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Deliverable D 5.2
Analysis of energy losses in the traction chain

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1. Executive Summary

The work presented in this Deliverable D5.2 has been carried out in the framework of the EU Project OPEUS. This deliverable presents the analysis of energy losses in the reference rail vehicle architectures described in previous OPEUS task 5.1 and an investigation on different vehicle parameters and strategies to improve energy consumption.

The first part of this report shows the energy loss distribution diagrams for all rail service categories or scenarios in order to identify the energy losses in the traction chain as well as the components having a higher influence in energy consumption. Component efficiencies are analysed for the operation modes. For rail vehicles with AC supply (which follow Topology T01[1]) it is concluded that the traction motor and transformer are the biggest contributors to energy losses, they together represent up to 71.46% of overall energy losses in the case of suburban, with a minimum of 66.34% in the case of intercity scenario. For rail vehicles with DC supply (which follow Topology T03) it is concluded that the traction motor is the biggest contributor to energy losses, accounting for 67.74% and 66.61% in the case of the tram and metro scenarios respectively.

Energy loss distribution is also analysed for a Tram with ESS, where the traction motor accounts for the majority of the energy losses too, with 45.67%. However, in this case, the introduction of the ESS and its converter represents the second highest contributor to the energy losses, contributing to 33.8% of the overall energy losses. Despite the additional weight of the ESS components, the consumed traction energy at the catenary is nearly the same regarding the one of the reference scenario. But in addition, the ESS scenario allows for halving the power peaks at the catenary which is beneficial for the net characteristics.

An analyses on the operational phases is made for the different rail scenarios to quantify the energy losses during acceleration, cruising, coasting and braking. Depending on the service and route characteristics the losses are concentrated in different phases, e.g.: in urban services the major energy losses are concentrated in the acceleration phase and also in no traction phases (coasting and stops at stations), while main line services like freight or high speed have considerably energy losses during cruising operational phase.

The last part of the report makes a sensitivity analysis to investigate the impact in the energy consumption of different vehicle parameters and strategies:

- The effect of auxiliary loads occurring during the different operational phases are investigated in the tram scenario.
- Traction motor switch-off strategy is implemented in all scenarios, finding out that urban and regional services have the biggest energy savings, achieving 9% energy savings in the case of the tram scenario.
- The influence of the tare mass parameter (+/- 10 %) is analysed in all scenarios, having considerable energy improvements for lighter trains: up to 8.25% energy savings in the case of the metro.

[1] Check Appendix 1 to see vehicle architectures or topologies.

- The effect of the aerodynamic drag of the train vehicle is investigated through the resistance factor k_4[2], resulting that a 10% reduction in factor k_4 causes a 5.66% reduction in HS300 energy consumption.
- Finally, the influence of the rotating masses is also investigated, finding out hardly influence on energy consumption.

The analysis concludes that in both AC and DC rail vehicles, the traction motor is the highest contributor to energy losses, especially during no load operation. Therefore, the implementation of partial switch-offs of traction components has the most significant effect on energy savings, if it is utilised on a service with long coasting phases or standstill at stations. Due to the high portion of standstill and coasting, urban and regional services offer the most significant potential for the application of this operating strategy. However, if a service has hardly coasting times and a high time percentage of traction phases other strategies may apply. In the last case a train mass reduction can be very interesting, as acceleration power is directly related to the hauled mass. In addition, the improvement of aerodynamics will significantly improve the energy efficiency in high speed services. Finally, it is expected that new E-transformers, with higher energy efficiency than conventional transformers, contributes to reduce overall energy losses in rail vehicles with AC supply. This is checked in OPEUS Deliverable 3.4 [7], which provides an overview of some innovations of the Shift2Rail technical demonstrators, including the improved energy efficiency of the transformers.

[2] Total driving resistance: $F_{res} = k_0 + k_1 v + k_2 m_{train} + k_3 m_{train} v + k_4 v^2 + k_5 m_{train} v^2$, please refer to D2.1 [2]

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
AC	Alternating Current
CCA	Cross Cutting Activity
DC	Direct Current
DoD	Depth of Discharge (refers to ESS)
ESS	Energy Storage System
FINE1	Future Improvement for Energy and Noise. EU S2R Project, Grant Agreement Number: 730818
FrMain	Freight Mainline service
HS300 or High Speed 300	High Speed service at 300km/h
HS250 or High Speed 250	High Speed service at 250 km/h
IC	Intercity service
Reg160	Regional service at 160 km/h
Reg140	Regional service at 140 km/h
SOC	State of Charge (refers to ESS)
Suburb	Suburban service
WP	Work Package

3. Background

The present document constitutes the Deliverable D5.2 “Analysis of energy losses in the traction chain” in the framework of WP05 In-vehicle energy losses study of OPEUS project (S2R-OC-CCA-02-2015).

This report uses WP02 and WP03 results, as well as task 5.1 and contributes to Deliverable 3.4 [7] and to WP07 of OPEUS Project. Results of this report contributes to objectives of FINE1 project and CCA energy group of Shift2Rail.

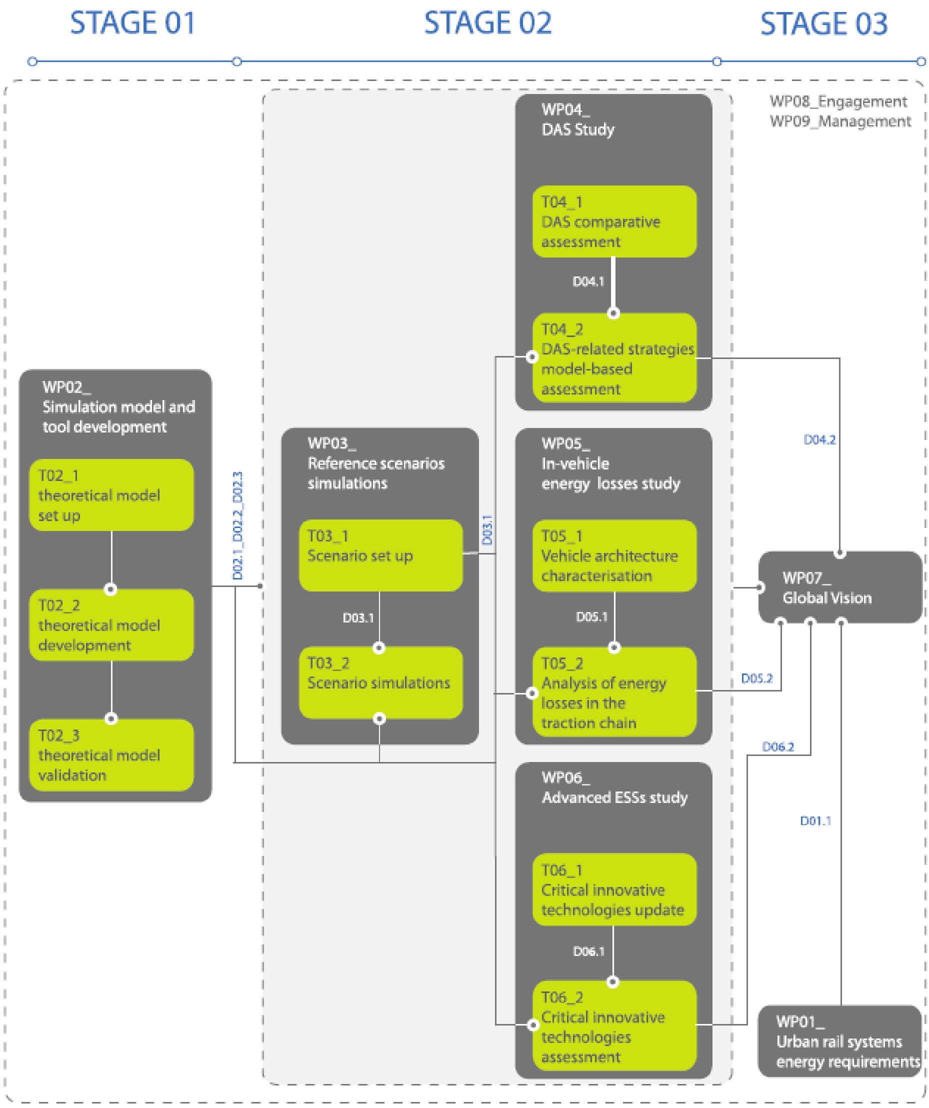


Figure 1: Relationship between the different activities included in the OPEUS work plan

4. Objective/Aim

The objective of this deliverable is to investigate the energy losses in the reference vehicle architectures described in task 5.1 for the four operational phases (acceleration, cruising, coasting and braking), identifying the components having a higher influence in energy consumption and providing energy loss diagrams.

This report also has the objective to investigate the impact in the energy consumption of different vehicle parameters and energy strategies in order to identify what strategies are more suitable for the different rail scenarios.

This aim is linked to the objectives of FINE1 and CCA energy group of Shift2Rail.

5. Energy loss distribution

Energy loss distributions diagrams have been done for all service categories or scenarios in order to identify the energy losses in the traction chain as well as the components having a higher influence in energy consumption.

The simulations used as reference for this energy study have been done with OPEUS Tool V6, using coasting speed profile according to the timetable and a maximum amount of coasting, as indicated in the green curve in Figure 2 (see baseline definition in OPEUS Deliverable 3.2 [8]). The scenarios or services considered are the ones defined in OPEUS Deliverable 3.1 [1], which was done in collaboration with FINE1 partners.

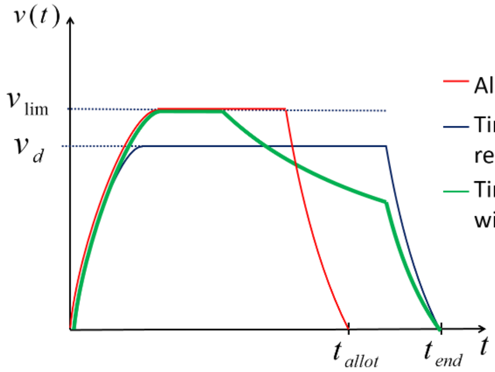


Figure 2: Possible trajectory modes

The next sections (5.1, 5.2, 5.3 and 5.4) present the different energy diagrams for each of the different scenarios. Every energy loss analysis is made from the energy consumption at the catenary to the energy at the wheel. The simulations, in analogy to real trains, take into account the regeneration of braking energy, therefore every diagram shows the energy flow of both the traction energy as well as the regenerated energy. Traction energy is indicated in white numbers, while regenerated energy is indicated in (black numbers). Furthermore, the energy losses for every component are indicated. These losses indicate the overall energy losses of the component in the specific service, including traction, regeneration and no load losses. The diagrams also show that part of the recuperated energy of motor converters at DC-Link is used to cover part of the auxiliaries and on board battery blocks requests. The rest of the energy is fed back to the catenary.

The service categories are:

- Urban: including tram, metro and suburban services.
- Regional: including Reg140 and Reg160 services.
- High-speed: including High Speed 300, High Speed 250 and intercity services.
- Freight, which refers to freight main line services.

Section 5.5 presents an analysis of the efficiency characteristics for every traction chain component for vehicles that have an architecture according to Topology T03, while vehicles that follows Topology T01 are included in section 5.6. Tram and metro vehicles use DC power supply and have an architecture according to topology T03, while the other vehicles use AC power supply and follow topology T01.

Topologies have been presented in several previous OPEUS deliverables (Deliverables 2.1 [2], 3.1 [1] and 5.1 [3]), but here are included again in the Appendix 1: Vehicle architectures. Topologies for reference. In order to check vehicle and services characteristics refer to OPEUS Deliverable 3.1 [1] and FINE1 Deliverable 3.1 [4].

5.1. Urban service

This chapter presents the energy loss distributions for the tram, metro and suburban services.

5.1.1. Tram service

Figure 3 presents the energy flow of the tram scenario. For each component absolute numbers, for traction and regenerated energy are indicated. As mentioned above, white numbers refer to traction energy, while (black numbers) refer to regenerated energy. The energy losses indicate the overall energy losses of the component during the tram service, including traction and regeneration operation as well as idle losses during no load operation.

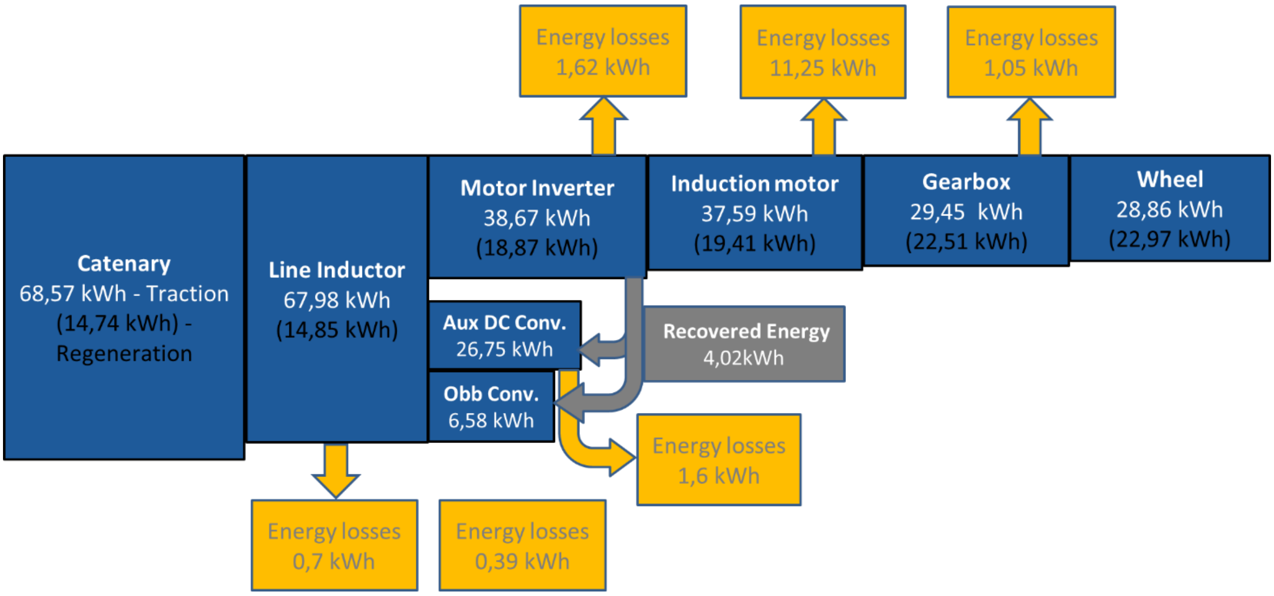


Figure 3: Tram energy loss diagram

The main numbers that can be deducted from the above diagram are:

- Total energy consumption at the catenary is 68.57 kWh.
- Recuperated energy at the catenary is 14.74 kWh.
- Recuperation factor[3] is 21.5%.

[3] Recuperation factor is calculated as the ratio between the recuperated energy at the catenary and the total energy consumption at the catenary.

- Total auxiliary consumption is 33.3 kWh.
- Traction energy at wheel is 28.86 kWh.
- Overall energy losses are 16.61 kWh.

Figure 4 shows the energy losses percentage for every component, so with both figures it is easier to analyse what component has the major influence on energy losses.

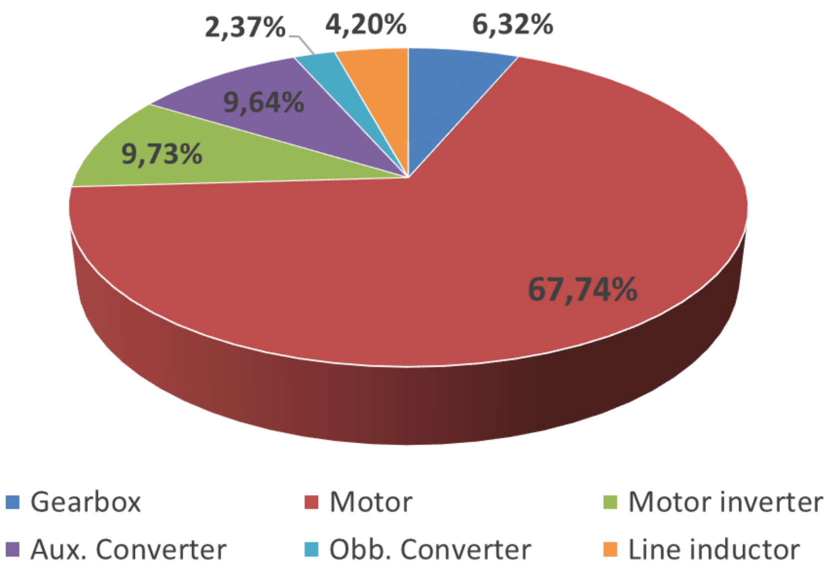


Figure 4: Tram energy losses % per component

The energy losses in the traction motor represents the biggest majority, with a 67.74%, followed by the motor inverter and the auxiliary converter that account for 9.73% and 9.64% respectively. Therefore, in a tram vehicle an increase of the traction motor efficiency (either in components efficiency or motor control strategy) will result in major benefits in terms of energy consumption. Check section 5.5 for more information on tram component efficiency and energy losses analysis.

5.1.2. Metro service

Figure 5 presents the energy flow of the metro scenario. The components are the same as in the tram service, as they both uses the same vehicle Topology T03. As mentioned above, white numbers refer to traction energy, while (black numbers) refer to regenerated energy. The energy losses indicate the overall energy losses of the component during the metro service, including traction and regeneration operation as well as idle losses during no load operation.

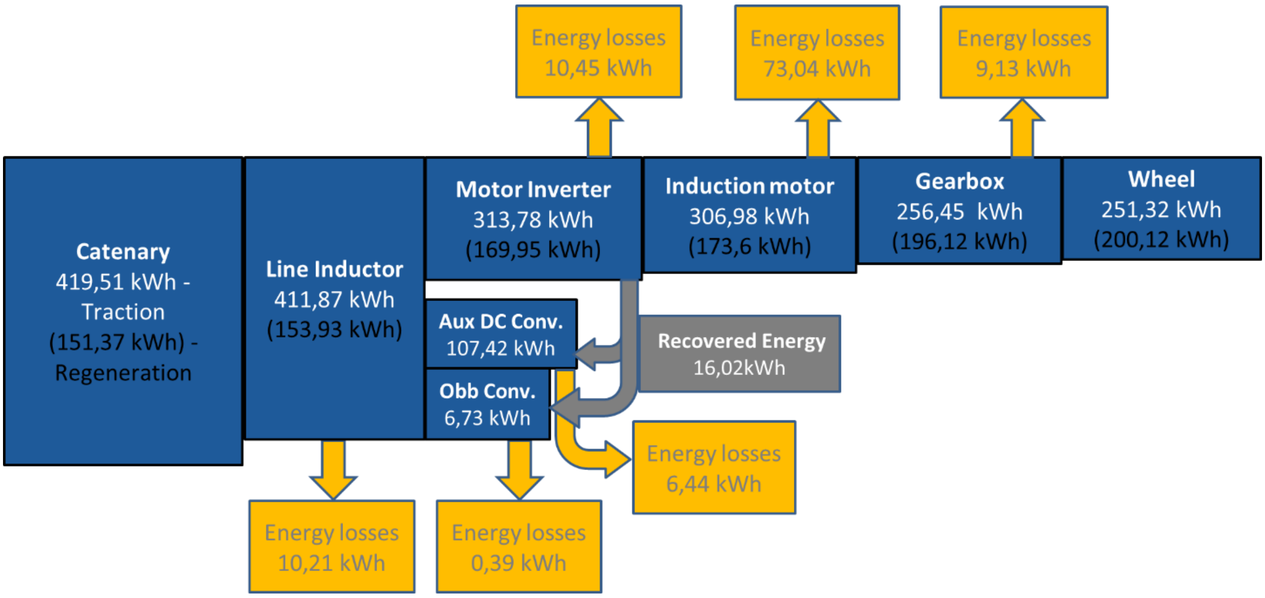


Figure 5: Metro energy loss diagram

The main numbers that can be deducted from the above diagram are:

- Total energy consumption at the catenary is 419.51 kWh.
- Recuperated energy at the catenary is 151.37 kWh.
- Recuperation factor is 36%.
- Total auxiliary consumption is 114.1 kWh.
- Traction energy at wheel is 251.32 kWh.
- Overall energy losses are 109.66 kWh.

Figure 6 shows the energy losses percentage for every metro traction chain component.

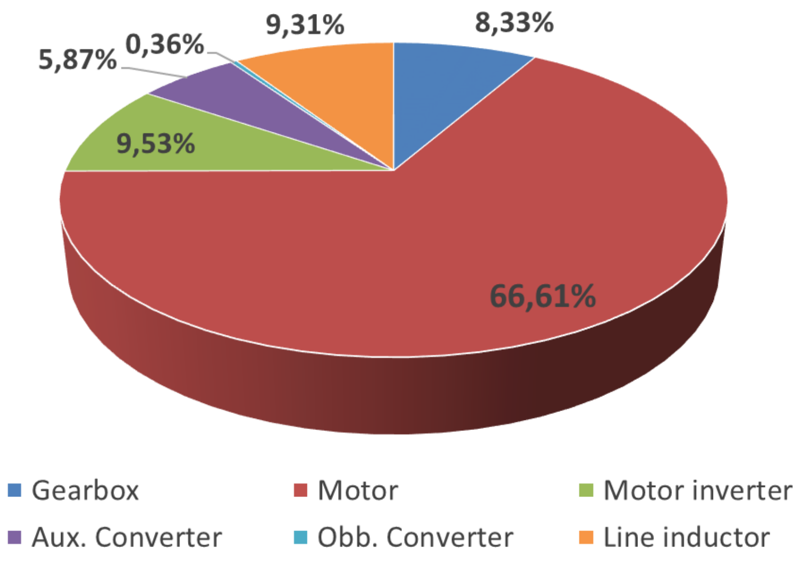


Figure 6: Metro energy losses % per component

The energy loss distribution of the metro services is very similar to the tram one: Both have the major losses on the traction motor component. The same conclusions are applicable to both rail urban services. Check section 5.5 for more information on metro component efficiency and energy losses analysis.

5.1.3. Suburban service

Figure 7 presents the energy flow of the suburban scenario. As for the other vehicle diagrams, white numbers refer to traction energy, while (black numbers) refer to regenerated energy. The energy losses indicate the overall energy losses of the component during the suburban service, including traction and regeneration operation as well as idle losses during no load operation.

Suburban scenario operates with 15 kV AC (16.7Hz) power supply and follows Topology T01, therefore Figure 7 presents the traction components of this vehicle architecture.

The main numbers that can be deducted from Figure 7 are:

- Total energy consumption at the catenary is 717.13 kWh.
- Recuperated energy at the catenary is 202.89 kWh.
- Recuperation factor is 28.3%.
- Total auxiliary consumption is 120.4 kWh.
- Traction energy at wheel is 425.04 kWh.
- Overall energy losses are 262.5 kWh.

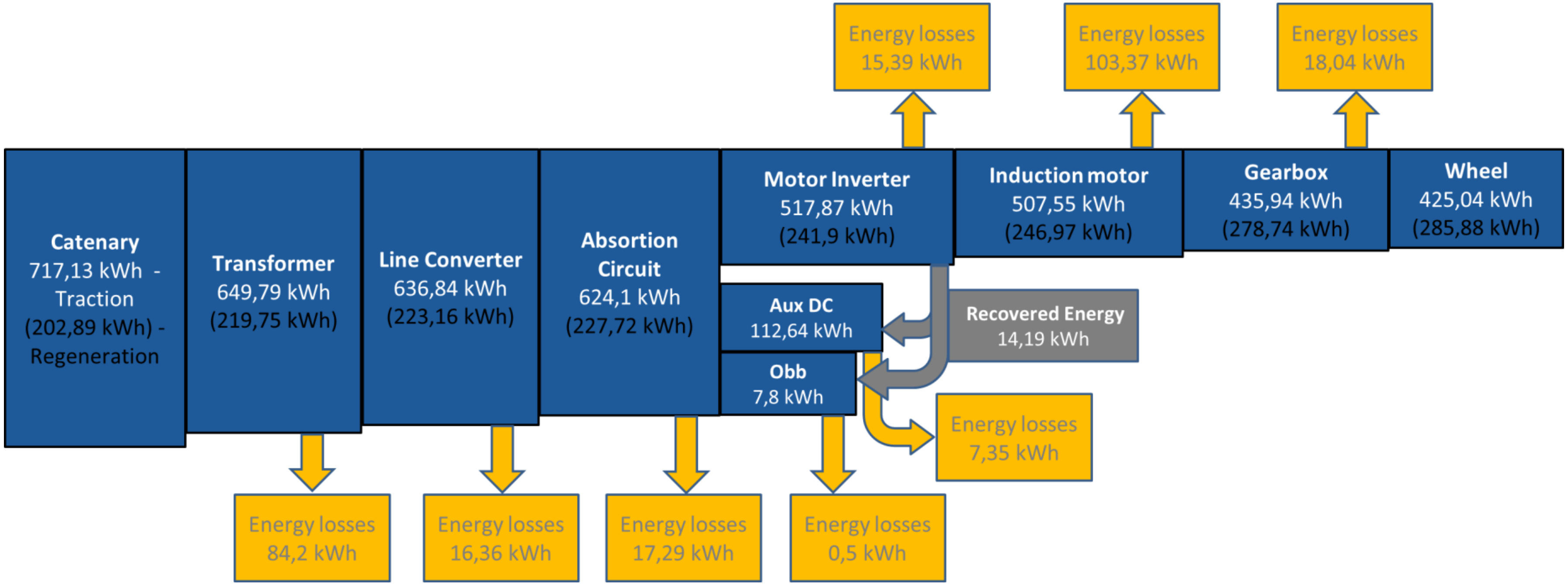


Figure 7: Suburban energy loss diagram

Figure 8 shows the energy losses percentage for every suburban traction chain component.

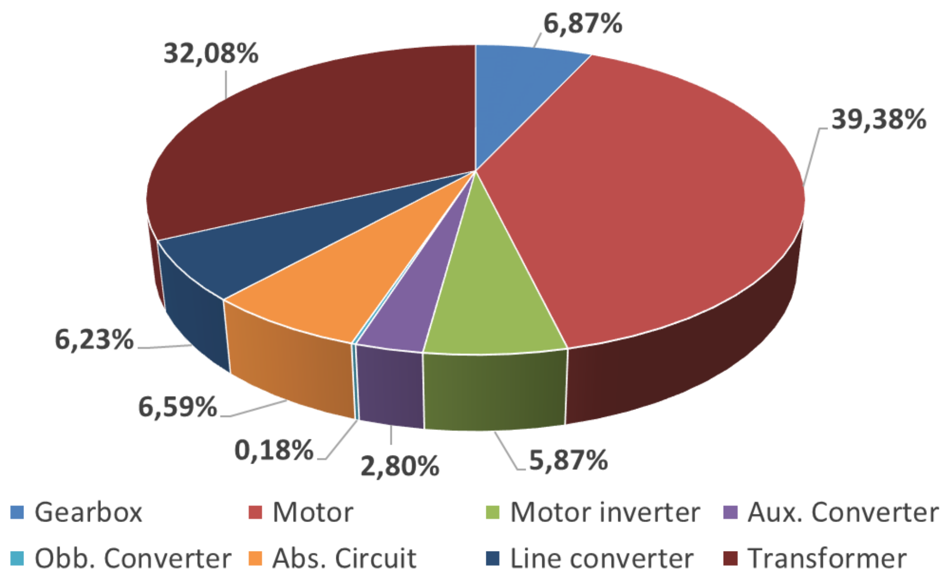


Figure 8: Suburban energy losses % per component

As can be seen above, two traction chain components are responsible for more than 71% of the total suburban energy losses: the traction motor represents the biggest majority, with a 39.38%, followed by the transformer that accounts for 32.08%. Check section 5.6 for more information on suburban component efficiency and energy losses analysis.

5.2 Regional service

This chapter presents the energy loss distribution of the two regional services considered: scenario Reg140 (as described in prEN 50591) and scenario Reg160 (serviced based on Intercity from prEN 50591, but limited to 160km/h and 7 additional stops). As indicated in the introduction of chapter 5, please refer to OPEUS Deliverable 3.1 [1] and FINE1 Deliverable 3.1 [4] to check vehicle and route services characteristics.

5.2.1 Reg140 service

Figure 9 presents the energy flow of the Reg140 scenario. White numbers refer to traction energy, while (black numbers) refer to regenerated energy. Overall energy losses of the component during the Reg140 service, including traction and regeneration operation as well as idle losses during no load operation are shown.

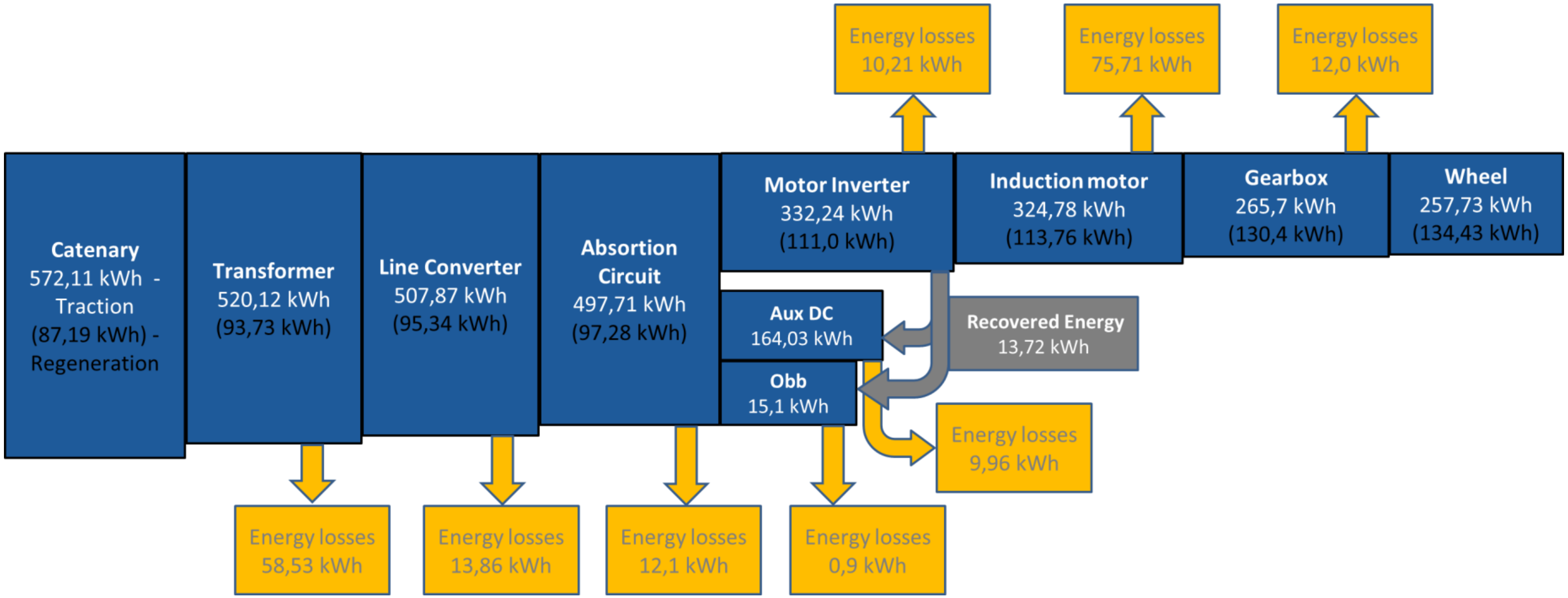


Figure 9: Reg140 energy loss diagram

Reg140 vehicle scenario follows Topology T01 and can operate with 15 kV AC (16.7Hz) or 25 kV AC (50Hz) power supply.

The main numbers that can be deducted from Figure 9 are:

- Total energy consumption at the catenary is 572.11 kWh.
- Recuperated energy at the catenary is 87.19 kWh.
- Recuperation factor is 15.24%.
- Total auxiliary consumption is 179.1 kWh.
- Traction energy at wheel is 257.7 kWh.
- Overall energy losses are 193.28 kWh.

Figure 10 shows the energy losses percentage for every Reg140 traction chain component.

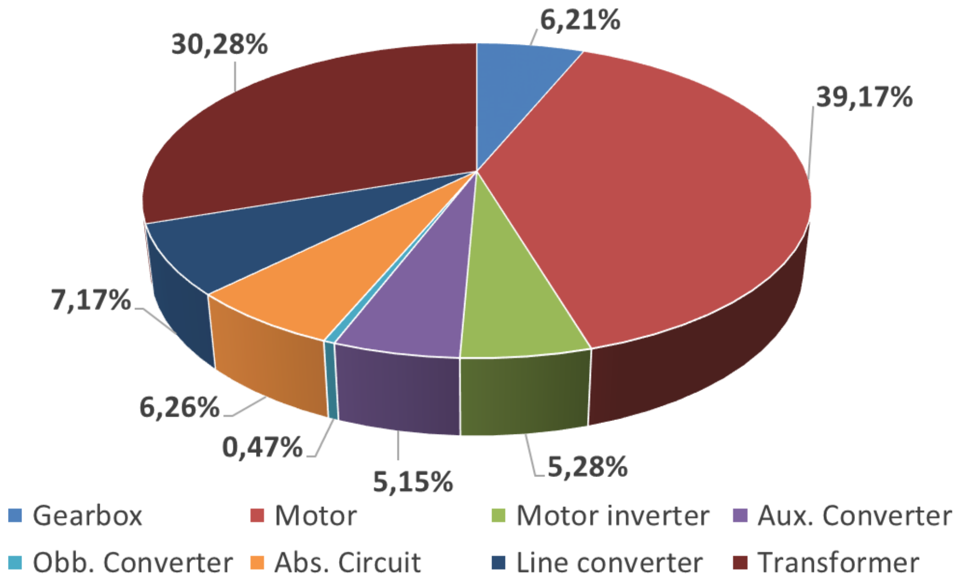


Figure 10: Reg140 energy losses % per component

As in the suburban, in the Reg140 scenario the traction motor and the transformer accounts for the majority of the total vehicle energy losses, with 39.17% and 30.28% respectively. Check section 5.6 for more information on Reg140 component efficiency and energy losses analysis.

5.2.1 Reg160 service

Figure 11 presents the energy flow of the Reg160 scenario. White numbers refer to traction energy, while (black numbers) refer to regenerated energy. Overall energy losses of the component during the Reg160 service, including traction and regeneration operation as well as idle losses during no load operation are shown.

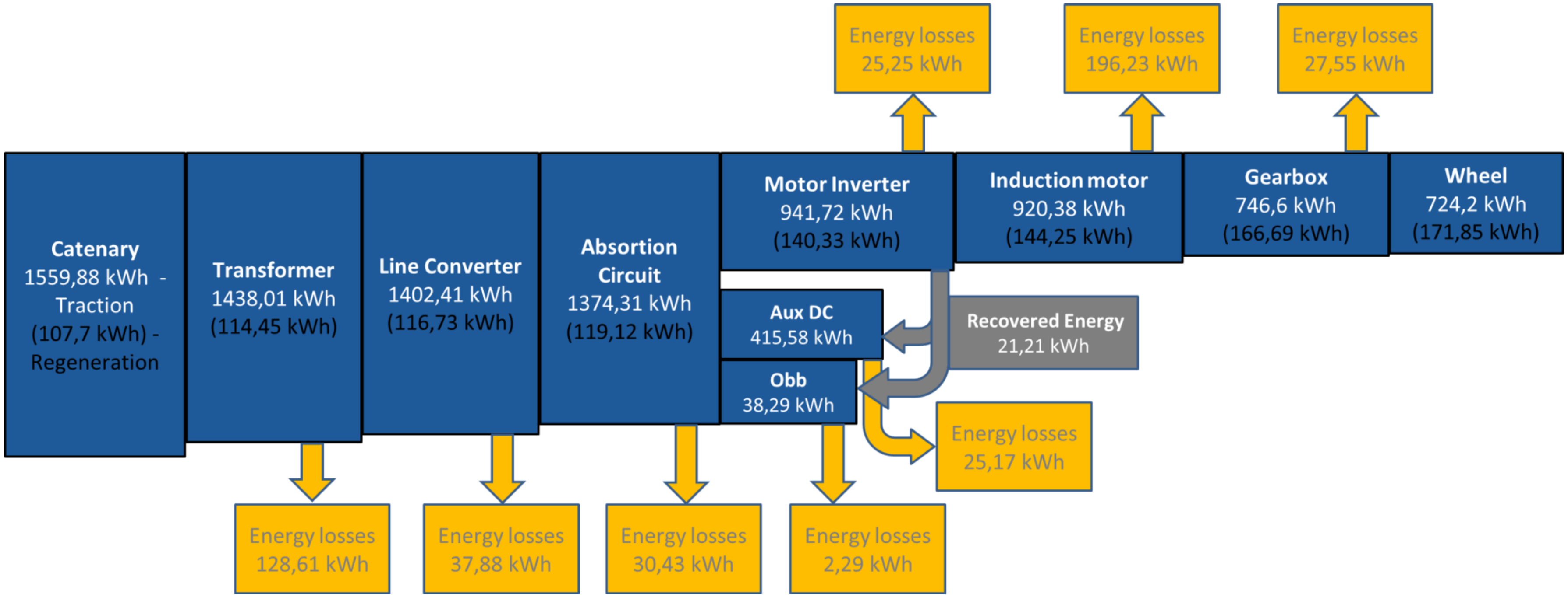


Figure 11: Reg160 energy loss diagram

As Reg140, Reg 160 vehicle scenario follows Topology T01 and can operate with 15 kV AC (16.7Hz) or 25 kV AC (50Hz) power supply.

The main numbers that can be deducted from Figure 11 are:

- Total energy consumption at the catenary is 1559.88 kWh.
- Recuperated energy at the catenary is 107.7 kWh.
- Recuperation factor is 6.9%.
- Total auxiliary consumption is 453.8 kWh.
- Traction energy at wheel is 724.2 kWh.
- Overall energy losses are 473.4 kWh.

Figure 12 presents the energy losses percentage for every Reg160 traction chain component.

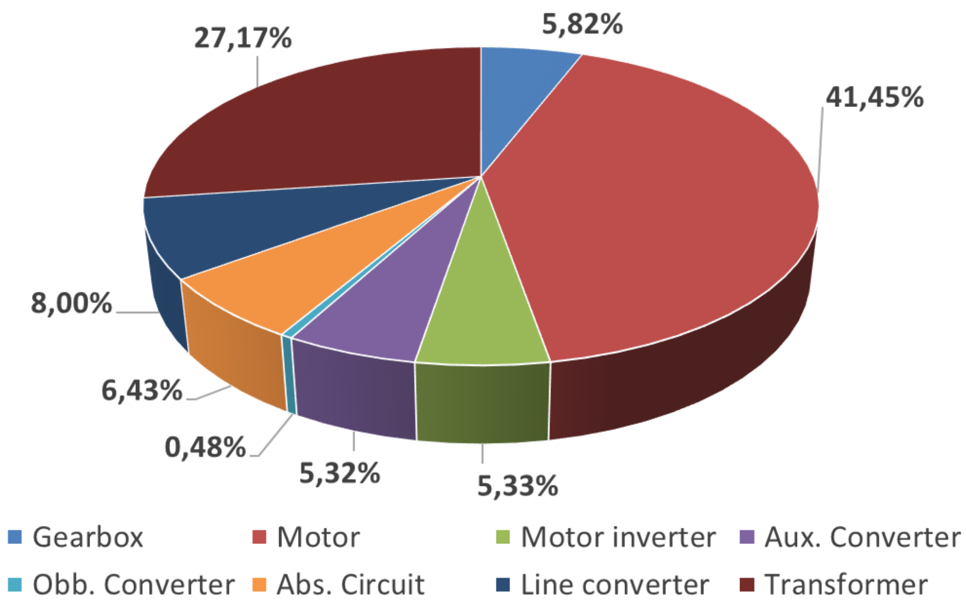


Figure 12: Reg160 energy losses % per component

As in the suburban or Reg140 scenarios, in the Reg160 scenario the traction motor and the transformer accounts for the majority of the total vehicle energy losses, with 41.45% and 27.17% respectively. Check section 5.6 for more information on Reg160 component efficiency and energy losses analysis.

5.3 High Speed service

This chapter presents the energy loss distribution of the high speed and intercity services: Scenario High Speed 300 (as described in prEN 50591), scenario High Speed 250 (based on scenario High speed from prEN 50591, but limited to 250km/h and with 2 additional stops), and intercity service (as described in prEN

50591). As indicated in the introduction of chapter 5, please refer to OPEUS Deliverable 3.1 [1] and FINE1 Deliverable 3.1 [4] to check vehicle and route services characteristics.

5.3.1 High Speed 300 service

Figure 13 presents the energy flow of the High Speed 300 scenario. As for the other vehicle diagrams, white numbers refer to traction energy, while (black numbers) refer to regenerated energy. The energy losses indicate the overall energy losses of the component during the High Speed 300 service, including traction and regeneration operation as well as idle losses during no load operation.

High Speed 300 scenario operates with 25 kV AC (50Hz) power supply and follows Topology T01.

The main numbers that can be deducted from Figure 13 are:

- Total energy consumption at the catenary is 5135.92 kWh.
- Recuperated energy at the catenary is 80.89 kWh.
- Recuperation factor is only 1.5%.
- Total auxiliary consumption is 553.08 kWh.
- Traction energy at wheel is 3502.63 kWh.
- Overall energy losses are 1154.5 kWh.

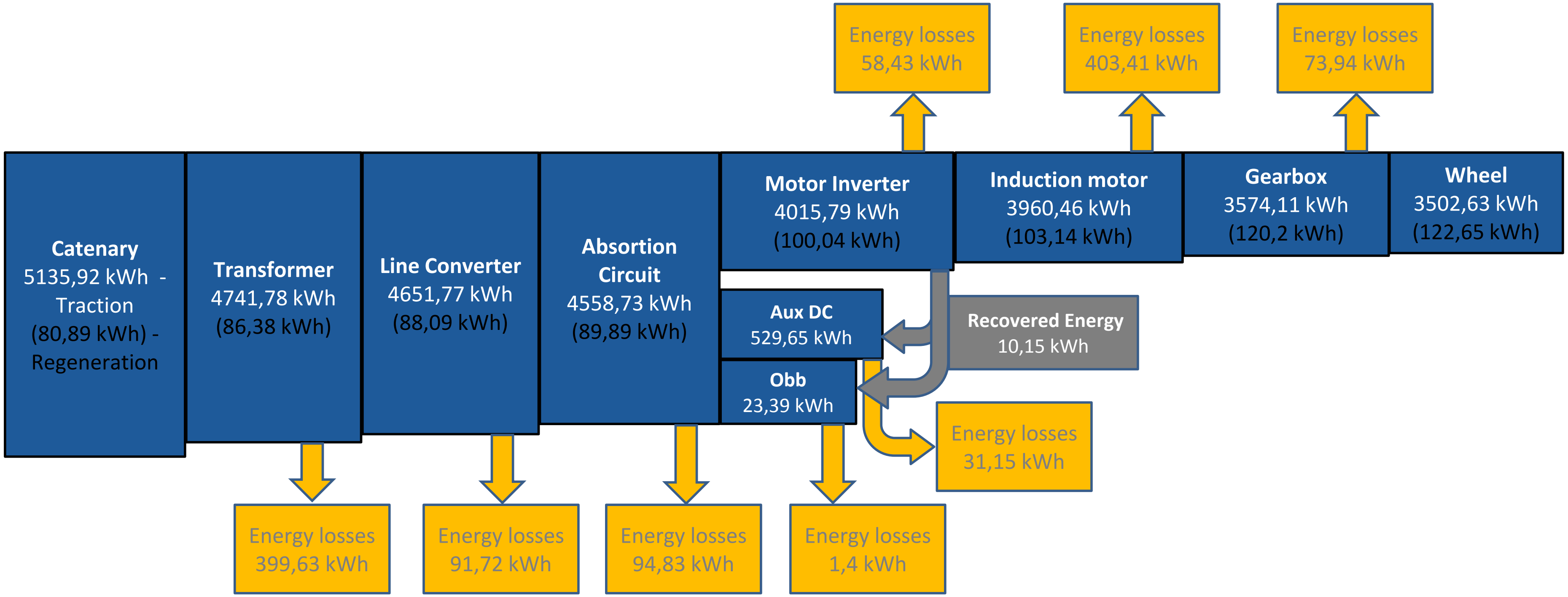


Figure 13: High Speed 300 energy loss diagram

Figure 14 presents the energy losses percentage for every High Speed 300 traction chain component.

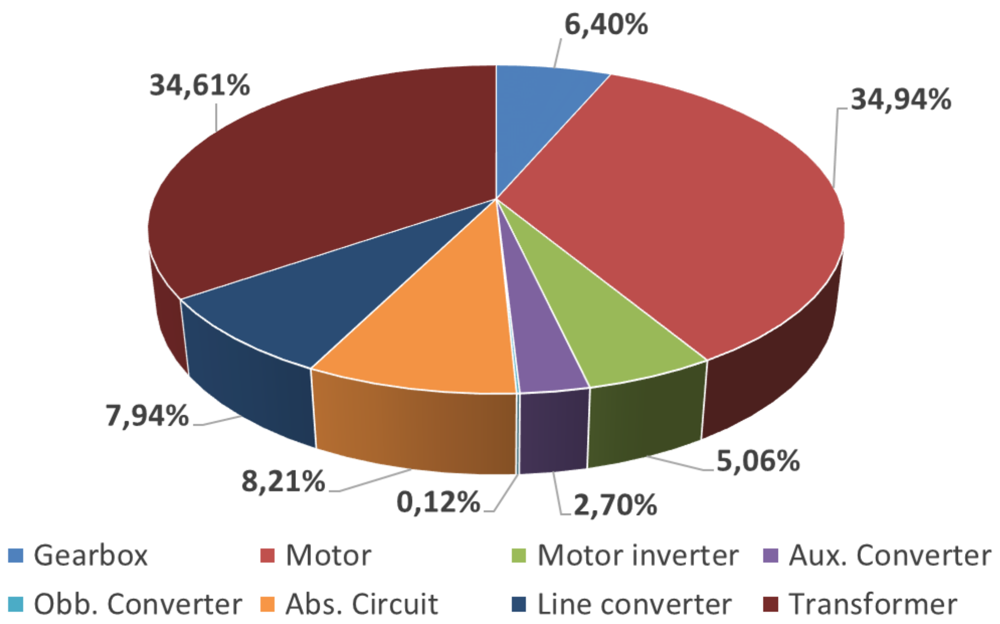


Figure 14: High Speed 300 energy loss % per component

As can be seen from Figure 14, traction motor and transformer have nearly the same contribution to energy losses, approximately 35% each. The two systems together account for the majority of the energy losses. Check section 5.6 for more information on High Speed 300 component efficiency and energy losses analysis.

5.3.2 High Speed 250 service

Figure 15 presents the energy flow of the High Speed 250 scenario. White numbers refer to traction energy, while (black numbers) refer to regenerated energy. Overall energy losses of the component during the High Speed 250 service, including traction and regeneration operation as well as idle losses during no load operation are shown.

High Speed 250 scenario operates with 15 kV AC (16.7Hz) power supply and follows Topology T01.

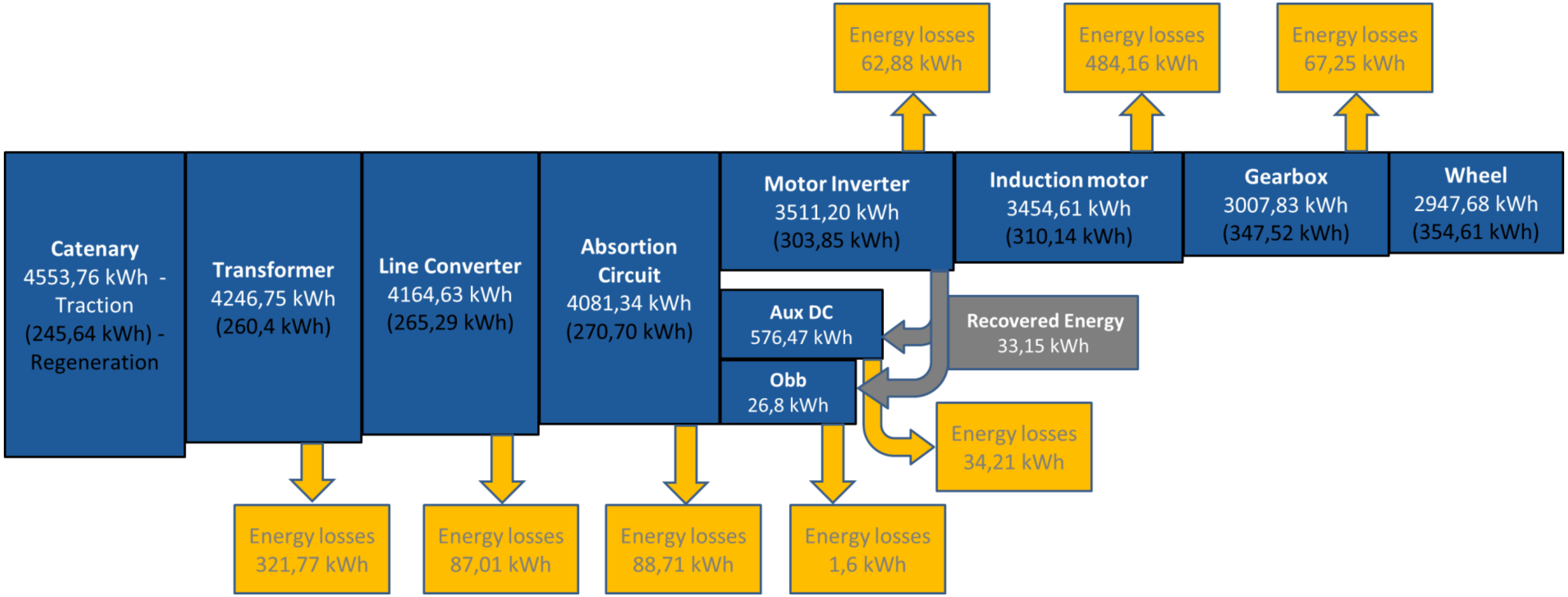


Figure 15: High Speed 250 energy loss diagram

The main numbers that can be deducted from Figure 15 are:

- Total energy consumption at the catenary is 4553.76 kWh.
- Recuperated energy at the catenary is 245.64 kWh.
- Recuperation factor is 5.4%.
- Total auxiliary consumption is 603.29 kWh.
- Traction energy at wheel is 2947.68 kWh.
- Overall energy losses are 1147.6 kWh.

Figure 16 presents the energy losses percentage for every High Speed 250 traction chain component.

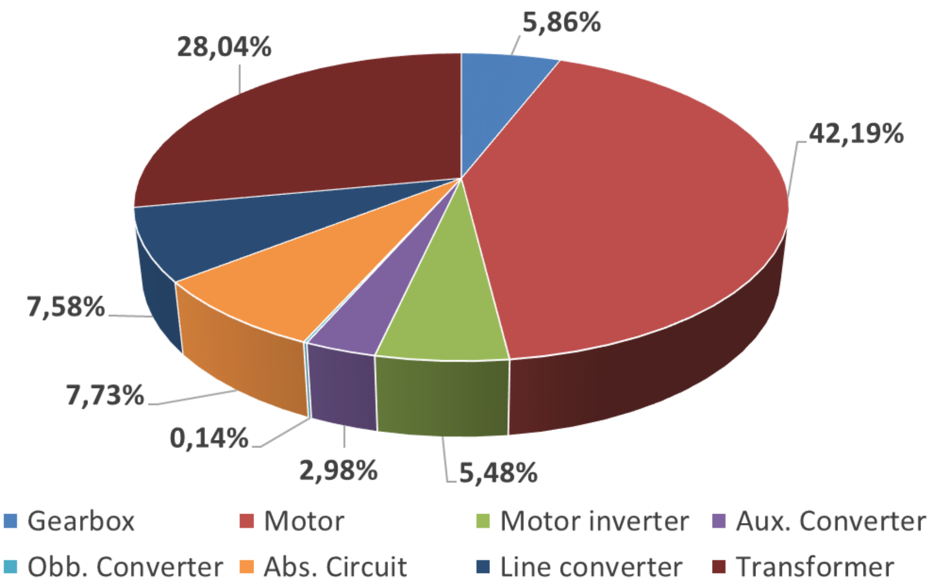


Figure 16: High Speed 250 energy loss % per component

In the High Speed 250 scenario the traction motor and the transformer, again, accounts for the majority of the total vehicle energy losses, with 42.19% and 28.04% respectively. Check section 5.6 for more information on High Speed 250 component efficiency and energy losses analysis.

5.3.3 Intercity service

Figure 17 presents the energy flow of the intercity scenario. White numbers refer to traction energy, while (black numbers) refer to regenerated energy. Overall energy losses of the component during the intercity service, including traction and regeneration operation as well as idle losses during no load operation are shown.

Intercity scenario operates with 15 kV AC (16.7Hz) power supply and follows Topology T01.

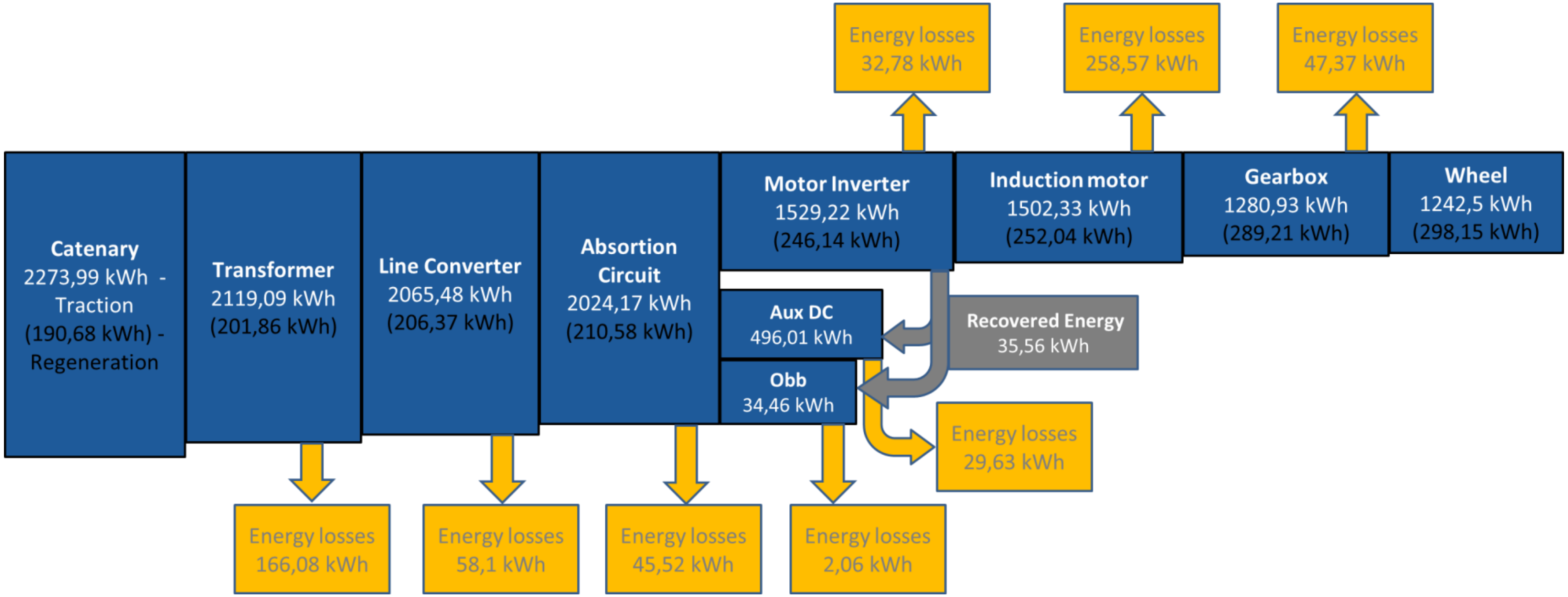


Figure 17: Intercity energy loss diagram

The main numbers that can be deducted from Figure 17 are:

- Total energy consumption at the catenary is 2273.99 kWh.
- Recuperated energy at the catenary is 190.68 kWh.
- Recuperation factor is 8.4%.
- Total auxiliary consumption is 530.47 kWh.
- Traction energy at wheel is 1242.5 kWh.
- Overall energy losses are 640.1 kWh.

Figure 18 presents the energy losses percentage for every intercity traction chain component.

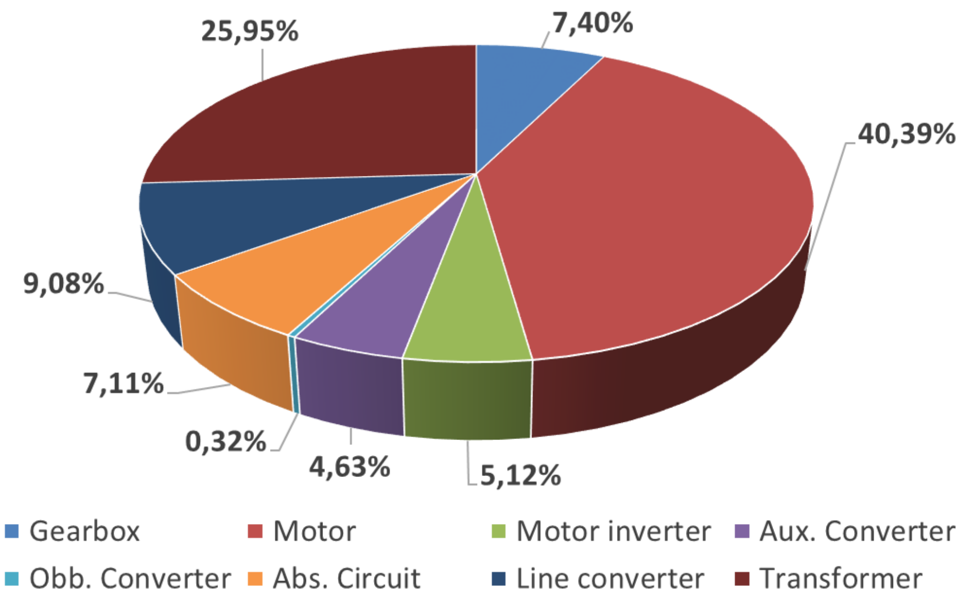


Figure 18: Intercity energy loss % per component

Intercity scenario is very similar to the High Speed 250 in terms of energy losses % per component. The traction motor and the transformer accounts for the majority of the total vehicle energy losses, with 40.39% and 25.95% respectively. Check section 5.6 for more information on intercity component efficiency and energy losses analysis.

5.4 Freight main line service

Figure 19 presents the energy flow of the freight main line scenario. White numbers refer to traction energy, while (black numbers) refer to regenerated energy. Overall energy losses of the component during the freight service, including traction and regeneration operation as well as idle losses during no load operation are shown.

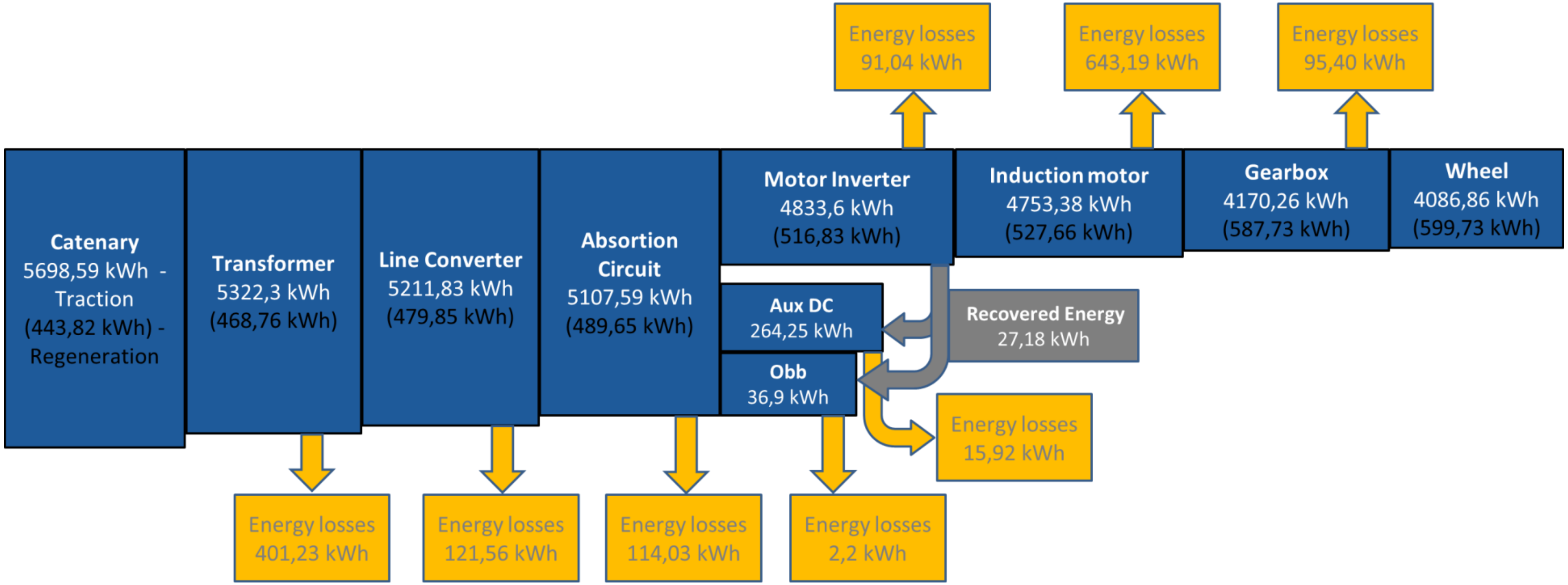


Figure 19: Freight main line energy loss diagram

The main numbers that can be deducted from Figure 19 are:

- Total energy consumption at the catenary is 5698.59 kWh.
- Recuperated energy at the catenary is 443.82 kWh.
- Recuperation factor is 7.8%.
- Total auxiliary consumption is 301.15 kWh.
- Traction energy at wheel is 4086.86 kWh.
- Overall energy losses are 1484.6 kWh.

Figure 20 presents the energy losses percentage for every freight locomotive traction chain component.

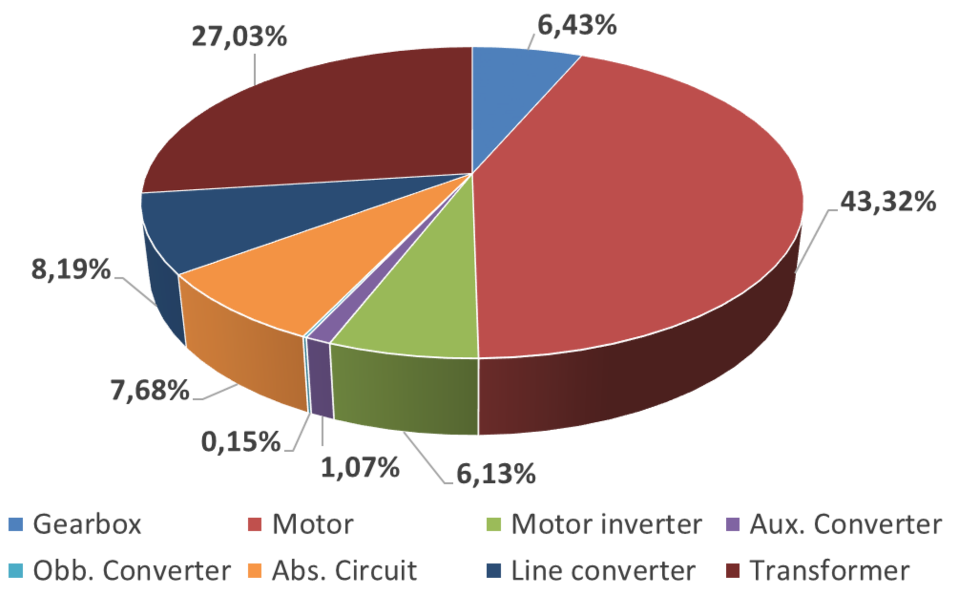


Figure 20: Freight main line energy loss % per component

In the Freight scenario the traction motor accounts for the majority of the total vehicle energy losses, with 43.32%. The transformer contributes to 27.03%. Check section 5.6 for more information on freight component efficiency and energy losses analysis.

5.5 Components efficiency in Topology T03: DC supply

This section shows the efficiency of every component for the tram and metro services, having both the same vehicle architecture (Topology T03) and operating with 750V DC power supply. As seen in Sections 5.1.1 and 5.1.2 above, both services have a very similar energy loss distribution among the traction components.

In order to make a better analysis, traction, regeneration and global efficiencies are shown in Table 1. Here, “traction” represents the driving operations with $P_{wheel} \geq 0kW$ – more specific: acceleration, cruising, coasting as well as standstill phases. In analogy, “regeneration” is representing the braking phases of the service. The global efficiency describes the ratio of the total output energy versus the total input energy of a single component. This also considers the idle losses during driving states when the traction load of the specific component is $P_{load} = 0kW$ – representing the coasting phases as well as the standstill at the station (in this case, only auxiliary consumption and idle losses are considered). Note that the overall component efficiency for the specific service corresponds to the overall component energy losses, which is the one represented in the diagrams of Figure 3 and Figure 5.

Components EFFICIENCY	Axle Gear	Induction Motor	Motor Converter	Auxiliary Converter	Obb Converter	Line Inductor
Tram Service						
Traction Eff.	98%	78.33%	97.21%	-	-	99.14%
Reg. Eff.	98%	86.20%	97.22%	-	-	99.26%
Overall Eff.	**98%**	**38.1%**	**91.8%**	**94.01%**	**94.02%**	**98.7%**
Metro Service						
Traction Eff.	98%	83.54%	97.83%	-	-	98.18%
Reg. Eff.	98%	88.52%	97.90%	-	-	98.34%
Overall Eff.	**98%**	**45.2%**	**92.7%**	**94.01%**	**94.10%**	**96.2%**
Note: For no load operation there is no definition of the efficiency for the motor as the required power is $P_{mot} = 0W$. Nevertheless, idle losses are considered during no load operation.						

Table 1: Components efficiency in topology T03

As can be seen, every traction component has different efficiency (different performances and energy losses) when working in traction or regeneration. The lowest efficiency corresponds to the traction motor, with an approximate overall efficiency of 38.1% in the case of the tram and 45.2% in the case of the metro. This low overall efficiency for the traction motor is caused by the consideration of the idle losses of the motor during no load operation, see Table 2. Therefore, if the service has long times of no load operation, the overall energy losses will be increased.

Sections 5.1.1 and 5.1.2 have shown that the traction motor is responsible for the majority of the tram and metro energy losses, with a 67.74% contribution in the case of the tram and 66.61% of the metro. Because of the traction motor high contribution to energy losses in both cases a deeper analysis of this traction component has been done, quantifying its energy losses in each operational mode. This analysis is summarized in Table 2, where indications on how much time the traction motor runs on every operational phase are given too.

It results that a big percentage of the traction motor energy losses occurs at $P_{load} = 0$ kW of traction power (no load – standstill at the stations or coasting). In the tram service, 38.84% of the traction motor energy losses are caused during no load operation, while in the metro service this is nearly 30%. In both cases much energy is lost in no load operation and this contributes to the big proportion of traction motor energy losses compared to the other components, as seen in Figure 4 and Figure 6.

A control strategy that minimizes the no load operation mode will decrease the traction motor energy losses, and therefore will increase the overall vehicle energy efficiency. When using the switch-off strategy, the operation mode of traction motors running at P_{load} =0 kW is avoided and therefore major energy savings are achieved (see section 7.2 Traction motor switch-off of the present deliverable to check quantify results).

Traction Motor Operation mode	Traction	Braking	No load
Tram Service			
Energy Losses, kWh	3,77	3,11	4,37
Energy Losses %	33,53%	27,63%	38,84%
Time in every phase, %	13,9%	12,5%	73,6%
Metro Service			
Energy Losses, kWh	28,52	22,61	21,91
Energy Losses %	39,05%	30,96%	29,99%
Time in every phase, %	15,0%	12,9%	72,1%

Table 2: Tram and metro traction motor energy losses, depending on operational mode

5.6 Components efficiency in Topology T01: AC supply

This section shows the efficiency of every component for the vehicle services that operates with AC power supply (either 25kV 50Hz or 15kV 16.7Hz), having a vehicle architecture according to topology T01. Then, the following service categories are included:

- Urban: only suburban services
- Regional: Reg140 and Reg160 services.
- High-speed: High Speed 300, High Speed 250 and intercity services.
- Freight main line services.

As done in the section above, Table 3 shows efficiencies per vehicle component, indicating the efficiency for traction, regeneration and overall component efficiency for the specific service.

Components EFFICIENCY	Axle Gear	Induction Motor	Motor Inverter	Auxiliaries	On board batteries	Absorption Circuit	Line Converter	Transformer
Suburban								
Traction Eff.	97,5%	85,89%	98,01%	-	-	98%	98,01%	90,61%
Reg. Eff.	97,5%	88,61%	97,95%	-	-	98%	98,47%	92,33%
Overall Eff.	**97,5%**	**60,33%**	**94,42%**	**93,48%**	**94,09%**	**95,82%**	**96,19%**	**83,63%**
Reg160								
Traction Eff.	97%	81,12%	97,73%	-	-	98%	97,52%	92,19%
Reg. Eff.	97%	86,54%	97,28%	-	-	98%	98,04%	94,10%
Overall Eff.	**97%**	**74,72%**	**96,85%**	**93,94%**	**94,02%**	**97,63%**	**97,14%**	**91,14%**
Reg140								
Traction Eff.	97%	81,81%	97,76%	-	-	98%	97,64%	90,91%
Reg. Eff.	97%	87,24%	97,58%	-	-	98%	98,32%	93,02%
Overall Eff.	**97%**	**64,12%**	**95,39%**	**93,93%**	**94,02%**	**97,07%**	**96,75%**	**87,93%**
High Speed 300								
Traction Eff.	98%	90,24%	98,62%	-	-	98%	98,1%	92,33%
Reg. Eff.	98%	85,81%	97,00%	-	-	98%	98,06%	93,65%
Overall Eff.	**98%**	**89,54%**	**98,51%**	**94,12%**	**94,02%**	**97,92%**	**98,03%**	**92,09%**
High Speed 250								
Traction Eff.	98%	87,07%	98,39%	-	-	98%	98,07%	93,26%
Reg. Eff.	98%	89,24%	97,97%	-	-	98%	98,16%	94,33%
Overall Eff.	**98%**	**84,60%**	**98,04%**	**94,07%**	**94,02%**	**97,73%**	**97,82%**	**92,53%**
Intercity								
Traction Eff.	97%	85,26%	98,24%	-	-	98%	97,47%	93,19%
Reg. Eff.	97%	87,15%	97,66%	-	-	98%	97,82%	94,46%
Overall Eff.	**97%**	**79,32%**	**97,44%**	**94,03%**	**94,02%**	**97,55%**	**96,97%**	**92,03%**
Freight Main Line								
Traction Eff.	98%	87,73%	98,34%	-	-	98%	97,92%	93,4%
Reg. Eff.	98%	89,78%	97,95%	-	-	98%	97,69%	94,68%
Overall Eff.	**98%**	**84,78%**	**97,89%**	**93,98%**	**94,02%**	**97,59%**	**97,50%**	**92,36%**

Table 3: Components efficiency in topology T01

Here again, the lowest efficiency corresponds to the traction motor, with an overall efficiency that varies from the low values of 60.33% or 64.12% in the case of Suburban and Reg140 services respectively to the high values of 89.54% or 84.78% in the case of HS300 service and Freight respectively. The differences in the overall traction motor efficiencies are due to the characteristics of the route services and how much time the traction motor is running on no load mode operation. Table 4 shows the time percentage that the traction motor is running on traction, braking or no load operation. In the case of the Suburban and Reg140, which has the lowest and second lowest overall traction motor efficiency, the time running at no load (where the traction motor has its lowest efficiency) is as high as 71.87% and 80.77%, while for HS300 and Freight, which has the highest and second highest overall traction motor efficiency, the time at no load is only 38.36% and 32.41%, and therefore, the overall traction motor efficiency is very different between these services.

Time in every phase, %	Traction	Braking	No Load
Suburban	18,82%	9,31%	71,87%
Reg160	31,90%	4,60%	63,50%
Reg140	12,0%	7,23%	80,77%
High Speed 300	59,91%	1,73%	38,36%
High Speed 250	62,08%	5,08%	32,84%
Intercity	48,48%	6,22%	45,29%
Freight	59,42%	8,17%	32,41%

Table 4: Time % depending on traction motor operational mode for vehicles with Topology 01

As seen in sections 5.1.3, 5.2, 5.3 and 5.4 the traction motor is also the component that contributes most to absolute energy losses. Therefore, in all services an increase of the traction motor efficiency, either in components efficiency or motor control strategy, such a switch-off strategy (see section 7.2 of the present deliverable to check quantified results), will result in major benefits in terms of energy consumption.

In second place, sections 5.1.3, 5.2, 5.3 and 5.4 have also shown that the transformer is the second biggest contributor to energy losses, from 25.95% in intercity scenario to 34.61% in High Speed 300 scenario. Table 3 shows that overall service transformer efficiency goes from 83.63% in the suburban scenario to 92.53% in the HS250 scenario.

Energy losses within the transformer are mainly based on the ohmic losses which occur within the windings of the transformer coils and the magnetic losses in the core of the transformer. The transformer converts the AC voltage from the catenary voltage level to the train voltage level, being the first traction component on the train and the second greatest contributor to overall energy losses, therefore a small increase in its efficiency will impact positively in the overall traction efficiency. For that reason, future rail vehicles will benefit for the higher efficiencies of the E-transformer, compared to conventional transformers. This is checked in OPEUS Deliverable 3.4 [7], which provides an overview of some innovations of the Shift2Rail technical demonstrators, including the improved energy efficiency of the transformers.

5.7 Energy loss distribution for rail vehicles with ESS

This chapter shows the energy loss diagram and energy loss % per component of a Tram with ESS, in order to see the difference between baseline Tram and Tram with ESS. In this chapter, OPEUS Tool V7 is used.

In this deliverable Tram with ESS refers to scenario III as described in OPEUS Deliverable 6.2 [6]: Conventional tram with a battery of 3 branches charging at every 4th stop and SOC balancing at the end of the course.

Despite the additional weight of the ESS components, the consumed traction energy at the catenary is nearly the same regarding the one of the reference scenario. But in addition, the ESS scenario allows for halving the power peaks at the catenary which is beneficial for the net characteristics.

Figure 21 presents the energy flow of the tram with ESS scenario. For each component absolute numbers, for traction and regenerated energy are indicated. As mentioned above, white numbers refer to traction energy, while (black numbers) refer to regenerated energy. The energy losses indicate the overall energy losses of the component during the tram service, including traction, regeneration and no load losses.

The main numbers that can be deducted from Figure 21 below are:

- Total energy consumption at the catenary is 68.65 kWh.
- Recuperated energy at the catenary is 2.33 kWh.
- Recuperation factor is only 3.4%.
- Total auxiliary consumption is 34.24 kWh.
- Traction energy at wheel is 29.6 kWh.
- Overall energy losses are 25.6 kWh.

Considering the numbers deducted from Figure 3 for the conventional tram, and in combination with the above numbers deducted from Figure 21, Table 5 gives a comparison on the two services:

	Conventional Tram	Tram with ESS	% Difference
Total energy consumption at the catenary, kWh	68,57	68,65	0,12%
Recuperated energy at the catenary, kWh	14,74	2,33	-84,19%
Recuperation factor	21,5%	3,4%	-84,19%
Total auxiliary consumption, kWh	33,3	34,24	2,82%
Traction energy at wheel, kWh	28,86	29,6	2,56%
Overall energy losses, kWh	16,61	25,6	54,12%

Table 5: Comparison between conventional Tram and Tram with ESS

The addition of the ESS, in this case a battery of 3 branches, is adding a total of 1528.2 kg to the train mass. This explains the slightly higher (+2.56%) traction energy at wheel required for the tram with ESS. However the recuperation energy at the catenary for the Tram with ESS is much lower, 84.19% less in comparison to the conventional Tram, as most of the braking energy is stored at the ESS for later use. Overall energy losses are also 54.12% higher in the case of the Tram with ESS, mainly due to the losses at the ESS and the additional cooling power required by the ESS.

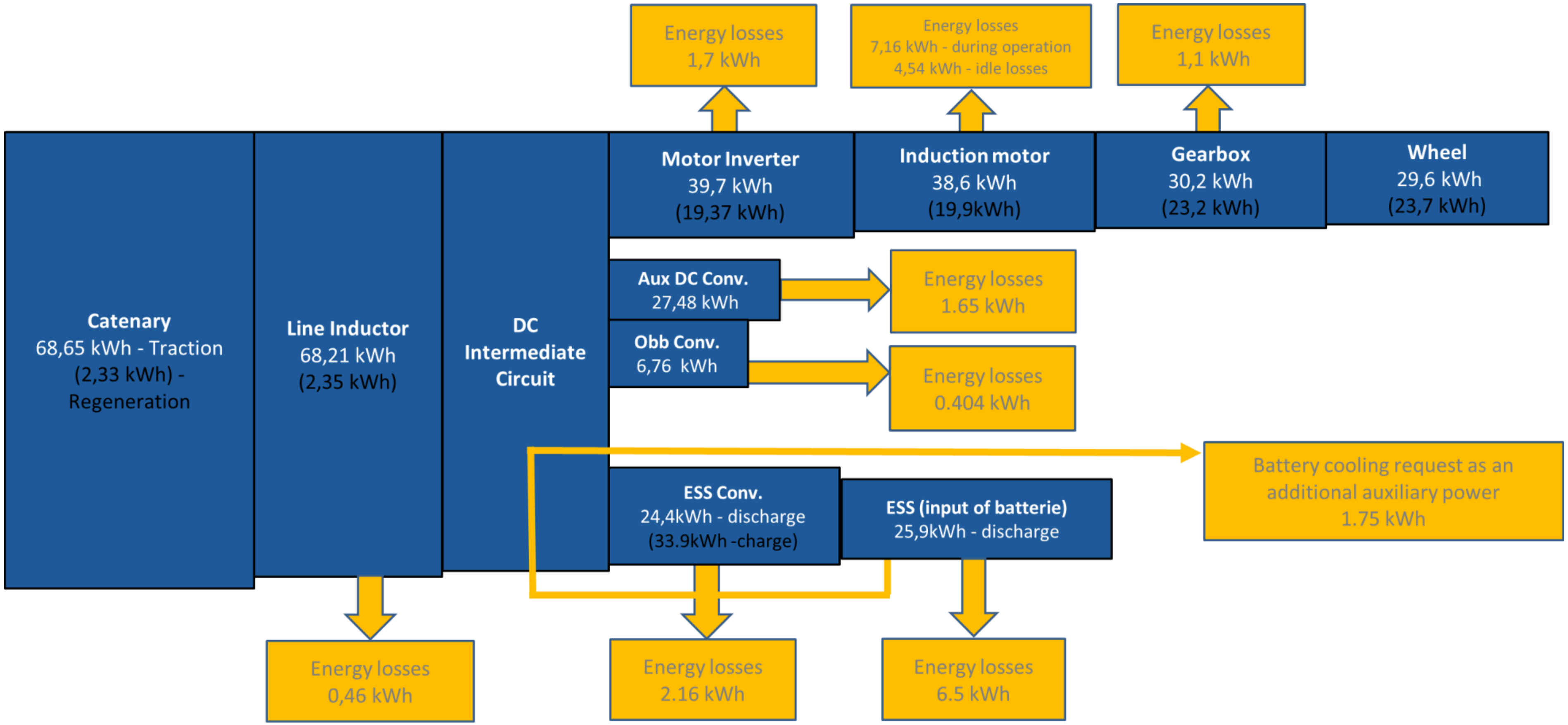


Figure 21: Tram with ESS energy loss diagram

Figure 22 presents the energy losses percentage for every traction chain component in the Tram with ESS.

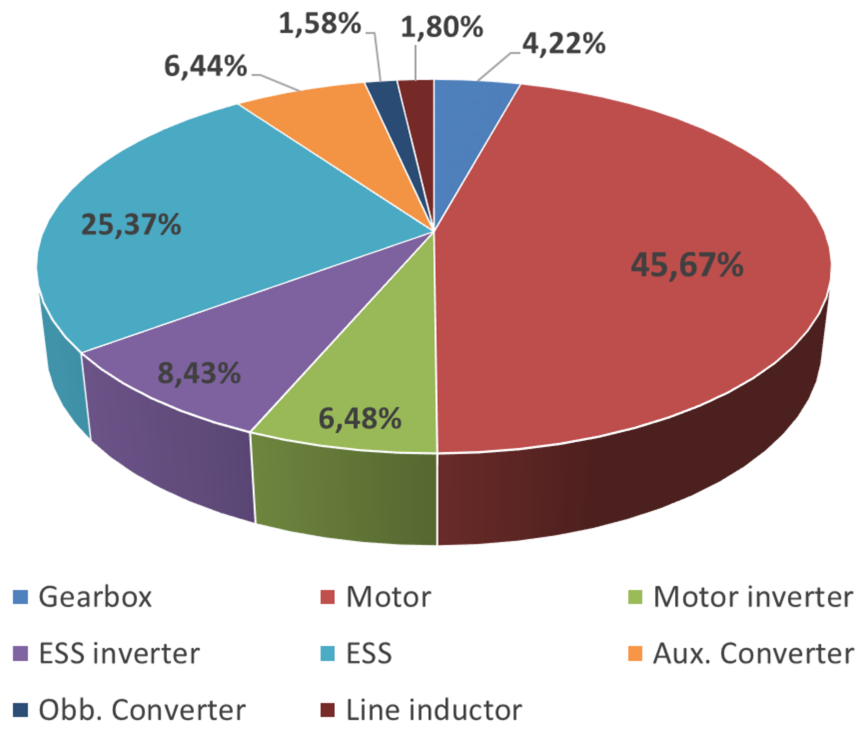


Figure 22: Tram with ESS energy loss % per component

As in the case of the conventional Tram service and also, as for the other services, the traction motor accounts for the majority of the energy losses, with 45.67%. However, in this case, the introduction of the ESS and its converter represents the second highest contributor to the energy losses, contributing to 33.8% of the overall energy losses.

To give further analysis, Table 6 shows the component efficiency of the Tram with ESS in comparison with the conventional Tram, while Table 7 indicates the time % on the different operational modes for both services.

Components EFFICIENCY	Axle Gear	Induction Motor	Motor Conv.	Aux. Conv.	Obb Conv.	ESS	Line Inductor
Conventional Tram Service							
Traction Eff.	98%	78.33%	97.21%	-	-	-	99.14%
Reg. Eff.	98%	86.20%	97.22%	-	-	-	99.26%
Overall Eff.	**98%**	**38.1%**	**91.8%**	**94.01%**	**94.02%**	**-**	**98.7%**
Tram with ESS Service							
Traction Eff.	98,0%	78,24%	97,20%	-	-	97,00%	99,36%
Reg. Eff.	98,0%	85,78%	97,24%	-	-	95,50%	99,15%
Overall Eff.	**98%**	**37.4%**	**91.8%**	**94.0%**	**94.0%**	**75.1%**	**99.3%**

Table 6: Components efficiency for conventional Tram and Tram with ESS services

	Acceleration	Cruising	Coasting	Braking	Stop @ Station
Conventional Tram	13.92%	0.00%	40.09%	12.46%	33.52%
Tram with ESS	13.61%	0.00%	39.02%	12.13%	35.25%

Table 7: Time % in operational phases for the conventional Tram and Tram with ESS

As can be seen, the efficiency of the different energy components is very similar on both services, conventional Tram and Tram with ESS, but the last is adding a new component with an overall efficiency of 75.1%, which reduces the overall efficiency of the vehicle. The time % on the different operational phases is also very similar between the two services.

As mentioned in OPEUS Deliverable 6.2 [6], this ESS scenario is performed with a small Depth of Discharge (only 6% DoD), which ensures a very high lifetime of the battery in cycling and the peak power reduction will enable to increase the tramway with ESS circulation without increasing the power at catenary. However, a deeper analysis on the specific service may lead to optimize (reduce) the size of the ESS, having a higher DoD but a lower energy consumption with an optimized traction energy distribution.

6. Operational phases analysis

This chapter presents an analysis of the energy losses in the different rail scenarios during the different operational phases: acceleration, cruising, coasting and braking. Stops at stations periods have also been included. The same simulations used in chapter 5 are the basis for this analysis.

Table 8 shows the energy losses according to operational phase. The total energy losses in kWh per vehicle scenario are included too.

Train Service	Energy losses per operational phase					
	Acceleration	Cruising	Coasting	Braking	Stop @ Station	Total kWh
Tram	34,33%	0,00%	21,01%	26,92%	17,74%	16,6
Metro	41,87%	0,43%	15,78%	30,83%	11,08%	109,7
Suburban	48,54%	2,18%	14,69%	26,61%	7,98%	262,5
Regional 160	34,20%	26,94%	22,14%	9,44%	7,28%	473,4
Regional 140	45,05%	1,27%	24,44%	17,91%	11,33%	193,3
High Speed 300	26,75%	62,42%	6,88%	2,81%	1,15%	1154,5
High Speed 250	44,13%	38,89%	7,18%	6,82%	2,97%	1147,6
Intercity	31,83%	41,20%	10,87%	11,68%	4,41%	640,1
Freight	13,18%	73,95%	3,21%	8,85%	0,82%	1484,6

Table 8. Energy losses according to operational phases.

The same information is given in Figure 23, where coasting and stop station data has been added up to have the total energy losses in no load mode operation (column grey). It can be seen that:

- In the three urban services the major energy losses are concentrated in the acceleration phase. This is due to the urban services characteristics, with short distance between stations and high number of stations. Because of this, urban services has none or hardly cruising operational phase. Urban services are also characterized by important coasting and stops at stations.
- On the contrary, main line services like freight, high speed 300, high speed 250 and intercity, have considerably energy losses during cruising operational phase.
- Regional services, depending on route service characteristics, will have energy loss distributions similar to urban services or main line ones, as can be seen below.

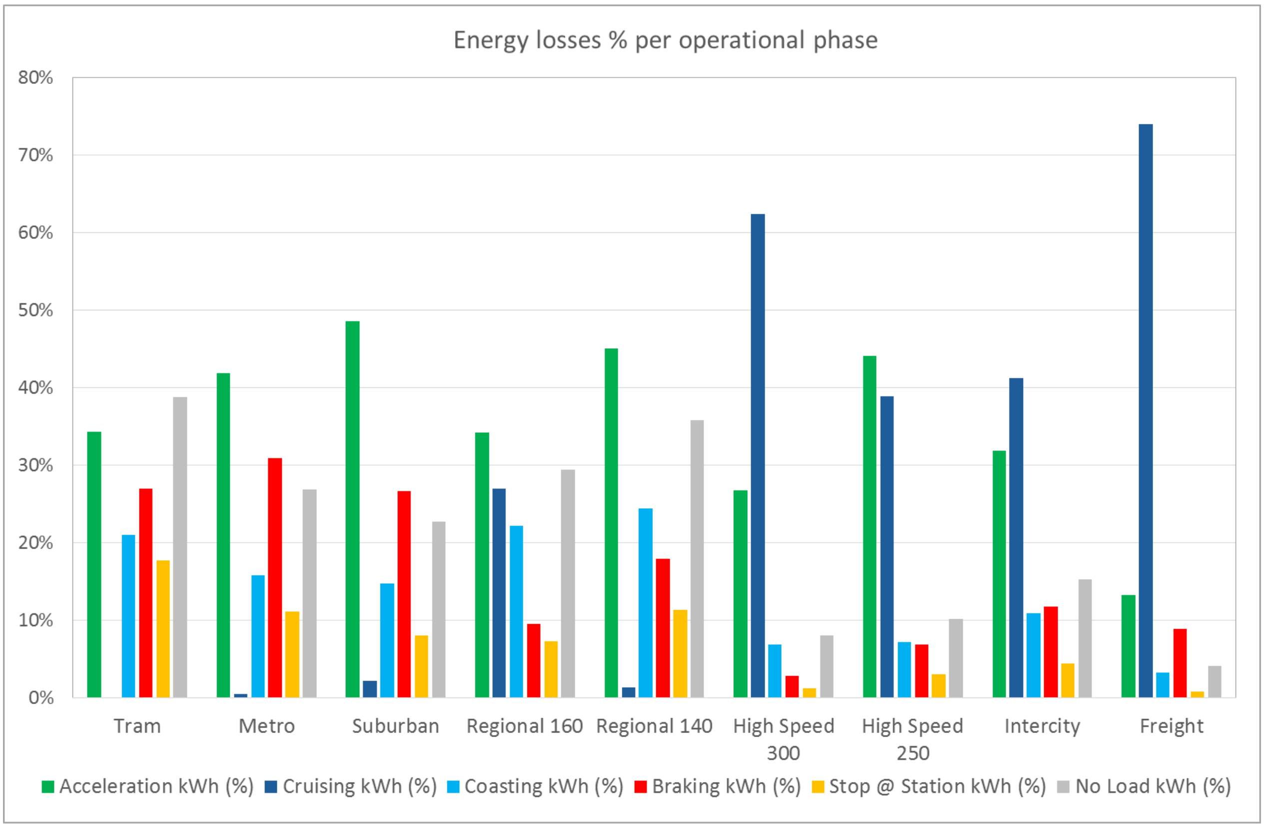


Figure 23: Energy losses % according to operational phases

When analysing the operational phases and proposing energy strategies to minimise energy consumption it is also important to check the time in each operational phase out of the total service time. If a service has a high time percentage of coasting then energy strategies such as switch off one or more traction motors can be very interesting. However, if a service has hardly coasting times and a high time percentage of traction phases other strategies may apply. In the last case a train mass reduction can be very interesting, as the required power during acceleration is directly related to the hauled mass.

Therefore Figure 24 presents for each service the expended % time in each operational phase. Again coasting and stop station data has been added up to have the total time in no load mode operation (column grey).

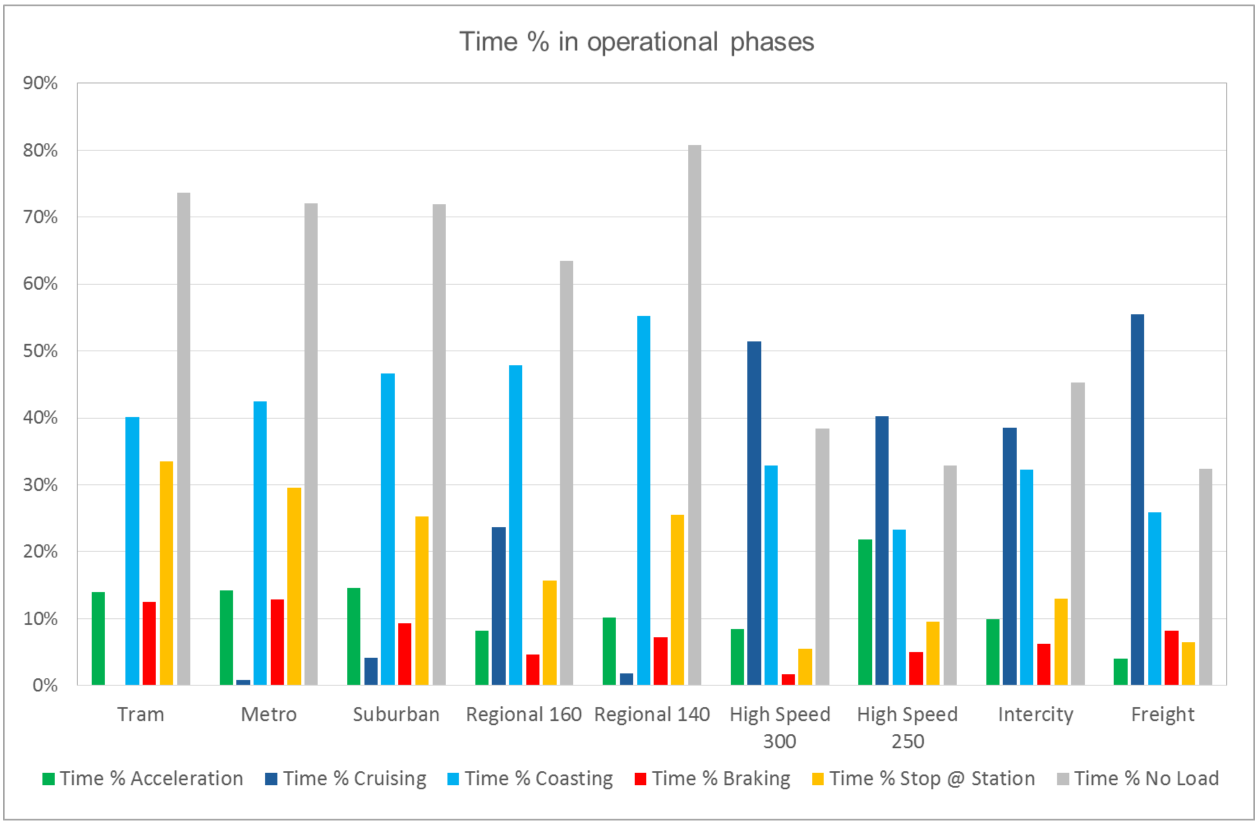


Figure 24: Time % in operational phases

Observing Table 8 and Figure 23 and Figure 24, it is expected that in urban and regional services partial switch-offs allow for decent energy savings, caused by the large phase of coasting as well as the standstill times in the high number of stops (for the specific defined services and vehicles), where the traction components can be switched-off and do not produce any idle losses.

7. Energy strategies and parameter variations

In this chapter the energy strategies proposed in OPEUS Deliverable 5.1 [3] as well as some additional parameter variation are implemented. In order to show the possible improvements at least one scenario has been considered for each proposal, though in the case of the switch-off strategy or the mass parameter all vehicles have been analysed.

7.1 Auxiliaries operation

Auxiliary systems are described and defined in Annex A of Deliverable 2.1 [2]. The aim of this section is to investigate the effect of an auxiliary load occurring during different time periods of the duty cycle: acceleration, cruising, coasting and braking. In order to assess the influence of the auxiliary consumption, from a theoretical point of view, different situations can be considered:

- The reference or basic case has a constant auxiliary load over the entire cycle.
- In the worst case, all the auxiliary load applies during the acceleration phase. In this case, the regenerated braking energy has to be fed back to the catenary 100%, as there is no auxiliary consumption during the braking phase.
- In the best case the auxiliary load only occurs during the braking process. In this last case, the regenerated braking energy can be used for auxiliaries operation.

For comparison reasons the total amount of auxiliary energy consumed is kept the same for all cases, which means that not only the time but also the total amount of power will be varied in the different proposed scenarios. The case study has been done for the conventional tram service, which has an overall auxiliary energy consumption of 33.3 kWh, 4.02kWh of them being used from regenerated braking energy in the basic case, as it is shown in Figure 3 and Table 9. The total recuperated energy of motor converters at DC link in the tram service is 18.87 kWh, as shown also Figure 3. This is the available energy to supply the auxiliary power request. For example, this energy will be used in its majority to supply the auxiliaries in the best case scenario.

Table 9 shows the final auxiliary energy consumption in the tram service for the different scenarios. Indications on the recovered energy to supply the auxiliaries and the % of the regenerated braking energy from the motor inverter are given too.

Scenario	Case	Final Auxiliary Energy Consumption (kWh)	Recovered energy used to supply auxiliaries (kWh)	% of available braking energy used for auxiliary supply
AUX in braking phases	Best	15.1	18.2	96.4%
AUX in non-traction phases (coast, brake, stop)	-	28.7	4.6	24.4%
Constant AUX in all phases	Basic	29.3	4.02	21.3%
AUX in acceleration phases	Worst	33.3	0	0%

Table 9: Results for auxiliary operation, Tram

As can be seen, in the best case, 96.4% of the regenerated braking energy from the motor inverter can be used to supply the auxiliaries, and then the final auxiliary energy consumption is only 15.1 kWh, which is 48.46% less than in the basic case. In the worst case scenario, the braking energy cannot be used to supply the auxiliaries and then the final auxiliary energy consumption is 33.3 kWh (all auxiliary consumption supply from the catenary), which is 13.6% more than the final auxiliary consumption in the basic case.

In reality, the power consumption for auxiliary loads is best approximated with a constant load. The best and worst cases are only theoretic scenarios and have been analysed to show the effect on energy consumption. However these scenarios give a hint on the positive effect a system with an ESS could have. The ESS could store the available energy during the braking process and release it over time to feed the auxiliary load.

7.2 Traction motors switch off

As seen in previous sections, the traction motor is the biggest contributor to energy losses, and its lowest efficiency occurs at no load. Therefore, a switch off strategy will improve the energy efficiency.

The objective of this section is to present the simulation results with the implemented strategy: switch off of traction components. In this section, the expression “traction components” includes both the traction motors as well as the corresponding motor converters. The simulations for this energy study have been done with OPEUS Tool V6, using as trajectory mode timetable with coasting, applying switch off strategy.

The investigated operating strategy is based on the avoidance of a low load operation for the traction components. For low-load operation, the efficiency of the components decreases (compared to high-load operation) leading to a higher amount of energy losses. Furthermore, the residual traction components are forced to handle a higher power request, which increase the resulting efficiency of the remaining applied components. Additionally, this approach does not account for the idle losses of the components, as long as the components are switched off.

For this operating strategy, the minimum number of applied motors to fulfil the total power request are determined. According to the number of applied traction motors the number of applied motor converters are determined too. It is taken into account that the power split is only possible between motors which are supplied by different motor inverters (it is not permitted to split the power between two motors which are linked to the same inverter). For details on the implemented equations see OPEUS Deliverable 2.1 [2] and OPEUS Deliverable 3.3 Part 1 [5].

Table 10 presents the net energy consumption and energy savings for the single service categories, resulted from the simulations with the switch-off strategy. Figure 25 and Figure 26 illustrate this information.

Switch-off vs Baseline cases	Net energy (Switch-off) kWh	Net energy (Baseline) kWh	Net energy savings kWh	Energy savings [%]
HS300	4941,78	5055,03	113,25	2,24
HS250	4060,71	4308,12	247,42	5,74
Intercity	1967,87	2083,3	115,44	5,54
Regional 160	1327,77	1452,12	124,35	8,56
Regional 140	447,15	484,92	37,76	7,79
Suburban	478,55	514,24	35,69	6,94
Metro	244,33	268,15	23,82	8,88
Tram	48,96	53,83	4,87	9,05
Freight	5040,31	5254,77	214,46	4,08

Table 10. Switch-off net energy consumptions and energy savings.

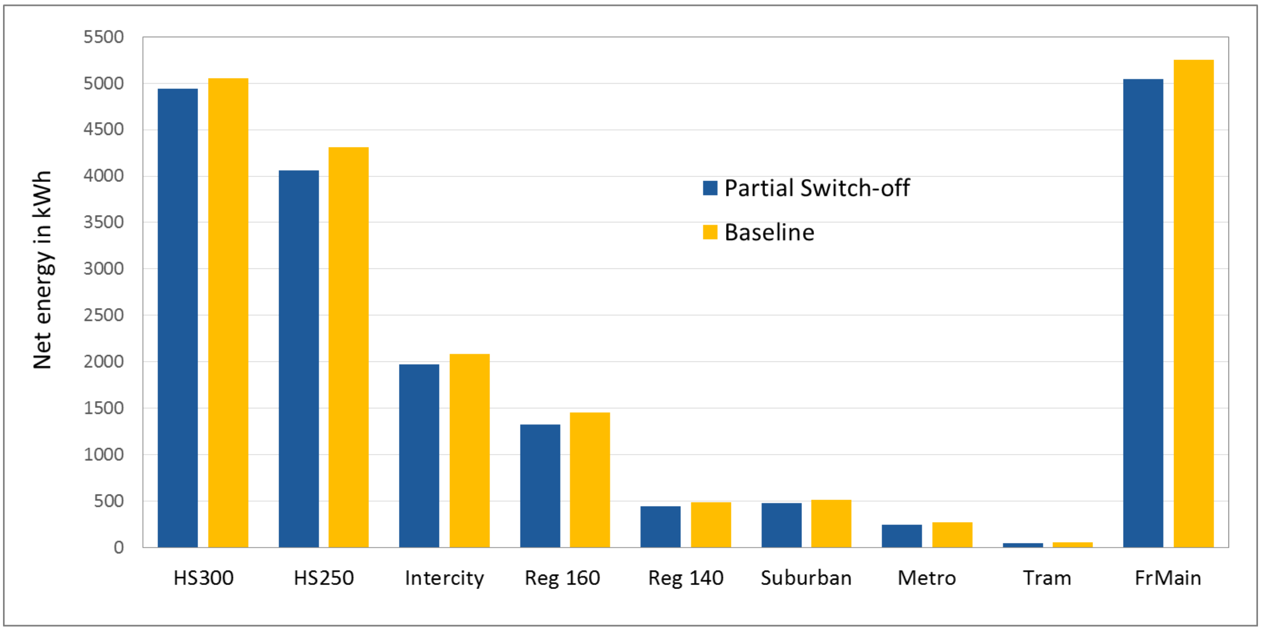


Figure 25: Comparison of net energy consumptions in baseline and partial switch-off scenarios.

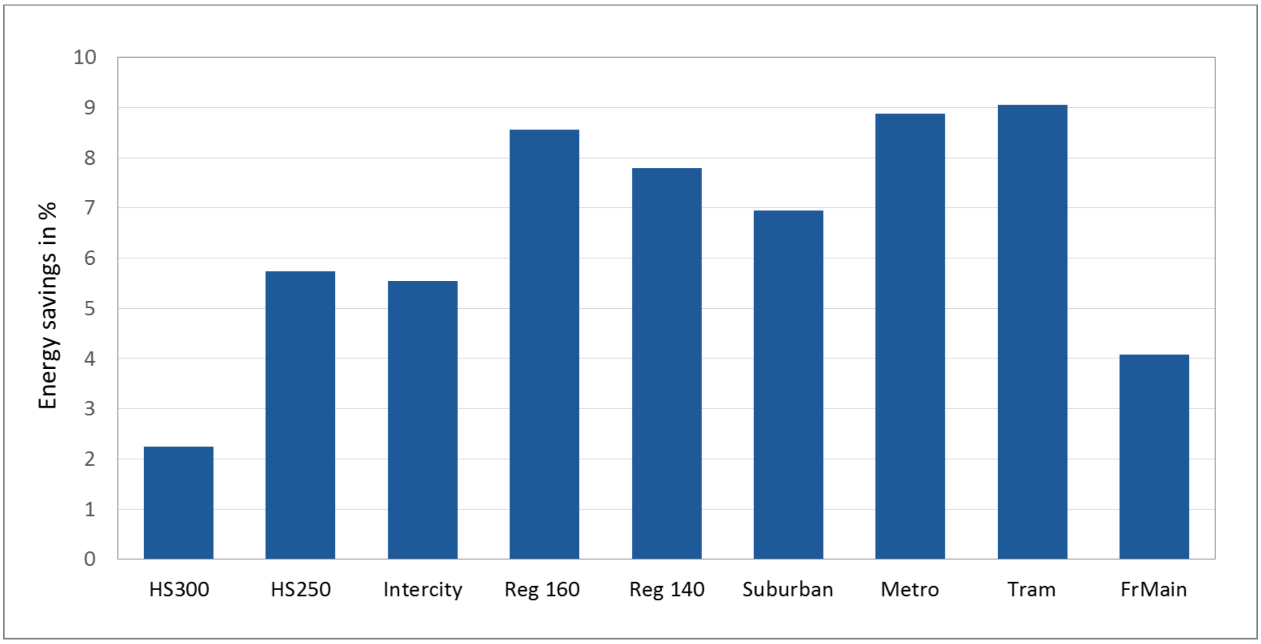


Figure 26: Energy savings in % caused by partial switch-offs for the defined drive cycles.

As can be seen, urban and regional services have the biggest energy savings, as was also predicted with the operational phase analysis in section 6: The low energy savings for High Speed 300 and Freight Mainline are caused by the high power demands in order to satisfy the required operating conditions of these services, with low coasting phases and few stops (low standstill time). Based on the specific track design and the specific vehicle, it is not possible to take advantages of partial component switch-offs in the same frequency as for the other service categories. On the other hand, for the urban applications (especially Tram and Metro) partial switch-offs allow for decent energy savings, caused by the large phase of coasting as well as the standstill times in the high number of stops (for the specific defined services and vehicles), where the traction components can be switched-off and do not produce any idle losses.

It can be concluded that the implementation of partial switch-offs of traction components has the most significant effect on energy savings if it is utilised on a service with long coasting phases (where no power is requested) or standstill at stations. Due to the high portion of standstill and coasting, Urban and Regional services offer the most significant potential for the application of this operating strategy.

As additional information, Appendix 2: Comparison of energy losses distribution between baseline and switch-off strategy show the energy loss % per component comparison between baseline simulations (trajectory mode timetable with coasting) and simulations with switch off strategy. It is observed that traction motor energy losses are reduced in all services, being the biggest reduction in the Tram service.

7.3 Mass reduction

The simulations done from sections 7.3 to 7.5 have been done with OPEUS Tool V6, using as trajectory mode timetable with coasting mode.
The mass of a vehicle has a significant impact on the energy consumption because it directly influences the weight related driving resistance of the vehicle. In addition to an increased driving resistance, a higher mass also leads to a reduced acceleration performance. This means that for a given timetable and vehicle, a lighter vehicle reaches the set speed of the track faster and spends therefore a higher amount of time with constant speeds or coasting, which in return leads to a reduced energy consumption. These considerations explain the obtained results for the correlation between the total design mass (tare mass) and the energy consumption [kWh] for a +/- 10 % variation of the tare mass, which is shown in Table 11 below.

Net Energy [kWh]	-10% tare mass	Reference (no mass variation)	+10% tare mass
HS300	5022,24	5055,03	5107,63
HS250	4182,76	4308,12	4439,04
Intercity	2052,42	2083,30	2135,75
Regional 160	1413,52	1452,12	1499,07
Regional 140	463,37	484,92	515,43
Suburban	479,64	514,24	568,80
Metro	246,02	268,15	290,38
Tram	52,74	53,83	54,92
Freight	5243,34	5254,77	5266,34

Table 11. Net energy consumptions due to mass variation.

Figure 27 shows the % net energy difference for a +/- 10 % variation of the tare mass. A 10% reduction of the vehicle tare mass leads to benefits in terms of energy consumption, being suburban and metro the vehicle scenarios with the highest benefits in terms of % energy savings, with 6.73% and 8.25% reductions respectively. It is important to take into account the absolute numbers too, as for example, in the HS250 scenario, a 10% tare mass reduction leads only to 2.9% reduction of net energy savings, but this % represents 125 kWh, which is an unneglectable saving.

With the future use of composite materials in carbody rail vehicles, or the lightening of vehicle components, the vehicle tare mass is expected to decrease, and hence the energy consumption. Another option could be that this achieved weight reduction thanks to the use of composites is used to introduce ESS or higher and heavier performance systems, keeping the original vehicle mass. OPEUS Deliverable 3.4 [7] provides an evaluation for specific improved weight characteristics.

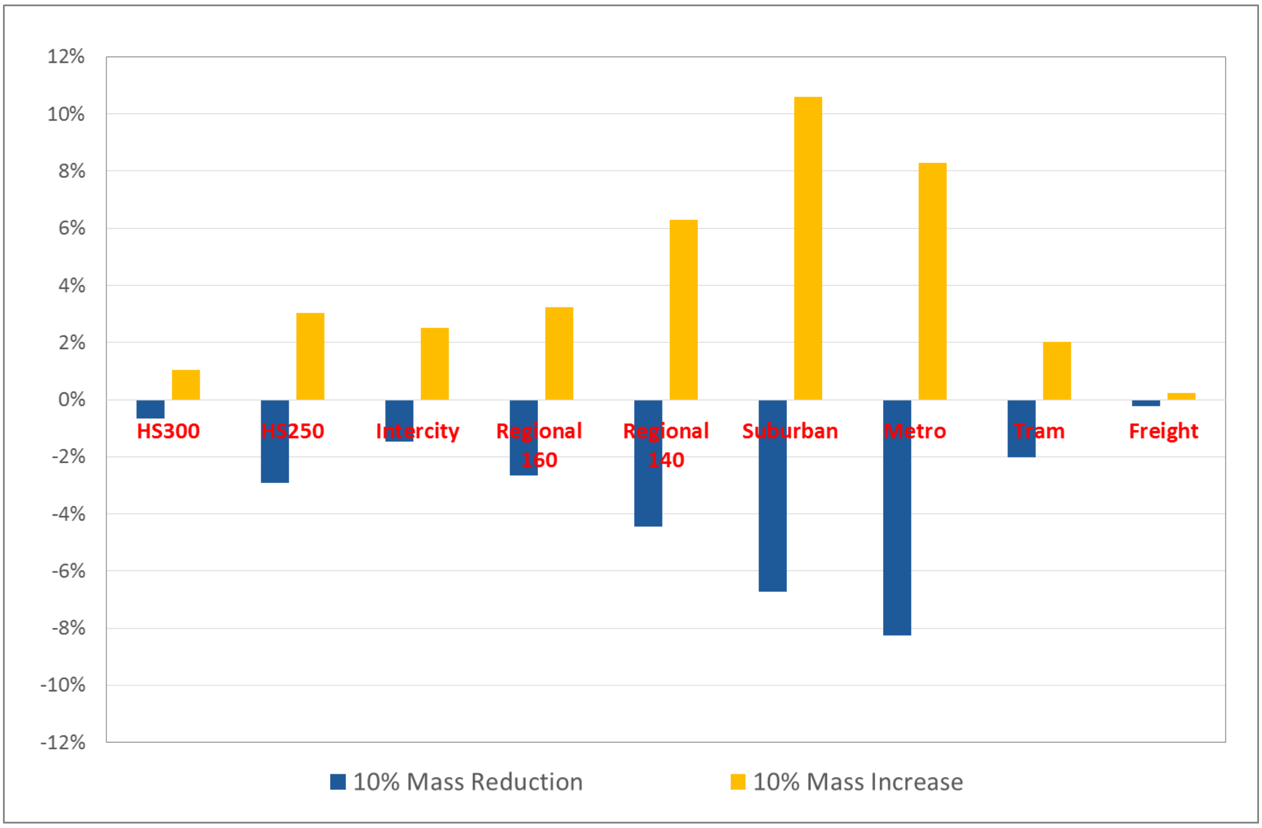


Figure 27: Mass influence on net energy consumption

7.4 Improved running resistance

The running resistance F_{res} [N] mainly represents the characteristic of the aerodynamic drop as well as the rolling resistance due to the wheel-rail contact. It is given by:

$$F_{res} = k_0 + k_1 v + k_2 M_{veh} + k_3 M_{veh} v + k_4 (v + v_w)^2 (1 + f)_t + k_5 M_{veh} (v + v_w)^2 (1 + f_t)$$

with v in m/s, M_{veh} in kg (train mass without rotational mass).

The coefficients can be checked on the vehicle parameter definition on AnnexA of OPEUS Deliverable 2.1 [2] or Appendix of FINE1 Deliverable 3.1 [4].

Coefficient k_5 was defined as 0 in all rail vehicles. The resistance factor k_4 is responsible for the calculation of the aerodynamic drag of the train vehicle. The force acting on the vehicle is obtained by multiplying the factor k_4 with the square of the current vehicle speed in m/s. In general, all vehicles (e.g. rail, road…) benefit from improved aerodynamics in terms of energy consumption but in the case of High Speed vehicles, this is more relevant due to the squared high speed value.

The analysis of the running resistance factor k_4 is made for the High Speed 300 service, were factor $k_4$value is 7.128 kg/m, according to above mentioned sources [2] or [4].

Figure 28 shows correlation between the resistance factor k_4 and the net energy consumption for a +/- 10 % variation of this factor.

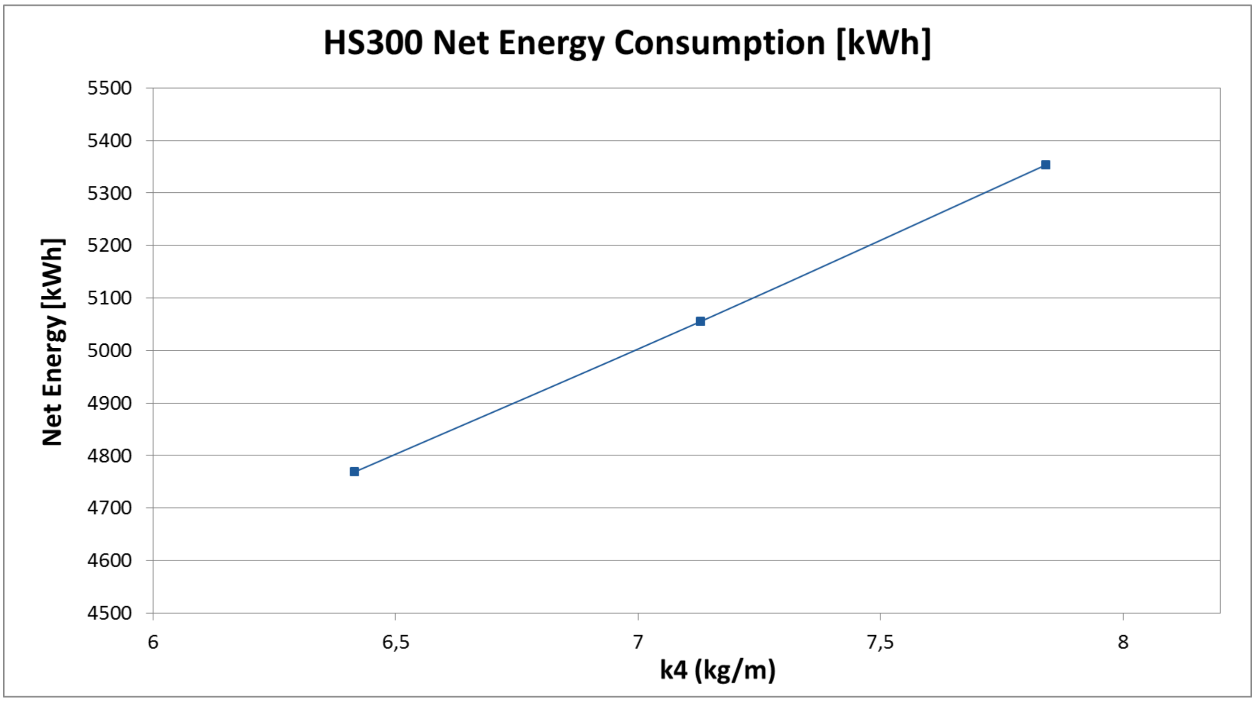


Figure 28: Correlation between the resistance factor k_4 and the net energy consumption for a +/- 10 % variation of k_4 for HS 300 service.

For the maximum simulated factor $\mathrm{k}_4 = 7.8408$kg/m (10% higher than defined) the highest net energy consumption of 5353,43 kWh is obtained. Going towards smaller values of factor k_4 a general reduction of energy consumption can be seen. The minimum value is 4768,91 kWh for a $k_4 =$ 6,4152kg/m (10% lower). An increase of 10% of the factor k_4 causes a 5.57% increase on the energy consumption, while a 10% reduction in the factor k_4 causes a 5.66% reduction in energy consumption. Therefore an improved aerodynamic vehicle design in high speed services will lead to significant energy savings. This is summarized in Table 12 bellow:

HS 300 scenario	- 10% in k_4	Baseline	+10% in k_4
k_4 (kg/m)	6,4152	7,128	7,8408
Net energy consumption (kWh)	4768,91	5055,03	5353,43
% Difference	-5,66%	-	+5,57%

Table 12: Influence of factor k_4 in net energy consumption of HS 300 scenario

7.5 Variation of rotating masses

The rotating mass for the simulation tool is calculated as a fixed percentage of the vehicle tare mass. The coefficients can be checked on the vehicle parameter definition on AnnexA of OPEUS Deliverable 2.1 [2] or Appendix of FINE1 Deliverable 3.1 [4].

This analysis has been made for one example, the Regional 160 service. In this case the standard value for rotating mass is 5 % according to mentioned above sources [2] and [4].

For the parameter variation a +/- 10 % range starting from the standard value has been simulated, i.e from 4.5t to 5.5t rotating mass. In Figure 29 the correlation between the rotating masses and the net energy consumption [kWh] is depicted.

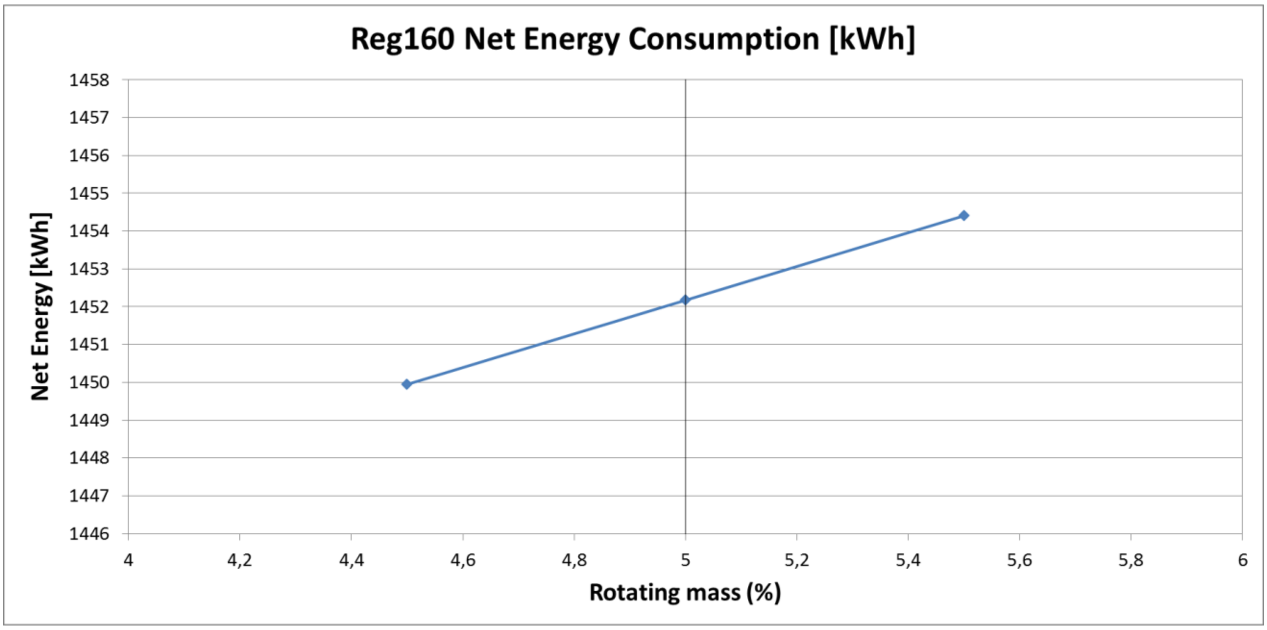


Figure 29: Correlation between the rotating masses and the net energy consumption for Reg160 service.

The highest net energy consumption of 1454.4 kWh is achieved for a value 5.5% of the rotating masses and corresponds to a 0.15 % increase compared to the baseline simulation result for the standard value of 5 % for the rotating mases. The lowest fuel consumption of 1449.9 kWh is achieved for a value of the rotating masses of 4.5 % and corresponds to a 0.15 % decrease in the net energy consumption. Therefore, the variation of the factor of the rotating mases has hardly effect on the overall energy consumption.

Reg160 scenario	- 10% in rot. mass	Baseline	+10% in rot. mass
Rotating mass coefficient %	4,5	5	5,5
Net energy consumption (kWh)	1449,95	1452,17	1454,41
% Difference	-0,15%	-	+0,15%

Table 13: Influence of rotating mass coefficient in net energy consumption of Reg160 scenario

8. Conclusions

This deliverable presents the analysis of energy losses in the reference rail vehicle architectures described in previous OPEUS task 5.1 and an investigation on different vehicle parameters and strategies to improve energy consumption.

The conducted energy loss analysis has concluded that the traction motor is the highest contributor to energy losses in all scenarios. For rail vehicles with AC supply (which follow Topology T01[4]) the traction motor and transformer are the biggest contributors to energy losses, they together represent up to 71.46% of overall energy losses in the case of suburban, with a minimum of 66.34% in the case of intercity scenario. For rail vehicles with DC supply (which follow Topology T03) it is concluded that the traction motor is the biggest contributor to energy losses, accounting for 67.74% and 66.61% in the case of the tram and metro scenarios respectively.

Energy loss distribution is also analysed for a Tram with ESS, where the traction motor accounts for the majority of the energy losses too, with 45.67%. However, in this case, the introduction of the ESS and its converter represents the second highest contributor to the energy losses, contributing to 33.8% of the overall energy losses. Despite the additional weight of the ESS components, the consumed traction energy at the catenary is nearly the same regarding the one of the reference scenario. But in addition, the ESS scenario allows for halving the power peaks at the catenary which is beneficial for the net characteristics.

An analyses on the operational phases is made for the different rail scenarios to quantify the energy losses during acceleration, cruising, coasting and braking. Depending on the service and route characteristics the losses are concentrated in different phases, e.g.: in urban services the major energy losses are concentrated in the acceleration phase and also in no traction phases (coasting and stops at stations), while main line services like freight or high speed have considerably energy losses during cruising operational phase.

The last part of the report makes a sensitivity analysis to investigate the impact in the energy consumption of different vehicle parameters and strategies:

- The effect of auxiliary loads occurring during the different operational phases are investigated in the tram scenario.
- Traction motor switch-off strategy is implemented in all scenarios, finding out that urban and regional services have the biggest energy savings, achieving 9% energy savings in the case of the tram scenario.
- The influence of the tare mass parameter (+/- 10 %) is analysed in all scenarios, having considerable energy improvements for lighter trains: up to 8.25% energy savings in the case of the metro.
- The effect of the aerodynamic drag of the train vehicle is investigated through the resistance factor k_4[5], resulting that a 10% reduction in factor k_4 causes a 5.66% reduction in HS300 energy consumption.

[4] Check Appendix 1 to see vehicle architectures or topologies.

[5] Total driving resistance: $F_{res} = k_0 + k_1 v + k_2 m_{train} + k_3 m_{train} v + k_4 v^2 + k_5 m_{train} v^2$, please refer to D2.1 [2]

- Finally, the influence of the rotating masses is also investigated, finding out hardly influence on energy consumption.

The analysis concludes that in both AC and DC rail vehicles, the traction motor is the highest contributor to energy losses, especially during no load operation. Therefore, the implementation of partial switch-offs of traction components has the most significant effect on energy savings, if it is utilised on a service with long coasting phases or standstill at stations. Due to the high portion of standstill and coasting, urban and regional services offer the most significant potential for the application of this operating strategy. However, if a service has hardly coasting times and a high time percentage of traction phases other strategies may apply. In the last case a train mass reduction can be very interesting, as acceleration power is directly related to the hauled mass. In addition, the improvement of aerodynamics will significantly improve the energy efficiency in high speed services. Finally, it is expected that new E-transformers, with higher energy efficiency than conventional transformers, contributes to reduce overall energy losses in rail vehicles with AC supply. This is checked in OPEUS Deliverable 3.4 [7], which provides an overview of some innovations of the Shift2Rail technical demonstrators, including the improved energy efficiency of the transformers.

9. References

[1] R. Palacin, “OPEUS Deliverable D3.1 - Scenario set up and discription”, EU-project OPEUS (S2R-OC-CCA-02-2015), 2017.

[2] L. Pröhl, “OPEUS Deliverable D2.1 - OPEUS simulation methodology”, EU-project OPEUS (S2R-OC-CCA-02-2015), 2017.

[3] M. Marsilla, “OPEUS Deliverable 5.1 Traction chain architecture characterisation”, EU-project OPEUS (S2R-OC-CCA-02-2015), 2017.

[4] J. Ernst, “FINE1 Deliverable D3.1 - Energy baseline”, EU-project FINE1 (S2R-CFM-CCA-02-2015), 2018.

[5] L. Pröhl, „OPEUS Deliverable DO3.3 - S2R innovation (state01) simulation results and periodic assessmant - Part1,“ EU-project OPEUS, 2018.

[6] NGUYEN Dinh An, “OPEUS Deliverable D 6.2 - Innovative technologies influence on energy usage assessment”, EU-project OPEUS, 2019.

[7] L. Pröhl, „OPEUS Deliverable D3.4 - SS2R innovation second periodic assessment” EU-project OPEUS, 2019.

[8] L. Pröhl, „OPEUS Deliverable DO3.2 - Baseline simulation results and assessment,“ EU-project OPEUS, 2018.

10. Appendix 1: Vehicle architectures. Topologies

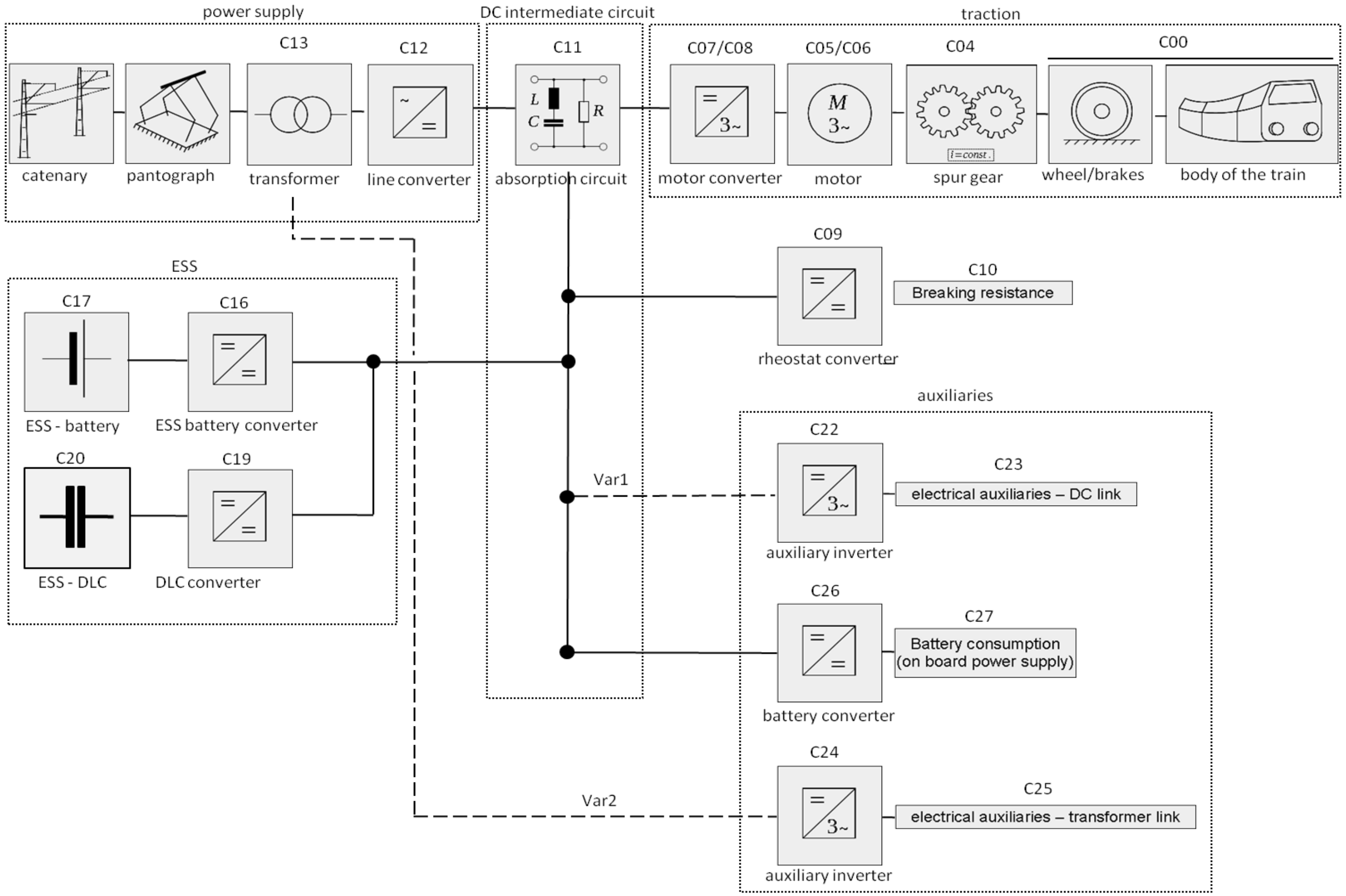


Figure 30: AC topology with conventional transformer (T01)

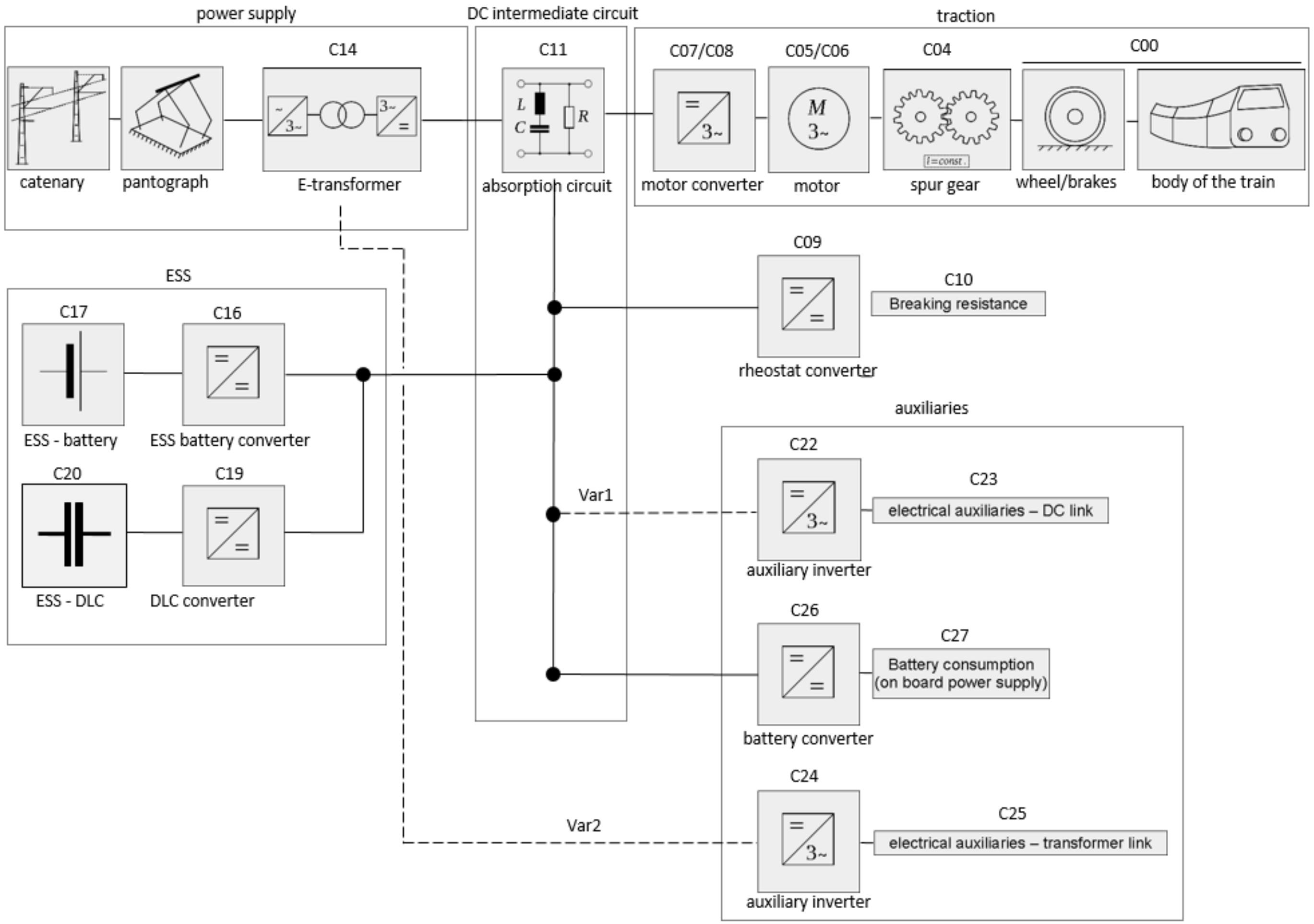


Figure 31: AC topology with e-transformer (T02)

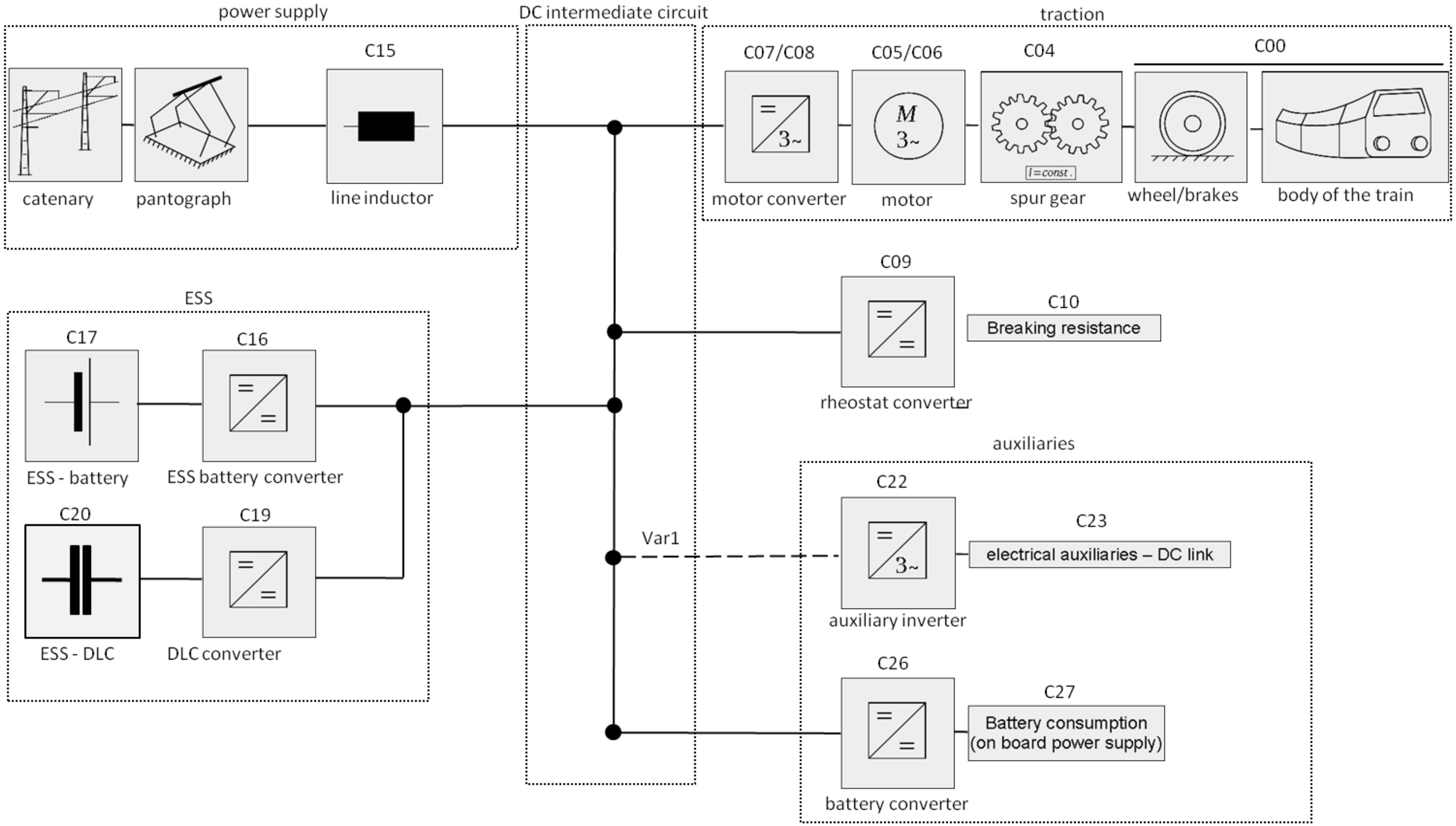


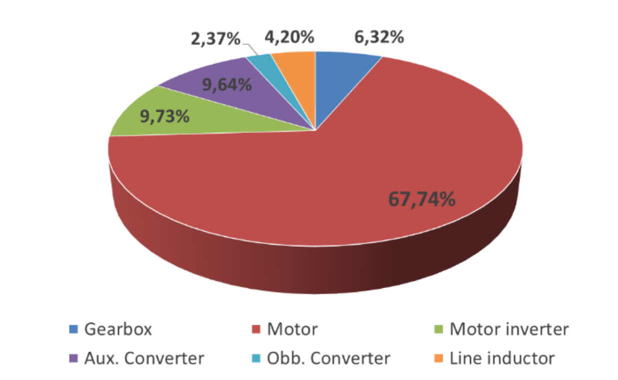
Figure 32: DC Topology (T03)

11. Appendix 2: Comparison of energy losses distribution between baseline and switch-off strategy

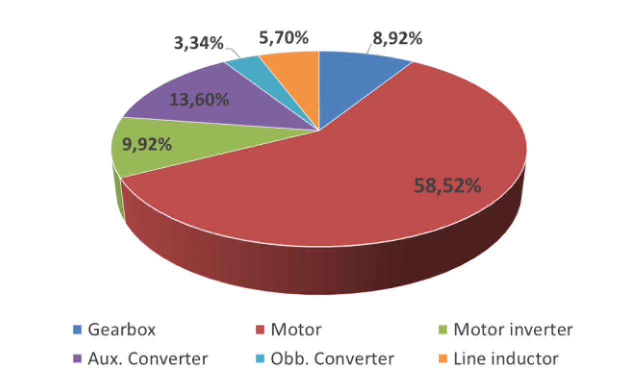
This appendix shows how the energy loss % distribution among the traction components change with application of the switch-off strategy. It is obviously seen that the traction motor energy losses are reduced in all cases. For vehicles with Topology T01, with AC supply, it is seen that the transformer energy losses % are increased, because of the high reduction of traction motor energy losses (as traction motor and transformer are the two components that account for the majority of the energy losses in this topology).

Comparison of energy loss % per component in conventional and switch-off services

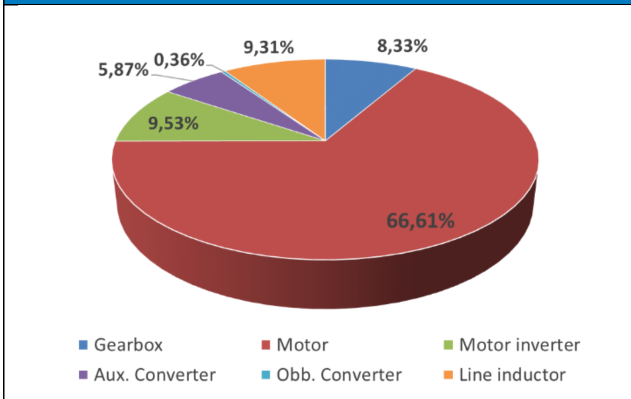
Baseline Tram Service



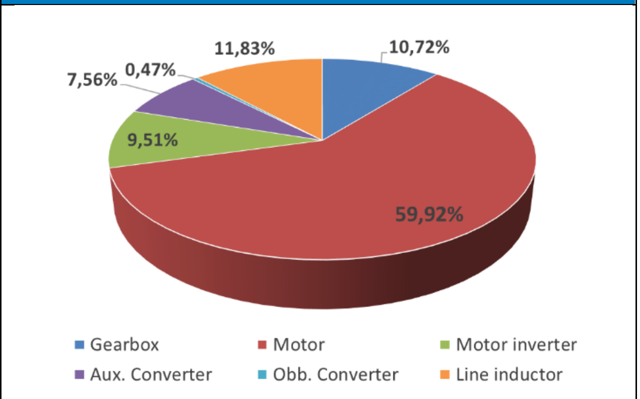
Switch-off Tram Service



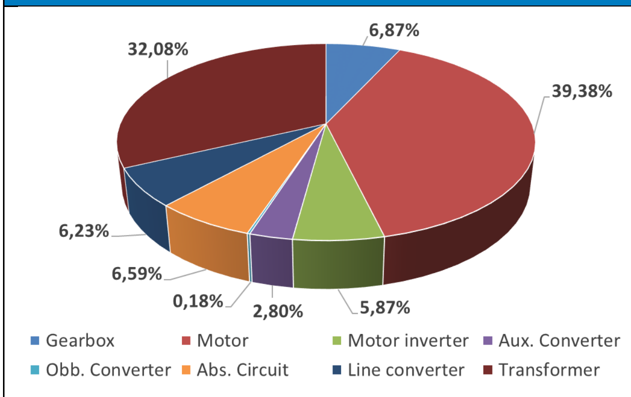
Baseline Metro Service



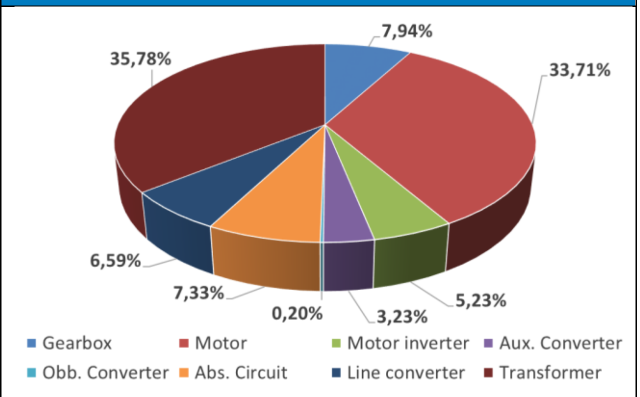
Switch-off Metro Service



Baseline Suburban Service

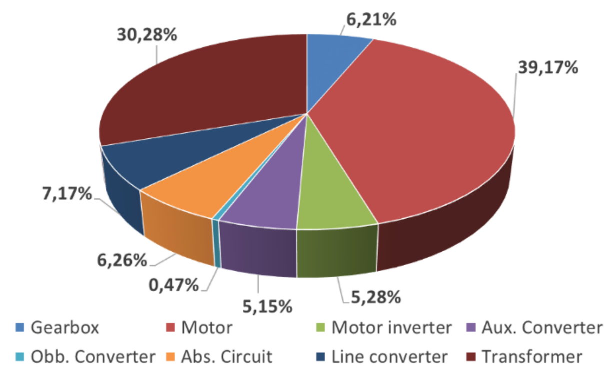


Switch-off Suburban Service

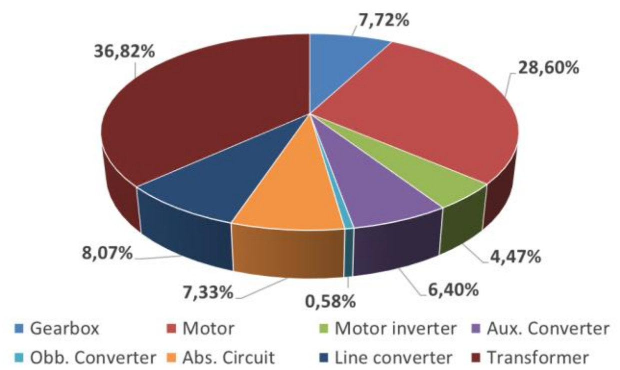


Comparison of energy loss % per component in conventional and switch-off services

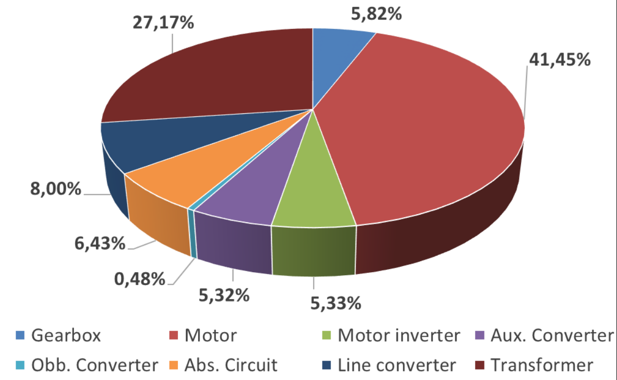
Baseline Reg140 Service



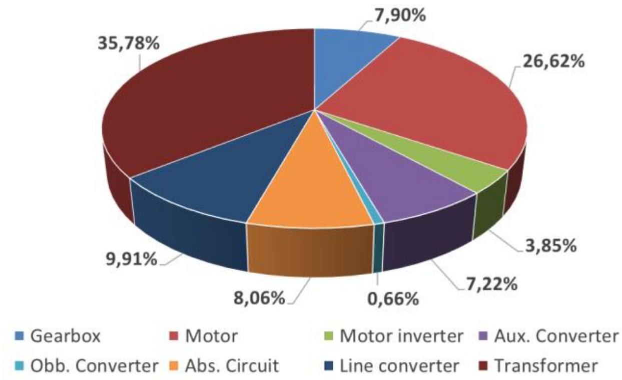
Switch-off Reg140 Service



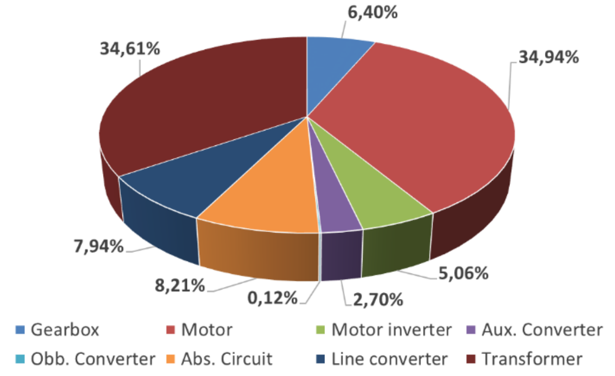
Baseline Reg160 Service



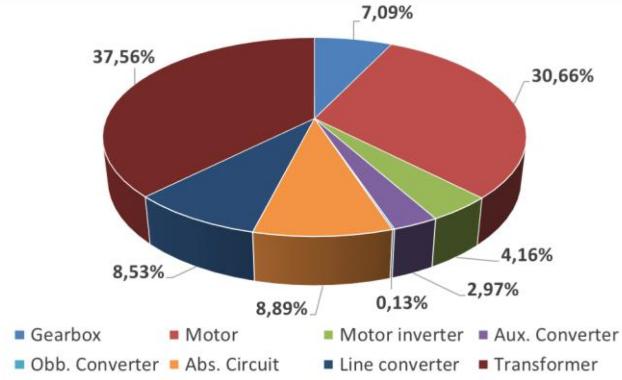
Switch-off Reg160 Service



Baseline High Speed 300 Service

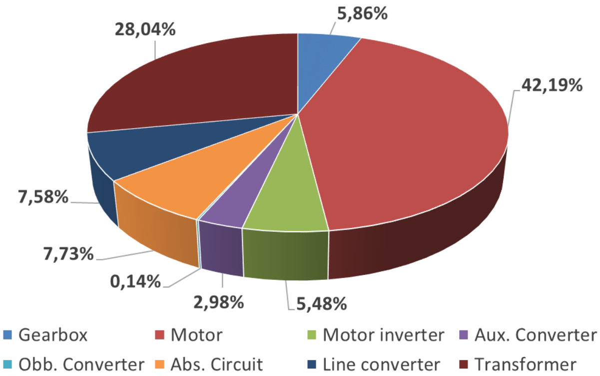


Switch-off High Speed 300 Service

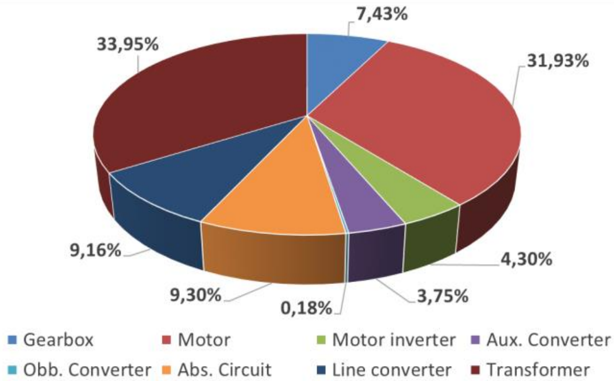


Comparison of energy loss % per component in conventional and switch-off services

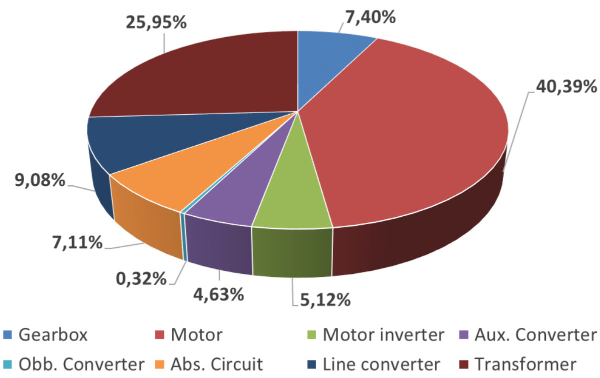
Baseline High Speed 250 Service



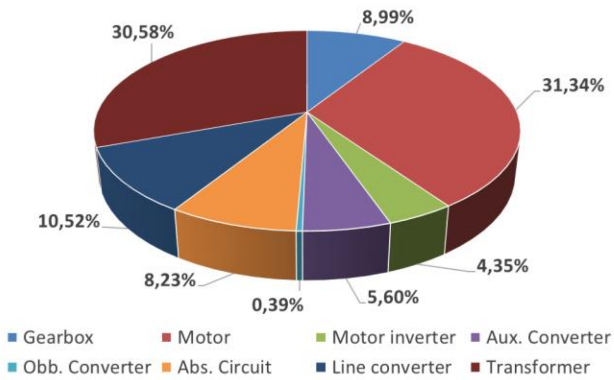
Switch-off High Speed 250 Service



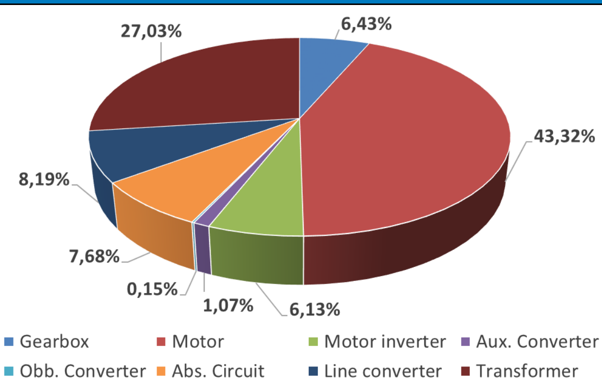
Baseline Intercity Service



Switch-off Intercity Service



Baseline Freight Service



Switch-off Freight Service