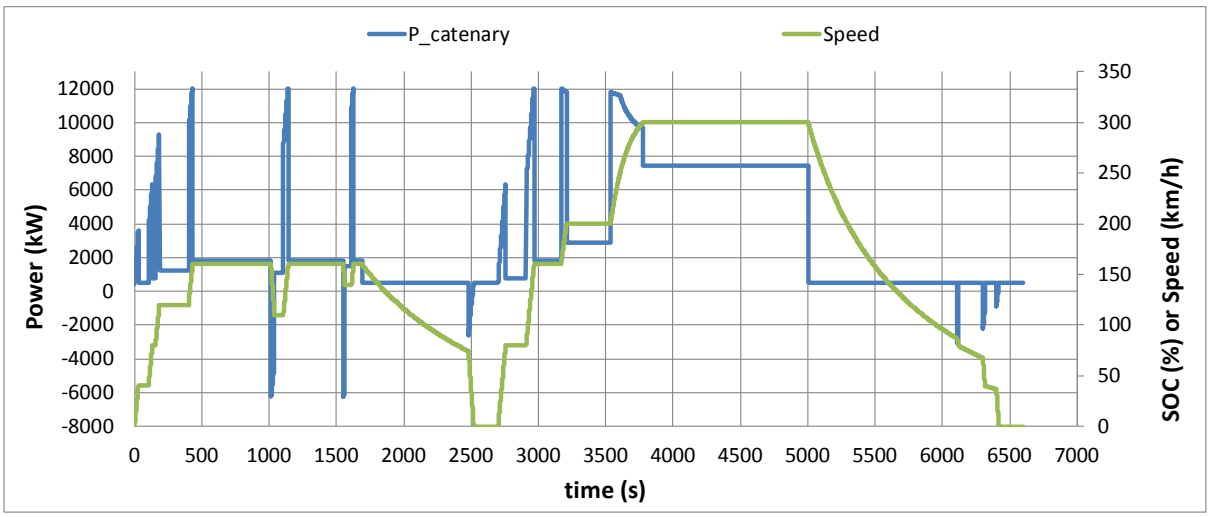

Figure 51. Simulation result without battery (Reference scenario). HS300 service category

According to the HS300 speed profile, there are only one stop along the trajectory. Furthermore, the power requirement for train acceleration is very important with the maximum peak of 12011kW. These reasons lead to the fact that the scenario with the recharge at every stop is less interesting than the other service categories Reg160 and Reg140. The battery size is considered with 20 branches in parallel.

9.1.2. SOC balancing at the end with 20 branches – Scenario II

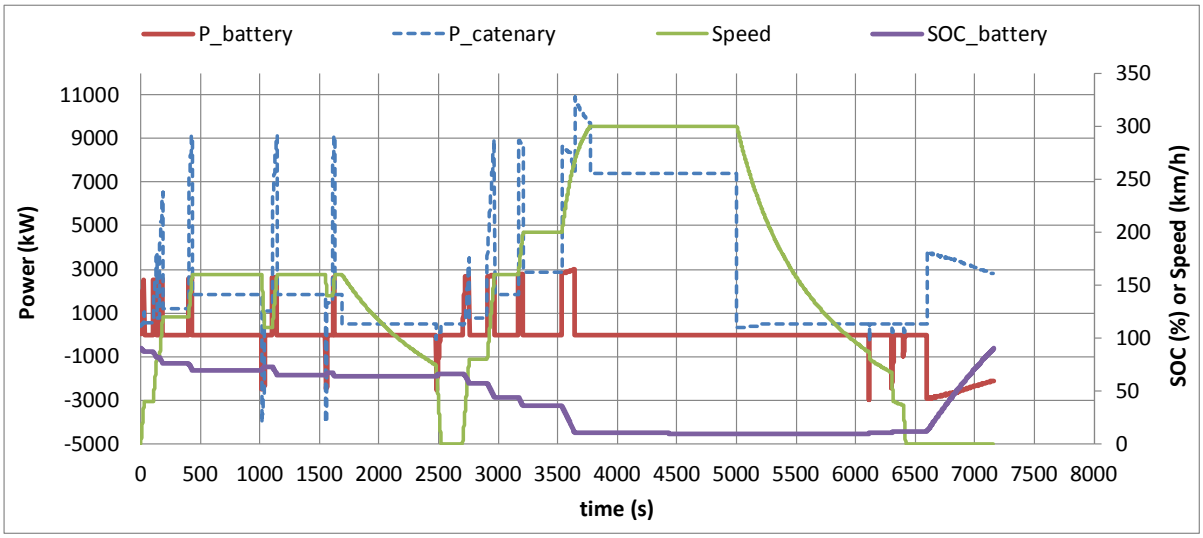

Figure 52. Simulation result with SOC balancing at the end of the course. Battery of 20 branches in parallel. HS300 service category. Scenario II

Figure 52 shows the results of the scenario II, Table 7. The battery recharges at the end of the course within 9.3 minutes to reach the initial value of SOC.

According to the duty cycle in terms of electric power at the motor converter, the battery is fully utilized during the first half of cycle so that the SOC drops from 90% to 10% (minimum authorized for the battery).

In Figure 53, the SOC very quickly reaches the minimum value of 10% after 3641s. The maximum peak power of 10930kW at the catenary can support during the acceleration. That means the presence of the battery of 20 branches lighten the electric power demand (-10%) at the catenary regarding the same peak power at the same moment in the case without battery (12011kW).

Figure 53 shows that from the instant t=3641s, the battery can't support the catenary to partially feed the power demand from the acceleration (red curve) and reach its minimum SOC (10%). That explains the maximum power peak of the catenary (10930kW).

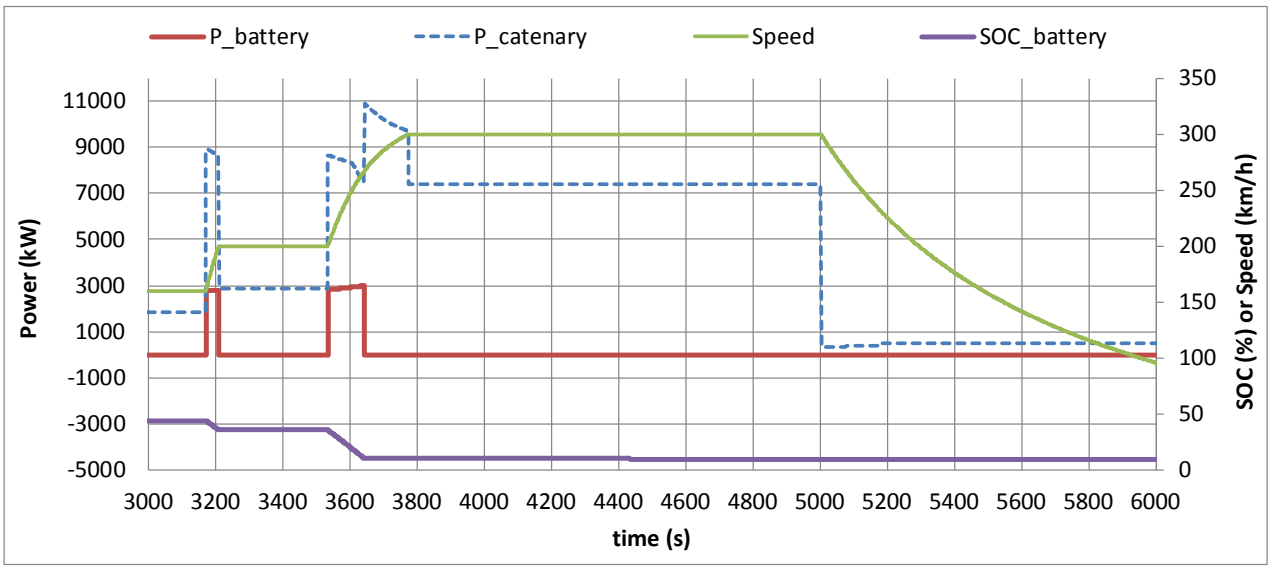

Figure 53. Simulation result with SOC balancing at the end of the course. Battery of 20 branches in parallel. HS300 service category. Scenario II. Zoom 3000s-6000s

9.1.3. SOC balancing at the end and partial electrification with 20 branches – Scenario III

The scenario III is adopted with the places where there is no electrical network to feed the train. Four non-electrified zones (for 2km, 3km, 4km and 5km) are defined, where the train operates in cruising mode (constant speed) as below:

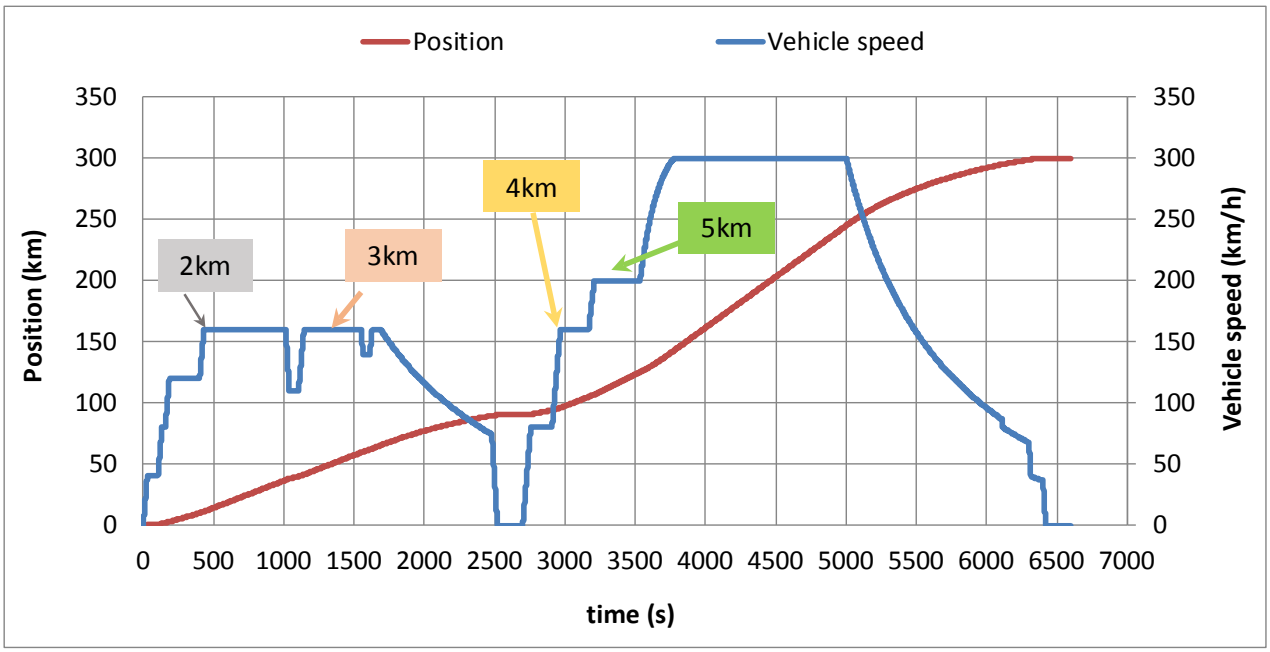

Figure 54: Definition of 4 non-electrified zones according to the speed and position. HS300 service category. Scenario III.

The defined 4 non-electrified zones respectively have 2km, 3km, 4km and 5km of distance and are presented the Figure 54.

The four positive peaks of the battery discharge power (corresponding to 4 important drops of SOC) represent four zones without infrastructure.

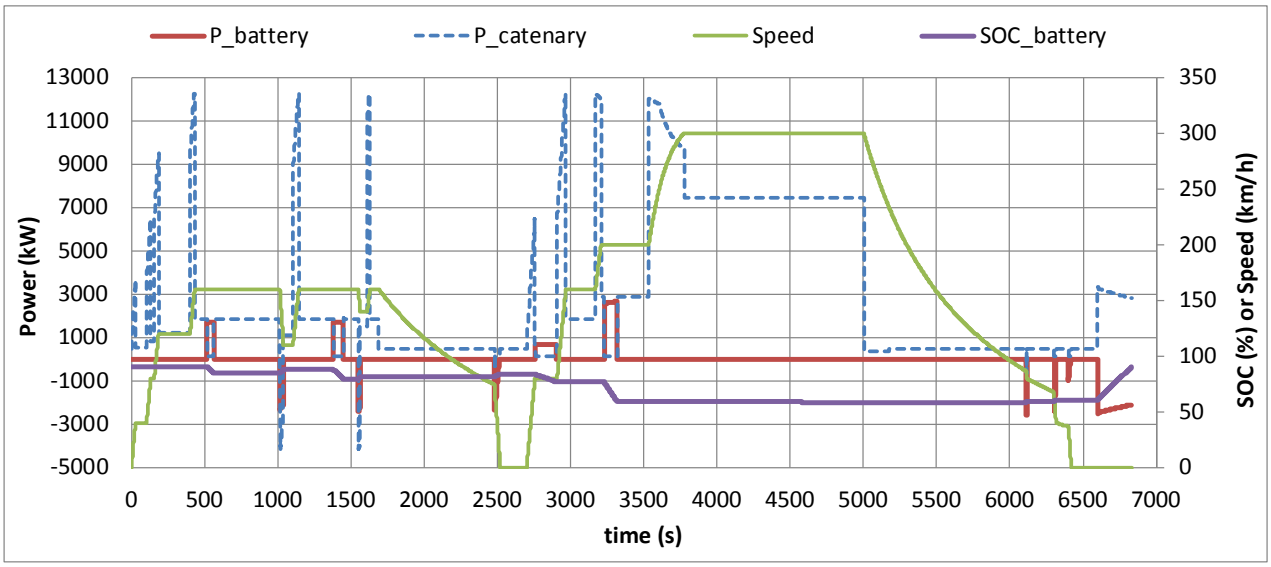

Figure 55. Result with SOC balancing at the end of the course. Battery of 20 branches. HS300 service category. Scenario III

Without the mainline (4 positive peaks of the red curve, Figure 55), the battery needs to ensure all electric power requirements so that the size of the battery is considered with 20 branches in parallel.

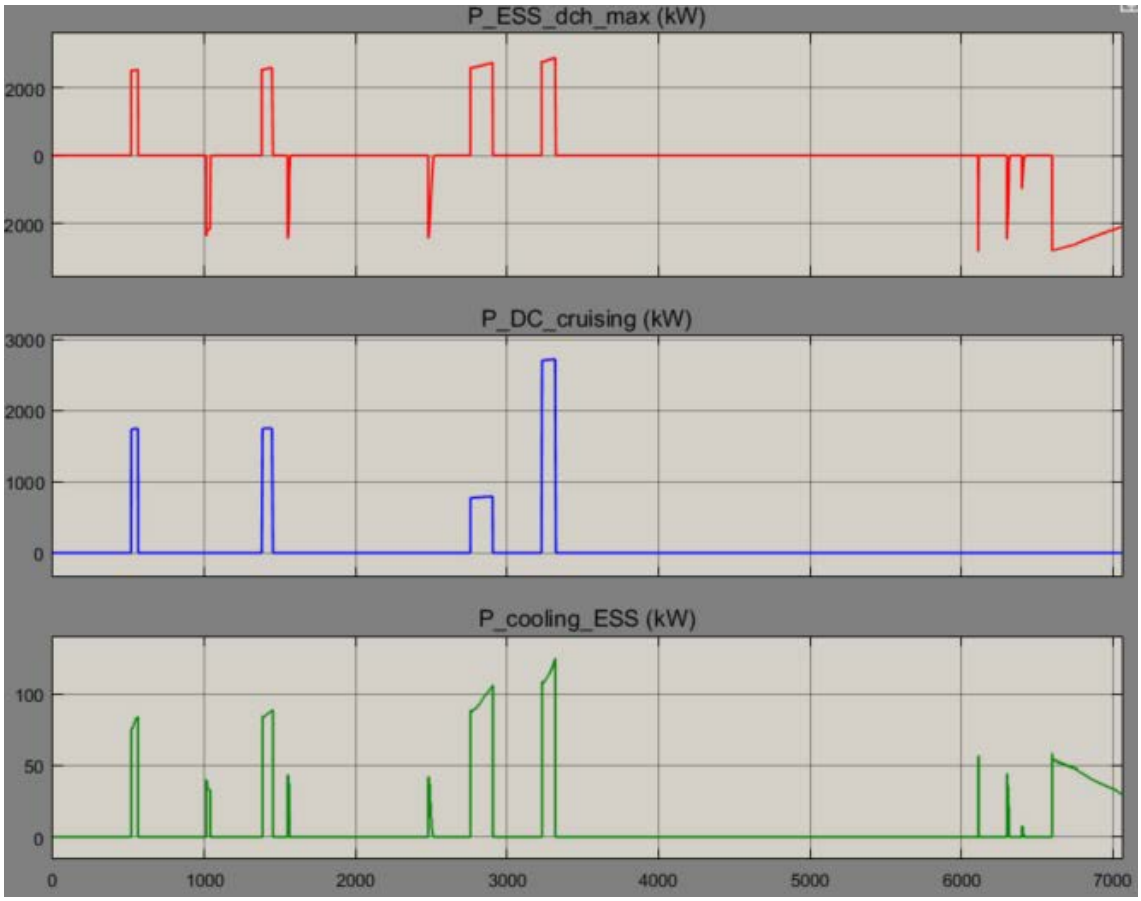

Figure 56. Max discharge power of the battery, electric demand and cooling power. Battery of 20 branches. HS300 service category. Scenario III

In the Figure 56, $P_{DC,cruising} = P_{DC,trac} + P_{DC} + P_{ESS,cooling}$ is the total power demand during the 4 non-electrified zones (blue curve). The maximum power in discharge of the battery (red curve) is always higher than $P_{DC,cruising}$. The cooling power of the battery is dynamically represented by the green curve with the RMS value is 20kW. For the whole trajectory, the DoD of the battery is 32%.

9.1.4. SOC balancing at the end with 20 branches – peak shaving approach – Scenario IV

The presented peak shaving approach is an operating strategy to limit the high-power peak requirement during the acceleration phases, by allying the ESS system. For a given battery of 20

branches in parallel 27% of DC traction power request comes from the battery in acceleration. This battery size ensures the partial support of the battery to the catenary and maintains the SOC at 10% before the end of the course.

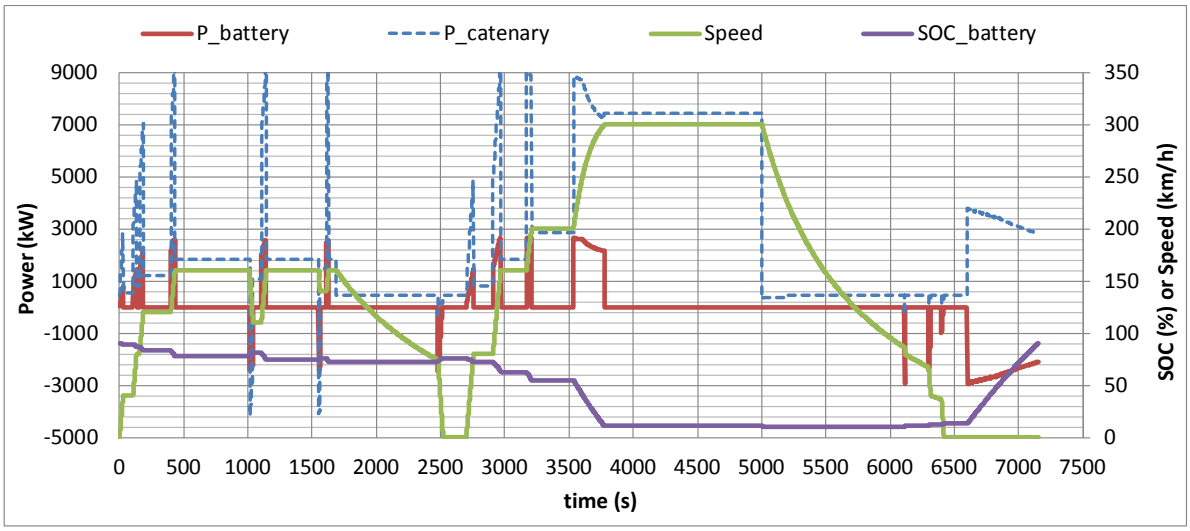

Figure 57. Simulation result with SOC balancing at the end of the course and partially electrified. Battery of 20 branches. HS300 service category. Scenario IV.

During the course, the SOC of the battery drops to 10.7% and the battery needs 9 min to recharge to 90%. The maximum power peak (10623kW) at 3641s in the case of scenario II is replaced by the smaller one of 9194kW with the support of the battery in case of the current scenario IV. The maximum power peak from the catenary represent 88% of the one of the reference scenario (12011kW).

9.1.5. Comparison between scenarios

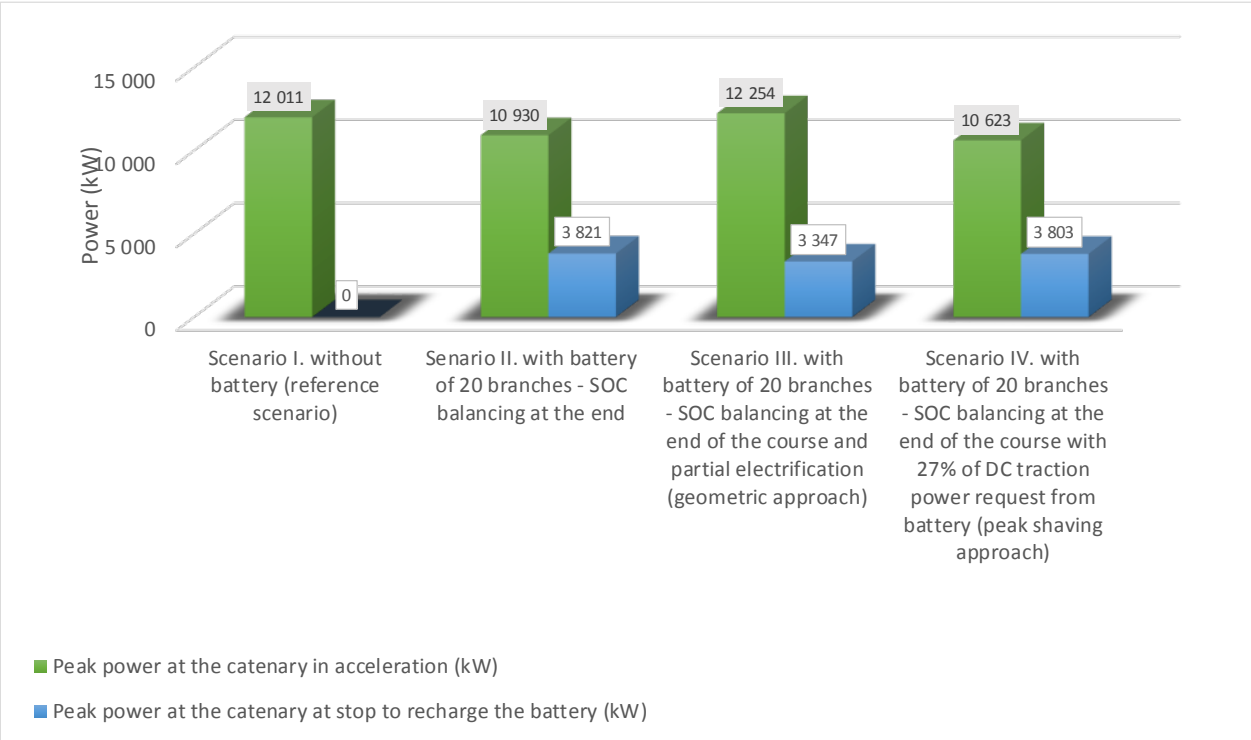

Figure 58: Peak power (in kW) for different scenarios. HS300 service category

The scenario III results in traction energy at the catenary of 12254kW that is higher than the one 12011kW of the scenario I. This small difference can be explained by the fact, out of no-mainline zones, the auxiliary of the ESS battery (including the cooling power for the battery) need to be fed by the catenary.

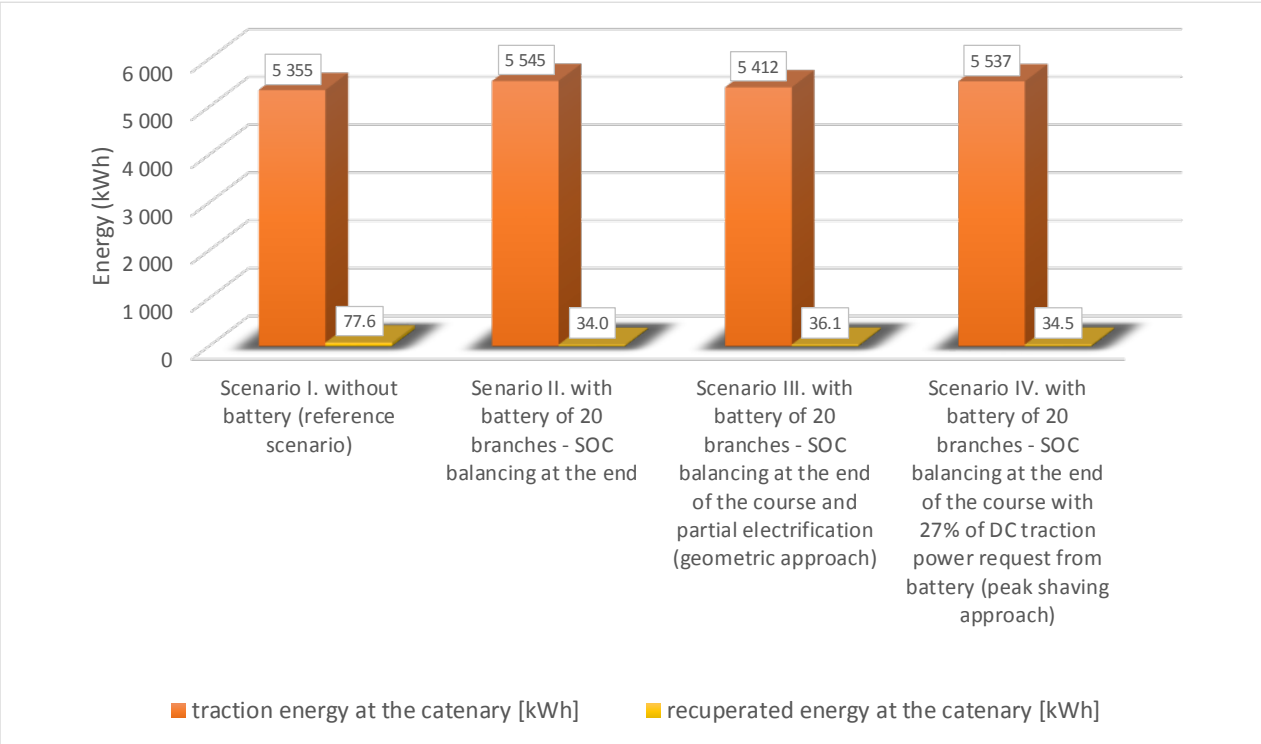

Figure 59: Traction and recuperated energy (in kWh) at the catenary. HS300 service category

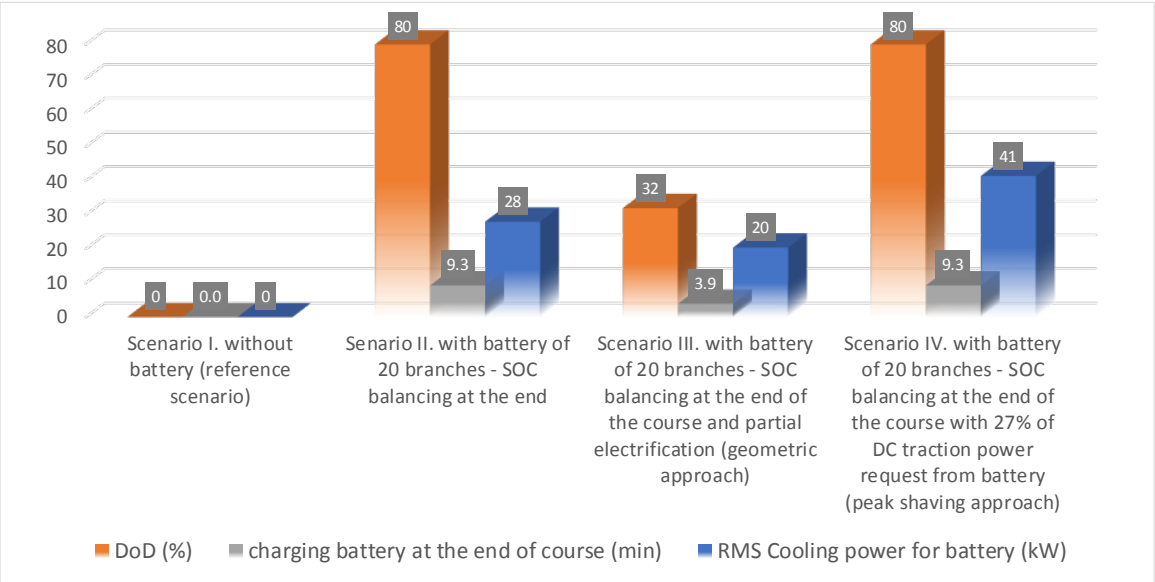

Figure 60: DoD, charging time and RMS cooling power of the battery. HS300 service category

The High-Speed 300 service category is highlighted by a speed profile with only one stop during the trajectory. Additionally, the most of time, the train operates in cruising mode. The power supply for the four no-mainline zones could be ensured by the battery of 20 branches, which is not

the case with the HS250 train (31 branches in parallel). In terms of peak power during acceleration and of traction energy consumption, the scenario III doesn't technically demonstrate the advantage despite the infrastructure costs.

The scenario II shows that the battery reaches its minimum SOC (10%) after the first half of the course due to many acceleration phases. However, this scenario gives the peak power less important (-9%) than the one without battery.

9.2. HS250 service category

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: HS250
  - Track profile: HS250
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T01 (DC power supply)
- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: no double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: 90%
  - The ESU battery size will vary according to the specific case.
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.
  - The battery needs to ensure all electric power requirements so that the size of the battery mustn't be too small. According to the regional scenario, the minimum battery size will be estimated

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 20 branches - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**20**	240 VL30PFe cells in serial
III	With battery of 31 branches - SOC balancing at the end of the course and partial electrification (geometric approach) *-discussed with SNCF [5]	The battery discharge ensures its auxiliary requirement, fully support the DC link auxiliaries and power demand during 4 non-electrified zones and recharge at the end of the course	**31**	

IV	With battery of 20 branches - SOC balancing at the end of the course with 27% of DC traction power request from battery (peak shaving approach) *-discussed with SNCF [5]	The battery only accepts 27% of (DC traction power request and the auxiliaries at DC link & on-board ESU) in acceleration	**20**	
V	With battery of 10 branch – energy optimal strategy according to section 6	Energy optimal operating strategy, SOC balancing during the process of the course	**10**	

Table 8: Considered scenarios with the presence of ESU-battery, HS250 service category

9.2.1. Reference scenario – Scenario I

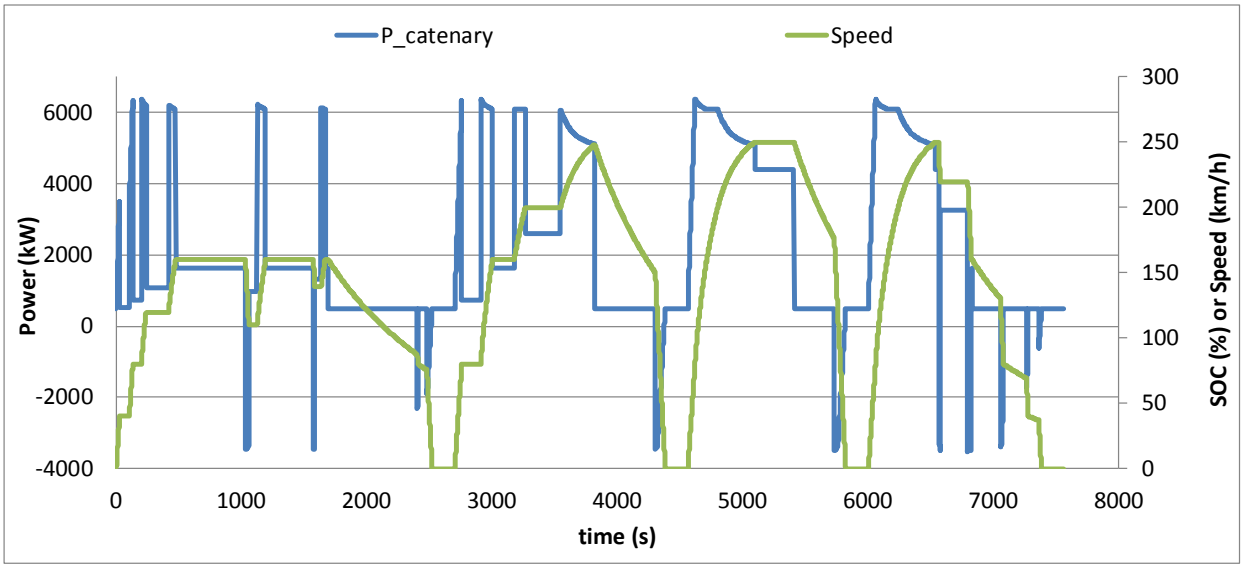

Figure 61. Simulation result without battery (Reference scenario). HS250 service category

According to the HS250 speed profile, there are only one stop along the trajectory. Furthermore, the power requirement for train acceleration is very important with the maximum peak of 6000kW. These reasons lead to the fact that the scenario with the recharge at every stop is less interesting than the other service categories Reg160 and Reg140. The battery size is considered with 20 branches in parallel.

9.2.2. SOC balancing at the end with 20 branches

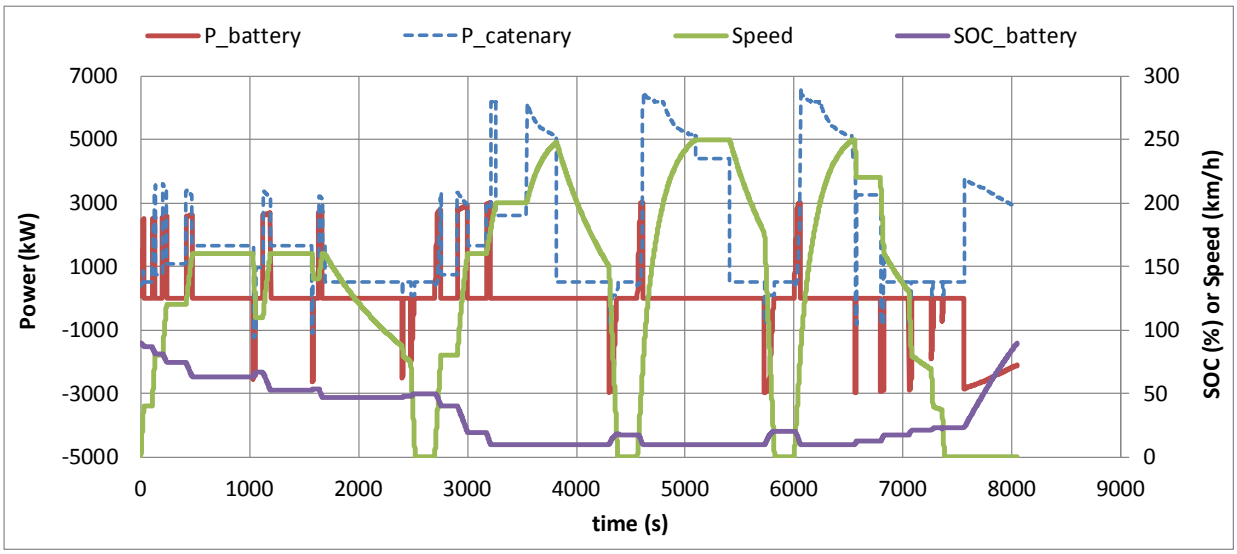

Figure 62. Simulation result with SOC balancing at the end of the course. Battery of 20 branches in parallel. HS250 service category. Scenario II

Figure 62 shows results of the scenario II, Table 8. The battery recharges at the end of the course within 8 minutes to reach its initial value of SOC.

In the Figure 69, the SOC reaches the minimum value of 10% at 3227s and then the battery can't support the battery to justify the power demand. The maximum peak power of 6682kW is at the catenary can support during the acceleration. This value is higher than the one of the reference scenario without battery (6368kW). The different is that the catenary must feed the auxiliary of the on-board battery during the trajectory.

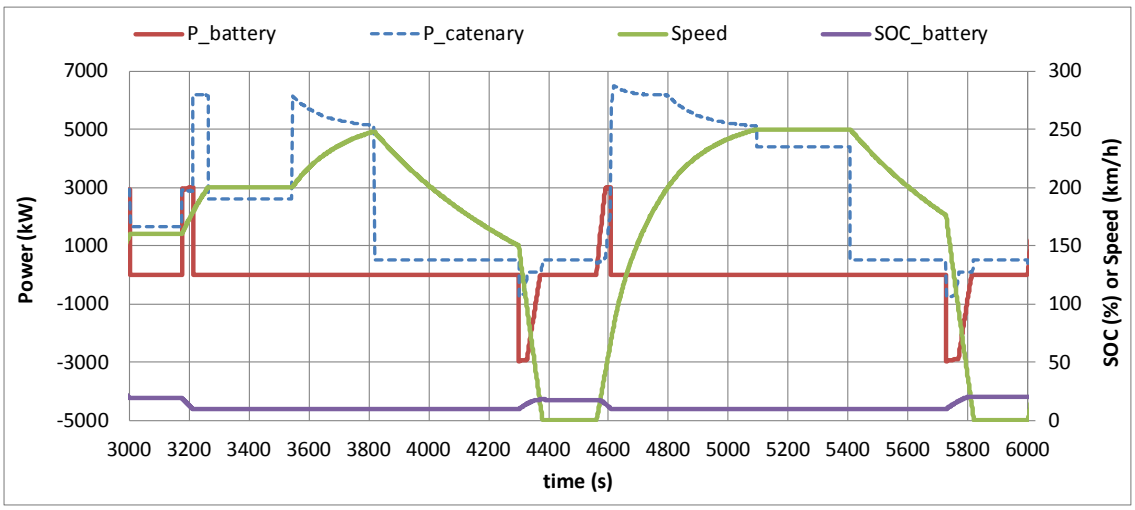

Figure 63. Result with SOC balancing at the end of the course. Battery of 20 branches in parallel. HS250 service category. Scenario II. Zoom 3000s-6000s

9.2.3. SOC balancing at the end and partial electrification with 31 branches – Scenario III

The scenario III is adopted with places with no electrical network to feed the train. Four non-electrified zones (for 2km, 3km, 4km and 5km) are defined, where the train operates in cruising mode (constant speed) as below.

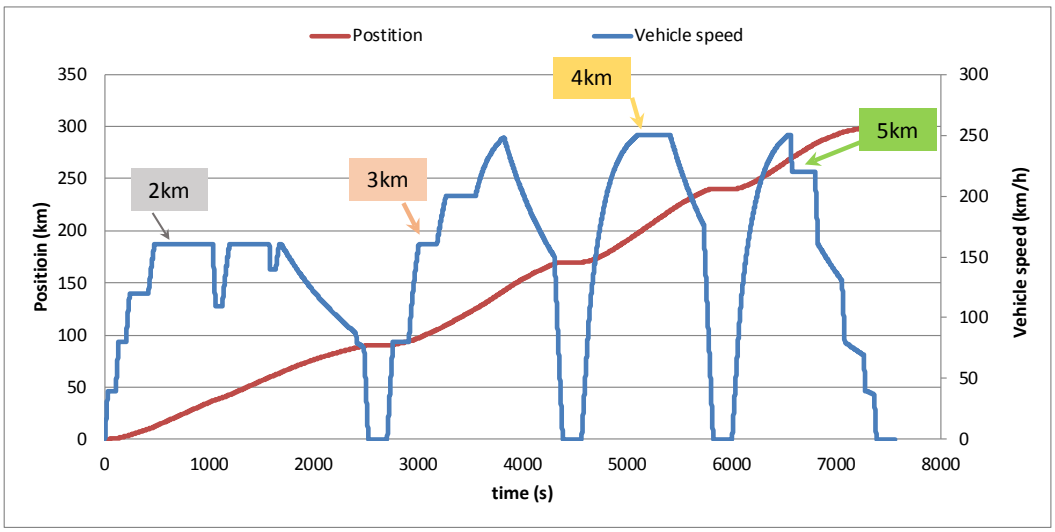

Figure 64: Definition of 4 non-electrified zones according to the speed and position. HS250 service category. Scenario III.

The defined 4 non-electrified zones respectively have 2km, 3km, 4km and 5km of distance and are presented in Figure 64.

The four positive peaks of the battery discharge power (corresponding to 4 important drops of SOC) represent four zones without infrastructure.

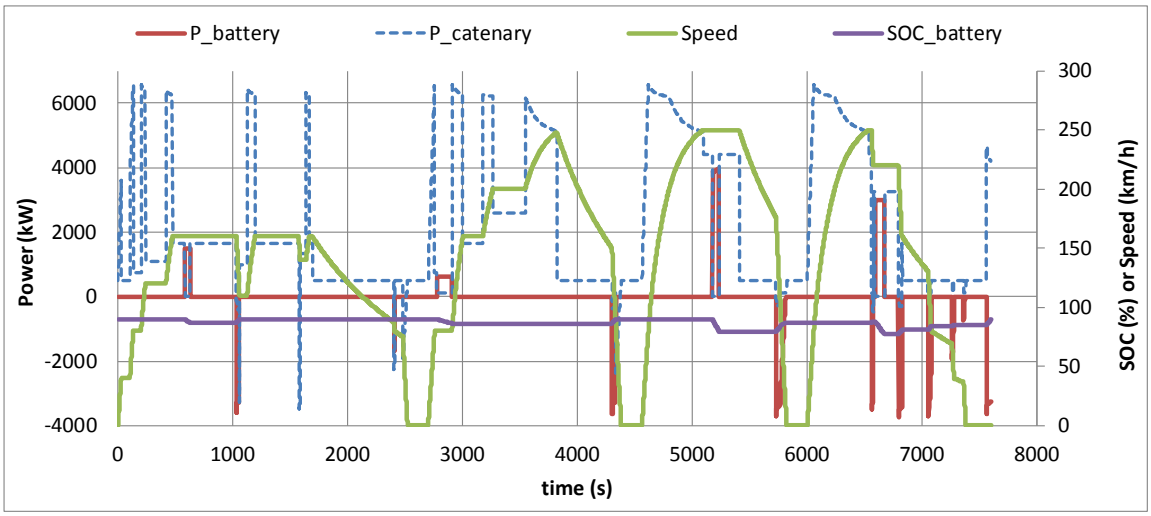

Figure 65. Simulation result with SOC balancing at the end of the course. Battery of 31 branches. HS250 service category. Scenario III

Without the mainline (4 positive peaks of the red curve, Figure 65), the battery needs to ensure all electric power requirements. The resulting size of the battery is considered with 31 branches in parallel.

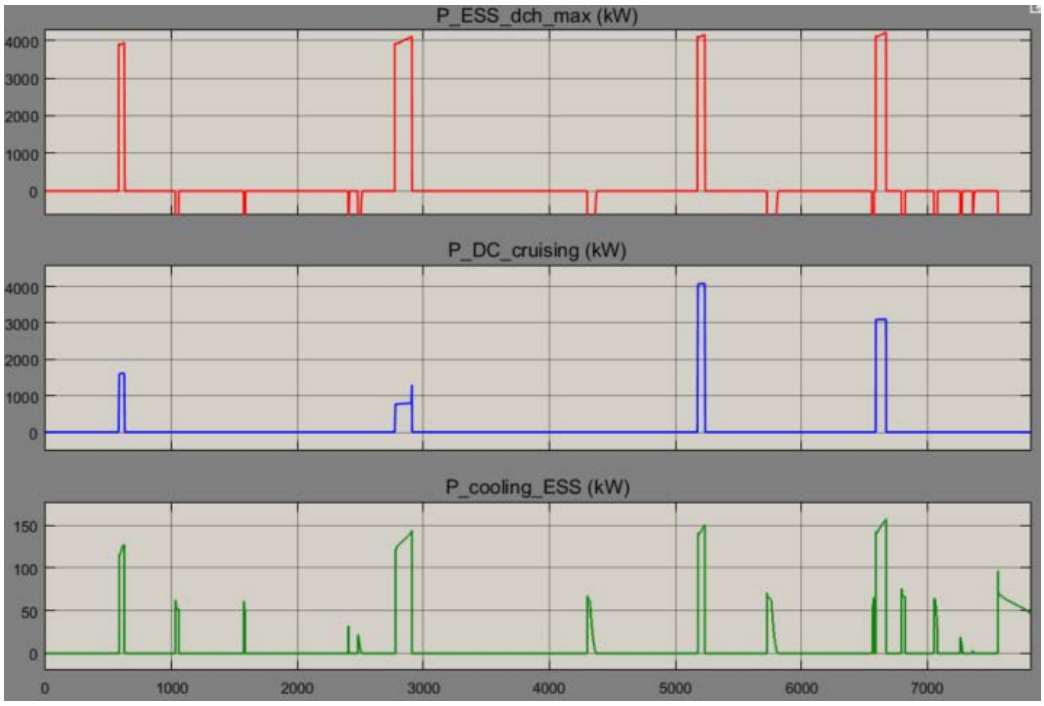

Figure 66. Max discharge power of the battery, electric demand and cooling power. Battery of 31 branches. HS250 service category. Scenario III

In the Figure 66, $P_{DC,cruising} = P_{DC,trac} + P_{DC,aux} + P_{DC,cooling}$ is the total power demand during the 4 non-electrified zones (blue curve). The maximum power in discharge of the battery (red curve) is always higher than $P_{DC,cruising}$. The cooling power of the battery is dynamically represented by the green curve with the RMS value is 23kW. For the whole trajectory, the DoD of the battery is 24% and the battery.

9.2.4. SOC balancing at the end with 20 branches – peak shaving approach –Scenario IV

The presented peak shaving approach is an operating strategy to limit the high-power peak requirement due to the application of the battery during acceleration phases. For a given battery of 20 branches in parallel20% of DC traction power request comes from the battery in acceleration. This battery size ensures the partial support of the battery to the catenary and maintains the SOC higher than its value 10% before the end of the course,

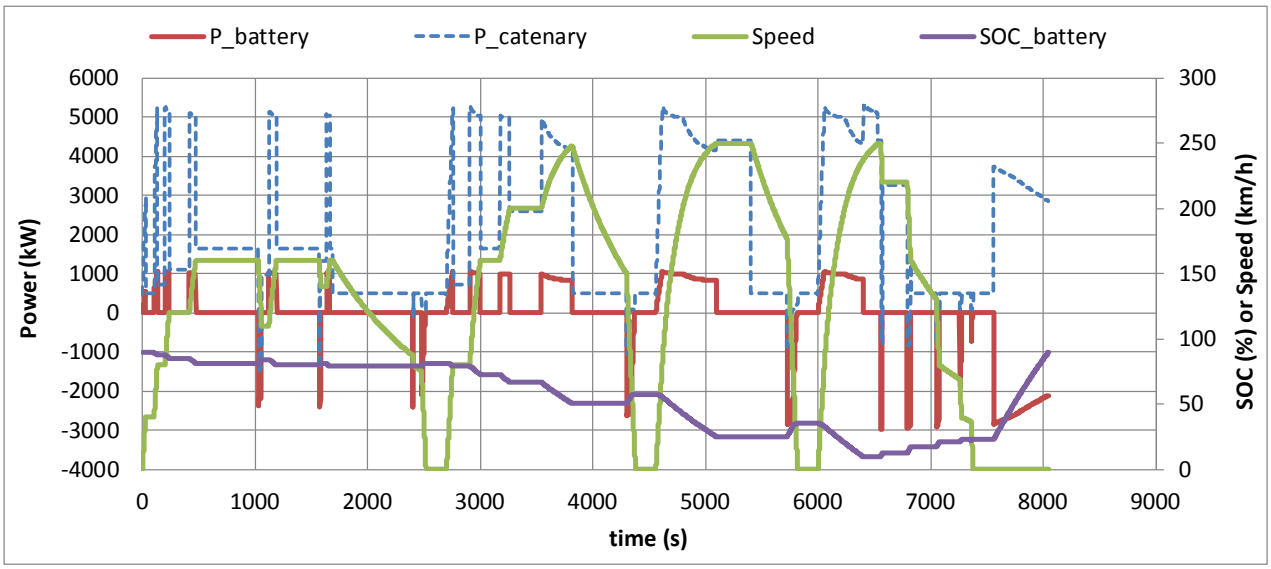

Figure 67. Simulation result with SOC balancing at the end of the course and partially electrified. Battery of 20 branches. HS250 service category. Scenario IV.

During the course, the SOC of the battery drops to 10% (at 6420s) and the battery partly recharges, thanks to several braking phases, till the end of the course. At the end the battery needs 9 min to recharge to the initial value of 90%. The maximum power peak (5294kW) represents 83% of the maximum power peak at the catenary of the reference scenario (6368kW).

9.2.5. Energy optimized operating strategy – Scenario V

For the presented scenario V for the High-Speed 250 service category, the ESS covers 2% of the traction power ($\varepsilon_{trac} = 0.02$) and 5% of the auxiliary ($\varepsilon_{aux} = 0.05$) as 100% of the braking power is recuperated ($\varepsilon_{rec} = 1$).

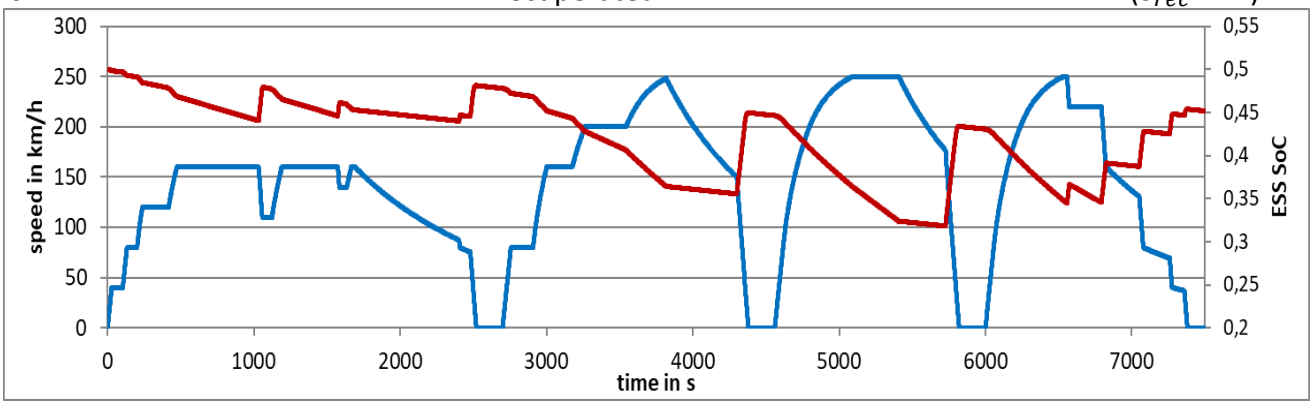

Figure 68. Simulation result with SOC balancing during the course. Battery of 1 branch. High-Speed 250 service category. Scenario V

9.2.6. Comparison between scenarios

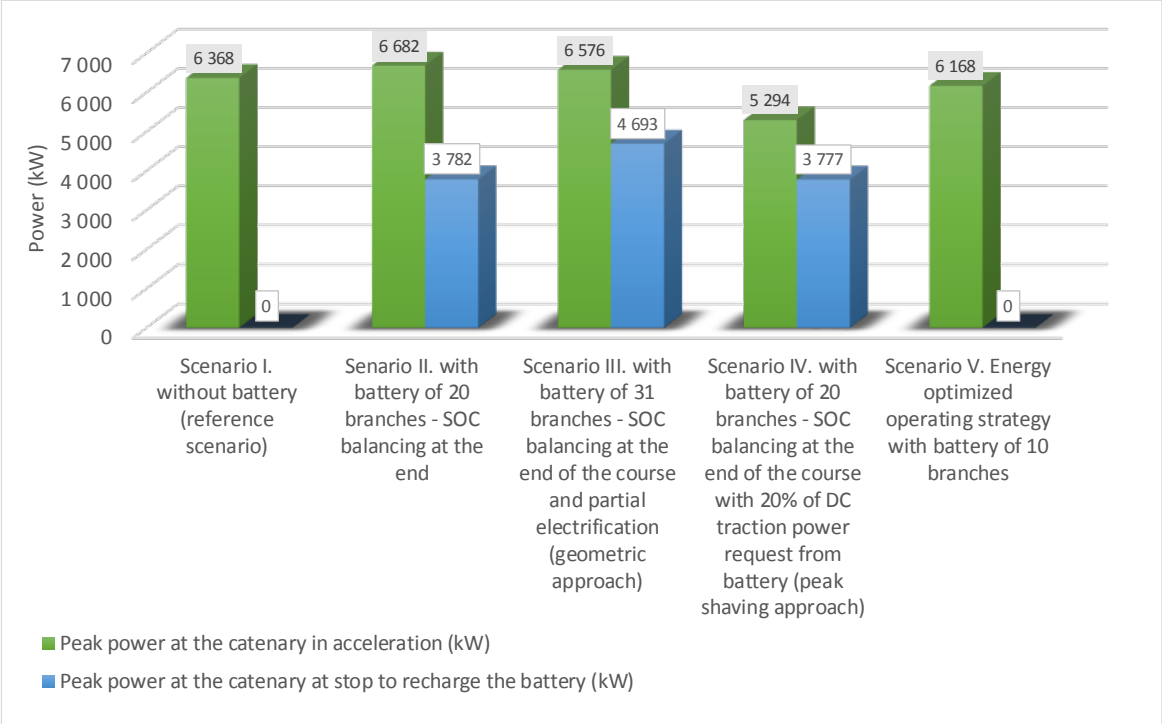

Figure 69: Peak power (in kW) for different scenarios. HS250 service category

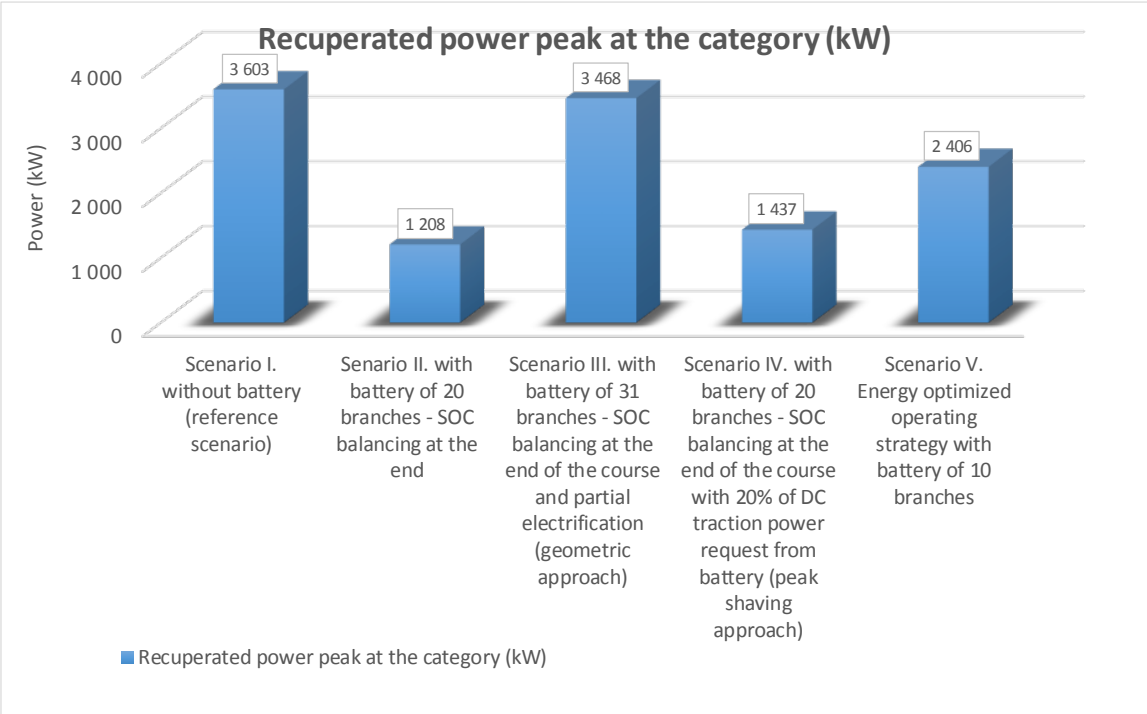

Figure 70: Recuperated peak power (in kW) for different scenarios. HS250 service category

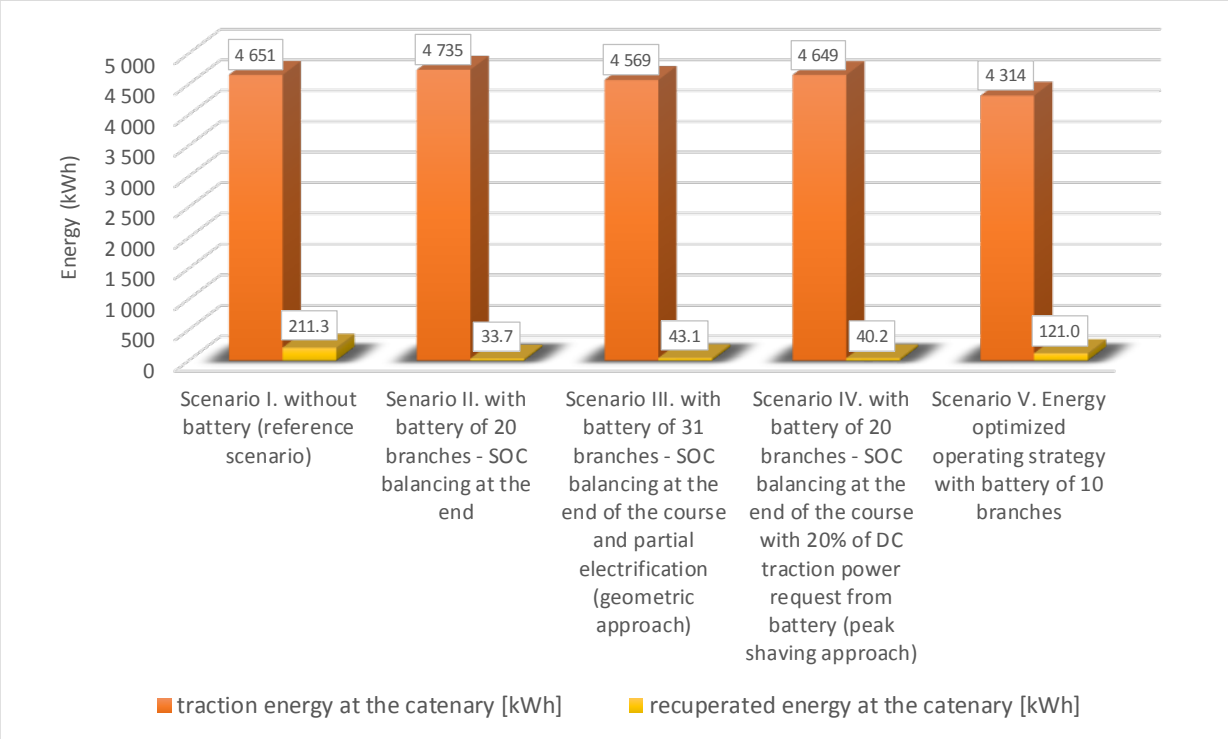

Figure 71: Traction and recuperated energy (in kWh) at the catenary. HS250 service category

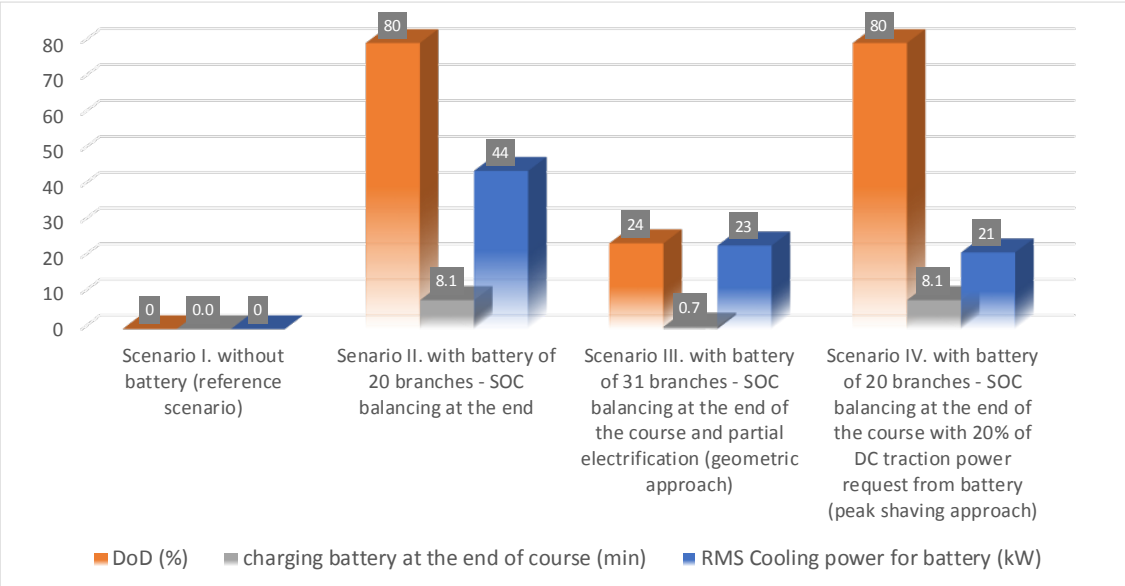

Figure 72: DoD, charging time and RMS cooling power of the battery. HS250 service category

The required power for the four no-mainline zones could be ensured by the battery of 31 branches in parallel. Here, the scenario simulation utilizes a bigger battery compared to the HS300 use-case.

This could be explained by the definition of the no-mainline zones. In case of HS250 train, the zones of 4km and 5km are selected when the traction load are very important (between 3500kW and 4200kW).
The scenario IV illustrates that the power peak is less important (-17%) and a slight consumption of traction energy occurs compared to the reference case without battery.

10. Freight service

10.1. Freight mainline service category

The main initial conditions for the below simulation results (general inputs) are as follows:

- At rail vehicle level (access from the OPEUS_Input.xlsx file):
  - Type of rail vehicle: Freight Mainline
  - Track profile: Freight Mainline (**the power profile is dedicated to the altitude track**)
  - Trajectory mode: timetable
  - Pre-calculated trajectory: yes
  - Season mode: winter
  - Partial switch-off of traction components: off
  - Partial load distribution: off
  - Topology: T01 (DC power supply)
- At ESS level (definition from C17_ESSbattery_Tram.xlsx file):
  - ESS-DLC: no double layer capacitor presence
  - ESS-battery: 1 ESU-battery integrated
  - Cell technology for Anode/Cathode active material: Super Iron Phosphate (sLFP)/Graphite
  - Initial state of charge: 90%
  - The ESU battery size will vary according to the specific case
  - The on-board battery will only support the power demand in case of acceleration. The auxiliaries from the DC links or on-board ESS will be charged by the catenary during the course.
  - The battery needs to ensure all electric power requirements so that the size of the battery mustn't be too small. According to the regional scenario, the minimum battery size will be estimated

Definition of the simulation scenarios				
	Scenario	**Main description**	battery size in branch //	1 branch configuration
I	Without battery	Baseline scenario	-	-
II	With battery of 20 branches - SOC balancing at the end of the course	At the end of the course, the battery recharge till its initial SOC	**20**	240 VL30PFe cells in serial
III	With battery of 14 branches - SOC balancing at the end of the course and partial electrification (geometric	The battery discharge ensures its auxiliary requirement, fully support the DC link auxiliaries and power demand during 4 non-electrified	**14**	

	approach) *-discussed with SNCF [5]	zones and recharge at the end of the course		
IV	With battery of 20 branches - SOC balancing at the end of the course with 45% of DC traction power request from battery (peak shaving approach) *-discussed with SNCF [5]	The battery only accepts 45% of (DC traction power request and the auxiliaries at DC link & on-board ESU) in acceleration	**20**	
V	With battery of 10 branch – energy optimal strategy according to section 6	Energy optimal operating strategy, SOC balancing during the process of the course	**10**	

Table 9: Considered scenarios with the presence of ESU-battery. Freight mainline service category

10.1.1. Reference scenario – Scenario I

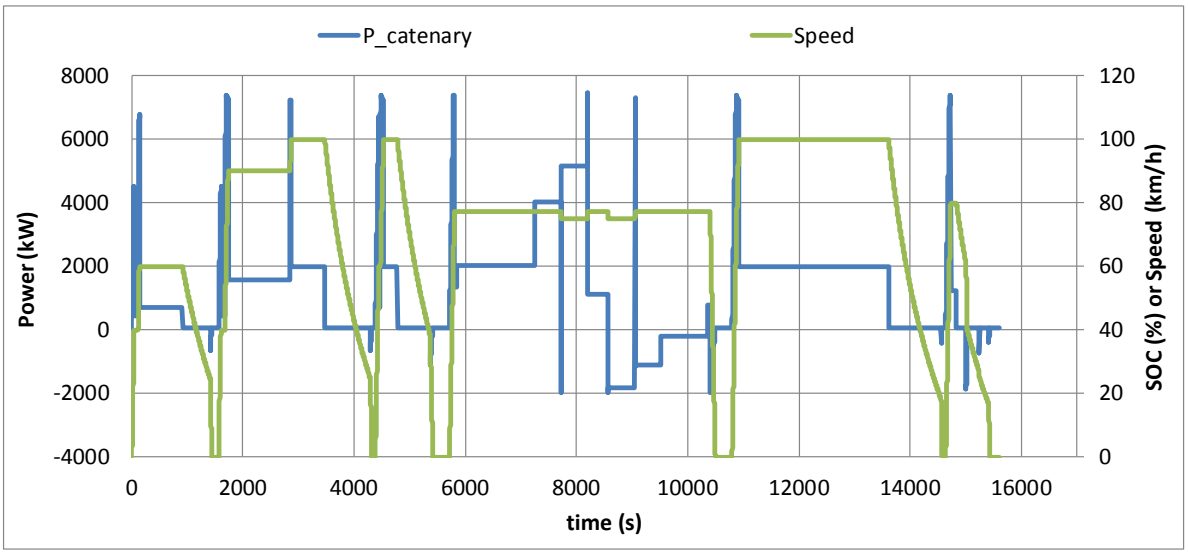

Figure 73. Result without battery (Reference scenario). Freight mainline service category

According to the Freight main speed profile, the power requirement for train acceleration is very important with the maximum peak of 7456kW. For this service profile, the battery size is considered with 20 branches in parallel.

10.1.2. SOC balancing at the end with 20 branches – Scenario II

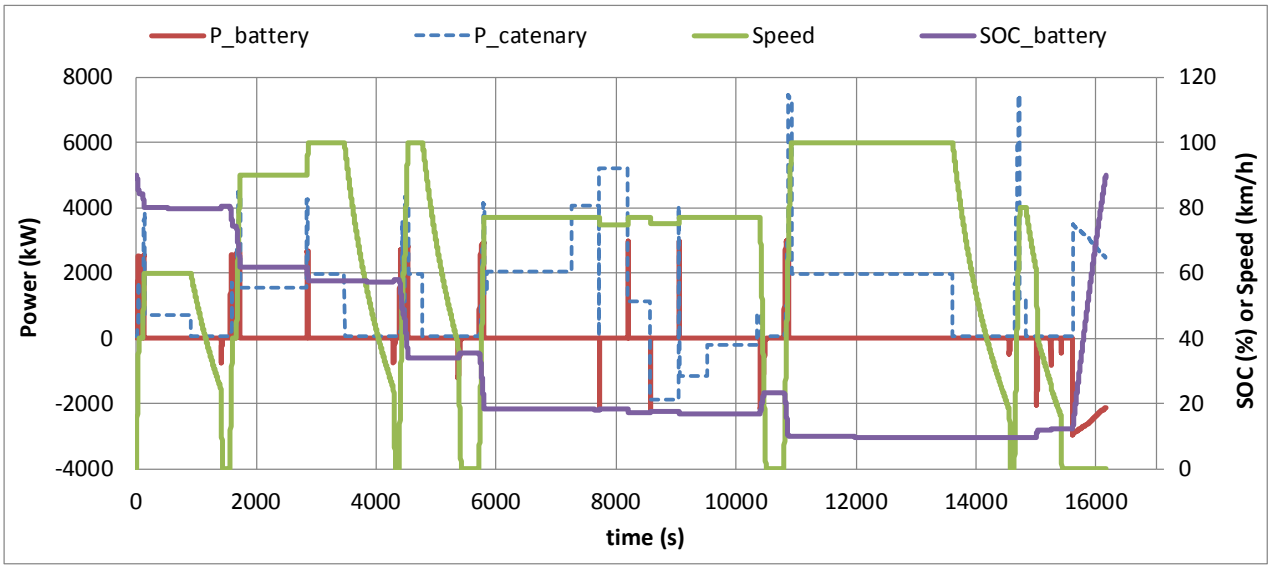

Figure 74. Simulation result with SOC balancing at the end of the course. Battery of 20 branches in parallel. Freight mainline service category. Scenario II

Figure 74 shows the simulation results of the scenario II, Table 9. The battery recharges at the end of the course within 3 minutes to reach its initial value of SOC.

7471kW is the maximum peak power of the catenary can support the acceleration. This value is higher compared to the maximum peak power (7456kW) in case of scenario without battery due to the auxiliary from the on-board battery.

10.1.3. SOC balancing at the end and partial electrification with 14 branches

The scenario III is adopted with the places where there is no electrical network to feed the train. Four non-electrified zones (for 2km, 3km, 4km and 5km) are defined, where the train operates in cruising mode (or when the speed is constant) as below.

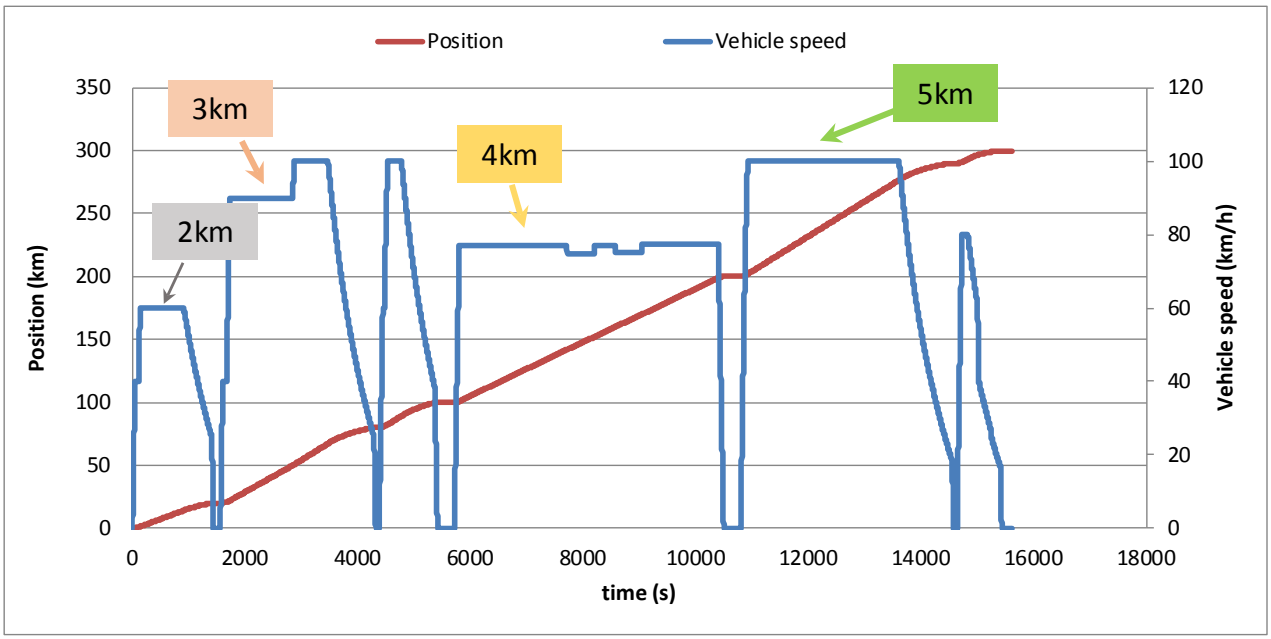

Figure 75: Definition of 4 non-electrified zones according to the speed (and position. Freight mainline service category. Scenario III.

The defined 4 non-electrified zones of respectively 2km, 3km, 4km and 5km of distance are presented in the Figure 75.

The four positive peaks of the battery discharge power (corresponding to 4 important drops of SOC) represent the four zones without infrastructure.

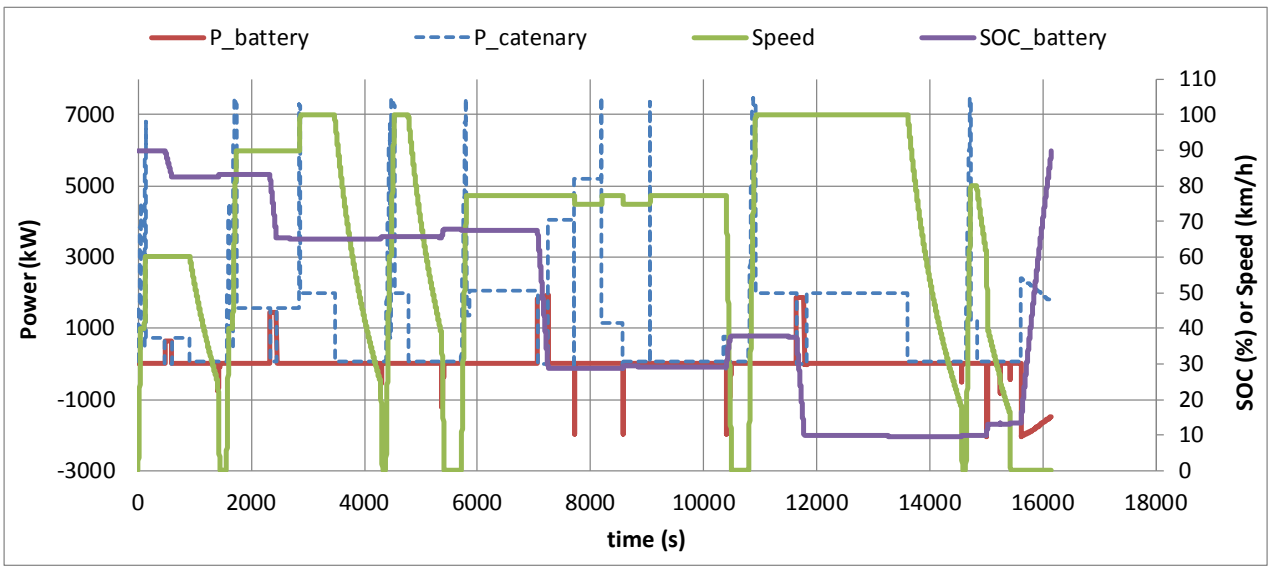

Figure 76. Result with SOC balancing at the end of the course. Battery of 14 branches. Freight mainline service category. Scenario III

Without the mainline (4 positive peaks of the red curve, Figure 76), the battery needs to ensure all electric power requirements so that the size of the battery is considered with 14 branches in parallel.

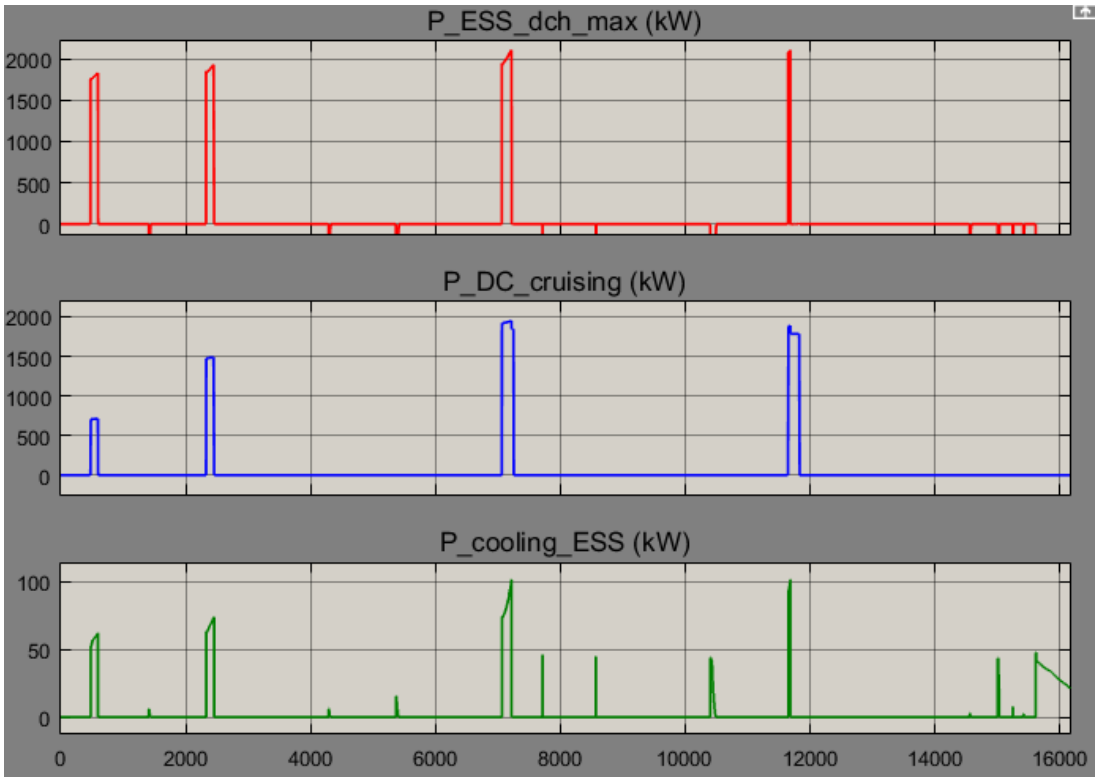

Figure 77. Max discharge power of the battery, electric demand and cooling power. Battery of 14 branches. Freight mainline service category. Scenario III

In Figure 66, $P_{DC,cruising} = P_{DC,trac} + P_{DC,aux} + P_{ESS,cooling}$ is the total power demand of the 4 non-electrified zones (blue curve). The maximum power in discharge of the battery (red curve) is always higher than $P_{DC,cruising}$. The cooling power of the battery is dynamically represented by the green curve with the RMS value is 18kW. For the whole trajectory, the DoD of the battery is 80%.

10.1.4. SOC balancing at the end with 20 branches – peak shaving approach – Scenario IV

Peak shaving approach is an approach to limit the high-power peak requirement by using the battery during the acceleration phases of the train. For a given battery of 20 branches in parallel 45% of DC traction power request comes from the battery in acceleration. This battery size ensures the partial support of the battery to the catenary and maintains the SOC higher than its value 10% before the end of the course

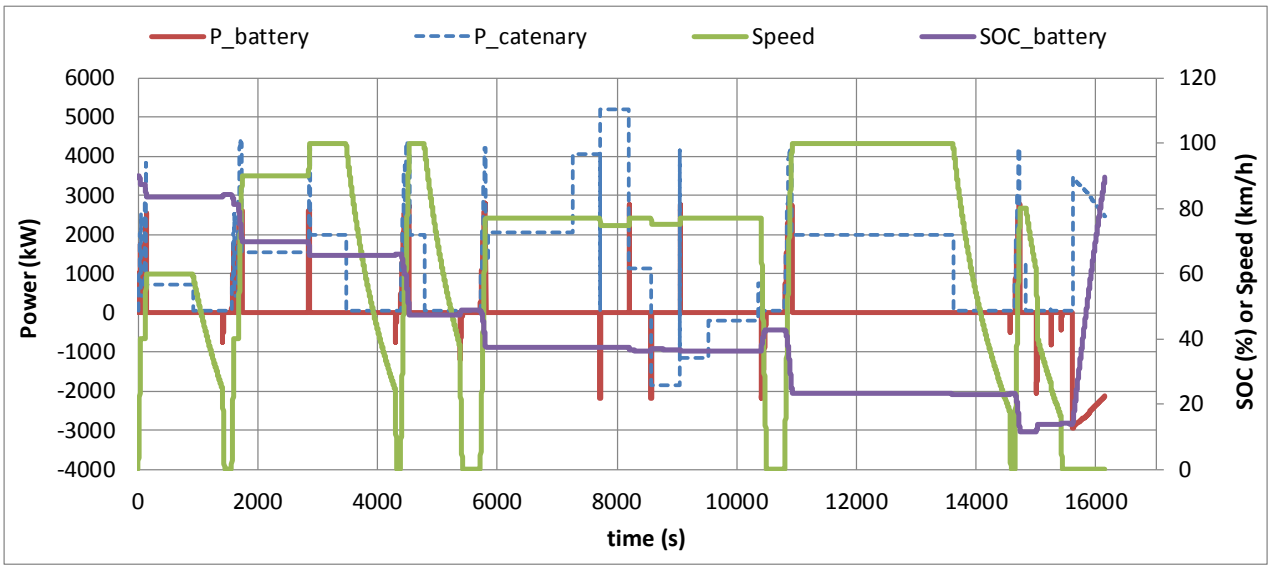

Figure 78. Simulation result with SOC balancing at the end of the course and partially electrified. Battery of 20 branches. Freight mainline service category. Scenario IV.

During the course, the SOC of the battery drops to 10% (at 15000s). Nevertheless, the battery recharges caused by several braking phases till the end of the course. At the end the battery needs 9 min to recharge to 90% of SOC.

10.1.5. Energy optimized operating strategy – Scenario V

For the presented scenario V for the Freight Mainline service category, the ESS covers 2.5% of the traction power ($\varepsilon_{trac} = 0.025$) and 48% of the auxiliary ($\varepsilon_{aux} = 0.48$) as 100% of the braking power is recuperated ($\varepsilon_{rec} = 1$).

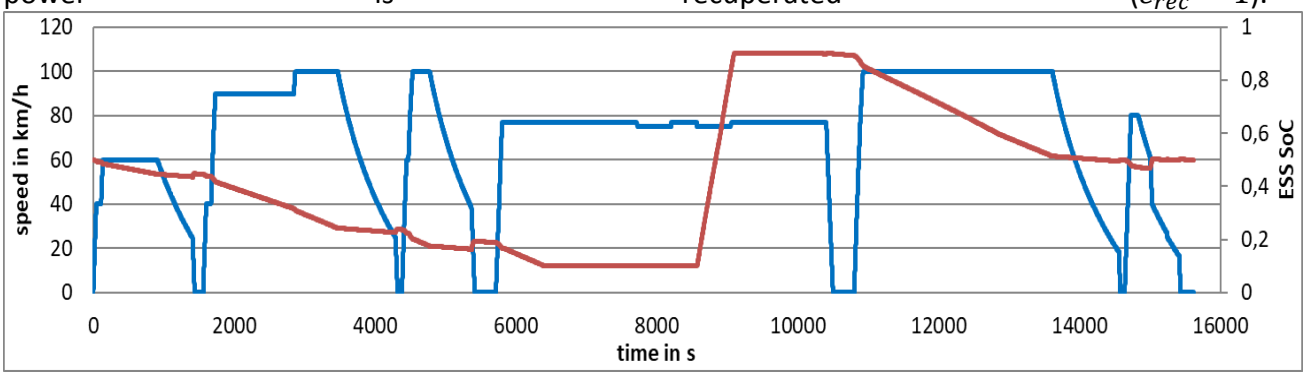

Figure 79. Simulation result with SOC balancing during the course. Battery of 10 branch. Freight Mainline service category. Scenario V

10.1.6. Comparison between scenarios

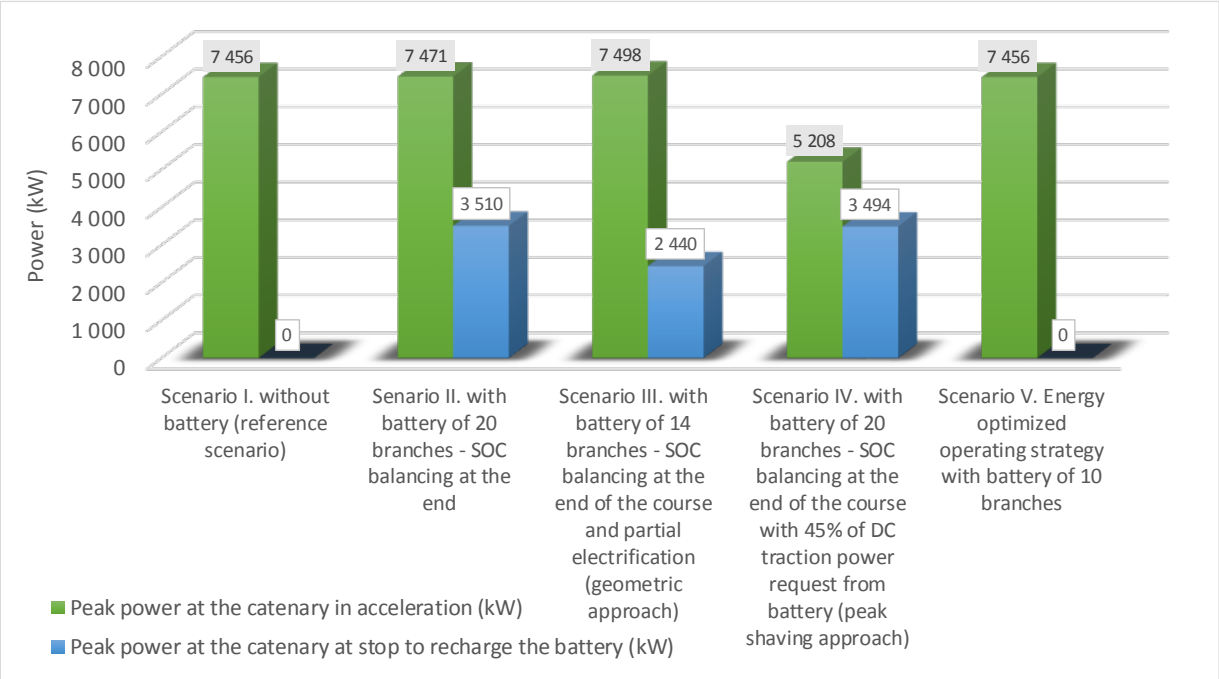

Figure 80: Peak power (in kW) for different scenarios. Freight mainline service category

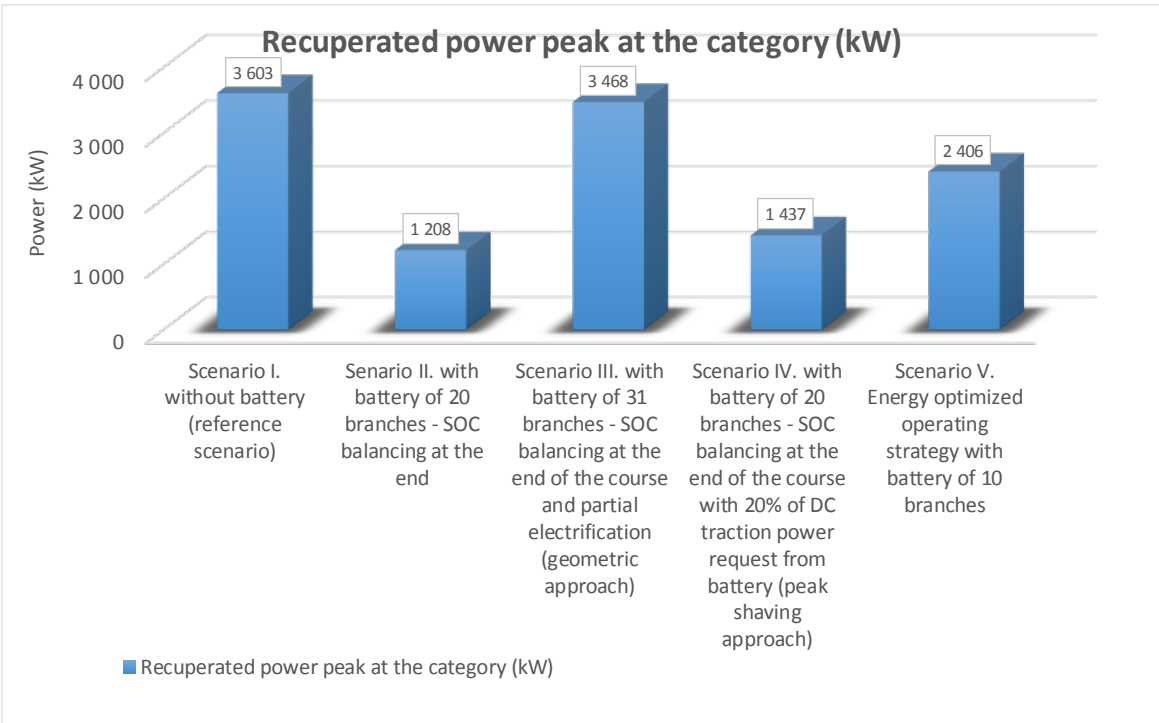

Figure 81: Recuperated peak power (in kW) for different scenarios. Freight mainline service

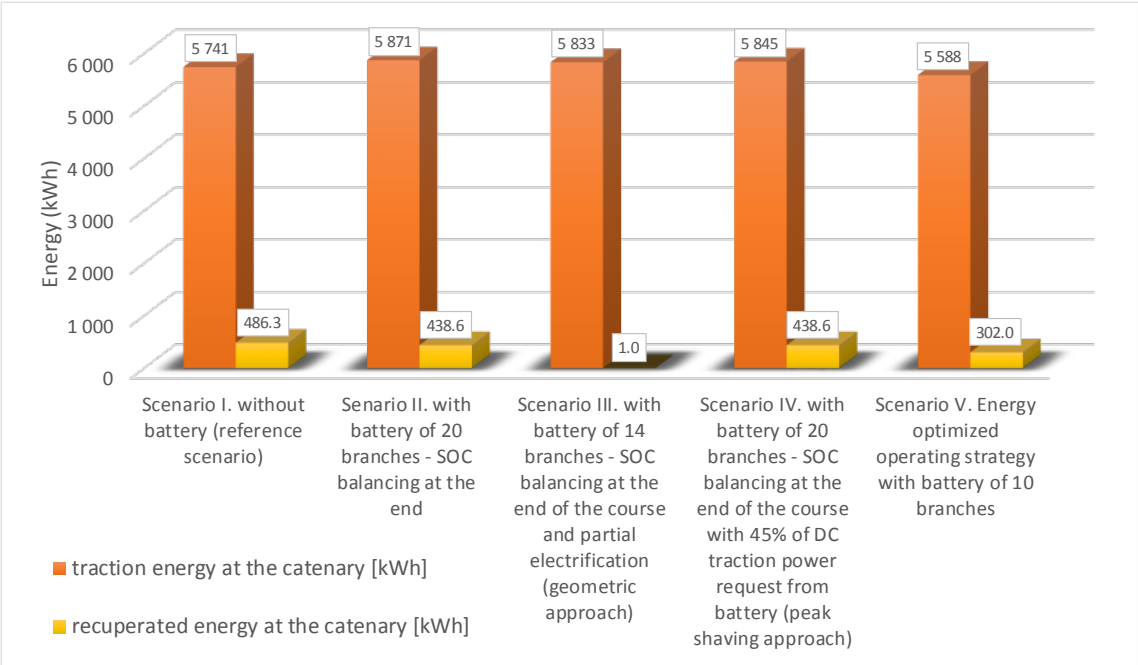

Figure 82: Traction and recuperated energy (in kWh) at the catenary. Freight mainline service category

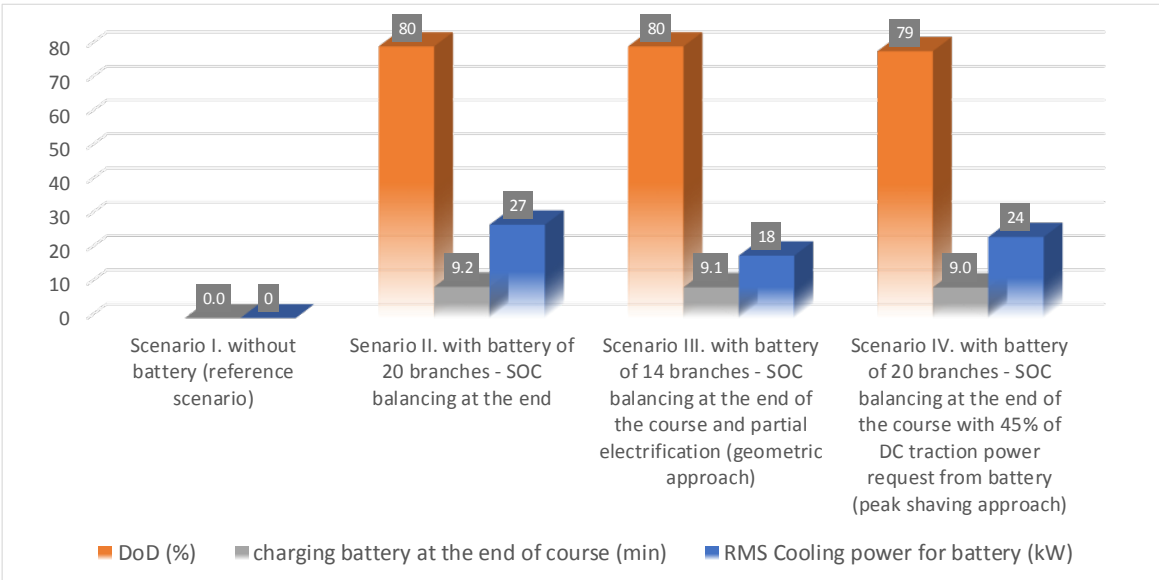

Figure 83: DoD, charging time and RMS cooling power of the battery. Freight mainline service category

The scenario IV illustrates the power peak less important (-30%) compared to the reference case without battery.

11. Conclusions

Several strategies for on-board battery operation into the rail vehicle system are reminded and updated according to the electrification of the rail vehicle. The aim is to evaluate the role of the on-board battery in acceleration by decreasing the power flow from the catenary. The OPEUS simulation allows to assess the energy usage with the on-board battery by studying different scenario and finding out the optimum strategy for each service category.

Concerning the Tramway and Metro services, the scenario III (battery recharging during braking phase and at intermediate stops) allows for halving the peak power and consume less traction energy (-12% and -13% respectively) at the catenary regarding the one of the reference scenario. This scenario is performed with a small Depth of Discharge (6%DoD and 14%DoD) that ensure a very high lifetime of the battery in cycling. In the case of Tramway, the peak power reduction will enable to increase the tramways circulation without increasing the power at catenary with a lower energy consumption. In other case studies of Metro service, the saving peak power will re-distribute to other Metro lines operating under the same network.

For the Regional160 service, the scenario III (4 non-electrified zones, recharge at the end) allows to avoid the electrification of expensive area for infrastructure with a slight consumption of traction energy at the catenary. The scenario IV (peak shaving approach) does allow to reduce by 37% of peak power and consume without increasing significantly the traction energy consumption.

The scenario II (recharge at the end) of the Regional140 service shows the peak shaving advantage (-38%) of peak power in acceleration of the reference scenario by slightly reducing the consumption of traction energy at the catenary.

The High-Speed 300 service requires a lot of traction energy. Thanks to the scenario II, the peak power during acceleration in case with the battery can save 10% of the peak power compared to the case without the battery. Otherwise, the scenario IV (peak shaving approach) of HS250 train illustrates the power peak is less important (-17%) and a slight lower consumption of traction energy than the reference case without battery.

The freight mainline train has the scenario IV (peak shaving approach) with a battery of 20 branches which show the peak power at the catenary (-30%) lower than the one of the scenario I.

The work of UROS on the optimization of the operating strategy was integrated and represented by the scenario V in this deliverable. The cost function based on the total net energy at the catenary and at the end of the course and the dynamic SOC was minimized. The aim of using SOC dependency is to avoid an additional recharge or discharge at the terminal station. The operating parameters of the power split ε_{trac}, ε_{aux} and ε_{rec}, were determined (see section 5) by minimizing the cost function.

The weight of the on-board battery is integrated in the simulation tool. Nevertheless, the limitation in term of weight and of volume installed in the vehicle need to be communicated to realize the pre-sizing of the battery before carrying out the simulation in the detail. Depending on the criteria of optimization in term of CO2 emission or in term of energy cost, further strategies/scenarios of battery operating can be analyzed with the OEMs or the operators of the rail vehicles.

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13. Appendices

TERMS AND DEFINITIONS:

- BOL: Begin Of Life, point at which the battery system has the rated capacity or energy fully available as minimum performance at manufacturer's delivery
- BMS: Battery Management System, system associated with a battery pack which monitors and/or manages its state, disconnect or isolate the battery pack, calculates secondary data, communicates data outside of the battery system and/or controls its environment to influence the battery's safety, performance and/or service life
- BTMS: Battery Thermal Management System, system associated with a battery pack which monitors and/or manages its thermal behavior to maintain the temperature of the battery pack in the intended range for operational pattern agreed between the integrator and the battery system manufacturers
- ESS: Energy Storage System, physical system which consists of one or more ESUs and the other equipment required to connect to the DC link such as converters, control and monitoring systems, inductors, protection devices, cooling systems, etc.
- ESU: Energy Storage Unit, physical equipment which is comprised of an energy storage technology, especially lithium-ion traction battery system in the context of this standard
- EOL: End Of Life, point at which the battery system cannot fulfil the required functionality or operational pattern as initially agreed among the user/ the integrator and the manufacturers
- KPI: Key Performance Indicators
- OCV: Open Circuit Voltage
- Lower limit discharging voltage of cell: lowest discharging voltage in the cell operating region from a safety stand point specified by the cell supplier
- Maximum voltage of the battery system: highest voltage of the battery system in which the maximum voltage of any individual cell is below the upper limit charging voltage of cell and any components operate in
- Nominal voltage: suitable approximate value of voltage used to designate or identify the voltage of a cell or battery system
- Rated capacity: capacity value of a cell or battery determined under specified conditions and declared by the manufacturer
- SEI: Solid Electrolyte Interphase
- Self-discharge: phenomenon by which a cell or battery system loses energy in other ways than by discharge into an external circuit
- SOC : State Of Charge. remaining capacity to be discharged, normally expressed as a percentage of full capacity by 303 selected expression as defined in Annex A of IEC 62864-1:2016
- SOE: State Of Energy
- Upper limit charging voltage of cell: highest charging voltage in the cell operating region from a safety stand point specified by the cell supplier