Comprehensive assessment of the carbon neutrality actions from the automotive sector

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Abstract

The aim of this paper is to analyse and demonstrate the carbon neutrality actions of a special facility in the context of the automotive sector. In order to analyse the emissions, a carbon simulation model is developed. Offsetting options are also overviewed in a systematic way. We provide a methodology for a systematic analysis of greenhouse gas (GHG) emissions and offsetting opportunities of an automotive facility. We compile an inventory of the carbon emissions, identify offsetting options and prepare a cost–benefit analysis of the mitigation actions. The relevance of United Nations Sustainable Development Goals (SDGs) is also assessed. We examine the GHG emissions of an automotive proving ground, ZalaZone in Zalaegerszeg, Hungary, as a case study. Four scenarios with various shares of decarbonisation options have been proposed to achieve the vision of net zero GHG emissions. It was found that net zero emission is achievable. The CBA concluded that the net present value is negative; however, there are significant external benefits. It was revealed that the operation of the facility contributes to multiple SDGs and provides different pathways to carbon neutrality.

Keywords Carbon neutrality · Emission calculations · Carbon offsetting · Carbon simulation · Automotive sector

1 Introduction

Globally, the transport sector is a key element of the sustainability transition (Bassi et al., 2022; Rodrigue, 2020). The sector also has a substantial role in decarbonisation and climate change mitigation (Runsen & Junyi, 2021). The automotive sector is a significant contributor to GHG emissions in Europe, the share of road transport is 72%, and it is responsible for nearly 30% of the EU's total CO_2 emissions (EP, 2019). The transition of

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automotive sector towards sustainable development is strongly interlinked with the sector's green innovation (Gohoungodji et al., 2020), which should also contribute to carbon-neutral transport systems.

A key theoretical question is whether there is untapped potential in the decarbonisation of the automotive value chain. One of the essential infrastructure elements of automotive innovation is the proving facilities (test tracks). The test tracks of future vehicles are the key starting elements of the innovation chains in the automotive sector (Vaz et al., 2017). Although there are expanding arrays of research on the sustainability and climate change aspects of some elements of the automotive innovation value chain, the decarbonisation performance of the proving facilities has not been investigated. Consequently, we have posed the research question: Is carbon neutrality possible on test tracks? We assumed that the high sustainability performance of the test tracks may directly and indirectly contribute to deploying carbon-neutral and green research and developments in the automotive sector. These spillover effects of decarbonisation are widely assessed (i.e. Prillwitz & Barr, 2011), and the (i) measurable (monitored) targets and (ii) proper communication with the stakeholders are among the most important success factors.

Rapid technological innovations contribute to the importance of committed companies to use adequate tools in GHG emission reduction and offsetting, especially in sectors with high emissions. Overviewing the literature about offsetting, it was found that most empirical studies focus on the behaviour and attitude of individuals or consumers. The most frequently analysed market is aviation (Mair, 2011; McLennan et al., 2014; Ritchie et al., 2021). The assessment of consumer preferences involves the analysis of the gap between the attitudes and behaviour of individuals (Denton & Chi, 2020), the impact of communication on voluntary purchasing of carbon offsets (Ritchie et al., 2021) as well as the identification of typical groups of customers (Mair, 2011). It was found that individuals prefer carbon offset schemes that support local programmes instead of international ones (Ritchie et al., 2021).

The reduction of CO_2 emission is also important as several articles found that with growing GDP and increasing energy consumption per capita (EC), GHG emission is growing, too (Abbas et al., 2021a; Abbas et al, 2021b and Sheraz et al., 2022), making the completion of United Nations Sustainable Development Goals (UN SDGs) more challenging.

Our research objective is to develop and apply a decarbonisation model enabling climate-neutral planning and operations of automotive test tracks. The primary aim of this paper is to provide a systematic analysis of greenhouse gas (GHG) emissions and offsetting opportunities of a modern automotive facility (see Sect. 2). The scientifically based assessment of decarbonisation options is highly needed and should not be limited to the exploration of the technical viability of carbon-related measures. Our research targeted the GHG emission estimation and the evaluation of offsetting options in order to provide a feasible decarbonisation mix for fulfilling the vision of net zero (or negative) emissions. The existing emission estimation methods were tailored, and a special tool—carbon simulation model (CSM)—had to be developed. The paper analyses the CSM, consisting of the GHG emission calculations and offsetting options which are presented, followed by the cost–benefit analysis of the selected offsetting portfolio.

In the framework of our research, we shed light on the automotive sector through an innovative service. We selected a high-scale state-funded project in Hungary: implementation of the automotive proving ground ZalaZone in Zalaegerszeg, Hungary. We provide a case study of ZalaZone focusing on innovation in the automotive sector (see Sect. 3). We analyse sustainability impacts beyond GHG mitigation, and an assessment of the impacts of the facility's general operations and mitigation efforts in the context of the United

Nations Sustainable Development Goals (UN SDGs) have been performed (see Sect. 4). Based on the model development and empirical findings, the results were compared with previous studies, and the adaptability of the model for other organisations in other regions or in countries outside the European Union was also demonstrated (see Sect. 5). Finally, some conclusions applicable by academics and practitioners are formulated, limitations are highlighted, and recommendations are given (see Sect. 6).

Besides ZalaZone's significant innovation potential to improve research and development in the automotive sector, its management decided to set an ambitious climate goal: to operate in a carbon-neutral way. Their clients are typically innovative industrial companies from the automotive sector, several of them setting climate goals themselves. Since the investment of ZalaZone is a state-funded project, lessons learnt can be useful for the public sector.

2 Materials and methods

The automotive sector has an influence on decarbonisation in some main thematic areas. They contribute to mitigation directly, by carbon-neutral operations and indirectly, by influencing their stakeholders, first of all, clients. Those companies that have clients from the private sector are especially important actors in this regard as well as innovative enterprises, having higher potential to implement new, innovative solutions. Before setting up the carbon simulation model, it is necessary to overview the state-of-the-art methods of different kinds of activities for decarbonisation, specifically in the automotive sector.

2.1 State-of-the-art methods of carbon monitoring and decarbonisation planning in the automotive sector

Most empirical research and model developments focus on the macro-level. Setiawan (2021) provide a macro-level analysis of emissions and the impact of policy measures implemented to reduce CO_2 emissions in Indonesia. Berscha et al. (2021) analyse the decisions regarding new product introduction in the automotive sector. The sustainability relevance of their method is that it can be useful to assess the transition to electric vehicle production. Liu et al. (2015) analyse the environmental impacts of the automotive sector on the national level in China, using a life cycle analysis (LCA), focusing on both the production and consumption phases. They emphasise that in case of China as the leading automotive market with growing production, environmental pressures also grow. They also provide some recommendations in order to decrease environmental impacts.

Jasinski et al. (2015) analyse the applicability of full cost accounting in case of the automotive sector. After a comprehensive literature review, they conclude that the most appropriate tool is the sustainability assessment model developed by British Petroleum and Aberdeen University. While most of the studies focus on GHG emissions or energy issues (Degen & Schütte, 2022), Cooper et al. (2017) analyse material throughput in the UK. They identify six interconnected socio-technical factors, influencing efficiency. The sustainability impact of electric cars is discussed in several contexts (Borgstedt et al., 2017; Degen & Schütte, 2022).

Gebler et al. (2020) focus on the factory level and GHG emissions, presenting a life cycle assessment case study. Besides following an LCA approach, several studies concentrate on a specific section of the whole life cycle. Some focus on the manufacturing phase

(Giampieri et al., 2020; Stoycheva et al., 2018), the use phase (Vdovic et al., 2021), while others on the end-of-life product (Wong et al., 2018; Xun et al., 2020).

On the one hand, the model we have developed differs from the decarbonisation models known in the literature in terms of its scope, since, as indicated above, no similar model has been developed for test tracks. On the other hand, our model provides a comprehensive, innovative framework which is able to provide readily available real-time information for the management.

2.2 Description of carbon simulation model (CSM)

As the first step, the appropriate and general method for our purposes should be selected. We have chosen the GHG Protocol (WBCSD & WRI, 2004 and WBCSD & WRI, 2014) as the procedure for the investigations. System boundaries of the operation are defined based on the three different scopes of the protocol:

- Scope 1: direct GHG emissions occur from sources that are owned or controlled by the company,
- Scope 2: indirect GHG emissions (e.g. related to purchased electricity consumed),
- Scope 3: other indirect GHG emissions (e.g. all other purchased materials, including fuels).

GHG protocol provides an assessment tool for the calculation of carbon emissions. Based on the results of the calculations, further steps have to be done to create an entire carbon simulation framework. In this chapter, we will show the elements of the carbon simulation model and the additional methodological tools: carbon emission reduction and offsetting, cost–benefit analysis and possible applications.

We developed a carbon simulation model using the estimates and other relevant information to extend and generalise the calculation procedure in a unified emission modelling framework. The purpose of this model is to fully estimate and forecast emissions based on operational data of the company, as well as to display them graphically. The modelling concept was based on the following principles and expectations, among others:

- Strategic planning of processes; trend analysis over the design period of the facility (15 years),
- Controlling with the comparison of the estimated values with the facts on a quarterly basis,
- Display and graphical visualisation of the main results,
- Extensibility (possibility to include new activities later).

Considering the principles above, the carbon simulation effect model consists of four main modules: INPUT (parameters) module, PLANNING (calculation) module, MONITORING (estimation/fact) module and REPORTING module. The logical structure of the model is illustrated in Fig. 1.

2.2.1 Methodology for calculation of GHG emissions

GHG emissions are usually related to transport movements and to the energy consumption and material flows of buildings. For the calculation of emissions of transport
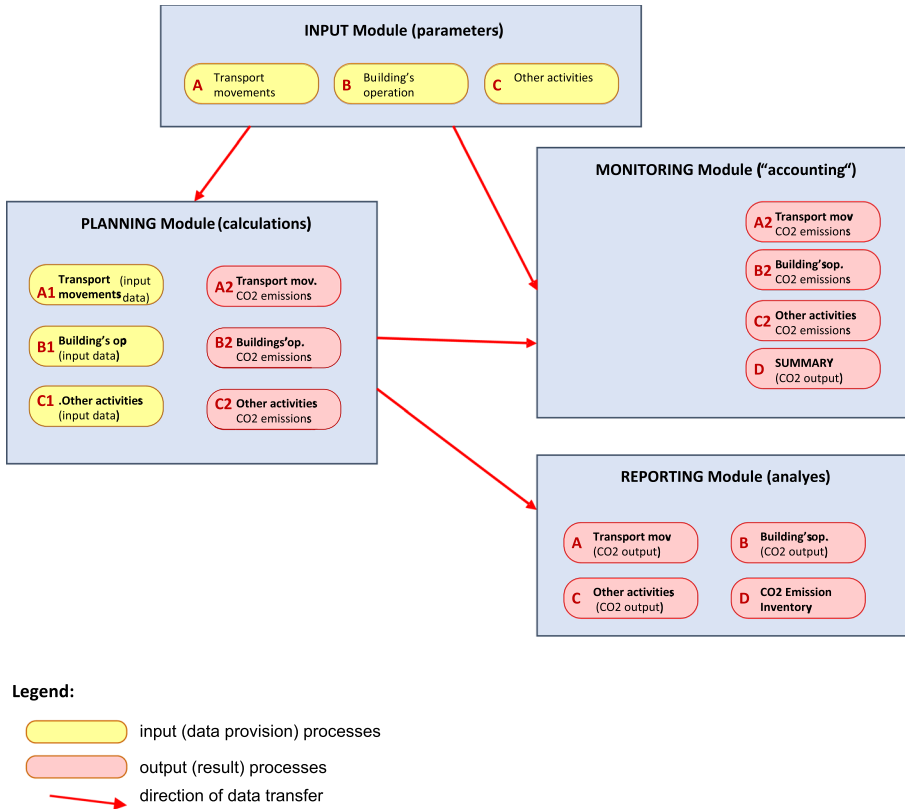
Fig. 1 Logical framework of the carbon simulation model

movements, we can use the methodology for the calculation of the emission of transport-related activities based on the standard EN 16258:2012 titled "Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers)" (European Standards, 2018). Estimation of CO_2 equivalent emissions from gasoline or diesel fuels can be performed using conversion factors of the Tank-to-Wheels approach as an assessment related to the energy consumption of the propulsion system of the vehicle. In addition to emissions related to the vehicles with internal combustion engines, emissions from electric and hybrid vehicles can be also estimated. The estimation for the average energy consumption is a value of 300 Wh/km, calculated with a national emission factor (for example: 350 g/kWh in Hungary).

Direct and indirect emissions from transport-related operation of the site depend on the number of vehicle kilometres travelled during the various trips that are part of the organisation's operation. These GHG emissions are comparable to the emissions associated with the transport movements on the test tracks. According to the GHG protocol and based on the input data, we can calculate the number of journeys made annually and then estimate the emissions using the previously applied conversion factors. Direct effects are caused by commuting of employees with vehicles owned and/or operated by the organisation, business trips, transportation of customers and visitors within the site and on-site patrols.

The indirect effects of air travel can be quantified according to the guide "Update of the Handbook on External Costs of Transport". The cost per 1 passenger kilometre for flights between 1000 and 1500 km is 1.25 EURcent/passenger-km. This value is to be understood as a cost of EUR 90/tonne of CO_2 (at 2010 prices). If we divide the marginal cost by this, we get the specific emissions per 1 passenger-km.

Emissions from the energy use of the buildings on the site can be determined on the basis of the lighting, heating, hot water, ventilation and cooling energy consumption of the buildings. We can examine the effect of the choice of the electricity emission factor (design value, national value, value corresponding to the local energy production mix). We can take into account the number of occupancy hours during the year (i.e. less functions are used in winter and more in summer). Other activities of the company can be also evaluated, and the methodology for calculation of GHG emissions related to specific activities depends on their significance. The method should be fitted to the complexity and availability of related input data.

2.2.2 Methods of decarbonisation planning: reduction of carbon emissions and offsetting

The demand for carbon offsetting has radically increased in every sector of the economy. For example, in the aviation sector within one decade it grew from 0.3 million tonnes of CO_2 to 42.8 million tonnes in 2018 (Hamrick & Gallant, 2018). We can presume that people welcome offsetting in other sectors, including the automotive, too. The most frequently analysed offsetting measure is forestation or forest management (Fouqueray et al., 2021; Grassi et al., 2019). However, the comprehensive evaluation and comparison of various offsetting options are lacking.

Based on the mapping and estimation of emissions and considering the realistic possibilities, we can formulate recommendations for emission reduction for ZalaZone. We can continue with the analysis of offsetting options, and usually several opportunities are available. After overviewing several offsetting measures, including various forms of renewable energy production and carbon sequestration, taking into consideration the climatic conditions, three alternative actions are the most common ones: establishment of a photovoltaic (PV) farm, sequestration by forestation and the plantation and utilisation of energy crops. It should be mentioned that the typical size of the sites of automotive companies mainly in urban areas is usually not enough for plantation or forestation.

The next step is to estimate the offsetting potential of the measures, and thereby, the size of the necessary territory could be estimated. While the offsetting potential of PV is constant, or slightly decreasing, that of forestation is relatively low in the first years, reaching its maximum in 10–20 years or even later. Energy crop plantation or forestation has a very low potential in the first years, with a relatively long time to reach the maximum values. Nowadays, the range of applications of PV technology is growing significantly worldwide, the investment and operating costs are relatively low compared to other energy production technologies.

We can outline some possible scenarios that represent different ratios of the possible offsetting measures based on their potential and territory requirements. The advantage of using mixed offsetting scenarios is the diversity; however, it also increases the complexity of the offsetting efforts. The next step is the formulation of the final version of the offsetting scenario and the calculation of the investment and operational costs and benefits.

2.2.3 Cost–benefit analysis of offsetting measures

The specific carbon efficiency t [CO_2e]/ha/year depends on the method of offsetting that is why we need to select the offsetting scenarios carefully. It is very favourable from an environmental point of view if the offsetting rate can be higher than 100%. For the selection of the best option, we elaborated a financial analysis using a cost–benefit analysis (CBA) method. The estimated costs and benefits of the CO_2 offsetting options can be compared by examining the selected deployment portfolio from a financial perspective and with the examination of the social benefits. The latter are not realised by the investor, but by external stakeholders, therefore, they can be considered as positive externalities. We can use the general EU (COM, 2014) and—if it is available—the national guides for transport projects as a framework for our analysis, taking into account the methodological challenges of the CBA as an assessment tool described in Vörös (2018) and Laird et al. (2014). CBA could be the most important part of the project appraisal for such a special facility. The general principles written in Mishan (1971) have to be adjusted to this unique project.

In the financial analysis, we calculate the costs and revenues for the realisation of the offsetting measures. The financial costs of an investment can be divided into the following groups: investment costs (land purchase and installation costs) and operating (maintenance) costs. The residual value is reported in the last year of the assessment period, if applicable. Revenues consist of the following items: investment-related returns (e.g. sales of previously degraded acacia) and operating returns (e.g. electricity or biomass sold). The calculations can be performed for an evaluation period of 15 years. After installation, the operating period starts. The first year of the investment is considered the starting year of the analysis, i.e. the base year. During the analysis, we calculate at a constant price (the price fixed for the starting year) and the financial discount rate is 4%.

The most important indicators of financial analysis are: financial net present value (F NPV), internal rate of return (IRR) and benefit–cost ratio (BCR). The purpose of the compensation is not to make a profit, but to meet sustainability goals. Generally, significant external social benefits—from reducing GHG emissions—are present.

For the method of calculating the monetary value of social benefits, the starting point is that offsetting is also beneficial to society, whose monetary value can be determined. The social impact of climate change can be quantified through the specific monetary value of CO_2 emissions (CE Delft, 2019). According to a widely accepted methodological approach, the carbon allowance price is the specific monetary value of emissions. The social benefits can be calculated as the product of the specific costs of climate change multiplied by the CO_2 equivalent emissions offsetted. The assumptions for the periods are the same as those described in the financial analysis, and the social discount rate is 5%.

3 Application of carbon simulation model (CSM) for ZalaZone

Our methodological approach is applicable for any organisations or projects that operate vehicles and buildings. However, there could be some differences in the magnitude of the emission of greenhouse gases of the activities. Based on the nature of the activity, our research has focused on the development of a carbon simulation model, from portfolio development to their financial and social utility quantification, with the aim of achieving carbon neutrality. In order to examine the degree of applicability in other areas, we

explored the main characteristics of applicability and potential barriers as limitations of the assessing tools.

The carbon simulation model we have developed is suitable for assessment by projecting accurate, reliable data on GHG emissions for different periods of operation. Of course, the estimation of emissions is only the first step, followed by the planning and implementation of reduction and offsetting measures. The carbon neutrality target can be reached in a different emission structure, but with similar methodological steps.

The facility that can apply our model is ZalaZone: linear facilities, vehicle movements and buildings can all play a significant role in emissions. ZalaZone is a full-range validation facility for the vehicles and communication technologies, enabling multi-level testing opportunities from prototype tests till serial products development. Figure 2 shows the layout of the test track modules (including Smart City Zone) and the buildings.
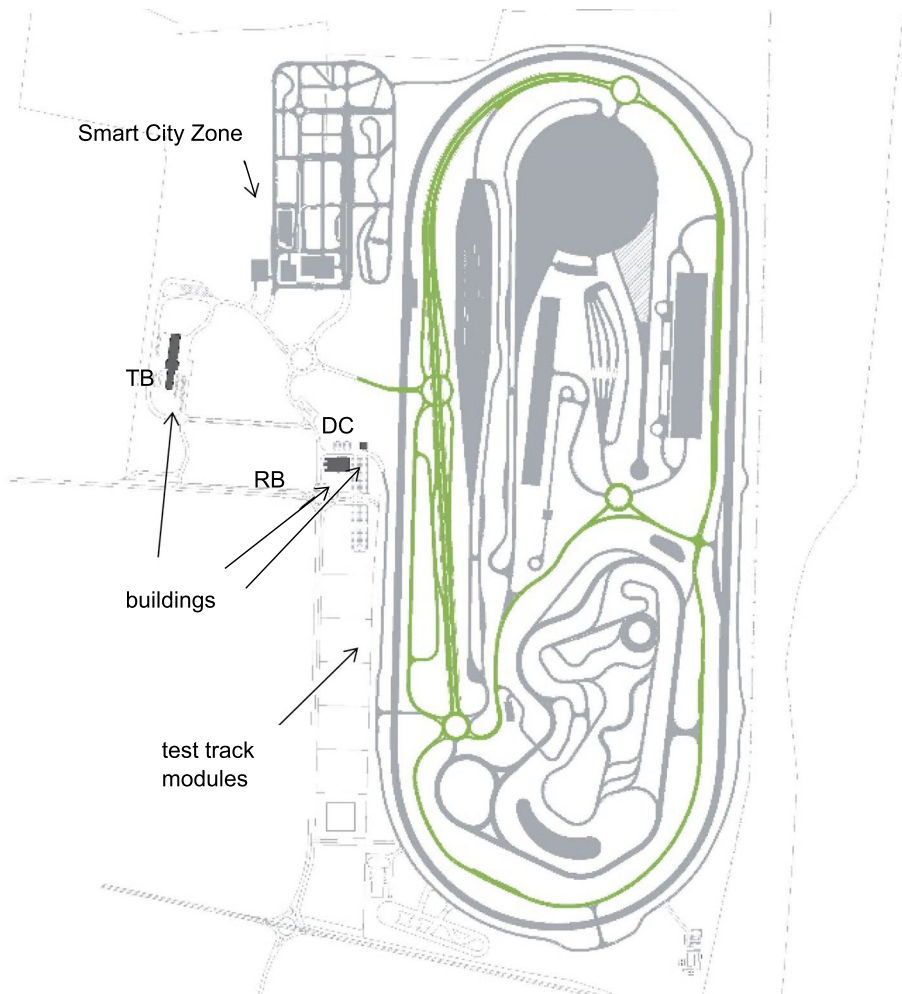

Fig. 2 Layout of the test tracks (Source: ZalaZone)

3.1 Calculation of GHG emissions

GHG emissions were estimated for vehicle movements on the test tracks, the traffic-related operation of the site, and then, we quantified the emissions related to the energy consumption and material flows of the buildings as well.

1. For the calculations of emissions related to the operation of test vehicles with internal combustion engines, the following input data were needed: characteristics of vehicle types tested, main technological parameters of engines and fuel consumption by vehicle types. The assessment has been made by taking into consideration the geometric shape of the test platforms, the number and type of test vehicles and the typical distance-speed diagrams of passenger cars, trucks and buses. Results of the calculation show the highest value (107.7 metric tons CO_2e/year) for the test track module of "Rural road, highway, motorway" indicated with green colour in Fig. 1. It is caused by the relatively high number of test vehicles and the long length of the track. Further details about the results would be found in Pálvölgyi et al. (2022).
2. In addition to emissions related to the operation of the test vehicles with internal combustion engines, emissions from testing of electric and hybrid vehicles were also estimated. Annual vehicle mileage for electric and hybrid vehicles is 5% of the annual mileage of all test vehicles. Calculated with a national emission factor of 350 g/kWh, based on electricity and mileage, emissions are 2.81 metric tons CO_2e/year.
3. Direct and indirect emissions from transport-related operation of the site depend on the number of vehicle kilometres travelled during the various trips that are part of the organisation's operation. These GHG emissions are comparable to the emissions associated with the transport movements on the test tracks. According to the GHG protocol and based on the input data received from ZalaZone, we calculated the number of the journeys made annually and then estimated the emissions using the previously applied conversion factors. Direct effects are caused by commuting of employees with vehicles owned and/or operated by the organisation, business trips, transportation of customers and visitors within the site and on-site patrols.
4. The indirect effects of air travel were quantified base on the annual flight length of 116,000 km, which means 16.11 metric tons of emissions.
5. Emissions from the energy use of the buildings on the site were determined on the basis of the lighting, heating, hot water, ventilation and cooling energy consumption of the buildings: Dispatch Centre, Technical Building and Receptional Building.

As a sum of the values of the examined activities, the total estimated annual CO_2 equivalent emissions were 474.38 tonnes for an average year of operation. The share of each activity is illustrated in Fig. 3.

3.2 Carbon reduction and offsetting

Examples of the on-site and off-site carbon reduction measures could be the increase of the number of electric cars within the organisation's fleet owned and/or operated, assessment of the mobility characteristics of employees and preparation of a mobility plan for them. Furthermore, conducting more detailed energy audits for the first 10 largest sources of CO_2 equivalent emissions associated with buildings and preparation of a detailed energy review
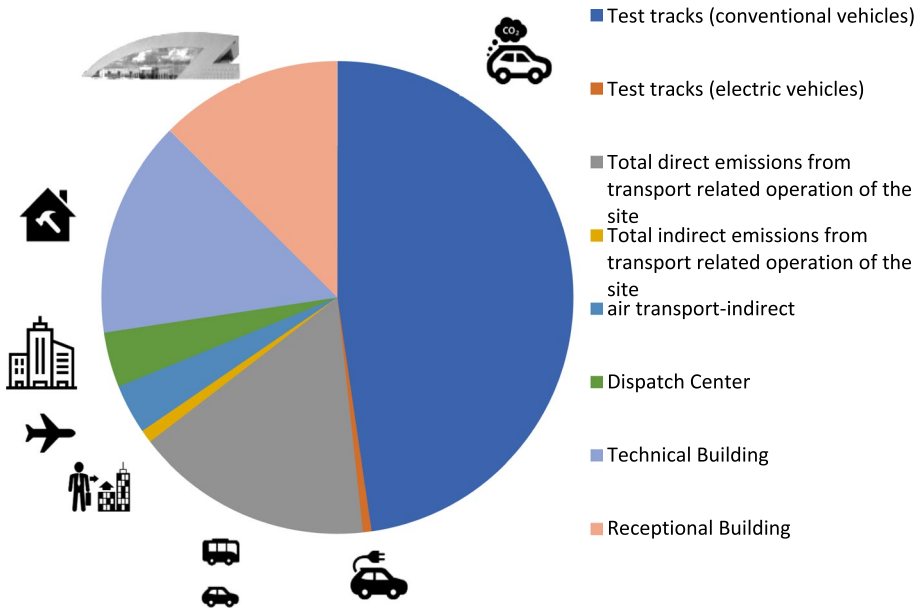
Fig. 3 Total calculated yearly CO_2 equivalent emissions of ZalaZone

of the technical building is also desirable. We have outlined four possible scenarios that represent different ratios of the three possible offsetting measures based on their potential and territory requirements, see Fig. 4.

The smallest territory: 2.57 ha is needed in the solely photovoltaic farm-based Scenario 1, because this measure has the highest decarbonisation potential. The minimum land requirement for Scenario 1 is accompanied by the immediate "switching on" of the
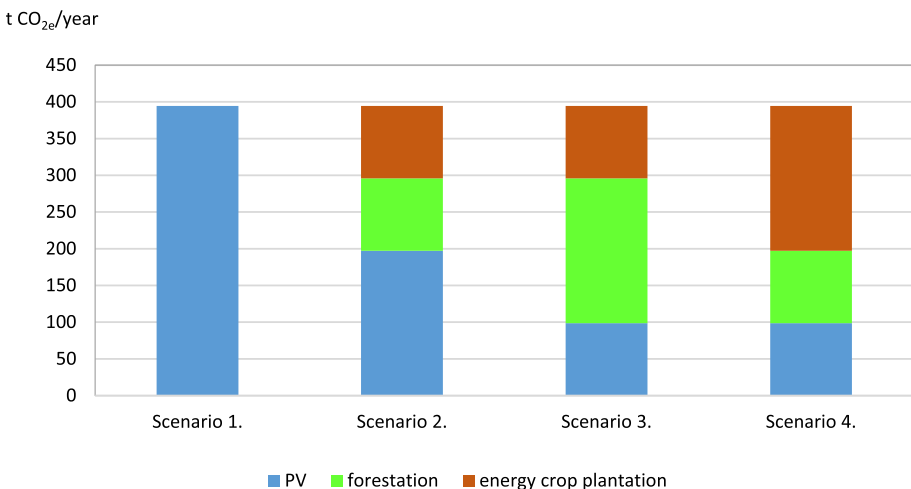
Fig. 4 Offsetting scenarios

offsetting measure. Energy crop plantation or forestation have a very low potential in the first years, with a relatively long time to reach the maximum values. Nowadays, the range of applications of PV technology is growing significantly worldwide, and the investment and operating costs are relatively low compared to other energy production technologies.

The advantage of using mixed offsetting scenarios (scenarios 2–4) is the diversity; however, it also increases the complexity of the offsetting efforts. The impact of energy crops or forestation varies over a wide range, as decarbonisation potential values for tree species show significant differences. The total territory needed is 20.11–30.41 ha, depending on the selected scenarios.

Taking into account the above-mentioned aspects, a mixed portfolio, different from the theoretical scenarios, was selected. The solar power plant was built on a territory of 1.5 hectares in 2019 and an additional 1.5 hectares in 2021. Forestation of oaks, beech, maple and other species would take place on an internal territory of 10 hectares, while off-site measures have been refused. Energy crop plantation is also implemented, inside the territory of the proving ground. Taking into consideration local climatic and soil conditions, two species have been selected: energy willow and emerald tree.

3.3 Cost–benefit analysis of the offsetting measures

The specific carbon efficiency measured in tonnes of CO_2 equivalent $[CO_2e]$/ha/year depends on the method of offsetting, and the time series for this can be found in Table 1. Forestation and energy crops have a gradually growing potential, and these values were assigned to each year by interpolation. The data set for CO_2e (t/year) saved by offsets are also shown. If we compare the annual savings with the base case emissions to be compensated, we can state that from year 3 (due to the solar power plant to be built) offsetting value significantly exceeds the overall value of 474.4 t CO_2. We have found that the offsetting rate is higher than 100%.

For the elaboration of CBA, we used the Hungarian guide (Trenecon, 2018). Based on the results of the financial analysis of the project, it can be stated that the NPV of the

Table 1 Calculation of CO_2 equivalent savings [t/year]

Offsetting options	Years							Aggregated CO_2e savings [t/year]
	1.	2.	3.	4.	5.	…	15.	
1. PV	247.7	247.7	495.3	495.3	495.3	…	495.3	6934.6
2. Energy crop plantation	18.2	67.8	90.6	101.1	36.5	…	90.6	1064.4
Emerald tree	8.2	30.5	40.8	45.5	54.6	…	78.6	749.8
Energy willow	18.2	67.8	90.6	101.1	36.5	…	90.6	1064.4
3. Forestation	7.7	45.7	52.6	59.5	66.5	…	135.7	1277.6
Common oak	1.0	10.4	12.2	14.0	15.8	…	33.8	310.6
Sessile oak	0.0	8.6	9.1	9.7	10.2	…	15.5	168.8
Beech, maple	1.0	19.7	23.1	26.5	29.9	…	63.9	585.9
Other trees	5.8	7.0	8.2	9.4	10.5	…	22.5	212.2
Total CO_2 savings [t]	273.6	361.2	638.5	655.9	598.2	…	721.7	9276.6
Offsetting value	218.68	393.88	452.97	474.37	474.37	…	474.37	
Offsetting rate	125%	92%	141%	138%	126%	…	152%	

installation project calculated from a financial point of view is negative: − 278.4 thousand EUR, the IRR is lower than the applied social discount rate: 1.3%, and the BCR is also less than 1: 0.83. Thus, offsetting measures as a project cannot be considered financially effective in itself under the assumptions used.

According to a widely accepted methodological approach, the carbon allowance price is the specific monetary value of emissions. As a significant part of the emissions is transport related, we used the mean values of the specific costs of the national cost–benefit analysis guide for transport projects. For the period after 2030, the increase in the unit price level was corresponded to the expected annual value of the GDP growth rate (1.5%).

The result of the calculation of the monetary value of the social benefits (see Table 2) shows cost savings related to climate change mitigation with a present value of 245.8 thousand EUR. For the society, the cost savings can be interpreted as a benefit of the offsetting measures and underline the importance of the efforts made by the organisation to reduce carbon intensity of its operation.

4 The relevance of the UN Sustainable Development Goals (SDGs)

The United Nations SDGs (UN General Assembly, 2015) are the most widely accepted set of criteria for the analysis of the realisation of sustainability both on national and corporate level. Although it has received some criticism (Dawes, 2020), it is still a useful guidance for various organisations. Several companies identify and declare, which SDGs they contribute to.

The analysis of the relevance of Sustainable Development Goals in case of the automotive sector—one of the leading global industries—intensified at the beginning of the 2020s. Lisowski et al. (2020) developed a criteria-based approach to select relevant SDG indicators for the automobile industry. The selected indicators belong to 12 SDGs, indicating the industry's broad influence on sustainability issues. The outcome of the article is a procedure for selecting relevant environmental SDG indicators, which can be used by companies from the automotive sector but can be adapted to other sectors as well.

Perello-Marin et al. (2022) analyse the relevance of SDGs in the automotive sector by investigating corporate (sustainability) reports, focusing on companies with manufacturing activity in Europe (seven companies). They link GRI (Global Reporting Initiative) metrics to SDGs and investigate, how many companies apply the various indicators.

Lenort, et al. (2023) performed a global analysis regarding the relevance of SDGs in the automotive sector. They found that SDG 8: Decent work and economic growth was the

Table 2 Summary of the calculation of social benefits

Offsetting options	Years							Present value
	1.	2.	3.	4.	5.	…	15.	
Specific value of climate change (EUR/t, CO_2)	31	32	32	33	34	…	41	–
Total CO_2e savings [t]	273.56	361.16	638.51	655.94	598.24	…	721.66	–
Social benefit of offsetting [thousand EUR]	8.4	11.4	20.7	21.9	20.5	…	29.8	245.8

most popular, adopted by 81% of companies investigated, followed by SDG 3: Good health and well-being, 5: Gender equality, 12: Responsible consumption and production, 13: Climate action, and 4: Quality education, which had similar frequencies of occurrence. These above six SDGs were adopted by at least 66% of companies. The analysis confirms that SDG priorities are highly dependent on the location.

There are other studies, for example: Lukin et al. (2022), which also intends to analyse the sector on the global level; therefore, they selected the top five companies. They performed a qualitative analysis, and based on company reports they conclude that most of the SDGs are mentioned and monitored, indicating good sustainability performance.

We overviewed what are the relevance of SDGs in case of ZalaZone automotive proving ground, in order to determine the sustainability performance of its operation. Therefore, the relevance of the United Nations SDGs for ZalaZone has been analysed. Since it is a state-funded project, we can assume that several SDGs are supported by its activities.

Although it is not related to the core competences of the facility, it contributes to:

SDG 4: "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (UN General Assembly, 2015, p. 14), by cooperating with universities, providing internship programmes as well as organising awareness-raising events for local children and students. Since the main target group is local students, it can contribute to regional development, too.

SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all" (UN General Assembly, 2015, p. 14) is only relevant because of the climate neutrality efforts, as the offsetting activities involve the establishment of a PV farm and planting energy forest.

SDG 8: "Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" (UN General Assembly, 2015, p. 14) is an SDG which is supported by the core competence and basic activities of ZalaZone. Since it is located in a region which is less developed within the EU, the economic and employment impact is especially important.

SDG 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" (UN General Assembly, 2015, p. 14) is the most important SDG for ZalaZone, which is in perfect harmony with its core competence. The main activity of the proving ground is innovation. It directly contributes to "making the domestic RDI system internationally competitive" (Ministry of Foreign Affairs & Trade, 2018, p. 37–38).

SDG 10: "Reduce inequality within and among countries" (UN General Assembly, 2015, p. 14) is also supported by the facility. It has the potential to improve the competitiveness of the country's automotive sector, and as mentioned above, to the development of the city, county and region, thus reducing inequality within the country.

SDG 11: "Make cities and human settlements inclusive, safe, resilient and sustainable" (UN General Assembly, 2015, p. 14) is also helped by ZalaZone, contributing to the economic, social and—with the offsetting attempts—environmental sustainability of Zalaegerszeg city and nearby settlements.

SDG 12: "Ensure sustainable consumption and production patterns" (UN General Assembly, 2015, p. 14) is promoted in an indirect way by ZalaZone, by providing a climate-neutral testing environment for automotive manufacturers and related industries. However, the amount of emissions during the testing is only a small, negligible share of total emissions.

The climate neutrality attempts clearly support SDG 13: "Take urgent action to combat climate change and its impacts" (UN General Assembly, 2015, p. 14). It is forward-looking that the offsetting measures took place together with the construction of the facility,

enabling net zero emissions not long after the start. The large territory enabled the realisation of multiple offsetting measures, improving the demonstration impact and example-setting role of ZalaZone.

Finally, SDG 15: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" (UN General Assembly, 2015, p. 14) is also helped by the offsetting measure forestation. Although the highest offsetting potential is reached by the PV farm, taking into consideration other aspects, such as the communicational value or contribution to biodiversity protection, it was decided to realise mixed measures, including planting forest, thanks to which SDG 15 is also supported.

Overviewing the relevance of the seventeen SDGs in case of ZalaZone, we can conclude that some of them, such as SDG 8 and 9, are supported directly by the core activities, some others (e.g. SDG 4 and 10) can be seen as "positive side-effects", and additional SDGs (such as SDG 7, 13 and 15) are tackled thanks to the carbon neutrality efforts. SDG 11 and 12 are slightly supported by the core activities and offsetting measures, too. The impacts of ZalaZone main activities and GHG offsetting measures on UN SDGs are represented in Fig. 5.
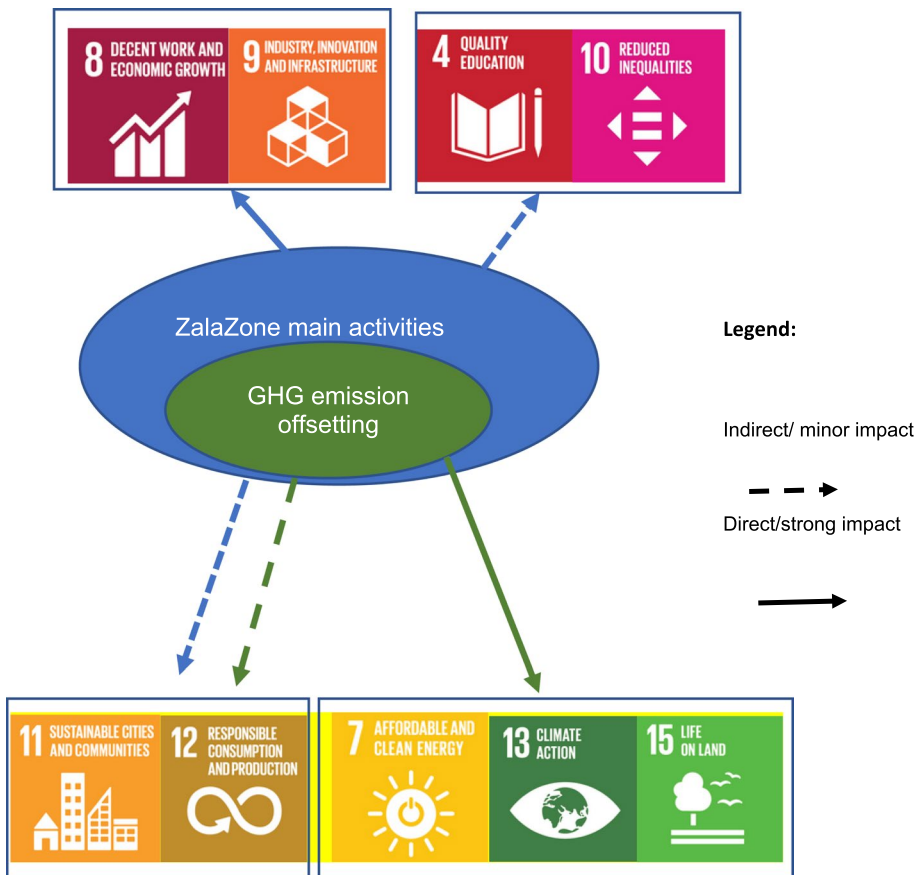

Fig. 5 The relevance of SDGs in case of ZalaZone

The analysis of SDGs is helpful to understand and measure sustainability on organisational or project level. Since the offsetting measures include forestation, strong sustainability—that is, the preservation of natural capital in a long term—is supported (Málovics et al., 2008). Regular revision of the contribution to SDGs would be desirable.

5 Discussion

Our research contributed to understanding measuring GHG emissions in case of complex systems as well as the comprehensive assessment of offsetting efforts. As one of our key findings, we demonstrated that an automotive facility could develop diverse tools (models, methods) that promote direct and spillover decarbonisation. Our research filled research gap of the above: help the implementation and application of a carbon simulation model—in the field of GHG mitigation—in the planning phase of the operation of automotive companies. They can exploit the opportunities of indirect decarbonisation by motivating their customers and suppliers for climate change commitments and actions. Their behaviour may catalyse special climate change targeted economic cooperation, especially in case of organisational networks. Comparison of the results of this research with previous studies shows that appropriate methodology for emission calculation would support integration of the offsetting planning and monitoring activities into one simulation model and provides options for decision making.

Our case study is about the Automotive Proving ground in Zalaegerszeg which is a unique investment with various functions and with a vision of net zero—or lower—GHG emission It was found that companies need further assistance to improve their sustainability performance. A detailed, transparent analysis of GHG mitigation efforts may assist companies in putting responsibility into practice. At the company level, methodological guidelines and standard procedures can be used to assess carbon emission of the selected organisation, to define efficiency goals and to prepare offsetting or carbon reduction action plans. ZalaZone is engaged in ambitious climate targets, with exemplary efforts to calculate GHG emissions and a careful evaluation of offsetting options.

We have developed four scenarios to realise net zero emission, taking into consideration local circumstances. The company has selected a 5th scenario of mixed measures, which can guarantee climate neutrality from the 3rd year of its operation. Mixed measures are useful from the point of view of maximisation of social acceptance and increasing the demonstrational value of the project. The cost–benefit analysis revealed that the NPV of selected offsetting measures is below zero. However, significant external social benefits are realised.

Our model differs from the decarbonisation models known in the literature in terms of its scope: no similar model has been developed for test facilities. Since we have developed a module-based carbon simulation model based on the widely accepted approaches of international standards, it is relatively easy to prepare a similar one for other organisations in other regions or in countries outside the European Union, especially with similar activities. Material flows-related emissions were negligible in case of ZalaZone, but can be important and significant in case of other sectors, e.g. industrial production. Innovative companies should implement similar measures in order to reach climate neutrality and integrate their carbon-related activities into one simulation model. In case of ZalaZone, the territory is rather large; therefore, on-site offsetting measures were feasible. In case of other organisations, it is very likely that off-site measures would be indispensable.

We have found that decarbonisation is not necessarily profitable for a company, but is in the public interest because of its significant social benefits. These mitigation efforts require strong commitment from corporate management. Decarbonisation may establish a partnership among the companies by targeting climate change mitigation on a voluntary basis. In case of more efficient internalisation of external costs of GHG emission, such measures may become profitable. The improvement of the GHG emission reduction activities can contribute to the total improvement of environmental performance, and it can be revealed in the sustainability report.

In order to put our research into a broader context, the relevance of the UN Sustainable Development Goals was investigated. We can conclude that ZalaZone contributes to several SDGs (e.g. SDG 8, 9) as a result of its core competence, being an innovative organisation. It has a high potential, among others, in reducing regional disparities. Thanks to the GHG mitigation and offsetting efforts, further SDGs (e.g. SDG 13, 15) are also supported.

6 Conclusion

The carbon mitigation efforts of ZalaZone, presented comprehensively in our article, have a huge potential in example setting for the whole automotive sector, since test tracks are the key starting elements of the innovation process (Vaz et al., 2017). Direct contribution includes the mitigation efforts of the organisation, while indirect contribution—enabled by motivation of other actors in the sector—has even greater potential.

The main contribution of the research is the development of a carbon simulation method, applicable for a special facility, which contains the methodology of calculation of emissions, and offsetting measures of the proposed actions. This new reference method can be the basis of the development of sustainable business models; furthermore, they support industrial application and support policymakers (including authorities) to provide more suitable regulations for carbon reduction. Carbon neutrality is feasible on a corporate level and multiple benefits of offsetting efforts could be achieved. The main advantage of our carbon simulation model is the adaptability to other organisations in other countries or regions, and there are no territorial restrictions.

Our research also contributed to the improvement of the institutional and regulatory background of sustainability management, by providing guidelines for practitioners and decision-makers that can be tailored to other facilities or organisations. Application of the carbon simulation model is also discussed as similar measures are highly needed to assist the sustainability transition of various actors.

In relation to the analysis of SDGs in case of ZalaZone, we can conclude that leading companies in the automotive sector tend to pay attention to the relevance of SDGs of their own operations. Therefore, it might be an important motive to choose this proving grand which made attempts to measure its sustainability performance and the relevance of SDGs.

In the future, the carbon simulation model could be extended. One of the limitations is that our research has focused on mobility and buildings' emissions. A broader application of the model would be possible by developing the methodology of measuring emissions from manufacturing processes. This would enable application by other actors from the sector, primarily car manufacturers. Seeing their attempts to improve sustainability performance, the demand for the CSM is underpinned. Other limitation of the CSM model is related to the availability and detailedness of the input data sets, which can modify the

accuracy of the results. That is why organisations are encouraged to integrate this model into their management information system and upload it with real-time data.

Further issues to be examined include the validation of the emission model, by comparing estimated and actual data—provided by the company—in case of all modules, as well as the development and adaptation of our model for other sectors and organisations. In case of several companies of the supply chain developing similar company-specific tools or integrated models—covering a significant part of the whole supply chain—our model might be relevant. It is obvious that new theoretical and empirical solutions are needed for the assessment and implementation of carbon neutrality projects, as an important component of sustainability performance. Our carbon simulation model may also serve as a sample for the development of similar tools in other areas of the measurement of sustainability performance such as material flow management or energy efficiency calculations.

The carbon simulation method presented in this paper has the potential to provide real-time data for urban, regional or national climate policy monitoring. The climate policy objectives at each territorial level must be based on the commitments of the economic actors in the region. The method described above may contribute to regional climate policy co-planning and the development of regional climate policy initiatives. Moreover, the carbon simulation method implemented by ZalaZone can facilitate partnership-based governance. Decarbonisation partnerships (e.g. involvement of citizens, entrepreneurs and municipalities) can be an appropriate tool for open climate policy planning, and adaption of our carbon simulation model to other countries and regions could be suitable for the integration of climate policy into the national development frameworks.

Data availability The data sets analysed during the current study are not publicly available due to the unique nature of the input data describing the operational characteristics of a company (APZ Ltd.), but are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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