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Technical aspects of the selection of an engine-generator set for a dual-drive locomotive

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The use of dual-drive rolling stock is a relatively new solution in the railway market. Vehicles with such type of powertrain are more versatile because it combines the advantages of using diesel vehicles and electric vehicles that consume energy from overhead electric traction. The concept of using such vehicles is highly innovative and has many advantages. However, the design and construction process is more complicated and requires more work than in the case of conventional systems. This article presents the methodology and process of selecting an engine-generator set for a dual-drive locomotive. Indicators and procedures crucial in the process of selecting a dual-drive system for a locomotive, were described and evaluated. All the above mentioned in the work were used during the real design process of a fully Polish locomotive with both diesel and electric drives. The locomotive in Diesel mode was to have an output power of circa 1560 kW for cargo transport. Calculations for the locomotive's power balance are included, showing power losses in the system and for locomotive's own needs. It has been shown that in cargo transport 77% of the maximum engine power is used as tractive power, and in passenger transport 58.6%.

Key words: *dual-drive locomotive, railway, diesel engine, generator set, design process*

1. Introduction

Railway lines can be divided into two types, those with electric traction and those that are not electrified. In the case of Poland, in 2021, the total length of the railway network was 19.3 thousand km, of which 62.8% were electrified standard-gauge lines [11]. Most railway lines have electric traction. However, only vehicles with an independent power source can move on 37.2% of the lines. In practice, this means the use of a vehicle with an internal combustion engine (ICE), mainly Diesel [8, 9]. The use of this type of drive is associated with exhaust emissions, which combined with the average age of diesel rolling stock in Poland, about 40 years old [25], may cause local air pollution [1, 5, 13, 15, 16, 30] and increased fuel consumption [2].

According to the European Environment Agency (EEA), rail transport is responsible for 0.4% of total transport greenhouse gas (GHG) emissions of the European Union (EU) [12]. As a whole, compared to other modes of transport, the emission is negligible. However, the EU policy aimed at reducing exhaust emissions and CO_2 influenced the introduction of strict emission standards also covering rail vehicles. Ambitious zero-emission transport plans [29, 33], led to the development of alternative power sources [4] in the vehicle sector of Non-Road Mobile Machinery (NRMM) [14], which also includes rail vehicles [5, 18, 28]. A particularly discussed issue is the use of hydrogen in rail vehicles [31], mainly using Fuel Cells (FC) [12, 19, 27, 32]. The use of alternative power sources brings benefits, but at the moment, this solution is very expensive and requires huge financial outlays and government subsidies [8].

Therefore, despite their shortcomings, ICEs in railways are widely used and will probably continue to be used for a long time. The reason is the versatility, affordability, and independence of a vehicle with ICE from the railway infrastructure. A diesel vehicle can move on any type of railway line, while an electric vehicle is limited by the availability of electric traction. For this reason, on railway connections that are partly equipped with overhead electric lines, it is common practice to use one electric locomotive on an electrified line and one diesel locomotive on a non-electrified line [24]. However, this solution requires the use of two vehicles, and additional time is required to switch vehicles.

In order to avoid the use of two vehicles for one railway connection, one of the solutions is to use a rail vehicle with two power sources. Combining the most popular drives on the railway – electric and diesel – and installing them on one vehicle brings benefits in the form of using the advantages of both drives. This increases the versatility and flexibility of using such a vehicle on a railway line. Vehicles of this type are not yet so popular a solution on the railway market. However, this solution can be used in any type of railway vehicles, including rail-road vehicles [20, 21, 34], locomotives [22], Multiple Unit (MU) [10], and auxiliary rail vehicles.

The design process of a rail vehicle is characterized by a significant degree of complexity requires experienced design staff in every field, knowledge of railway standards and regulations and a well-thought-out layout of assemblies and subassemblies on the vehicle. In the case of dual-drive vehicles, this is even more challenging due to the two different drivetrains mounted on one vehicle. So far, publications related to the planning, management and implementation of railway projects have been published [17], and related to the selection of the engine-generator set during the locomotive modernization process [23] and auxiliary ICE in special purpose rail vehicle [35]. However, there is still lack of data related to the process and the selection criteria used by designers during the design process of a rail vehicle.

This article presents the most important information regarding the selection process of an engine-generator set for a dual-drive 111DE locomotive from the technical perspective and proceeding scheme of individual stages of the project. The assumptions and requirements for the design of the real locomotive tested on railway lines were also presented. Additionally, in the article, the power balance calculations, which are necessary to determine the energy consumption of the locomotive operating in diesel mode, are also described.

2. Proceeding scheme and assumptions for the selection method of the engine-generator set of a dual-drive locomotive

The design process of a rail vehicle is characterized by a significant degree of complexity and consists of many subsystems and the selection process of devices based on the developed studies and calculations. In the case of selecting an engine-generator set for a dual-drive locomotive, the process is even more complex due to the use and installation of two drive systems on one vehicle. In order to systematize the engine-generator set selection procedure, it was divided into several key stages. In Figure 1, in the form of a block diagram, the sequence of procedure is presented.

The first stage when designing a rail vehicle with two drive systems is to discuss with the ordering party on the detailed technical requirements for the vehicle. These requirements consist primarily of details regarding traction capabilities, i.e. the length and weight of cars that the locomotive will be able to pull, and assumptions regarding the drive systems used. The requirements also include information on maximum speeds depending on operating conditions (dry or wet track, track inclination).

An important element is also specifying the requirements for locomotive equipment. This has a significant impact on the power consumption of the locomotive in diesel mode. An important element is the calculation of a vehicle energy balance. Thanks to this, it is possible to pre-estimate energy consumption, and then based on this information, it is possible to calculate locomotive's traction capacity, both in diesel and electric mode.

If the vehicle is to be built without the participation of the ordering side (e.g. a demonstrator vehicle or in order to expand the company's offer), the process is similar to the one described above, but the requirements are determined on the basis of the experience of the design team and the vehicle manufacturer. During the design process, detailed technical requirements for a dual-drive locomotive were developed in cooperation with the potential user of the locomotive and the manufacturer.

During the process of selecting an engine-generator set, one of the stages is a multi-directional analysis of applicable standards and regulations, in particular regarding the possibility of using ICE and traction generators in railways. The above analyzes are aimed at developing requirements for the engine and generator and starting to call for offers from potential suppliers of these assemblies. Offer analysis and technical consultations require extensive knowledge of the integration of a diesel engine with a generator and, later an engine-generator set with a locomotive.

The next required stage is to carry out analysis regarding the selection of peripheral systems, such as the cooling system or the exhaust aftertreatment system (EAS), which are the subject of commercial offers received from manufacturers. The result of the above activities is the resulting studies and analysis regarding:

- engine and generator life cycle costs, taking into account the load program of the ICE
- exhaust aftertreatment methods and level of exhaust emissions reduction to the assumed/required standard
- mechanical installation of the power unit and determination of permissible loads on the locomotive frame
- mass analysis and its distribution on the vehicle
- service availability
- economic analysis.

Based on the above activities, the final result is the selection of the engine-generator set, along with the necessary systems, as well as the development of the engine-generator set assembly method on the locomotive. Each decision in the design process requires individual analysis and research due to, for example, approval of assembly or approval of using devices in railway vehicles, due to compliance with standards or compliance with the requirements of the project. For this reason, the stages were

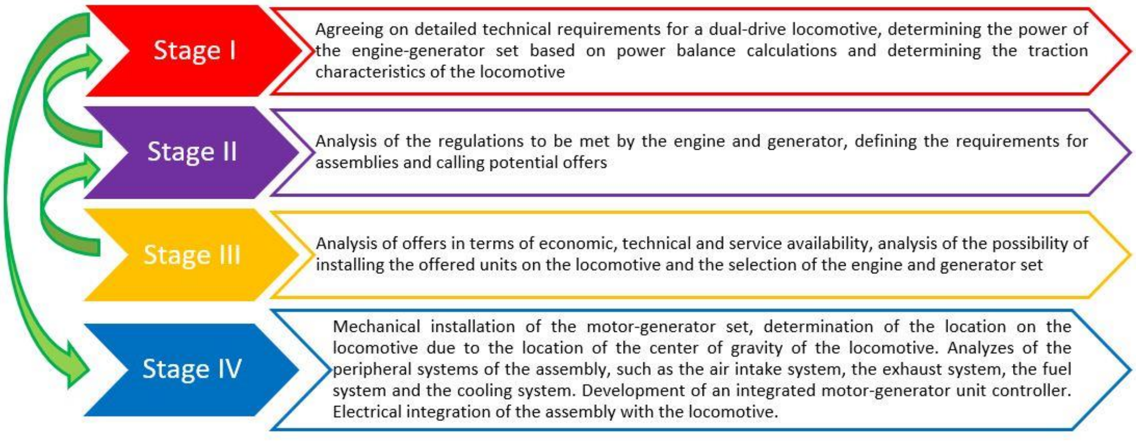


Fig. 1. Block diagram of the stages of selection of the engine-generator set

linked by a "feedback". In the event that the initial element of the layout is adopted, its impact on the rest of the layout must also be traced, which requires "going back" to the previous step.

After completing all the above steps, the last stage consists in the mechanical assembly of the selected engine-generator set. A vehicle with two propulsion systems requires determining the appropriate location of individual units on the locomotive. The even mass distribution of the electrical and diesel systems is a very important factor because it affects the maximum axle loads of the vehicle. These, in turn, are standardized depending on the railway lines and only vehicles with permissible axle load can move on them. During the development process, peripheral circuits and systems were also analyzed. At the same time, analyzes were being carried out to integrate the assembly with the locomotive in electrical and electronic terms. In addition, an integrated controller for the engine-generator set and the control of electric and diesel propulsion systems was being developed.

3. Technical requirements for the vehicle

The project involved designing and building a locomotive with two power sources, where:
- from electric traction line 3 kV DC (Electric mode – E)
- from engine-generator set 3 kV DC (Diesel mode – D).

The dual-drive locomotive was to be a standard-gauge 4-axle locomotive with a power, depending on the mode:
- 2800 kW (E)
- 2000–2200 kW (D).

Table 1. Preliminary detailed design assumptions of a dual-drive locomotive – type 111DE

Parameter	Description
Purpose	passenger/freight
Power supply	3kV DC – railway electric traction and 3 kV DC – diesel power generator – AC-DC-AC transmission
Track gauge	1435 mm
Total length	≤ 20,000 mm
Loading gauge	PN-EN 15273-2 G1
Maximum operating speed	160 km/h
Wheel diameter new/worn	1250 mm/1170 mm
Design mass of the vehicle ready to work	86 t
Load of the wheelset on the track	max. 211 kN
Starting tractive force max.	300 kN adhesion factor (0.3 – dry track)
Locomotive continuous power in cargo transport	electric – 2800 kW diesel engine – c. 1560 kW
Number and arrangement of axles	4, B'o-B'o
Operating speed for passenger trains	Electric traction – 160 km/h Diesel traction – 120 km/h
Operating speed for cargo trains	Electric traction – 110 km/h Diesel traction – 80 km/h
Curve radius of the track	min. 80 m when V ≤ 5 km/h
The longitudinal inclination of the track on which a locomotive can move	max. 40‰
Auxiliary circuit voltage	3×400 V AC; 24 V DC
Control circuit voltage	24 V DC
Multiple traction	up to 2 vehicles

The locomotive's drivetrain was designed to consists of four asynchronous motors powered by traction converters. Electrodynamic, recuperative, and resistive braking was possible. The locomotive was also to be equipped with one or two auxiliary power converters, powered by 3 kV DC, to supply:
- auxiliary voltage network 3×400 V/50 Hz with IT system; some circuits were to be powered by a separate circuit with a voltage of 230 V/50 Hz, powered from a three-phase network by a transformer, and variable-frequency converters controlling the fans operation,
- 24 V DC on-board network, from which the battery was to be charged, and circuits such as control, lighting, railway traffic security, signalling, registration and communication were to be powered.

In passenger traffic, the locomotive was to supply the wagons with 3 kV DC voltage and power up to 400 kW. In power supply mode D, it is provided that the power will be supplied from the power generator, while in mode E, basically from the electric traction. The most important data on design assumptions are presented in Table 1.

One of the two full-fledged power sources in the project was the diesel drive, where the ICE was to drive the electric generator producing a voltage of 3 kV DC. The most important requirements for ICE Diesel are listed in Table 2.

Table 2. Technical requirements for the diesel engine of the 111DE locomotive

Parameter	Requirement
Operating ambient temperature range	–25°C – +40°C
Operating temperature range for electronic devices	–25°C – +70°C
Max. height above sea level	1200 m
Relative humidity of the ambient air	max. 90% at 20°C, annual average 75%
Type of the engine	4-stroke, V-type
Engine power	2000–2200 kW
Rated rotational speed	1800 rpm
Flywheel housing	SAE 00
Adaptation to traction generator drive	Type of the generator construction: single-bearing generator preferred
Electronic engine controller	Yes
Supply voltage of the exciter system's voltage regulator	24 VDC
Exhaust aftertreatment system	Stage IIIB (F cycle) Stage V (for deliveries from 2021)
Design and strength (fastening of accessories and engine to the locomotive)	Acceleration in the: – x axis: ±3 g (longitudinal) – y axis: ±1 g (transverse) – z axis: ±2 g (vertical)
Calculation of engine operating costs – LCC	Post-order delivery required

In the case of the generator, the most important requirements are presented in Table 3. An important indicator in the selection process is the generator power, which in electrical cases is given as apparent power (VA). Apparent power is an electrical indicator where the phase of voltage relative to current (cos φ) for AC must be taken into account. In turn, mechanical power–active power (W), is the real power based on the mechanical efficiency of the generator system and is needed to energy balance calculations. Additionally, for the device that had matching the power of the generator to the power of the engine in the entire rev range, the requirements for the bearings used in the device were specified, the most important of which were:

- possibility of regreasing
- insulated
- temperature measurement required
- bearing design:
  - fixed bearing (no axial displacement of the generator rotor)
  - bearing resistant to micro-vibrations during electric traction (stationary generator)
  - minimum durability of 25,000 hours of operation.

Table 3. Technical requirements for the generator of the 111DE locomotive

Parameter	Requirement
Operating ambient temperature	–30°C – +70°C
Cooling air inlet temperature	–30°C – +40°C
Max. height above sea level	1200 m
Relative humidity of the ambient air	max. 90% at 20°C, annual average 75%
Casing protective level	min. IP 23
Type of work	S9
Type of construction of the generator	synchronous, brushless with built-in generator and rotating rectifier, single-bearing
Diaphragm coupling design	SAE J620
Installation of the generator	claws for mounting flexible supports – two support points
Rated apparent output power	2100–2400 kVA
Rated active output power	~ 1950–2350 kW
Rated generator speed	1800 rpm
Min. generator speed	700 rpm
Rated output voltage (after the rectifier)	3600 V DC
Minimum output voltage (after the rectifier)	2100 V DC
Winding insulation class	H

4. Technical solutions

4.1. Combustion engine

The key stage is the selection of the appropriate drive system, in this case the power generator. On the basis of the previous stages, where technical requirements for the generating set were defined, technical specifications of the sets for suppliers were developed. Based on technical offers, the method of evaluating the selection of a diesel engine and a generator for a dual-drive locomotive project was presented.

In the process of selecting an ICE, potential manufacturers were MTU, Cummins, Liebherr, and CAT. These manufacturers have considerable experience in supplying ICEs for railway applications. In addition, some of the listed companies participated in earlier joint railway vehicle projects.

In the design of the 111DE locomotive, the most important assumptions for the diesel drive were the required power range of the unit 2000–2200 kW and the Stage IIIB or higher emission standard. During the implementation of the project, Liebherr and CAT did not offer engines that meet the requirements in terms of power and the emissions level, which was reflected in the technical assessment.

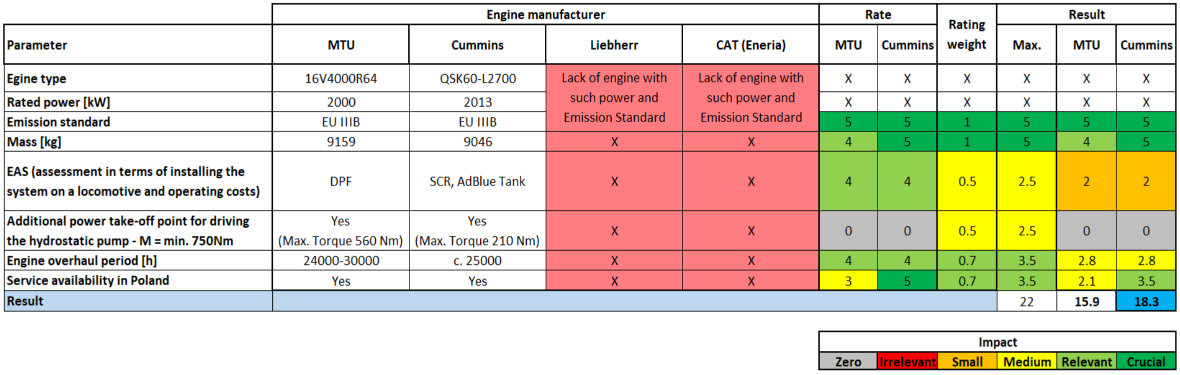
The remaining offers of the two companies were subjected to technical evaluation, of which the most important factors were:

- emission standard, where Stage IIIB was the highest emission standard available for rail applications
- engine mass – a key element, especially in the aspect of permissible locomotive axles loads
- Exhaust aftertreatment system – assembly possibilities and operating costs
- additional take-off point for driving the hydrostatic pump with a minimum torque of 750 Nm – drive of the hydraulic pump of the hydrostatic fan drive system of the ICE cooling system
- engine overhaul period – ICE durability and life cycle
- availability of the service in Poland and the number of available points in the country for efficient operation.

The process of technical assessment of the available ICEs is presented in Table 4. It was decided to evaluate each of the listed factors individually on a scale from 0 to 5 in terms of benefits for the project. In addition, each factor had its individual degree of significance (rating weight), based on the authors' experience from previous projects, where these factors were assigned from the least to the most significant, respectively: 0.5, 0.7, and 1. The most important for the assessment were: emission standard and mass. Indicators of medium importance were: overhaul period and service availability, and indicators with a low importance were: additional take-off point and development possibilities and EAS operating costs.

Each rating for individual factors was multiplied by the rating weight. The obtained results were marked with the appropriate color depending on the impact factor for the final assessment of the ICE, and then summed up. According to the assessment, with the boundary conditions set by the designers, a more favorable solution for the purposes of the project was the use of the QSK60-L2700 Cummins engine with a rated power of 2013 kW.

Table 4. Technical requirements for the diesel engine of the 111DE locomotive



Parameter	Engine manufacturer				Rate		Rating weight	Result		
	MTU	Cummins	Liebherr	CAT (Eneria)	MTU	Cummins		Max.	MTU	Cummins
Egine type	16V4000R64	QSK60-L2700	Lack of engine with such power and Emission Standard	Lack of engine with such power and Emission Standard	X	X	X	X	X	X
Rated power [kW]	2000	2013			X	X	X	X	X	X
Emission standard	EU IIIB	EU IIIB			5	5	1	5	5	5
Mass [kg]	9159	9046	X	X	4	5	1	5	4	5
EAS (assessment in terms of installing the system on a locomotive and operating costs)	DPF	SCR, AdBlue Tank	X	X	4	4	0.5	2.5	2	2
Additional power take-off point for driving the hydrostatic pump - M = min. 750Nm	Yes (Max. Torque 560 Nm)	Yes (Max. Torque 210 Nm)	X	X	0	0	0.5	2.5	0	0
Engine overhaul period [h]	24000-30000	c. 25000	X	X	4	4	0.7	3.5	2.8	2.8
Service availability in Poland	Yes	Yes	X	X	3	5	0.7	3.5	2.1	3.5
Result								22	**15.9**	**18.3**

Impact					
Zero	Irrelevant	Small	Medium	Relevant	Crucial

4.2. Generator

In diesel rail vehicles, ICE is mainly used to drive a generator that generates electricity to supply traction motors and auxiliary systems. In the case of the 111DE locomotive, an important element was the selection of a generator operating in appropriate conditions with an ICE. In addition, an important assumption of the design was similar electrical parameters during Diesel mode (D) and Electric (E) mode. The reason was the use of power electronic devices in the vehicle, which require appropriate operating conditions. In order to avoid duplication of systems and devices, such an idea was implemented.

On the basis of the requirements set out in the earlier stage, commercial offers for generators were received that could be used in the project. The considered generator manufacturers were: EMIT, Hitzinger, VEM, ABB, Elektroputere, and Jenoptik. The requirements for the generator were quite extensive, but the most important technical indicators presented in the article were:

- generated voltage at generator speed 700 and 1800 rpm
- rated output power 2100–2400 kVA at 1800 rpm
- generator mass
- bearing number
- delivery range.

As in the case of the technical assessment of ICEs, selected parameters of the generators were also assessed on a scale of 0 to 5, and the assessed parameters had a significance weight of 0.5, 0.7, 0.8 or 1. The most important parameters with a weight of 1 were generator operating parameters, i.e. voltage values for the minimum and rated speed, as well as rated output power. The weight of 0.8 was assigned to the mass, which, due to the limitations of the maximum locomotive axles loads, was the second most important factor. Mainly due to the minimization of the size of the system and the characteristics of the operation, it was decided to use one bearing, and the weight of this parameter was set at 0.7. The significance of the delivery range was set at 0.5. The devices considered in delivery range were: generator, voltage regulator, rectifier, connecting gusset and clutch. The evaluation results are presented in Table 5.

Assessing the generated voltage at 700 rpm, Hitzinger, VEM, and Elektroputere generators were the most favorable, where the minimum output voltage was at the required level, i.e. 2100 V. In the case of Emit wyk. I, Jenoptik and ABB the voltage levels were too low. For rated output speed, all generators except Emit – wyk. I met the requirement of 3600 V DC. The rated output power in the requirements was to be in the range of 2100–2400 kVA. However, this requirement was met by three generators. In addition, in the case of Elektroputere, the power was 2108 kVA, which is slightly above the lowest required power. In the remaining cases, three generators had too much power, and in one case, the power generated was insufficient for the requirements of the locomotive.

For non-utility parameters, the following data were assessed: mass, number of bearings and delivery range. The assumption for mass, was the lowest possible mass of the generator. This requirement was the most favorable for EMIT – wyk. I with 3700 kg. For ABB and Hitzinger products, the mass was slightly higher, 4270 kg and 4500 kg, respectively, but in the latter case, this value also included the connecting gusset and clutch. The VEM product was heavier than the Hitzinger by 110 kg, but did not include clutch in the statement. The other products were too heavy for the minimum mass requirement.

In the case of the bearings number, three generators were single-bearing: Hitzinger, ABB, Elektroputere. The remaining solutions contained 2 bearings, therefore they were rated 0. In the case of the delivery range that was to cover the order, the most important elements, due to the

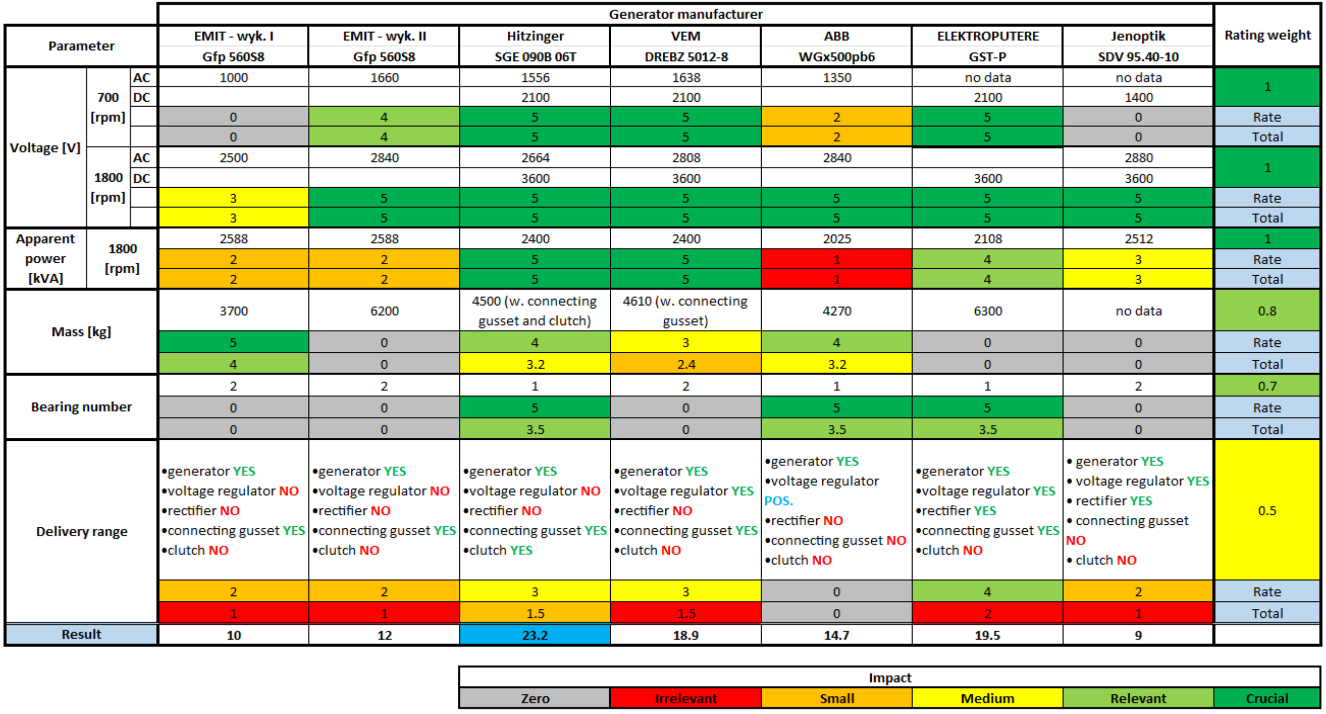


Table 5. Technical requirements for the generator of the 111DE locomotive, where: POS. – possible

Parameter			Generator manufacturer							Rating weight
			EMIT - wyk. I Gfp 560S8	EMIT - wyk. II Gfp 560S8	Hitzinger SGE 090B 06T	VEM DREBZ 5012-8	ABB WGx500pb6	ELEKTROPUTERE GST-P	Jenoptik SDV 95.40-10	
Voltage [V]	700 [rpm]	AC	1000	1660	1556	1638	1350	no data	no data	1
		DC			2100	2100		2100	1400	
			0	4	5	5	2	5	0	Rate
			0	4	5	5	2	5	0	Total
	1800 [rpm]	AC	2500	2840	2664	2808	2840		2880	1
		DC			3600	3600		3600	3600	
			3	5	5	5	5	5	5	Rate
			3	5	5	5	5	5	5	Total
Apparent power [kVA]	1800 [rpm]		2588	2588	2400	2400	2025	2108	2512	1
			2	2	5	5	1	4	3	Rate
			2	2	5	5	1	4	3	Total
Mass [kg]			3700	6200	4500 (w. connecting gusset and clutch)	4610 (w. connecting gusset)	4270	6300	no data	0.8
			5	0	4	3	4	0	0	Rate
			4	0	3.2	2.4	3.2	0	0	Total
Bearing number			2	2	1	2	1	1	2	0.7
			0	0	5	0	5	5	0	Rate
			0	0	3.5	0	3.5	3.5	0	Total
Delivery range			•generator YES •voltage regulator NO •rectifier NO •connecting gusset YES •clutch NO	•generator YES •voltage regulator NO •rectifier NO •connecting gusset YES •clutch NO	•generator YES •voltage regulator NO •rectifier NO •connecting gusset YES •clutch YES	•generator YES •voltage regulator YES •rectifier NO •connecting gusset YES •clutch NO	•generator YES •voltage regulator POS. •rectifier NO •connecting gusset NO •clutch NO	•generator YES •voltage regulator YES •rectifier YES •connecting gusset YES •clutch NO	• generator YES • voltage regulator YES • rectifier YES • connecting gusset NO • clutch NO	0.5
			2	2	3	3	0	4	2	Rate
			1	1	1.5	1.5	0	2	1	Total
Result			10	12	23.2	18.9	14.7	19.5	9	

Impact					
Zero	Irrelevant	Small	Medium	Relevant	Crucial

later assembly of the engine-generator set, were connecting the gusset and clutch. Due to this, the best offer was made by Elektroputere, where only the clutch was not included in the scope of delivery. The offers from Hitzinger and VEM were rated 3. The other bids were rated 2 or 0.

The rates were multiplied by the rating weight, and then the results for a generator were summed up. The highest score was achieved for the Hitzinger SGE 090B 06T generator – 23.2 points. The second result in the ranking was achieved by Elektroputere – 19.5, and the third by VEM – 18.9. For this reason, the Hitzinger SGE 090B 06T generator was used in the 111DE locomotive.

5. Dual-drive locomotive power balance

5.1. Auxiliary circuits – locomotive own's power demand

Based on the determination of the power balance, it is possible to specify the requirements for ordering devices, subassemblies and apparatuses, as well as to estimate the locomotive's energy demand for selected devices. Mechanism for assessment of energy balance for a 111DE rail vehicle operatingFtable in diesel traction with a maximum power of selected 2013 kW ICE has been shown. Rail vehicles operations in real conditions usually does not take place at maximum engine load, however, the calculations are important to demonstrate, among other things, maximum useful tractive power in different transport modes.

DC circuits

The locomotive consists of a number of devices and assemblies requiring DC power. It is therefore, necessary to estimate the energy consumption of these devices. Table 6 summarizes the most important auxiliary devices or their parts powered by direct current in diesel mode. Non-simultaneity of work resulting from traffic and climatic conditions was taken into account (winter-w and summer-s season).

Table 6. Power demand of DC auxiliary devices (w – winter, s – summer)

24V DC circuit or device	Power in D mode
External lighting – front + rear, solo driving	0.20 kW
Cabin A/C – active in 2 cabins	2 × 0.53 kW
Cabin heaters – active in 1 cabin	0.34 w/0 s kW
Diesel engine and AdBlue tank heaters	2 × 0.59 kW
Battery charging – I10	0.84 kW
Internal lighting (full)	0.15 kW
Control unit	~2 kW
Rest	~5 kW
In total:	10.77 w/10.43 s kW

AC circuits

In the case of AC circuits, the power demand is greater. The circuits or devices operate at 400 or 230 V AC. Figure 2 shows the power demand of AC auxiliary devices. Energy consumption is influenced by climatic aspects, where higher energy consumption is in the winter period. The graph shows that the largest consumers of energy from the AC system are: traction converters cooling (40 kW), main compressors (40 kW), and brake resistor tower fans (37 kW).

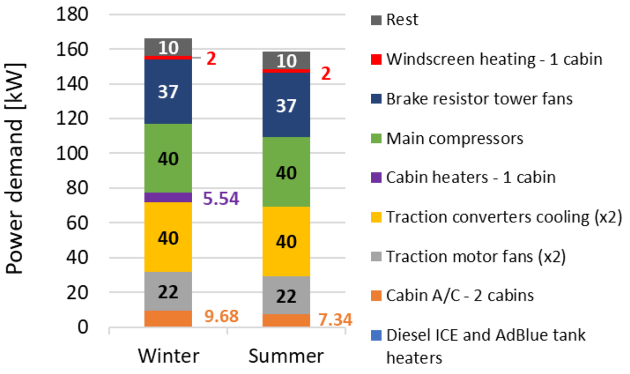


Fig. 2. Power demand of AC auxiliaries in 111DE dual-drive locomotive

High voltage power demand – own needs

The demand for electricity for the locomotive's own needs can therefore be divided into two types: AC circuit and DC circuit. The electricity generated by the power generator to supply both circuits must additionally pass through an auxiliary converter. Assuming the efficiency of the auxiliary converter η_C = 0.83, power demand for the locomotive's own purposes on the supply side 3 kV DC (P_{Ld}) can be calculated from formula (1), where: P_{DC} – DC circuit demand, P_{AC} – AC circuit demand.

$$P_{Ld} = \frac{P_{DC} + P_{AC}}{\eta_C} \tag{1}$$

Based on the formula (1), the maximum energy demand for own purposes of the dual-drive 111DE locomotive in diesel mode, was calculated depending on the season (Fig. 3). By far the largest share of power demand falls on AC circuit. In the case of a DC circuit, this demand is up to 5% of the total power demand for the locomotive's own needs. The diesel locomotive will have the biggest power demand in winter, mainly due to the need to heat the driver's cabins.

In the initial stages of calculation work, a much higher electric energy consumption rate was assumed in order to avoid unplanned energy deficits for traction purposes due to the energy consumption of on-board devices. After energy consumption analyzes of electrical devices selected in later stages, the maximum value of energy consumption for the locomotive's own purposes was adjusted and assumed at the level of 200 kW in diesel mode.

5.2. High voltage circuits

The calculations assumed the maximum power demand for traction purposes. In D mode, the power to the traction purposes is limited. At the assumed maximum power of the ICE P_{ICE} = 2013 kW, the power demand of the ICE's cooling system must be taken into account (P_c) assumed on the 80 kW. This means ICE net power (P_{nICE}):

$$\begin{gathered} P_{nICE} = P_{ICE} - P_c = \\ = 2013\ \text{kW} - 80\ \text{kW} = 1933\ \text{kW} \end{gathered} \tag{2}$$

Net ICE power (P_{nICE}) in the form of mechanical energy is then transferred to the generator with a rectifier, where DC electricity is generated (P_G). The efficiency of the traction generator with the rectifier was assumed to η_G = 0.96.

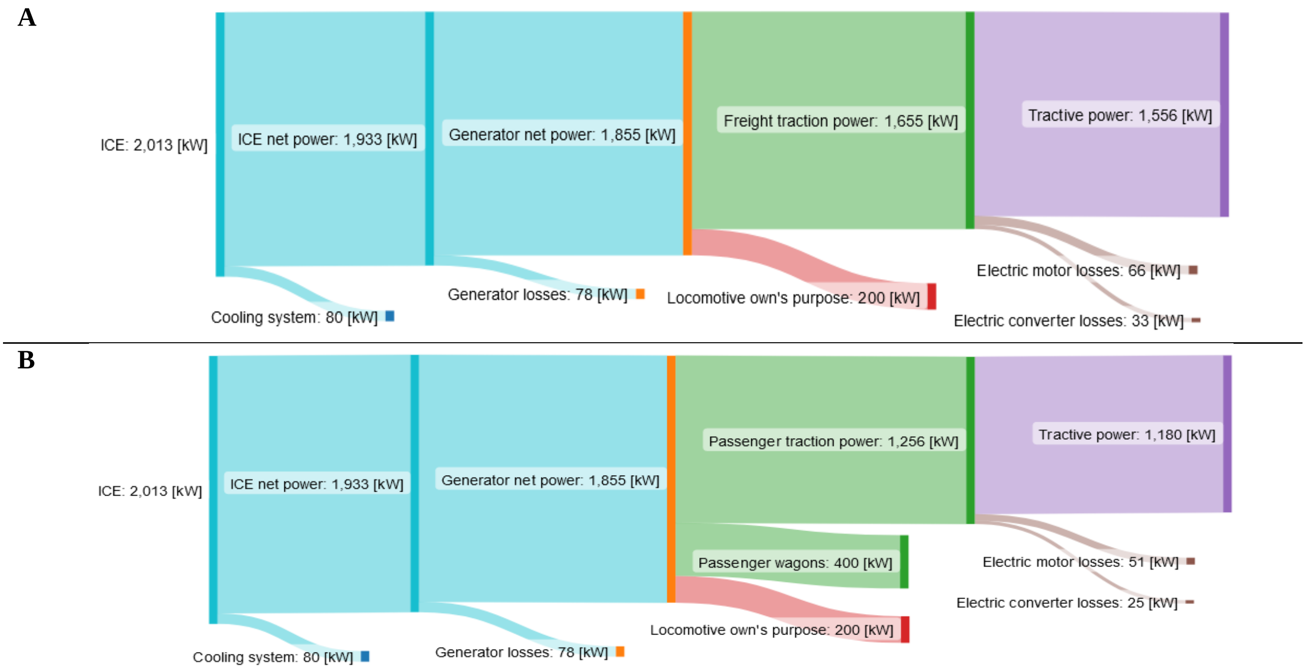


Fig. 4. Energy balance of the dual-drive 111DE locomotive in diesel traction at work: A – freight, B – passenger

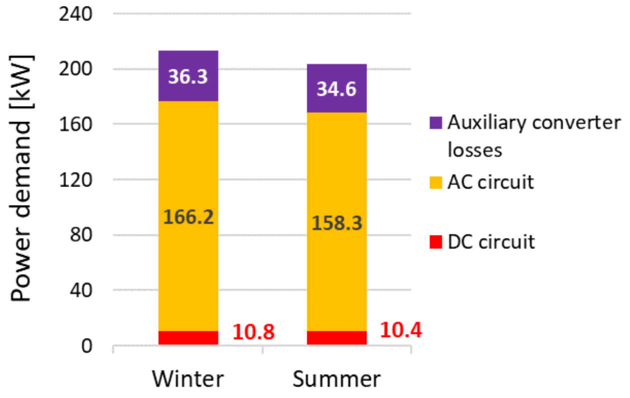


Fig. 3. Calculated total power demand for own purposes of 111DE dual-drive locomotive in Diesel mode

$$P_G = P_{nICE} \cdot \eta_G = 1933\ \text{kW} \cdot 0.96 = 1855\ \text{kW} \quad (3)$$

The locomotive consumes energy for its own purposes (auxiliary circuits) (P_{Ld}), where the demanded power is about 200 kW. This means that the net electric energy behind the generator for other purposes (P_{Gn}) is:

$$P_{Gn} = P_G - P_{Ld} =$$

$$= 1855\ \text{kW} - 200\ \text{kW} = 1655\ \text{kW} \quad (4)$$

In the case of passenger traction, an additional power supply of 400 kW is also required for the passenger wagons (P_{Pd}). This means that the remained available electric power in passenger traction (P_{Gp}) is:

$$P_{Gp} = P_{Gn} - P_{Pd} =$$

$$= 1655\ \text{kW} - 400\ \text{kW} = 1255\ \text{kW} \quad (5)$$

In the power balance for diesel mode, it is also required to take into account the efficiency of traction converters ($\eta_{Tc} = 0.98$) and electric traction motors ($\eta_{Te} = 0.96$). This means that the maximum tractive power in diesel mode for cargo (P_{Dc}) and passenger (P_{Dp}) purposes is as follow:

$$P_{Dc} = P_{Gn} \cdot \eta_{Tc} \cdot \eta_{Te} =$$

$$= 1655\ \text{kW} \cdot 0.98 \cdot 0.96 = 1556\ \text{kW} \quad (6)$$

$$P_{Dp} = P_{Gp} \cdot \eta_{Tc} \cdot \eta_{Te} =$$

$$= 1255\ \text{kW} \cdot 0.98 \cdot 0.96 = 1180\ \text{kW} \quad (7)$$

Figure 4 shows the energy balance of the dual-drive 111DE locomotive in diesel mode, depending on the type of work performed.

6. Summary

The process of selecting the engine-generator set in railway vehicles can be divided into several stages, the most important of which were presented in the article: determining the method and work plan, specifying the requirements for the locomotive and drive system, technical assessment of devices and calculations including, among others, vehicle's energy balance. Based on the mentioned steps, it is possible to select the appropriate engine-generator set for the designed vehicle.

Analyzing the presented process of evaluating the diesel drive system for a dual-drive locomotive, it can be concluded that the mass of the devices plays a very important role both for the engine and the generator. This is due to the very limited possibility of mounting and the permissible axles loads of the vehicle, which has two different sources of drive. Reliable operation of the vehicle is also important, and in the event of an ICE damage, taking the vehicle out of service can be costly [3]. For this reason, the availability of the service is also an important element in the technical assessment of the device.

For the assessment of the generator, the most important elements were the operating parameters of the device that had to work in the required conditions. In addition, the aforementioned mass was also of key importance, as well as the number of bearings used, where their number affected the possibility of installing other devices on the vehicle. The delivery range was not a very important element, but it facilitated the design process and assembly due to the elements properly selected by the manufacturer.

The energy balance of a dual-drive locomotive allows to determine the power demand when operating in Diesel mode. Properly performed calculations based on design assumptions are an important element at the stage of selecting devices and systems in the locomotive, including primarily the drive system, due to the estimation of power demand requirements. In the case of calculations for selected devices, they make it possible to determine the expected performance of the locomotive, e.g. in passenger and freight traction.

It is noteworthy that with the maximum engine power of 2013 kW in freight traction, the vehicle will have a maximum power (on traction motors) of 1556 kW, where about 23% of the power is lost mechanically and thermally or is available for locomotive own's purposes. In the passenger traction, the power of the locomotive in diesel mode is additionally reduced by 400 kW due to the wagon power supply. As a result, the useful power on the traction motors remains about 1180 kW, i.e. 58.6% of the initial power generated by ICE.

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Nomenclature

A/C	air conditioning
AC	alternating current
DC	direct current
DPF	diesel particulate filter
EAS	exhaust aftertreatment system
EEA	European Environment Agency
EU	european union
FC	fuel cell
GHG	green house gases
ICE	internal combustion engine
MU	multiple unit
NRMM	non-road mobile machinery
SCR	selective catalytic reduction

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