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Implementing Zero Impact Factories in Volkswagen's Global Automotive Manufacturing System: A Discussion of Opportunities and Challenges from Integrating Current Science into Strategic Management

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Abstract: The current exceeding of six out of nine planetary boundaries requires a significant transition of human societies towards absolute sustainability. Industrial manufacturing systems were and still are an important motor for socio-economic development but at the cost of a significant negative impact on the biosphere. Current concepts in absolute sustainability and sustainable manufacturing provide solutions for sustainability transitions in industry, but various methodological, technical and procedural challenges arise during their adaptation in industrial practice. The development and operationalization of a "zero impact factory" strategy by Volkswagen Group has identified various implementational challenges, which are discussed in this article. First, an overview of motivations for "zero impact" transformations in industry are pointed out. Second, relevant aspects for the strategic management of sustainability transitions in manufacturing companies are highlighted based on a literature analysis. Third, the strategy development process is explained based on a systematic structure, which includes design-thinking principles for sustainability transitions of large technical systems such as factories in global manufacturing systems. Fourth, the developed strategy content is presented, including (1) the strategy vision, (2) the defined quantified "zero impact" goals, (3) a system model and a prototype of a zero impact factory, (4) the developed "Impact Points" and the "Site Checklist" methods (for evaluating the environmental transformation of a factory) and (5) the definition of processes for strategic management during strategy operationalization. Finally, various organizational challenges and opportunities are pointed out, which are considered novel insights from industrial practice and relevant for the science-based strategic management within automotive companies and other global industrial manufacturing organizations, as well for advancing sustainability concepts in applied industrial science.

Keywords: zero impact; automotive manufacturing; absolute (environmental) sustainability

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1. Introduction

1.1. Sustainable Development in Industry

The exceeding of six out of nine planetary boundaries [1] shows that global societies require societal transformation to return to the "safe operating space for human mankind" [2]. Absolute sustainability refers to an ideal state where resilient ecosystems represent the basis for healthy societies in which economies can generate value for socio-economic development [3]. Sustainable development encompasses a global transitional process towards a state where socio-economic activities do not negatively impact ecological systems and where societal processes contribute to current and future human wellbeing and economic growth [4]. The United Nations have defined 17 UN Sustainable Development Goals (UN

SDGs), which describe a global agenda up to 2030 aiming at environmental protection, societal development and sustainable economic growth [5]. Industrial manufacturing plays a significant role in the societal transition towards absolute sustainability [6], as manufacturing systems represent complex interactions between natural resource systems and human economies [7]. The global industry faces the transformative challenge of delivering desired goods and services while considering ecological boundaries and contributing to human wellbeing [8]. UN SDG number 12, "Ensure sustainable consumption and production patterns", supportsdevelopment and management in industry that address sustainability with respect to the efficient use of resources, the handling of chemicals, the handling of waste (through prevention, reduction, recycling and re-use) and the promotion of an appropriate life-style [9].

1.2. Problem Statement

Despite broad implementation in industry, efficiency strategies [10] have failed to deliver the intended increase in environmental sustainability due to rebound effects and changing external circumstances [11]. This defines the need to manage the absolute impact [12] of industrial manufacturing on the environment by evaluating the transformative state of the global industry [13], an industrial sector [14], a manufacturing company [15] and a factory [16]. Factories transform energetic and material resources into defined products. They represent the central element of a manufacturing system and therefore determine the overall environmental impact of manufacturing systems significantly [17]. A factory operates as environmentally effective when negative impacts on the biosphere are completely neutralized or within an allocated "safe operating space" [18]. In this state, the system contributes to absolute environmental sustainability as it does not interfere with any ecological system [12]. Therefore, it is crucial to define states of a factory system with regard to absolute sustainability [19]:

- **Negative impact factory:** a factory system that generates emissions with influence on absolute sustainability along its value chain and causes detrimental effects on the resilience of ecosystems and/or human health.
- **Zero impact factory:** a factory system that avoids emissions with influence on absolute sustainability along its value chain into the environment and does not cause detrimental effects on the resilience of ecosystems and/or human health.

The effective configuration of a factory system represents a key prerequisite to avoiding further pressure on (partially exceeded) planetary boundaries [11]. Figure 1 summarizes properties of negative and zero impact factories based on [20].

Negative impact factories use fossil fuels, generate impacts on climate change, are embedded in linear resource flow systems, generate waste and emissions into the environment and do not support ecosystems sufficiently. **Zero impact factories** use renewable energy, avoid impacts on climate change, are integrated in circular resource flow systems with industrial companies, avoid emissions into the environment and adequately support and preserve ecosystems. The factory transformation requires a structured strategic management process to enable a shift from negative to zero impacts for absolute sustainability. The strategic management of a factory and/or a company should systematically evaluate external developments with relevance for the overall environmental impact and develop solutions for organizational alignment [21] to adapt to, e.g., legal and regulative requirements, stakeholder demands, global sustainability initiatives, finance and reporting schemes and external technical infrastructures.

However, the measurement of "zero impact" with regard to the planetary boundaries demands further methodological developments. The authors of [22] summarize that four major challenges need to be overcome ("(1) development of a common system of metrics that can be applied consistently at and across different scales; (2) setting 'distance from boundary' measures that can be applied at different scales; (3) development of global, preferably open-source, databases and models; and (4) advancing understanding of the interactions between the different [planetary boundaries]"). As [23] conclude, a large gap between theory and practice in the development of sustainability assessment tools is detectable, which imposes the need for applicable and manageable science-based tools in industry. Despite these scientific and methodological uncertainties, strategic corporate environmental management faces various organizational challenges from relevant legal, social, financial and technical systems. The successful strategic management of these complex and multi-faceted external developments represents a prerequisite for long-term prosperity and sustainable value creation in manufacturing companies.

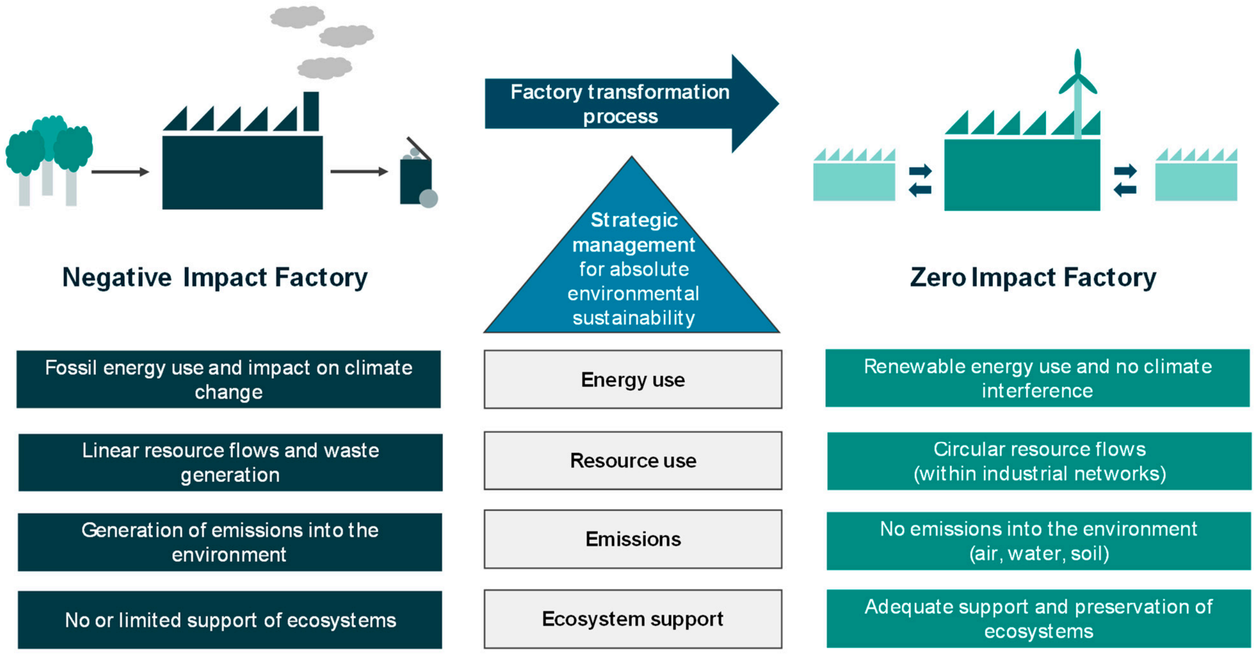

Figure 1. Properties of negative and zero impact factories.

1.3. Motivations to Develop and Implement Zero Impact Factories in the Global Automotive Industry

Various motivations can be stated for automotive manufacturing companies to implement transformative management strategies to produce future vehicles in zero impact factories. The shift towards electric mobility has risen consumer awareness concerning the environmental impact of the product life-cycle, which pushes manufacturing companies towards sustainable production practices [24]. This is combined with increasing demand by the financing industry to transfer business operations towards sustainable approaches [25]. Linking the current exceedance of six planetary boundaries with industrial manufacturing shows that industrial activities have largely interfered with the resilience of natural ecosystems and that a shift to absolute sustainable practices in the future is inevitable [11]. Climate impacts are identified as ecological risk factors at the local and regional level that increasingly interfere with supply chains and factory sites [26]. The current water scarcity in Catalonia (Spain) is an example, where the local authorities have limited the water consumption of industry due to drought and a lack of precipitation [27]. Therefore, resource scarcities and fluctuations in resource availability require new strategies to sustainably supply factories with required energy and resource flows [28]. Global and national climate goals determine the remaining carbon budgets for the industrial sector [29], which generates the need for adequate decarbonization plans within industrial companies [30]. Current political initiatives at the European level, such as the “Zero Pollution Action Plan” [31], “Net Zero Resources” [32] or “Zero Waste Europe” [33], aim at translating the scientific findings into policy strategies and represent current approaches aiming at neutralizing impacts from industrial activities on the environment. The required avoidance of industrial emissions and industrial waste through circular approaches requires technical and organizational changes in the factories to mitigate emissions before they enter the environment [34], to reorganize material flows to and from the factory and to establish circular resource ecosystems in a wider industrial network [16].

Global automotive organizations require complex strategic adaptations concerning environmental sustainability in order to stay competitive in dynamic and global markets and in changing environmental systems. This paper presents a "zero impact factory" strategy, which contains a strategic, methodological, technical and organizational approach for the transformation of Volkswagen's global manufacturing system. Section 2 summarizes relevant contextual, procedural and content-related strategic management elements for developing a strategy aiming to transform existing factories within a manufacturing company towards absolute environmental sustainability. Section 3 lays out the methodological foundations used during the strategy development and operationalization. Section 4 highlights the results from the strategic project, including a vision, strategic goals, an ideal factory system description, methods for steering the transformative process and necessary organizational structures for effective strategic management. Section 5 discusses opportunities and challenges of the strategic process to derive conclusions for an effective strategic management for absolute environmental sustainability transitions in manufacturing. The aim of this article is to provide insights from an industrial implementation and the strategic operationalization of "zero impact" targets and current concepts in sustainable manufacturing. The derived knowledge on opportunities and challenges for (global) manufacturing companies could support future strategic projects in industry and support the provision of science-based sustainability solutions for industrial applications.

2. Strategic Management of Environmental Sustainability in Manufacturing Organizations

2.1. Identification of Strategic Elements for Sustainability Transformations in Manufacturing

Strategic management aims at aligning organizational development with changing external environments [21]. In accordance with the integrated management approach [35], organizations aim at maintaining a "viability" to ensure organizational resilience and long-term market performance, which demands appropriate strategic management [36]. As [15] conclude, the integration of (environmental) sustainability into corporate activities and strategies requires an analysis of the (1) **strategic context** to consider relevant external and internal factors for strategy development and a (2) **strategic process** to coordinate required activities and to ultimately generate (3) **strategic content**, which comprehends the technical and organizational facilitation of the strategy. Supplementary S1.1 summarizes relevant contextual, procedural and content-related elements of strategic environmental sustainability in manufacturing for zero impact transformations, which were identified in a literature analysis.

The strategic context encompasses various external and internal aspects (e.g., scientific, organizational, economic and environmental) that are relevant for strategy formulation and determine its potential and limitations. Absolute sustainability [3] refers to the "Sustainable Development paradigm for the Anthropocene" [37], which claims a hierarchical order of the biosphere, human societies and economies as a pre-condition for sustainability. An ideal and absolute sustainable manufacturing system requires environmentally effective properties [20], which includes all relevant pre- and post-processes to enable a systemic perspective [17]. The factory design has a great influence on the overall environmental performance of the manufacturing system [16]. Legislation and regulations set legal environmental frameworks for manufacturing organizations and determine the development of future green factory technologies [38]. In the European Union, under the umbrella of the "Green Deal", the "Climate and Energy Framework 2030" [39], the "Circular Economy Action Plan" [40] and the "Zero Pollution Action Plan", with associated directives such as the "EU Industrial Emissions Directive" [31] and the "EU Taxonomy Regulation" [41], push an industrial transformation towards sustainability. Stakeholder demands occur along the manufacturing value chain and generate multiple challenges that need to be addressed in (environmental) sustainability management [42]. Industrial sites are interrelated with the local community and potentially affect the quality of living, e.g., through airborne emissions, noise, transportation or land use [43]. The integration of ecological design principles into a business model [44], a manufacturing strategy [45] or a factory system [46] is considered to deliver competitive advantage [47] and sustainable development. This requires the systemic consideration of upstream and downstream processes to supply the factory with energy, water and resources, as well to treat associated waste water and waste in connected infrastructures [48]. This results in several contextual requirements for strategic sustainability management in automotive manufacturing: (1) requirements for an environmentally effective factory need to be aligned with relevant planetary boundaries (climate change, fresh water, novel entities and land use); (2) strategic activities need to be aligned with the UN SDG numbers 8, 9 and 12; (3) existing factories need to be technically aligned with future environmental legislation; (4) a holistic environmental data management strategy needs to be established; (5) stakeholder management has to be set up to integrate societal demands in organizational processes; (6) technical and financial resources need to be provided for the development of sustainable factory systems.

The definition of a strategic process encompasses the transitional agenda for the manufacturing system and defines overall goals as well as relevant procedures and connects the strategy context with the strategy content [15]. The authors state innovation and technology management, collaboration, knowledge management, organizational processes, purchase and reporting are relevant elements of a strategic process for sustainability. In essence, this relates to (1) strategic goals, (2) the facilitation of transformative processes and (3) the measurability of the transformative progress. The definition of goals refers to the necessity of enabling absolute environmental sustainability in manufacturing [18]. Absolute goals must reflect the planetary boundary concept [49], organizational capabilities and contextual requirements and support sustainable development for an effective organizational change [15]. The goals must relate to a 1.5 °C climate mitigation pathway [50], enable net-zero water consumption [51], lead to zero pollution of anthropogenic substances [52] and avoid further land system change due to resource extraction [53]. Practical challenges arise when transposing planetary-boundary-related goals to manufacturing systems. Linking the “safe operating space” to organizational activities is far from trivial, as the space allocation is not yet standardized [54]. One major challenge is to increase the graphical resolution of planetary boundaries [18], as the pressure on a boundary, such as “freshwater use” [49], varies significantly at a regional scale. The facilitation of a transformative process towards “zero impact” demands strategic management within manufacturing organizations. Ref. [15] state that the implementation of an iterative development process at all organizational levels is inevitable, which establishes strategic content through innovation and learning and measures the organizational progress towards the defined goal. The measurability of the progress should be based on defined environmental aspects as well as established and accepted assessment methods [55]. Environmental reporting is required to communicate the organizational progress [15]. Innovation and learning processes for sustainability should aim at system innovation and be based on cooperation with external systems and stakeholder integration [56]. This results in several procedural requirements for strategic sustainability management in automotive manufacturing: (1) the definition of absolute strategic goals which aim at carbon-free factories, impact avoidance of factories in water-scarce regions, the avoidance of anthropogenic substance emissions through factories and the minimized use of natural resources in factory processes; (2) the implementation of impact-based methods to evaluate the factory transformation; (3) internal and external reporting processes for management and expert information.

Strategy content represents the output of the strategic process and encompasses the technical and organizational facilitation of the strategic measures [15]. To connect contextual aspects with the design of a factory, technologies and processes play a key role in enabling the transformation towards zero impact [7]. A zero impact factory design must integrate absolute sustainability thinking by applying appropriate design strategies and enabling desired environmental properties [20]. Zero impact factories exclusively use renewable energy to avoid having an impact on climate change [20], enable a circular economy [53] in material and water flows and utilize biogenic materials [48]. Zero impact factories apply effective and systemic management of compliance [57] and environmental organization [58]. Factory development processes apply life-cycle thinking in planning processes [59]. The production processes enable zero emissions due to effective processes and technologies [31], and cyber–physical production systems support operational processes in using energy and resources in a transparent and optimal manner [60]. Zero impact factories integrate ecological functions into their architecture, focus on an ecological appearance [61], manage biodiversity proactively to generate a no net loss due to industrial activities [62], prevent environmental hazards effectively and rehabilitate existing contamination [63]. Furthermore, a strong focus on sustainable transport and mobility solutions is laid [64]. This results in several content-related requirements for strategic sustainability management in automotive manufacturing: (1) developing an automotive factory (concept), which enables "zero impact" at the system and subsystem level; (2) detailing and characterizing factory elements with ecological and technical "zero impact" properties; (3) describing factory processes (for the identified "zero impact" properties).

The identified contextual, procedural and content-based requirements represent inputs for strategy development for zero impact in manufacturing companies. A structured procedure is necessary to integrate the identified information to the individual steps during the strategy development process. Furthermore, the developed strategy needs to be operationalized in existing environmental management schemes to connect strategic targets, method-based evaluations and transformative technical and organizational measures with existing processes in the environmental organization of a company.

2.2. Strategic Environmental Management at Volkswagen Group Production

Volkswagen represents a global automotive manufacturing company with, in total, 119 production facilities and 8.72 million vehicles produced in 2022 [65]. Currently, the department of Volkswagen Group Production governs the International Standardization Organization (ISO) standard 14001 for environmental management [55], which was implemented more than two decades ago at the Group, brand and site level to standardize environmental processes, to regularly audit its factories and to measure continuous improvement by combining impact-oriented methods with qualitative assessment schemes. From 2010 onwards, Volkswagen has pursued efficiency-related environmental goals for its manufacturing system and aimed at reducing the relative environmental impact of production (per vehicle or component part) by 45% until 2025 [66]. Within the past decade, the company has co-developed and integrated the impact-based method "SEBU-system" (SEBU—system for the analysis and assessment of environmental impacts (translated from German: System zur Erfassung und Bewertung von Umweltauswirkungen)) (see [67–71] for method documentation) into its environmental management, which represents an adaptation of the ecological scarcity method (ESM) for the purpose of assessing environmental impacts of its production sites. As a strategic response to various external factors, Volkswagen formulated and published the Group environmental mission statement "goTOzero" in 2019, which was updated in 2022 [72] to integrate an absolute environmental impact thinking within its Group-wide strategy. It encompasses four prioritized fields of action (protect climate, conserve resources, preserve ecosystems and ensure environmental compliance) to "*set the framework for all environmental activities of the Volkswagen Group*" [72]. Manufacturing-related environmental goals and processes are currently organized within the department of Group Production and governed under the novel "zero impact factory" strategy [73] with the aim to enable "zero impact" by 2050. This includes the transformation of existing factories as well as effectively designing future factories in 21 countries for passenger vehicles, light commercial vehicles (excl. trucks and buses) and component parts [73].

3. Procedural Steps for the "Zero Impact Factory" Strategy Development and Operationalization

The development of a strategy in manufacturing companies requires a structured procedure to facilitate the identified inputs to desired outputs [15]. Section 2 identified twelve contextual, procedural and content-related sustainability requirements for strategic management for manufacturing companies, which represent the input for strategy development. Ref. [74] presented the "*design for system innovation and transition*" approach, which is considered a structured process for strategy development and operationalization. It consists of five consecutive steps to develop large and complex system designs (such as factories) for absolute sustainability: (1) vision, (2) system thinking, (3) prototyping, (4) long-term innovation planning and (5) mindset change in business. The author states that "*businesses should strategise towards innovation with a strong sustainability approach*", which defines the need for a strong strategic vision including systemic understanding as well as long-term strategic planning to enable an organizational "*mindset change*", which can be considered successful if the vision is translated into a sustainable system design in effective operation.

This generic approach is considered suitable as it is developed to provide a structured procedure for moving large technical systems towards absolute sustainability. It is adapted for developing the zero impact factory strategy: First, the vision of a zero impact factory needs to be formulated including strategic goals based on the evaluation of contextual information. Second, a factory system model has to be established that integrates all relevant upstream and downstream processes for the purpose of defining an adequate system boundary as a basis for the impact-based evaluation of the zero impact transformation. Third, a prototype of an ideal zero impact factory must be derived to describe a technical and organizational blueprint of the strategic vision. Fourth, impact-related methods to measure the factory's impact on the environment need to be developed to support a long-term transformation with adequate evaluations. Fifth, a mindset change in business has to be established through the integration of the (previously developed) strategic results into strategic management processes with regard to auditing, reporting, communication and knowledge transfer.

Table 1 (next page) allocates the identified sustainability requirements (strategy inputs) with the five procedural steps (strategy process) to generate a detailed conceptualization of a zero impact factory (strategy output) for the transformation of Volkswagen's global manufacturing system. (1) The vision is defined by planetary boundaries, the UN SDGs and the definition of absolute goals. (2) The system model integrates the absolute sustainability principles of the vision, requires a conceptual factory system description and has to be aligned with the data management structure (for later methodological applications). (3) The prototype of a zero impact factory builds onto the previously developed system model, details technical and ecological factory elements, encompasses managerial and organizational factory processes and has to be aligned with future legislation. (4) The impact-based methods have to be aligned with the planetary boundaries and absolute goals (for quantitative evaluations) as well as to with desired factory elements and processes for zero impact (for qualitative evaluations). (5) The strategic management processes require a process description for the provision of technical and financial resources, reporting, stakeholder management and factory processes for zero impact organizations. The outputs of the process represent a formulated vision, a defined system model, a detailed prototype, applicable and impact-based methods and process descriptions for strategy management.

The five procedural steps have been coordinated by Group environmental experts in cooperation with representatives from brand and site departments, internal advisors and external partners from academia and consulting. The analysis and evaluation of contextual information and the development of a conceptual strategy have been facilitated through regular working group meetings, method testing and adaptation procedures, strategy implementation workshops and goal definition processes. The operationalization of the strategy was initiated by a decision of the Group Production Board in 2017, which formulated the task to calculate and define "zero impact" goals for the long-term transformation of Volkswagen's global manufacturing system by 2050.

Table 1. Allocation of the identified sustainability requirements to the five procedural steps.

INPUT: Identified Sustainability Requirements for Strategic Management to Achieve "Zero Impact" in Manufacturing Companies (Adapted from Section 2)		**PROCESS: Adapted Steps for Developing the Zero Impact Factory Strategy Based on the "Design for System Innovation and Transition" [74]**				
		(1) Vision of a Zero Impact Factory	**(2) Factory System Model**	**(3) Prototype of a Zero Impact Factory**	**(4) Methods to Measure the Transition**	**(5) Strategic Management Processes**
Strategy context	Alignment with planetary boundaries	x			x	
	Alignment with UN SDGs	x			x	
	Alignment with future legislation			x		
	Establishment of data management		x		x	
	Stakeholder management					x
	Provision of technical/financial resources					x
Strategy process	Definition of absolute goals	x				
	Development of impact-based methods				x	
	Establishment of reporting					x
Strategy content	Conceptual development of a zero impact factory system		x	x		
	Defining zero impact factory elements			x	x	
	Defining zero impact factory processes			x	x	x
OUTPUT: Defined elements of a zero impact factory as the result of the strategic process		Formulated vision	Defined system model	Detailed prototype	Impact-based methods	Process descriptions

4. Results

The results represent the developed output from the strategic process and are presented in accordance with the five procedural steps as laid out in Section 3. This section presents the derived strategic vision (Section 4.1), the definition of a system model (Section 4.2), the prototype (Section 4.3), the developed impact-based methods to evaluate the environmental transition (Section 4.4) and processes and organizational structures for strategic environmental management during strategy operationalization (Section 4.5).

4.1. Vision of a Zero Impact Factory

The vision of the zero impact factory defines the overall strategic agenda and defines the overall strategic goal of "zero impact". It is based on the Group environmental mission statement [72] and takes current sustainability concepts such as the planetary boundary framework [2], the UN SDGs [5] and current scientific literature in the field of sustainable manufacturing (e.g., [6,20,75,76]) into consideration. The strategic vision articulates the aim for the strategic environmental transformation and is defined as "*The vision of the "Zero Impact Factory" describes a factory that produces in a climate-, resource- and environmentally friendly manner and thus avoids environmental impacts in vehicle and component production.*" [77]. It represents a guiding principle for the later strategy development processes. Figure 2 highlights a graphical representation of the strategic vision, which has been generated to visualize the final transformative state of a zero impact factory.

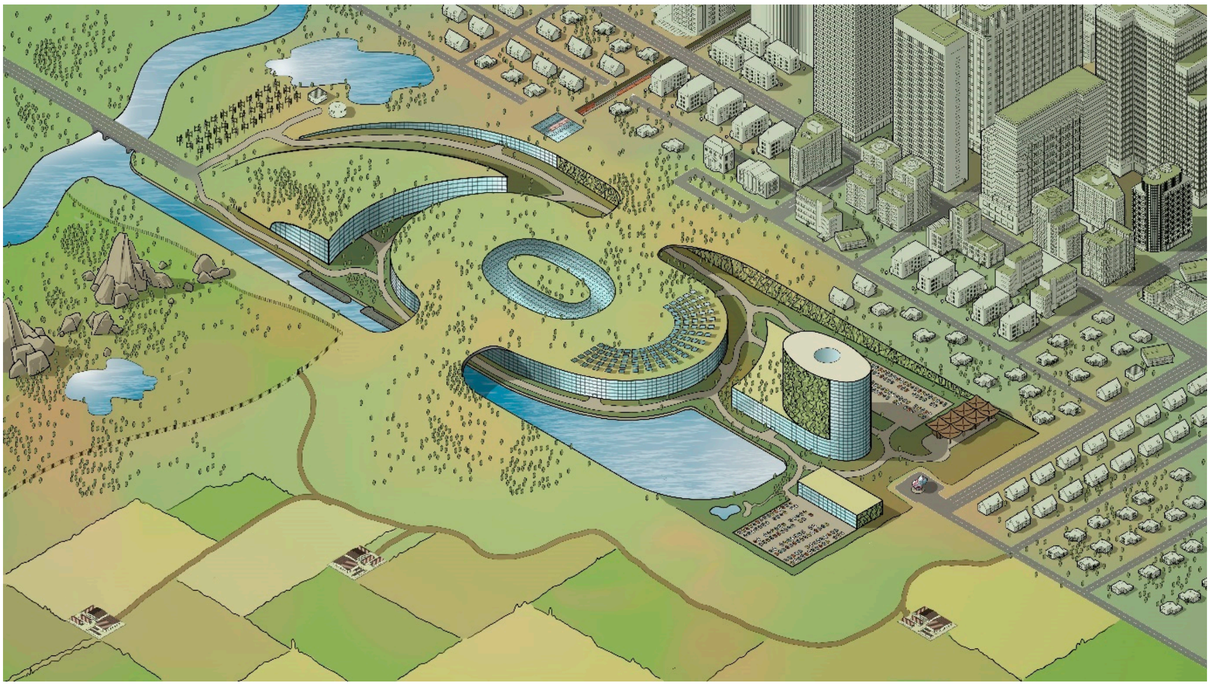

Figure 2. Vision of a zero impact factory.

The graphic shows a factory that is naturally embedded into its natural and urban environment and connects hydrological and ecological structures on site with external surroundings. The factory is exclusively powered by renewable energy and enables a circular economy. The buildings envision a sustainable and eco-positive appearance while employees and goods transport are facilitated by sustainable means. The idealized vision has been used to stimulate strategic activities and define strategic processes at the Group level, such as those outlined as follows:

- **Climate protection:** a high degree of energy efficiency in combination with a complete purchase of green electricity until 2030 was decided by top management to enable complete decarbonization until 2050 of all production sites in accordance with the 1.5 °C SBTI pathway of Group Production [78].
- **Resource conservation:** waste prevention measures are currently under development to enable complete recycling. A plastic-free factory is envisioned to abandon single-use plastics on site. The minimal use of fresh water marks a further characteristic to enable the efficient use of water and a circular water system, including the on-site treatment of pollutants [79].
- **Ecosystem preservation:** the strategy aims to minimize air pollution to avoid local pollution. Water and soil protection measures beyond local legislative requirements have been developed through adequate technical measures in the field of environmental engineering. Furthermore, biodiversity is promoted through the facilitation of projects, management and cooperation as laid out in the Volkswagen Group biodiversity commitment [80].

Currently, the strategic vision is further operationalized into concrete strategic activities, which encompass the definition of discrete technical roadmaps (e.g., for absolute CO_2 emission reductions at the brand and site level), the analysis of technical potentials and limitations in specific topics (such as "zero waste in manufacturing") and the evaluation of "novel" environmental management topics (such as biodiversity management in manufacturing companies).

Two overall strategic goals (**Note:** The presented goals represent Group internally defined strategic ambition levels. They are presented to highlight the quantified goal-setting process and should not be interpreted as binding obligations for the Volkswagen Group. Binding strategic targets are exclusively communicated in official reports and officially published communication documents.) are quantified at the Group level and define the "zero impact" ambition of the strategy. The aim of the overall strategic goals is to quantify ambition levels of the strategic vision for aligning strategy development and management processes with discrete long-term goals until 2050. Two types of strategic goals are defined: (1) an impact-related goal and (2) a goal that refers to the technical and procedural quality of a zero impact factory. The Impact-Points-based goal encompasses quantified impacts from measurable input and output resource flows of a factory (energy, CO_2 equivalents, air pollutants, fresh water, waste water and waste), whereas the Site-Checklist-based goal focuses on an evaluating factories from a technical and procedural perspective (based on 143 criteria). Both methods are considered comprehensive to generate a holistic evaluation of a factory.

The goals are defined by a goal value for 2050, which determines the long-term strategic ambition. Both goal values represent single scores and are expressed in the unit of "Impact Points" (comparable with eco points in the ecological scarcity method [81]) and the "percentage degree of fulfilment" of the Site Checklist, which represents a multi-criterial evaluation of the environmental aspects of a factory. Figure 3 highlights both goals in the context of a long-term strategic development between 2018 and 2050 (Impact Points) and 2022 and 2050 (Site Checklist).

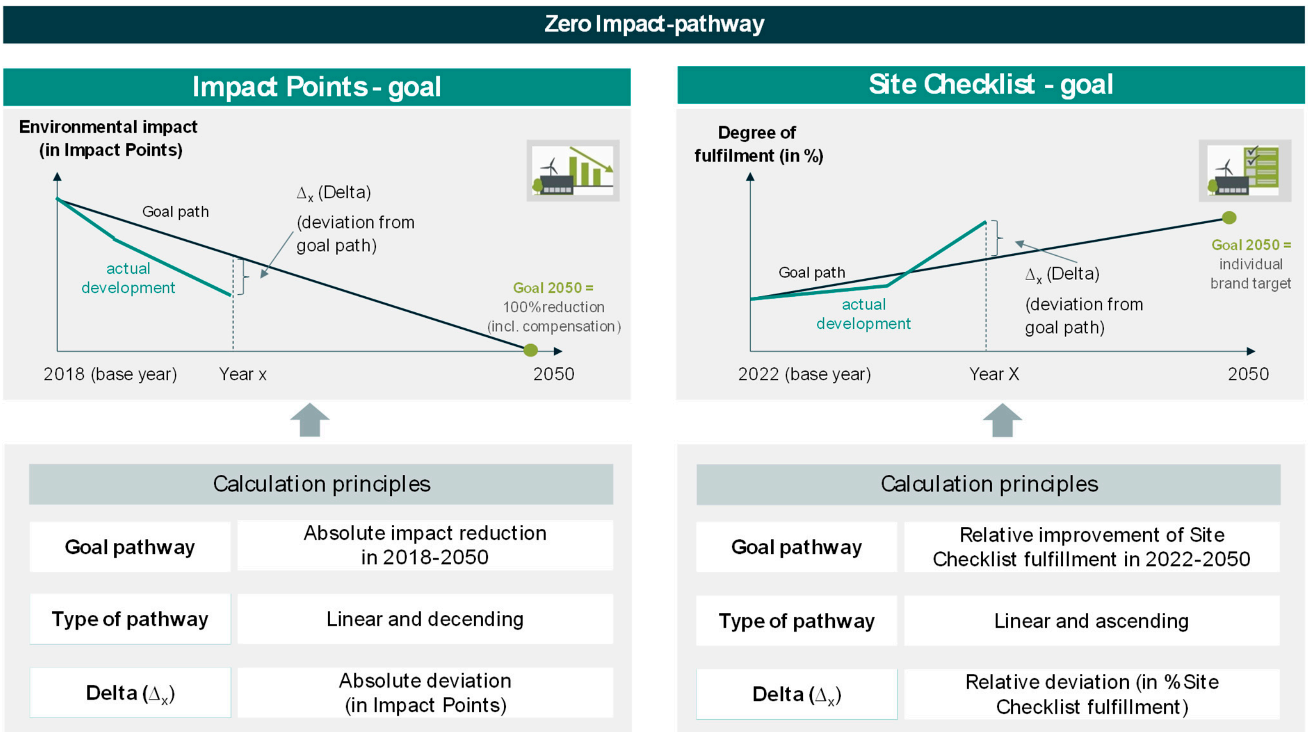

Figure 3. Zero impact pathway.

The Impact Points pathway defines a linear and descending reduction in environmental impacts expressed in Impact Points. The Site Checklist pathway defines a linear and ascending improvement measured in the percentage degree of fulfillment of the Site Checklist criteria. Both pathways can be set in relation to the actual development of Group production, which is expressed as the deviation of the pathway "delta" Δ_x in a year x. The Δ_x $(Impact\ Points)$ is defined as the difference between the impact goal $I_{x,goal}$ and the actual impact $I_{x,actual}$ (Equation (1)). The Δ_x $(Site\ Checklist)$ is defined as the difference between the goal degree of fulfilment $DF_{x,goal}$ and the actual degree of fulfilment $DF_{x,actual}$ (Equation (2)). The calculation principles are defined as follows:

$$\Delta_x(Impact\ Points) = I_{x,goal} - I_{x,actual} \tag{1}$$

$$\Delta_x(Site\ Checklist) = DF_{x,goal} - DF_{x,actual} \tag{2}$$

The calculation principle for the Impact Points and the Site Checklist pathway is standardized for strategic management processes at three organizational levels: (1) Group level, (2) brand level and (3) factory level. Table 2 defines the overall strategic goals for the zero impact factory expressed in the units of the "Impact Points" method and the "Site Checklist" (see Section 4.4 for detailed description). These goals represent an aggregated score on at the Group level that comprehends all brand goals. Each brand governs a specific number of factories.

Table 2. Overall "zero impact" goals of the zero impact factory (at Group level).

Assessment Method	Base Year Value ($I_{x,actual}$/$DF_{x,actual}$)	Base Year	Goal Value ($I_{x,goal}$/$DF_{x,goal}$)	Unit	Goal Reached by
Impact Points	51.2×10^{12} (Group level)	2018	0 (incl. compensation)	Impact Points	2050
Site Checklist	45% (Group level)	2022	85–95%	Degree of fulfillment (in %)	2050

The base year environmental impact of Group Production in 2018 with 51.2×10^{12} Impact Points determines the starting point for a linear reduction pathway, which implies a minimum reduction of 1.60×10^{12} Impact Points per year at the Group level. The Site Checklist defines a linear strategic pathway based on a base year degree of fulfillment of 45% in 2022 and aims to achieve a goal value of 85–95% by 2050. This leads to a minimum annual improvement rate of 1.43% across all sites and brands within Group Production.

4.2. System Model of a Zero Impact Factory

The systemic description of a zero impact factory sets the basis for a holistic impact analysis and defines the scope for strategy development. It is developed with the aim to evaluate an individual factory with the Impact Points method and the Site Checklist. After evaluation, the results can be used to aggregate to a brand and hence to a Group result. Figure 4 describes the system model for a factory analysis, which defines relevant input and output flows based on [68,82].

The systemic model comprehends energy and water input flows (plus associated power plant emissions due to energy generation and transmission) and CO_2 equivalent emissions, air pollutants, waste water and waste treatment as output flows. Table 3 (input flows, next page) and Table 4 (output flows, next page) specify the individual resource flows, which are defined as "indicators" by an internal inventory data standard. The standard defines the scope and the data acquisition method for each indicator to enable a standardized data acquisition across all sites within the Volkswagen Group. Each indicator describes a specific resource flow, which is considered relevant for the "zero impact" evaluation. In total, 133 resource flows are taken into account for an impact evaluation of a factory with the Impact Points method. On the input side, all relevant energy flows for factory operations, such as electricity, methane gas, or external cooling energy; power plant emissions of nitrous oxides (NO_x), particles, and non-methane volatile organic compounds (NMVOC); and relevant water supplies, which are used for technical and social purposes, such as fresh water from surface water or rain, are taken into account. On the output side, CO_2 equivalent emissions (Scope 1 and 2), air pollutants (NO_x, particles and NMVOC), waste water and associated pollutants (chemical oxygen demand (COD), nitrogen (N), phosphorous (P), nickel (Ni) and zinc (Zn)) and wastes for disposal, incineration, recycling and re-use are taken into account.

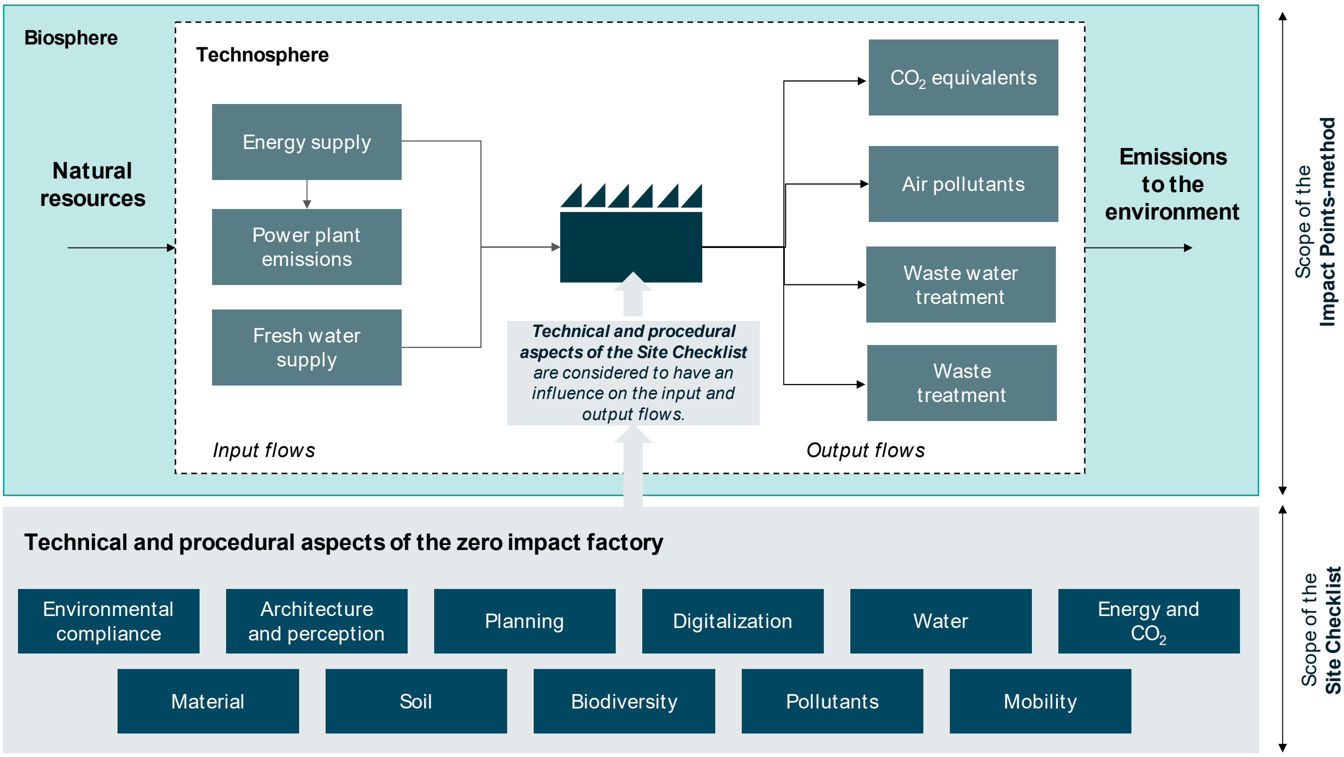

Figure 4. System model for a "zero impact" evaluation of a factory plus scope distinction between the Impact Points method and the Site Checklist.

Table 3. Definition of relevant resource input flows for a "zero impact" evaluation.

Input Flows	Types of Resource Flows	Number of Defined Indicators	Description
Energy (internal and external generation)	Electricity, methane gas, heat, cooling energy and fuels	28	All energy flows relevant for factory operations
Power plant emissions (external energy generation)	Nitrous oxides, particles and NMVOC	18	All identified emissions during energy generation and transmission
Water (internal and external supply)	Fresh water (surface and ground water and rainwater)	6	All relevant water supply flows

Furthermore, the system model presents a distinction between the scope of the Impact Points method and the Site Checklist. Figure 4 highlights the identified fields of action, which are considered relevant to describe technical and procedural aspects of a zero impact factory. The aspects have been developed and tested in an iterative process with experts at the Group, brand and factory level. Various factory workshops have been conducted in different countries to identify local, regional, national and practical barriers to overcome for the application of the Site Checklist. Table 5 summarizes the technical and procedural aspects, which are identified as relevant for the implementation of a zero impact factory.

Table 4. Definition of relevant resource output flows for a "zero impact" evaluation.

Output Flows	Types of Resource Flows/Emissions	Number of Indicators	Description
CO_2 equivalents	CO_2 (Scope 1 and 2) and CO_2 equivalents (Scope 1)	38	All carbon emissions from energy use, cooling equipment and emission treatment
Air pollution (Scope 1)	NO_x, particles and NMVOC	3	All on-site airborne emissions from production processes
Waste water (internal and external treatment)	Waste water and pollutants (COD, N, P, Ni and Zn)	19	All waste water flows and pollutants, which are treated in waste water treatment plants
Waste (internal and external treatment)	Non-hazardous and hazardous waste for treatment	21	All waste flows for disposal, incineration, recycling and re-use

Environmental compliance represents the "backbone" of all environmentally relevant processes and is managed in an environmental compliance management system, which strives to cover, manage and foresee all relevant legislations. It consists of Group internal regulations, process descriptions, guidelines and evaluation and data management tools. Its effectiveness is continuously analyzed by auditing processes on at the Group, brand and factory level while it determines a standardized procedure for all types of environmentally relevant incidents. Architecture and perception strive to create a positive and ecological factory appearance and a minimization of light and noise emissions and vibrations for employees and neighbors. The planning processes require a holistic and integrative consideration of environmental and energy aspects, which requires a total cost of ownership (TCO) approach in decision making to evaluate and optimize the total costs over the lifecycle of a project. Digitalization processes enable the transparent and optimized use of resources in factories through environmental data management from the machinery at the shop-floor level to the overall factory level. Water-related processes and technologies aim at not negatively impacting the local water system through high requirements for water extraction and the effective elimination of water pollutants. The management of energy and CO_2 strive for a carbon-neutral factory and for maximum energy efficiency. Material-related processes aim at maximum efficiency, the use of sustainable materials and the minimization of waste at a maximum recycling rate. The management of soil encompasses the restoration of natural soil function through restoration measures in addition to area management that aims at the minimization of ground sealing. Biodiversity management covers the integration of ecological aspects in the environmental management factory, including voluntary projects, measures and partnerships. Pollutant management covers the use of harmful substances and the minimization of emissions through the application of pollution prevention strategies within the factories. The implementation of a carbon-free mobility aims at neutralizing CO_2 emissions from employees and freight transport processes. The Site Checklist covers, in total, 143 criteria among the presented aspects, which are evaluated during a "zero impact" analysis of a factory.

Table 5. Relevant aspects for the technical and procedural "zero impact" evaluation of a factory.

Aspect of a Zero Impact Factory	Number of Site Checklist Criteria	Formulation of the "Zero Impact" Properties	Covered Aspects
Environmental compliance	18	Reinforcement of the environmental compliance management system (ECMS)	ECMS implementation, auditing/certification and environmentally relevant incidents
Architecture and perception	13	Positive external image of the factories and positive appearance to employees and neighbors	Employees and neighbors and building and site properties (light, noise, vibrations and air exchange)
Planning	10	Holistic and integrative planning processes that are based on total cost of ownership (TCO) evaluations	Planning processes and site planning
Digitalization	7	Optimal resource use through connected and transparent digital processes	Transparent and predictive factory
Water	11	No negative impact on the local water system	Requirements for water extraction and waste water
Energy and CO_2	18	Climate neutrality and maximum energy efficiency of the sites	Energy-efficient infrastructure, energy-efficient production and decarbonization
Material	18	Efficient and sustainable use of materials plus minimization of waste and maximum recycling	Material efficiency, waste, packaging and disposal products
Soil	6	No negative impact on soil through restoration of the natural soil function	Soil and area management
Biodiversity	11	Preservation and protection of biological diversity	Continuous management and voluntary projects, measures and partnerships
Pollutants	15	Avoidance of harmful emissions to the environment	Pollutant emissions and use of pollutants
Mobility	15	CO_2 neutral mobility and transportation	Employee mobility and freight transport

4.3. Prototype of a Zero Impact Factory

The prototype of a zero impact factory builds onto the vision (see Section 4.1) and the technical and procedural aspects of the "zero impact factory" (see Section 4.2). It encompasses an ideal factory state and should represent a blueprint for strategic and planning projects in factories within the global manufacturing system. Local, regional and national circumstances have to be taken account when implementing "zero impact" measures in a specific context (such as local water stress or local recycling infrastructure). Figure 5 highlights a prototype of a zero impact factory, which has been used to discuss "zero impact" properties with managers and experts during Group internal workshops, events and conferences.

The prototype of the zero impact factory is entirely supplied with regenerative energy, which either comes from external suppliers or internal generation. The material inputs originate from circular and biogenic sources. Material outputs are fully recycled within a recycling network, while the generation of toxic waste in the production processes is avoided. The factory applies adequate technologies to mitigate air pollutants for "zero pollution". A closed-loop water system minimizes the freshwater demands (only for loss compensation) and avoids the generation of waste water to neutralize the impact on the local water body. Digital resource management enables a highly efficient and transparent use of the required resources. Life-cycle-oriented factory planning integrates holistic impact considerations in factory development processes. The factory comprehends daylight elements for sustainable workplaces, green recreational spaces and a nature-based factory terrain for high quality in the socio-ecological design, in addition to water integration on site as well as green roofs and facades to integrate ecological principals into the building design. Biodiversity management coordinates nature protection projects on site and with external partners to support environmental development in the greater region. The protection of soil and ground water requires a high standard in the technical design of the factory to avoid spillages and other unintended environmental impacts. Furthermore, a zero emission approach avoids noise, smell and light emissions, which could negatively affect the local community. In urban areas, the urban integration of the factory avoids a negative visual impact, while a sustainable, CO_2-neutral mobility infrastructure for individual or public transport can be shared with the neighborhood.

Figure 5. Prototype model of a zero impact factory.

The prototype of a zero impact factory defines technical benchmark values, which are documented as criteria in the Site Checklist. Supplementary S1.2 presents selected benchmark values, which are briefly explained to highlight the technical details of the prototype. The definition of the benchmark values is mainly based on internal expert consultations, as the literature provides little information about technical "zero impact" thresholds. The EU Best Available Technologies reference (BREF) documentation under the "EU Industrial Emissions Directive" [83] defines technical benchmarks for surface treatment in automotive manufacturing (STS BREF), which have been taken into consideration. An ideal factory covers $\geq$ 50% of the building envelope with ecologically active surfaces, and $\geq$80% of the office space and production areas (where applicable) is supplied with daylight. The energy and data management covers 100% of all relevant facilities and centralizes the information in, e.g., a cloud-based system. The freshwater use is less than 1 m^3/vehicle or reduced by 50%/component part (compared to the base year 2022). Strict waste water discharge thresholds have been defined (for both direct and indirect discharge), which are beyond legal requirements. Various best-practice KPIs for energy efficiency in the energy infrastructure have been defined (e.g., annual efficiency $\geq$ 90% of the heat supply or compressed air generation efficiency $\leq$ 0.12 kWh_{el}/Nm^3). Renewable energy target values (e.g., 100% renewable energies in external electricity supply and $\geq$10% own generation of heat and electricity from renewable sources) determine the technical roadmap for the ultimate goal of 100% CO_2 equivalent neutral. Material-related benchmark values define challenging quotas for incineration ($\leq$10%), disposal ($\leq$1%) and recycling ($\geq$99% as an ultimate goal). The developed biodiversity tool calculates a factory KPI based on various ecological information, whereas the benchmark value should be $\geq$50%. Pollutant benchmarks refer to the maximum paint shop emission concentrations after exhaust air treatment (C_{tot} = 10 mg/Nm^3, CO = 100 mg/Nm^3, and NO_x = 100 mg/Nm^3) and to the VOC abatement ($\geq$8 g/m^2 (body surface) and total dust emissions ($\leq$1 mg/Nm^3)). Related to mobility, 90% of employees commute in a CO_2-neutral manner, and freight transport is 100% carbon-free.

4.4. Methods to Measure and Steer the Transitional Progress

As mentioned in Section 4.1, the zero impact factory strategy contains two methodological instruments to evaluate the progress towards "zero impact": the "Site Checklist" for the qualitative evaluation of various technical and procedural aspects regarding the environmental design of a factory and the "Impact Points" method for the quantification of manufacturing-related environmental impacts.

4.4.1. Site Checklist

The Site Checklist has been developed in cooperation with partners from academia as well as external consulting and with internal stakeholders. The full document is attached in Supplementary S2. As laid out in Section 4.3, the Site Checklist contains 143 environmental criteria, which are allocated to 11 major technical and procedural aspects ("fields of action") relevant for a factory transformation towards zero impact. These criteria rely on best-practice considerations, internal goals and literature references and are divided into three criteria levels to ensure a transformation consecutively:

- **Basis criteria** refer to legal and organizational requirements with regard to factory technologies, management and processes (e.g., emission standards).
- **Performance criteria** define benchmarks and qualities for optimal factory operation (e.g., energy efficiency values for the energy infrastructure).
- **Vision criteria** determine factory characteristics that ultimately reflect the goals and prototypical properties of the zero impact factory (e.g., carbon neutrality).

The application of the Site Checklist is implemented in the environmental management and audit schemes within Group Production, which ensures an annual factory evaluation. A responsible person conducts the site analysis, while the results are critically assessed during the regular environmental audits. The application of the Site Checklist requires both expertise in various fields and time for the experts to carefully evaluate each criterion. A Site Checklist guideline is provided to all applicants, which details all criteria and formulates prerequisites and requirements in order to consider a criterion as fulfilled (the criteria score is either "yes" (fulfilled) or "no" (not fulfilled)). This ensures a harmonized and standardized site evaluation within the global manufacturing system. The application of the Site Checklist determines a "percentage degree of fulfilment" as an overall score over all criteria to determine the environmental state of the factory. The degree of fulfilment DF_x in a year x is defined as the division between the number of fulfilled criteria $n_{fulfilled}$ and the total number of criteria n_{total}:

$$DF_x = \frac{n_{fulfilled}}{n_{total}} \tag{3}$$

The same calculation principle applies within a field of action y, where the specific degree of fulfilment $DF_{x,y}$ is calculated as follows:

$$DF_{x,y} = \frac{n_{fulfilled,y}}{n_{total,y}} \tag{4}$$

Figure 6 shows an exemplary overall score from an exemplary Site Checklist analysis. The results are clustered in accordance with four transformational levels: 55–70% equals a bronze label, 70–85% equals a silver label, 85–95% equals a gold label and above 95% indicates "zero impact". This legend should help to communicate the distance to target to production managers in order to decide factory-specific measures.

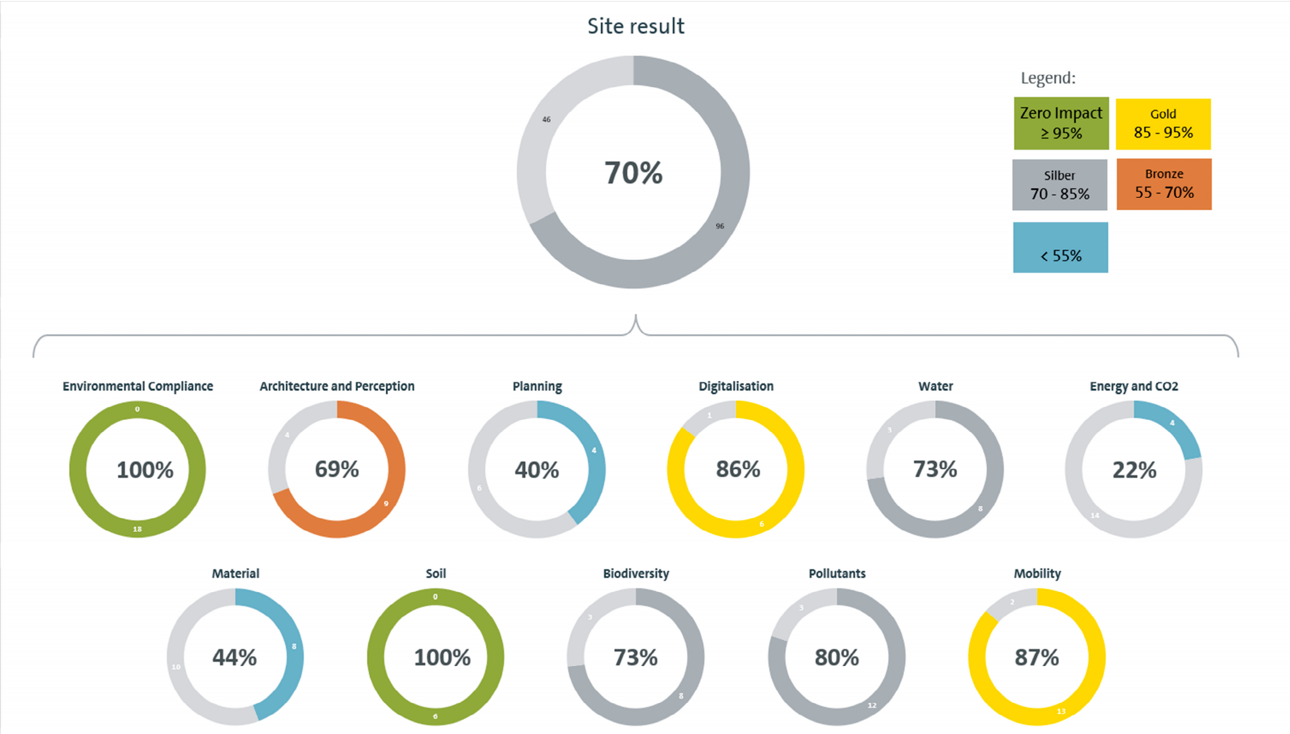

Figure 6. Exemplary result of a site analysis with the Site Checklist tool.

The exemplary evaluation shows an overall score of 70%, which reflects a significant transformative progress towards zero impact. The score per field of action ranges from 22% (energy and CO_2) to 100% (environmental compliance and soil), which shows that some aspects need further strategic consideration in order to raise the overall factory score. In total, 7 out of 11 fields of action lay above the total score, which leads to the conclusion that about two-thirds of the aspects are well managed towards "zero impact".

4.4.2. Impact Points System

The Impact Points system is based on the principles of the ecological scarcity method (ESM) as well as on the "SEBU" system of Volkswagen. It applies a methodological adaptation (see [68] for a detailed methodological description concerning normalizing environmental impacts from factories in different countries for an international aggregation to a Group (single) score) compared with ESM and SEBU to enable the aggregation of "Impact Points" from sites located in different countries to a brand and hence to a global system impact. The international aggregation represents a prerequisite to quantify the total environmental impact of Volkswagen's global manufacturing network. The Impact Points method applies ecofactors, which convert resource flow inventory data (see Section 4.2) into Impact Points. The ecofactors $EF_{R,x,y}$ express the "scarcity" of a resource $R_{x,y}$ within a specific system boundary y (e.g., a local water system or a national energy system) and a specific year x. The ecofactors were defined in a methodological project with partners from academia with the aim to develop an applicable science-based tool for impact evaluations in a global manufacturing company. The environmental impact $I_{x,\,y}$ of a factory-specific resource flow is calculated by multiplying the resource flow R_x with the corresponding ecofactor $EF_{R,x}$:

$$I_{x,y} = R_{x,y} \times EF_{R,x,y} \tag{5}$$

The aggregation of all factory-specific impacts to a total site impact $I_{x,total}$ in a specific year x is calculated as follows:

$$I_{x,total} = \sum_{i=i}^{n} I_{x,y} \tag{6}$$

Figure 7 shows an exemplary calculation result for an environmental impact of a site with data from the year 2022. The spread-sheet calculation tool comprehends the 133 site-specific resource flows (see Section 4.2) as inventory data, which were downloaded from a Group internal environmental database, and calculates the specific impacts through multiplication with the related ecofactors. The “Impact Points” tool enables an automated calculation for the years 2018–2023 by selecting merely the year and the factory with inventory data and ecofactors loaded from the tool’s internal databases.

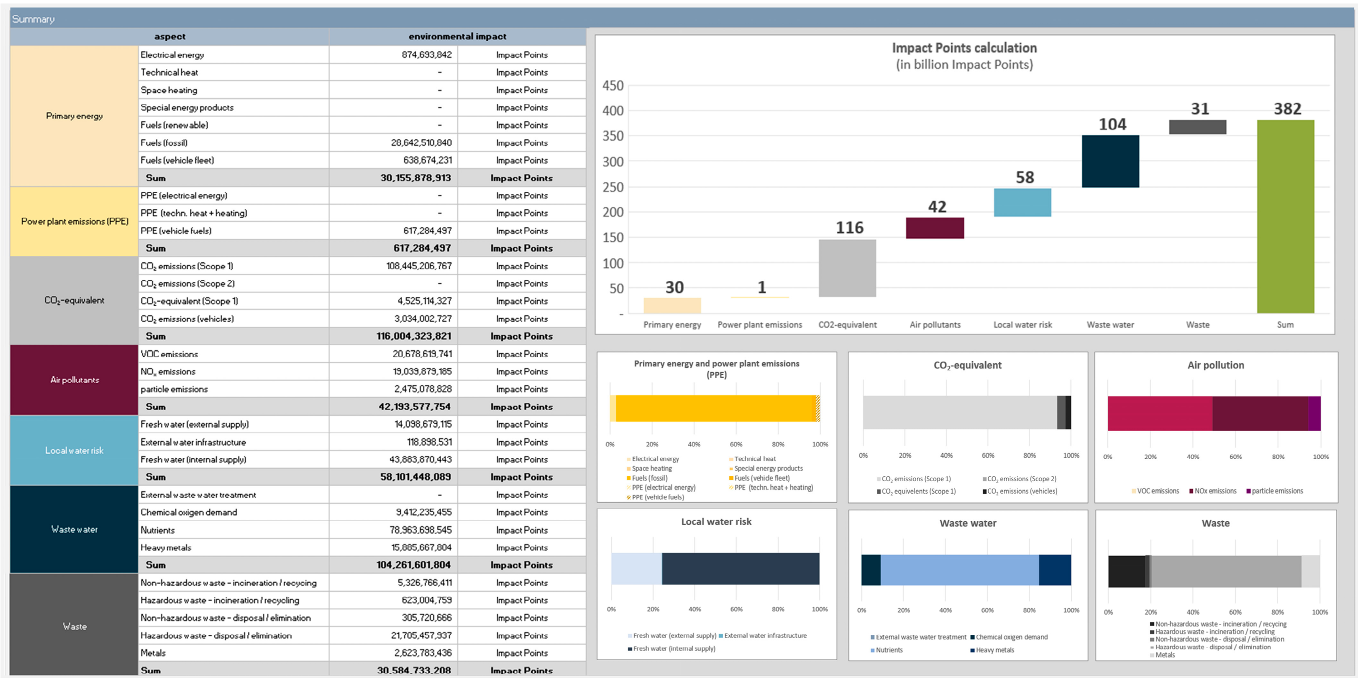

Figure 7. Exemplary environmental impact analysis of a site with the “Impact Points” tool.

In the exemplary calculation, the factory has generated 382 × 10^9 Impact Points in the year 2023. Water and waste water represent the hot spot within the factory and amount to a total of 162 × 10^9 Impact Points, equivalent to 42% of the total impact. Primary energy, power plant emissions and CO_2 equivalents generate a total of 147 × 10^9 Impact Points, equivalent to 38% of the total impact. The remaining 20% of the total impact is due to air pollutants (42 × 10^9 Impact Points, equivalent to 11% of the total impact) and waste (31 × 10^9 Impact Points, equivalent to 8% of the total impact). Impact reduction could be realized (1) by reducing fresh water demands on site through, e.g., water recycling, (2) by the elimination of heavy metals through, e.g., nickel-free coating processes and the ultrafiltration of paint shop waste water, and (3) by reducing natural gas consumption through, e.g., a substitution with biogas or an electrification of combustion processes for heat generation. The reduction potentials could be quantified with the “project assessment module" in the Impact Points tool, which is used in planning processes and for factory-specific calculations to supply transformative roadmaps towards "zero impact" with impact-based information.

4.5. Strategic Management of the Zero Impact Factory Strategy

The strategic management aims at successfully operationalizing the developed vision and goals (Section 4.1) through implementing transformative processes and activities at the Group, brand and factory level in order to steer the global manufacturing system towards a state of "zero impact". The strategic management plays a central role in facilitating the four major strategic processes between the Group, brand and factory. Figure 8 highlights the strategic management structure of Volkswagen Group.

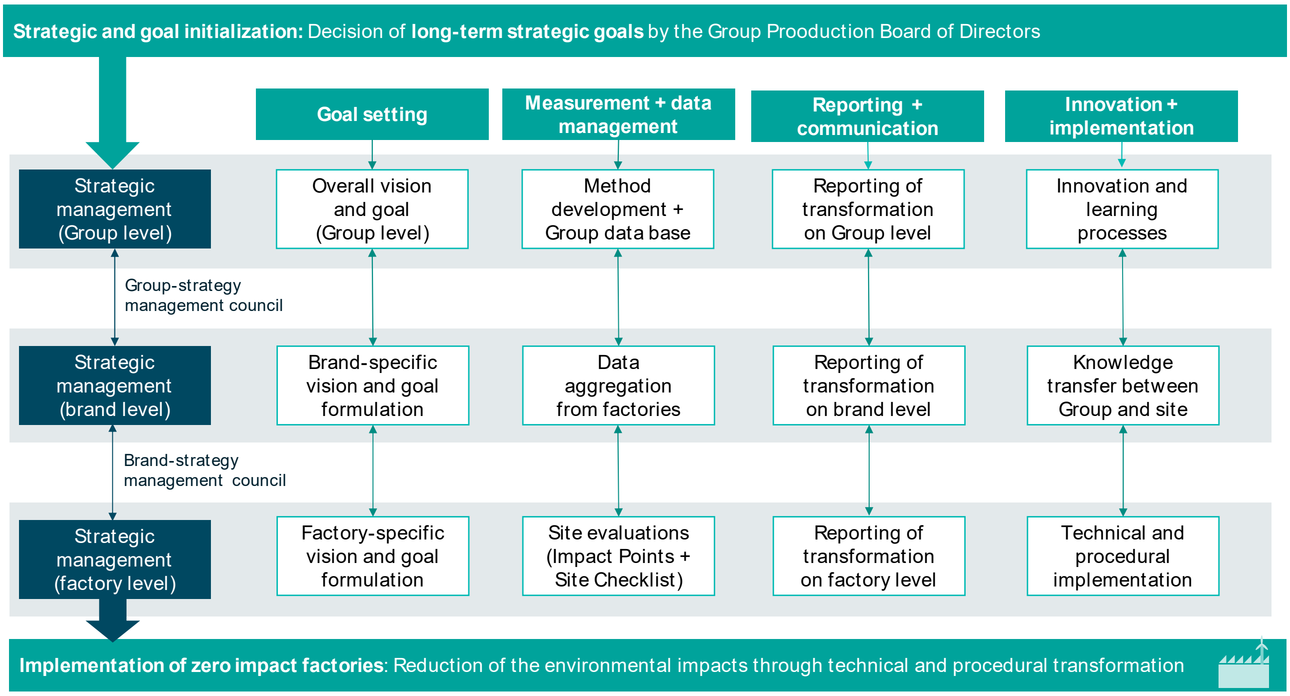

Figure 8. Strategic management of the zero impact factory strategy.

The initialization of the strategy including the formulation of "zero impact" goals has been conducted by the Group Production Board of managers. This was the starting point for installing the strategic management at the Group, brand and factory level to develop and operationalize the strategy in a harmonized and effective manner. Four major processes have been initialized: (1) goal setting, (2) measurement and data management, (3) reporting and communication and (4) innovation and strategy implementation. The frequent strategy alignment on current topics with internal and external stakeholders has led to the strategy results as presented in this section. The coordination of the gained insights has been discussed in strategy management councils at the Group and brand level.

The goal-setting process (see strategy results in Section 4.1) has been initiated by the Group strategic management. It facilitated a top–down goal-setting process (Impact Points) with a complete reduction of impacts in 2018–2050 towards "zero impact" decided for all brands and factories and a bottom–up goal-setting process (Site Checklist), where the Group goal is calculated from the mean average over all sites in 2022–2050. The decision preparation has been centrally coordinated at the Group level for the final decision of the long-term strategic environmental goals by 2050 by the Group Production Board of Directors.

The method development and operationalization process (see strategy results in Sections 4.2 and 4.4) encompasses the development and coordination of both presented methods, including tool development, guideline preparation, method testing and adaptation, initial data collection and implementation for operationalization. This implies the facilitation of workshops to enable knowledge transfer from the method developers to the user. Furthermore, various method development and adaptation workshops have been conducted to improve and broaden the methods. During operationalization, factories calculate the annual impact scores and provide the information to the brand coordinators, who aggregate the data for final data management in the Group environmental database.

The reporting and communication process builds onto the developed methods (see Section 4.4) and requires consistent data management of factory inventory data of input and output resource flows as well as calculated scores of environmental impacts (Impact Points method) and degrees of fulfillment (Site Checklist). Figure 9 shows exemplary Impact Points results for 2018–2022.

The results show a 34% reduction in environmental impacts at the Group level from 51.20×10^{12} to 33.28×10^{12} Impact Points in 2018–2022. This is due to the significant reductions in overall CO_2 emissions and decreases in the production volume due to the current political and economic circumstances. The environmental impact is about 11.51×10^{12} Impact Points below the goal of 44.79×10^{12} for the year 2022, which reflects a positive transformative status. This information is annually communicated to the environmental management teams in the Group, brand and factory departments to evaluate necessary strategic actions to stay "on track" for the long-term "zero impact" goal. In addition, further internal and external communication activities have been coordinated at the Group and brand level to highlight the strategic "zero impact" vision to all employees, as well as to external stakeholders such as customers, competitors and media representatives.

The innovation and implementation process (see results in Sections 4.2 and 4.3) aims to identify various novel and innovative concepts, technologies and organizational principles to provide applicable solutions for the effective reduction of environmental impacts on a measurable scale. This is achieved by (1) facilitating knowledge through workshops at the Group level with experts from subject-related working groups and through (2) transferring best-practice knowledge from brands and factories. The concepts and measures for "zero impact" transformations are documented in a "zero impact factory measure catalogue", which is prepared by Group experts for brands and factories. The knowledge transfer includes the evaluation of financial potentials as well as required investments.

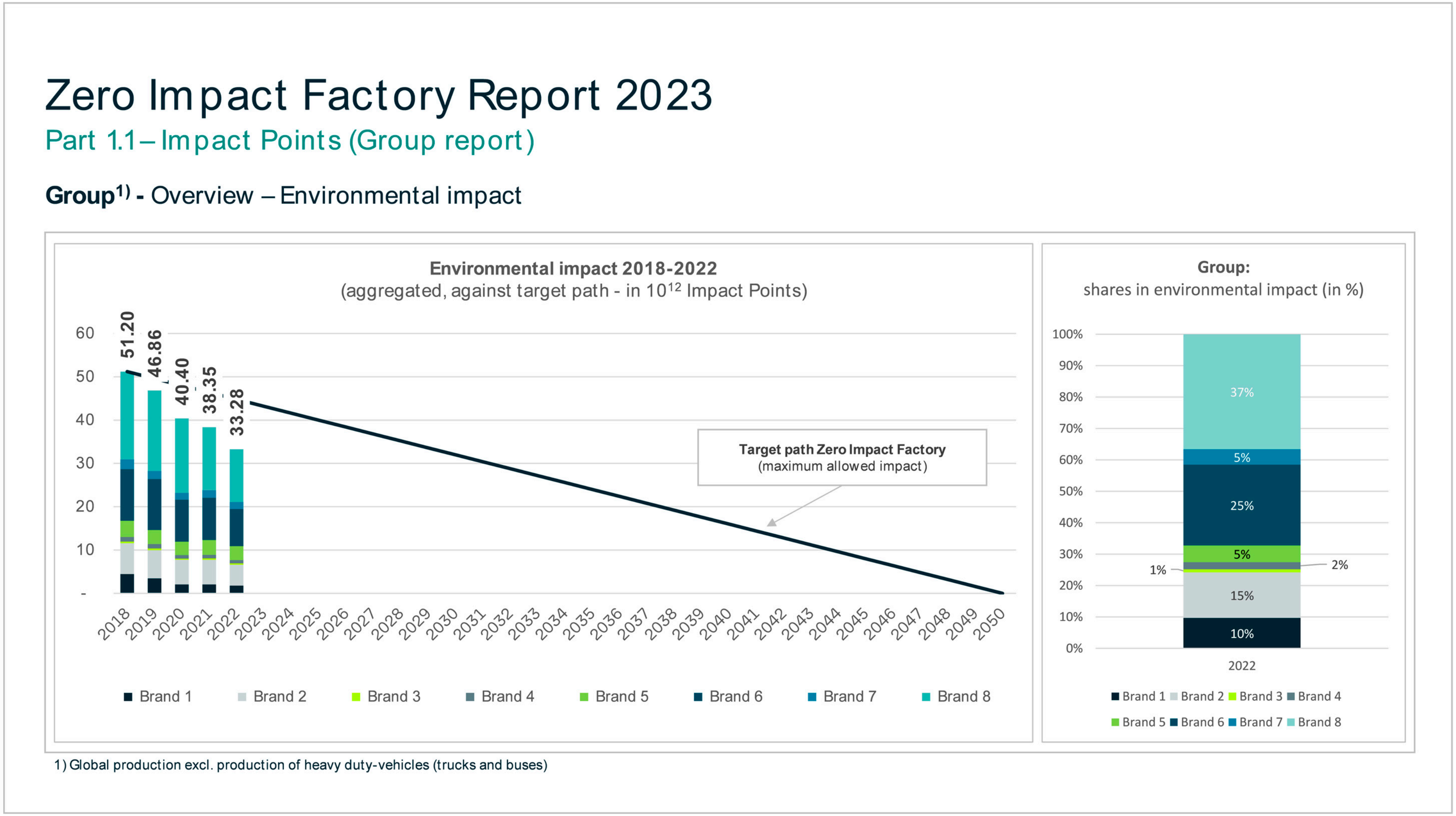

Figure 9. Exemplary Impact Points results from the Group report for the years 2018–2022.

However, the cost evaluations of "zero impact" measures are highly factory-specific, as each factory has individual infrastructural, technical, ecological, legislative and socio-economic circumstances:

- **Energy efficiency** measures often show a high economic potential due to currently high energy costs with a short return of investment with an ROI factor in between 1 and 3 years.
- **Renewable electricity** transitions can generate higher costs, especially in factories that are supplied with electricity of their own generation.
- **Renewable heat** transitions are highly dependent on the natural gas price, which has a strong influence on the cost effectiveness of electrification measures with industrial heat pumps and on the availability of substitutional energy carriers, such as biogas from local infrastructures or national markets.
- **Material-related measures** depend on case-specific circumstances, such as the availability of less-harmful substances (e.g., tensid-based alternatives compared to oil-based solvents in paint shops), the costs of purchasing eco-friendly materials in packaging (such as mycelium-based materials instead of polymers) and the local availability of measures, especially in waste management (e.g., advanced recycling technologies).
- **Water measures** often show a high return of investment, as water prices are relatively low despite fluctuations in availability, especially in regions at risk of drought. Despite this, valid arguments for the implementation of this measure are supply security and consumption restrictions from local authorities.
- **Biodiversity** investments do not show a direct return of investment but become more relevant for finance and reporting requirements. Despite this, societal stakeholders become more aware of a company's activity in the local context, whereas biodiversity projects with regional partners provide a good platform for ecological corporations regarding learning, networking and exchange.

Summarizing the results, strategy development builds onto a "zero impact" vision, including absolute zero impact goals and a transitional pathway to 2050. The system boundary and the method development support the initial goal setting and the annual evaluation of the transitional progress of the strategy. The prototype of a zero impact factory is useful to communicate the overall technical and procedural measures to internal and external stakeholders as well to identify, document and share useful innovations and measures. The strategic management at the Group, brand and factory level aims at coordinating processes concerning (1) goal setting, (2) method development and operationalization, (3) reporting and communication and (4) innovation and implementation. This is associated with various transitional challenges as well as with opportunities for the company, which are discussed in the next section.

5. Discussion of Challenges and Opportunities of the "Zero Impact Factory" Strategy

The presented zero impact factory strategy aims at integrating current scientific findings into industrial practice. The strategy has been developed in cooperation between industry, academia and consultancy and represents a novel attempt to enable an absolute environmental transformation of Volkswagen's global manufacturing system. The combination of strategic environmental sustainability [15] with the principles of design for system innovation [74] has proven to generate a holistic and technically detailed strategy in a top–down manner from the vision towards operative implementation. Various transformative challenges for the strategic management within the company as well as opportunities for the company are identified and documented in Supplementary S1.3.

5.1. Preparing the Top Management Decision for the "Zero Impact Factory Strategy"

The development of the strategic vision "zero impact" is based on current scientific concepts and findings, which resulted in three initial challenges to the strategic management: First, the top management had the need to understand the scientific background for developing a novel strategy thoroughly. This was facilitated through regular information meetings to build up knowledge among the decision makers. The initial decision to develop a strategic vision including targets has contributed to the liability of the strategy. Second, the development of the overall vision required a general strategic commitment by the company for the "zero impact" transformation concerning the required investments in the long term. The strategic management has built onto the existing Group environmental mission statement and has pointed out various opportunities, such as a positive customer awareness through sustainable manufacturing practices and biodiversity projects as well as resource security through circular economy measures. The strategic link to existing scientific findings (such as the planetary boundaries) has generated a convincing argument for science-based strategic communication measures. However, the strategic management had the challenge of facilitating and appropriately providing a significant amount of novel knowledge to internal stakeholders. Third, the definition of the goals and the linear long-term target path until 2050 required a coordination of internal stakeholders from brands and the generation of a strong commitment to the strategy and the goals despite individual circumstances within the brands and in the factories worldwide. The overall commitment has been generated through a top–down decision by the Group of Production Board of Directors for all brands, which has set the general strategic pathway.

5.2. Developing the Content of the "Zero Impact Factory Strategy"

After the initial decision, the development of the strategy content, including the system boundary, prototype, methods and strategic management processes, required coordination and management at the Group, brand and factory level. The strategic management faced four management challenges during the development phase: First, an interface management of information processes between the Group, brand and factory levels was necessary to facilitate various information flows in a structured manner. This was facilitated by installing a regular management council for strategic decision making as well as working groups for the development of strategic content. Knowledge management represented a further challenge, as various studies, concepts, methodological approaches, benchmarking activities and consulting recommendations needed to be facilitated in a structured manner. This was solved by detailing the strategy development into structured projects under the working groups for content development with responsible project managers at the Group level and project teams with experts from the brand and factory levels. Quality management was initiated through reviewing processes with (1) internal revision, (2) a scientific council of independent reviewers from academia and (3) an auditing company. This led to various insights concerning the scientific foundations of the strategy as well as the documentation of the strategy results (such as methods and processes) in a more consistent manner. Adaptation management is furthermore necessary to integrate novel developments (e.g., automotive battery recycling processes) into the strategy. This is facilitated through decision making and capacity provision for new strategy projects in the management council. The subsequent documentation of project results in either procedural and/or technical documents (such as the Site Checklist, process standards or the concept catalogue) enables consistent development of the strategy with novel technical and scientific trends. A structured integration of novel topics into the strategy is considered an opportunity for the company, as potentials for new business models are evaluated.

5.3. Prototype of a "Zero Impact Factory"

The prototype development was facilitated by Group experts to visually represent the overall vision. However, the ability to implement the vision in existing factories has been doubted. Through collecting best-practice examples of real-life solutions (of, e.g., wastewater-free factories, carbon-free factories, disposal-waste-free factories and low-emission factories), early criticism of the vision was mitigated. The acquisition and allocation of financial resources for the vision implementation has been an ongoing and major challenge for the overall strategy implementation. Therefore, the strategic management aims at prioritizing investments in measures, which provide the greatest reduction in environmental impacts by, e.g., calculating the specific impact reduction in "Impact Points per EUR of investment". This has led to a continuous impact reduction, which has also generated acceptance in the top management for further positive "zero impact" investment decisions.

5.4. Method Development (Impact Points Method and Site Checklist)

The method-developing process has faced four main challenges: First, the translation of current scientific knowledge concerning planetary boundaries into business practice is not trivial [18] and leads to general methodological allocation problems (e.g., what is the "safe operating space" for a company?) and to decisions that can be critical for critical stakeholders. The strategic management decided to develop the Impact Points method with an academic partner and publish the results in a peer-review process [68] to ensure an object scientific review on the methodological choices. The definition of "zero impact" as a strategic goal for the factory transformation represents an ambitious challenge, as a small impact remains due to technical and infrastructural circumstances (For example, the exclusive use of renewable energy generates little carbon emissions due to the remaining carbon emissions of powering the national grids. The mitigation of VOC emissions in factories cannot be completely reduced to 0 g VOC/m^2 (painted surface) despite highly effective abatement technologies, as various little emission sources (e.g., in re-work processes) exist. The recycling of waste furthermore generates environmental impacts due to carbon-intensive transports and the need to power the recycling facilities.). Therefore, adequate and transparent compensation mechanisms for environmental impacts beyond carbon offsetting (e.g., through monetary approaches [84]) need to be explored to reach a state of net-"zero impact" by 2050. Despite this, the impact-based approach for strategic steering represents an opportunity for the company to show its ambition for achieving the intended environmental transformation. The development of the Site Checklist is based on references to internal best-practice knowledge and benchmark values. The lack of quantified data and evidence in current scientific publications on "sustainable manufacturing" [7,16] and "green factories" [20,85] has led to the strategic decision to use internal references. The strategic management has faced the challenge of facilitating a significant amount of internal knowledge, which needed to be managed in a structured manner. Opportunities arose for the detailed factory analysis, which is enabled by the Site Checklist and the potential to provide information on a continuous improvement in auditing processes. Therefore, the Site Checklist is considered a valid complementary method to facilitate technical and procedural factory transformations, which can be ultimately measured in environmental impact reductions with the Impact Points method. The strategic steering of the methodological evaluations requires consistent data and information management to handle the significant amount of data. This is supported by the developed tools and databases to document strategic data in a structured manner. The data acquisition and management processes rely on a data standard, which has proven to be useful for the consistent data structure. The successful operationalization of the "zero impact" transformation process heavily relies on good data management; therefore, reliable standards, tools and databases are important prerequisites for strategic activities. The internal and external acceptance of the methods has been a major challenge for the strategic management, as a significant amount of internal knowledge needed to be transferred from developers to users. The internal knowledge transfer has been supported by various workshops to explain the methodological foundations, the functionality of the tools and the database requirements. Acceptance was generated through successful user applications of, e.g., assessing factory-specific projects with the Impact Points method for investment decisions. Methodological criticisms of the single-score result of both methods could arise, as single scores pose a risk of balancing positive and negative developments. A future publication of the strategic "zero impact" progress in the official company reporting is considered to support acceptance of the strategy. This might ultimately contribute to a positive company image.

5.5. Management of the Strategy

The operationalization of the strategy requires continuous strategy process management to facilitate goal setting, method application, reporting and communication and innovation and implementation activities. This includes active management of stakeholders as well as the facilitation of knowledge, reporting and communication activities. A clear organizational structure at the Group, brand and factory level is inevitable to successfully coordinate information flows and current developments. Furthermore, the facilitation of regular management council meetings with clear agendas and a common understanding of the overall strategic process supports the successful operationalization of the strategy. A high level of acceptance through sufficient knowledge and reliable data management represents an identified success factor for the overall strategic transformation towards "zero impact".

6. Conclusions

This article presents results from a strategic project facilitated within the central environmental department of a global automotive company with the aim to develop and operationalize a "zero impact factory" strategy within its global manufacturing system. The current environmental challenges and novel scientific concepts with regard to absolute sustainability and sustainable manufacturing provide various motivations to translate current academic knowledge into industrial practice. A design-thinking process has helped to structure the strategy development process based on a vision and goal formulation, a system definition and prototyping phase, methodological developments and process formulations for strategic management during strategy operationalization. The result is a technically and procedurally detailed strategy for "zero impact factory" transformation in a global context. Various challenges for the strategic management and opportunities for the company have been pointed out. These are considered novel insights for the development and implementation of science-based sustainability strategy approaches in highly technical business environments as well as for advancing sustainability concepts in applied industrial science.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16073011/s1, Supplementary S1. Additional information (zero impact factory). Supplementary S2. Site Checklist.

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Conflicts of Interest: Authors Malte Gebler, Jens Warsen, Roman Meininghaus, Meike Baudis were employed by the company Volkswagen AG. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S.E.; Donges, J.F.; Drüke, M.; Fetzer, I.; Bala, G.; von Bloh, W.; et al. Earth beyond six of nine planetary boundaries. *Sci. Adv.* **2023**, *9*, eadh2458. [CrossRef] [PubMed]
2. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *Nature* **2009**, *461*, 472–475. [CrossRef] [PubMed]

3. Hauschild, M.Z.; Kara, S.; Røpke, I. Absolute sustainability: Challenges to life cycle engineering. *CIRP Ann.* **2020**, *69*, 533–553. [CrossRef]
4. Rockström, J.; Sachs, J.D.; Öhman, M.C.; Schmidt-Taub, G. (Eds.) Sustainable Development and Planetray Boundaries: Submitted to the High Level Panel on the Post—2015 Development Agenda—Draft for Discussion. 2013. Available online: https://www.post2020hlp.org/ (accessed on 28 March 2024).
5. UN. Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed on 6 May 2020).
6. Chen, W.-Q.; Hauschild, M.Z.; Huang, B.-J.; Kara, S.; Sutherland, J.W.; Umeda, Y. Life cycle engineering and sustainable manufacturing for net-zero targets and environmental sustainability. *Resour. Conserv. Recycl.* **2022**, *186*, 106480. [CrossRef]
7. Bonnvoisin, J.; Stark, R.; Seliger, G. (Eds.) Field of Research in Sustainable Manufacturing. In *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives*; Springer International Publishing: Cham, Switzerland, 2017; pp. 3–20. ISBN 978-3-319-48514-0.
8. Rahimifard, S.; Stone, J.; Lumsakul, P.; Trollman, H. Net Positive Manufacturing: A Restoring, Self-healing and Regenerative Approach to Future Industrial Development. *Procedia Manuf.* **2018**, *21*, 2–9. [CrossRef]
9. UN. Sustainable Development Goal 12: Ensure Sustainable Consumption and Production Patterns. Available online: https://sustainabledevelopment.un.org/sdg12 (accessed on 28 May 2020).
10. World Business Council for Sustainable Development. *Vision 2050—The New Agenda for Business*; WBCSD: Geneva, Switzerland, 2009.
11. Hauschild, M.Z. Better—But is it Good Enough? On the Need to Consider Both Eco-efficiency and Eco-effectiveness to Gauge Industrial Sustainability. *Procedia CIRP* **2015**, *29*, 1–7. [CrossRef]
12. Bjørn, A.; Diamond, M.; Owsianiak, M.; Verzat, B.; Hauschild, M.Z. Strengthening the Link between Life Cycle Assessment and Indicators for Absolute Sustainability to Support Development within Planetary Boundaries. *Environ. Sci. Technol.* **2015**, *49*, 6370–6371. [CrossRef] [PubMed]
13. Sachs, J.D.; Schmidt-Traub, G.; Mazzucato, M.; Messner, D.; Nakicenovic, N.; Rockström, J. Six Transformations to achieve the Sustainable Development Goals. *Nat. Sustain.* **2019**, *2*, 805–814. [CrossRef]
14. Waltersmann, L.; Kiemel, S.; Amann, Y.; Sauer, A. Defining sector-specific guiding principles for initiating sustainability within companies. In Proceedings of the 52nd CIRP Conference on Manufacturing Systems (CMS), Ljubljana, Slovenia, 12–14 June 2019; Volume 81, pp. 1142–1147. [CrossRef]
15. Baumgartner, R.J.; Rauter, R. Strategic perspectives of corporate sustainability management to develop a sustainable organization. *J. Clean. Prod.* **2017**, *140*, 81–92. [CrossRef]
16. Despeisse, M.; Ball, P.D.; Evans, S.; Levers, A. Industrial ecology at factory level—A conceptual model. *J. Clean. Prod.* **2012**, *31*, 30–39. [CrossRef]
17. Despeisse, M.; Oates, M.R.; Ball, P.D. Sustainable manufacturing tactics and cross-functional factory modelling. *J. Clean. Prod.* **2013**, *42*, 31–41. [CrossRef]
18. Bjørn, A.; Sim, S.; King, H.; Patouillard, L.; Margni, M.; Hauschild, M.Z.; Ryberg, M. Life cycle assessment applying planetary and regional boundaries to the process level: A model case study. *Int. J. Life Cycle Assess.* **2020**, *25*, 2241–2254. [CrossRef]
19. Gebler, M.; Juraschek, M.; Thiede, S.; Cerdas, F.; Herrmann, C. Defining the "Positive Impact" of socio-technical systems for absolute sustainability: A literature review based on the identification of system design principles and management functions. *Sustain. Sci.* **2022**, *18*, 180. [CrossRef]
20. Herrmann, C.; Schmidt, C.; Kurle, D.; Blume, S.; Thiede, S. Sustainability in manufacturing and factories of the future. *Int. J. Precis. Eng. Manuf.-Green Tech.* **2014**, *1*, 283–292. [CrossRef]
21. Herrmann, C. *Ganzheitliches Life Cycle Management: Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen*; Springer: Berlin/Heidelberg, Germany, 2010; ISBN 978-3-642-01420-8.
22. Clift, R.; Sim, S.; King, H.; Chenoweth, L.J.; Christie, I.; Clavreul, J.; Mueller, C.; Posthuma, L.; Boulay, A.-M.; Chaplin-Kramer, R.; et al. The Challenges of Applying Planetary Boundaries as a Basis for Strategic Decision-Making in Companies with Global Supply Chains. *Sustainability* **2017**, *9*, 279. [CrossRef]
23. Moldavska, A.; Welo, T. Development of Manufacturing Sustainability Assessment Using Systems Thinking. *Sustainability* **2016**, *8*, 5. [CrossRef]
24. Okada, T.; Tamaki, T.; Managi, S. Effect of environmental awareness on purchase intention and satisfaction pertaining to electric vehicles in Japan. *Transp. Res. Part D Transp. Environ.* **2019**, *67*, 503–513. [CrossRef]
25. Bhutta, U.S.; Tariq, A.; Farrukh, M.; Raza, A.; Iqbal, M.K. Green bonds for sustainable development: Review of literature on development and impact of green bonds. *Technol. Forecast. Soc. Chang.* **2022**, *175*, 121378. [CrossRef]
26. Chen, H.-M.; Kuo, T.-C.; Chen, J.-L. Impacts on the ESG and financial performances of companies in the manufacturing industry based on the climate change related risks. *J. Clean. Prod.* **2022**, *380*, 134951. [CrossRef]
27. CNN. Spanish Region of Catalonia Declares Drought Emergency. Available online: https://edition.cnn.com/2024/02/01/climate/spanish-region-catalonia-drought-emergency-intl/index.html#:~:text=The%20current%20drought,%20the%20%E2%80%9Cworst,the%20regions%20continued%20to%20drop (accessed on 4 March 2024).
28. Bell, J.E.; Mollenkopf, D.A.; Stolze, H.J.; Autry, C.W.; Whipple, J.M. Natural resource scarcity and the closed-loop supply chain: A resource-advantage view. *Int. J. Phys. Distrib. Logist. Manag.* **2013**, *43*, 351–379. [CrossRef]

29. Simon, S.; Xiao, M.; Harpprecht, C.; Sasanpour, S.; Gardian, H.; Pregger, T. A Pathway for the German Energy Sector Compatible with a 1.5 °C Carbon Budget. *Sustainability* **2022**, *14*, 1025. [CrossRef]
30. Gebler, M.; Cerdas, J.F.; Thiede, S.; Herrmann, C. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production—A case study. *J. Clean. Prod.* **2020**, *270*, 122330. [CrossRef]
31. European Commission. Zero Pollution Action Plan. Available online: https://ec.europa.eu/environment/strategy/zero-pollution-action-plan_en (accessed on 20 April 2022).
32. EPA. Net Zero Resources. Available online: https://www.epa.gov/water-research/net-zero-resources (accessed on 20 April 2022).
33. Zero Waste Europe. About Zero Waste. Available online: https://zerowasteeurope.eu/about/about-zero-waste/ (accessed on 20 April 2022).
34. Singh, S.; Ramakrishna, S.; Gupta, M.K. Towards zero waste manufacturing: A multidisciplinary review. *J. Clean. Prod.* **2017**, *168*, 1230–1243. [CrossRef]
35. Malik, F. *Systemisches Management, Evolution, Selbstorganisation: Grundprobleme, Funktionsmechanismen und Lösungsansätze für komplexe Systeme*; Haupt Verlag: Bern, Switzerland, 2009.
36. Galpin, T.; Lee Whittington, J. Sustainability leadership: From strategy to results. *J. Bus. Strategy* **2012**, *33*, 40–48. [CrossRef]
37. Rockström, J. *Bounding the Planetary Future: Why We Need a Great Transition*; The Great Transition Initiative: Quincy, MA, USA, 2015.
38. Song, J.; Sun, Y.; Jin, L. PESTEL analysis of the development of the waste-to-energy incineration industry in China. *Renew. Sustain. Energy Rev.* **2017**, *80*, 276–289. [CrossRef]
39. EU. 2030 Climate & Energy Framework. Available online: https://ec.europa.eu/clima/policies/strategies/2030_en (accessed on 6 May 2020).
40. European Commission. Circular Economy Action Plan: The EU's New Circular Action Plan Paves the Way for a Cleaner and More Competitive Europe. Available online: https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en (accessed on 27 May 2022).
41. European Commission. EU Taxonomy for Sustainable Activities: What the EU Is Doing to Create an EU-Wide Classification System for Sustainable Activities. Available online: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en (accessed on 28 March 2024).
42. Laurin, F.; Fantazy, K. Sustainable supply chain management: A case study at IKEA. *Transnatl. Corp. Rev.* **2017**, *9*, 309–318. [CrossRef]
43. Goedkoop, M.; de Beer, I.; Indrane, D. *Product Social Impact Assessment: Handbook 2018*; PRé Sustainability: Amersfort, The Netherlands, 2018; Available online: https://www.social-value-initiative.org/wp-content/uploads/2021/04/20-01-Handbook2020.pdf (accessed on 22 March 2024).
44. Svensson, G.; Padin, C.; Eriksson, D. Glocal business sustainability—Performance beyond zero! *IJPM* **2016**, *9*, 15. [CrossRef]
45. Moldavska, A.; Welo, T. The concept of sustainable manufacturing and its definitions: A content-analysis based literature review. *J. Clean. Prod.* **2017**, *166*, 744–755. [CrossRef]
46. Lentes, J.; Mandel, J.; Schliessmann, U.; Blach, R.; Hertwig, M.; Kuhlmann, T. Competitive and sustainable manufacturing by means of ultra-efficient factories in urban surroundings. *Int. J. Prod. Res.* **2017**, *55*, 480–491. [CrossRef]
47. Bocken, N.M.P.; Short, S.W.; Rana, P.; Evans, S. A literature and practice review to develop sustainable business model archetypes. *J. Clean. Prod.* **2014**, *65*, 42–56. [CrossRef]
48. World Economic Forum; Ellen MacArthur Foundation; McKinsey & Company. *Towards the Circular Economy: Accelerating the Scale-up across Global Supply Chains*; World Economic Forum, Ellen MacArthur Foundation & McKinsey & Company: Geneva, Switzerland, 2014.
49. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
50. Science Based Targets Initiative. About the Science Based Targets Initiative: Science Based Targets Initiative. Available online: https://sciencebasedtargets.org/about-the-science-based-targets-initiative/ (accessed on 6 May 2020).
51. Englehardt, J.D.; Wu, T.; Bloetscher, F.; Deng, Y.; Du Pisani, P.; Eilert, S.; Elmir, S.; Guo, T.; Jacangelo, J.; LeChevallier, M.; et al. Net-zero water management: Achieving energy-positive municipal water supply. *Environ. Sci. Water Res. Technol.* **2016**, *2*, 250–260. [CrossRef]
52. Wang, Z.; Hellweg, S. First Steps Toward Sustainable Circular Uses of Chemicals: Advancing the Assessment and Management Paradigm. *ACS Sustain. Chem. Eng.* **2021**, *9*, 6939–6951. [CrossRef]
53. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
54. Bjørn, A.; Margni, M.; Roy, P.-O.; Bulle, C.; Hauschild, M.Z. A proposal to measure absolute environmental sustainability in life cycle assessment. *Ecol. Indic.* **2016**, *63*, 1–13. [CrossRef]
55. Gernuks, M.; Buchgeister, J.; Schebek, L. Assessment of environmental aspects and determination of environmental targets within environmental management systems (EMS)—Development of a procedure for Volkswagen. *Automob. Ind. Sustain.* **2007**, *15*, 1063–1075. [CrossRef]

56. Adams, R.; Jeanrenaud, S.; Bessant, J.; Denyer, D.; Overy, P. Sustainability-oriented Innovation: A Systematic Review. *Int. J. Manag. Rev.* **2016**, *18*, 180–205. [CrossRef]
57. Thimm, H. A continuous risk estimation approach for corporate environmental compliance management. In Proceedings of the 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), Rome, Italy, 10–13 June 2015.
58. Welford, R. *Corporate Environmental Management 1*; Routledge: Abington, UK, 2016; ISBN 9781315825120.
59. Dér, A.; Hingst, L.; Nyhuis, P.; Herrmann, C. A review of frameworks, methods and models for the evaluation and engineering of factory life cycles. *Adv. Ind. Manuf. Eng.* **2022**, *4*, 100083. [CrossRef]
60. Thiede, S. Cyber Physical Production Systems and Their Role for Decarbonization of Industry. In *Intelligent Decarbonisation: Can Artificial Intelligence and Cyber-Physical Systems Help Achieve Climate Mitigation Targets?* Inderwildi, O., Kraft, M., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 75–86. ISBN 978-3-030-86215-2.
61. Birkeland, J.; Knight-Lenihan, S. Biodiversity offsetting and net positive design. *J. Urban Des.* **2016**, *21*, 50–66. [CrossRef]
62. Aiama, D.; Edwards, S.; Bos, G.; Ekstrom, J.; Krueger, L.; Quétier, F.; Savy, C.; Semroc, B.; Sneary, M. *No Net Loss and Net Positive Impact Approaches for Biodiversity: Exploring the Potential Application of These Approaches in the Commercial Agriculture and Forestry Sectors*; International Union for Conservation of Nature (IUCN): Gland, Switzerland, 2015.
63. UBA. Current State and Future Prospects of Remedial Soil Protection: German Federal Environmental Agency. Available online: https://www.umweltbundesamt.de/publikationen/current-state-future-prospects-of-remedial-soil (accessed on 17 January 2023).
64. Stiel, F.; Michel, T.; Teuteberg, F. Enhancing manufacturing and transportation decision support systems with LCA add-ins. *J. Clean. Prod.* **2016**, *110*, 85–98. [CrossRef]
65. Volkwagen Group. Group Management Report 2022. Available online: https://annualreport2022.volkswagenag.com/group-management-report/sustainable-value-enhancement/production.html (accessed on 4 March 2024).
66. Volkwagen Group. Sustainability Report 2021. Available online: https://www.volkswagenag.com/presence/nachhaltigkeit/documents/sustainability-report/2021/Nonfinancial_Report_2021_e.pdf (accessed on 16 September 2022).
67. Wellge, S.; Schebek, L.; Ahbe, S.; Jansky, N.; Weihofen, S. *Methode der ökologischen Knappheit für Deutschland: Eine Initiative der Volkswagen AG*; LOGOS Verlag: Berlin, Germany, 2014; ISBN 3832538453.
68. Ahbe, S.; Weihofen, S.; Wellge, S. *The Ecological Scarcity Method for the European Union*; Springer Fachmedien Wiesbaden: Wiesbaden, Germany, 2018; ISBN 978-3-658-19505-2.
69. Muhl, M.; Berger, M.; Finkbeiner, M. Development of Eco-factors for the European Union based on the Ecological Scarcity Method. *Int. J. Life Cycle Assess.* **2019**, *24*, 1701–1714. [CrossRef]
70. Schebek, L.; Gassmann, A.; Nunweiler, E.; Wellge, S.; Werthen, M. Eco-Factors for International Company Environmental Management Systems. *Sustainability* **2021**, *13*, 13897. [CrossRef]
71. Gebler, M.; Witte, S.; Blume, S.A.; Muhl, M.; Finkbeiner, M. The "Impact Points"-method: A distance-to-target weighted approach to measure the absolute environmental impact of Volkswagen's global manufacturing system. *J. Clean. Prod.* **2023**, *386*, 135646. [CrossRef]
72. Volkwagen Group. Group Environmental Mission Statement "goTOzero". Available online: https://www.volkswagenag.com/presence/nachhaltigkeit/documents/Leitbild_Umwelt_2022_ENG_final.pdf (accessed on 28 January 2023).
73. Volkwagen Group. Zero Impact Factory. Available online: https://www.volkswagen-newsroom.com/de/bilder/detail/zero-impact-factory-36455 (accessed on 26 August 2022).
74. Gaziulusoy, A.I. A critical review of approaches available for design and innovation teams through the perspective of sustainability science and system innovation theories. *J. Clean. Prod.* **2015**, *107*, 366–377. [CrossRef]
75. Despeisse, M.; Mbaye, F.; Ball, P.D.; Levers, A. The emergence of sustainable manufacturing practices. *Prod. Plan. Control* **2012**, *23*, 354–376. [CrossRef]
76. Stark, R.; Seliger, G.; Bonvoisin , J. (Eds.) *Sustainable Manufacturing: Challenges, Solutions and Implementation Perspectives*; Springer International Publishing: Cham, Switzerland, 2017; ISBN 978-3-319-48514-0.
77. Volkwagen Group. Zero Impact Factory. Available online: https://www.volkswagen-group.com/en/zero-impact-factory-17307 (accessed on 4 March 2024).
78. Volkwagen Group. 1,5 Grad als Ziel: Science Based Targets Initiative (SBTi) Bestätigt Volkswagens Verschärfte Klimaziele in der Produktion. Available online: https://www.volkswagenag.com/de/news/2022/04/targeting-1-5-degrees--science-based-targets-initiative--sbti--c.html (accessed on 16 May 2022).
79. AUDI. Audi México Erinnert Anlässlich des Weltwassertags an die Maßnahmen im Werk. Available online: https://www.audi-mediacenter.com/de/pressemitteilungen/audi-mexico-erinnert-anlaesslich-des-weltwassertags-an-die-massnahmen-im-werk-13877 (accessed on 4 March 2024).
80. Volkwagen Group. Biodiversity Commitment of the Volkswagen Group. Available online: https://www.volkswagenag.com/presence/nachhaltigkeit/documents/policy-intern/20220127_Biodiversity-Commitment-of-the-Volkswagen-Group.pdf (accessed on 20 July 2022).
81. Frischknecht, R.; Steiner, R.; Arthur, B.; Norbert, E.; Gabi, H. Swiss Ecological Scarcity Method: The New Version 2006. Available online: https://esu-services.ch/fileadmin/download/Frischknecht-2006-EcologicalScarcity-Paper.pdf (accessed on 18 November 2022).

82. Gebler, M.; Cerdas, F.; Kaluza, A.; Meininghaus, R.; Herrmann, C. Integrating Life-Cycle Assessment into Automotive Manufacturing—A Review-Based Framework to Measure the Ecological Performance of Production Technologies. In *Progress in Life Cycle Assessment*; Schebek, L., Herrmann, C., Cerdas, F., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 45–55. ISBN 978-3-319-92237-9.
83. European Commission. BAT Reference Documents. Available online: https://eippcb.jrc.ec.europa.eu/reference (accessed on 4 March 2024).
84. Moore, D.; Bach, V.; Finkbeiner, M.; Honkomp, T.; Ahn, H.; Sprenger, M.; Froese, L.; Gratzel, D. Offsetting environmental impacts beyond climate change: The Circular Ecosystem Compensation approach. *J. Environ. Manag.* **2023**, *329*, 117068. [CrossRef]
85. Dornfeld, D.A. Moving towards green and sustainable manufacturing. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2014**, *1*, 63–66. [CrossRef]