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Life Cycle Assessment of a Gas Turbine Installation

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Abstract: Gas turbine installations (GTIs) are widely used to generate electrical and thermal energy, mainly by burning gaseous fuels. With the development of hydrogen energy technology, a current area of particular interest is the use of GTIs to burn hydrogen. In order to assess the prospects of using GTIs in this way, it is necessary to understand the carbon emissions of gas turbines within the larger context of the entire hydrogen life cycle and its carbon footprint. The article provides an overview of results from previously published studies on life cycle assessment (LCA) of complex technical devices associated with the production and consumption of fuel and energy, which are most similar to GTIs when it comes to the complexity of LCA. The subject of analysis was a set of GTIs located in Russia with a capacity of 16 MW. An assessment of greenhouse gas (GHG) emissions per MWh of electricity produced showed that at different stages of the GTI life cycle, the total carbon footprint was 198.1–604.3 kg CO_2-eq., of which more than 99% came from GTI operation. Greenhouse gas emissions from the production and end-of-life management stages are significantly lower for GTIs compared to those for other complex technical devices used to generate electricity. This is an indicator of the strong prospects for the future use of GTIs.

Keywords: complex technical devices; gas turbine installation; carbon footprint; life cycle assessment

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1. Introduction

Nowadays, the use of clean, reliable, and relatively inexpensive energy sources is essential, given the urgency of the climate agenda. Additionally, the development of industrial production technologies and the development of new energy sources in Russia means that research in fields related to strengthening renewable resources in the energy sector and optimizing power plant operating modes has become increasingly important in order to minimize greenhouse gas emissions and improve fuel efficiency. Hydrogen energy is a field that has sparked particular interest and where there have been ongoing research projects and recent developments. It is noteworthy that hydrogen is a fuel that does not produce greenhouse gases when burned, and it can be produced from inexhaustible energy sources (e.g., water and solar energy). Other factors that heighten the significance of hydrogen as a fuel are the limited availability of hydrocarbon energy sources, the negative environmental impact of traditional fuels, and the unsatisfactory efficiency of "green" energy. Unfortunately, most of the hydrogen currently produced belongs to the "grey" energy category—its production is accompanied by significant consumption of electricity derived from fossil fuels (e.g., steam methane reforming and coal gasification), and it leads to further CO_2 emissions [1].

Hydrogen is a promising energy resource for industrial decarbonization and can be used for transport and energy, both in energy carriers, such as fuel cells, internal combustion engines, or gas turbines, and in hydrogen power plants. However, in order to effectively and sustainably utilize hydrogen, it is necessary to reliably determine its carbon footprint over its entire life cycle, from the extraction of raw materials to final use, taking into account the consumption of basic resources, materials, and energy (electricity, heat, water, etc.). By applying the life cycle assessment (LCA) methodology, adapted to the specificities of each case, a solution can be found to address this problem.

Gas turbine power plants (GTPPs) are currently one of the most promising additional resources to support the use of hydrogen. In electricity production, the main advantage of combining hydrogen with gas turbines is that it leads to significantly lower greenhouse gas emissions. The most popular gas turbines are those found in low-power gas turbine installations (from 2.5 to 25 MW) and which are made by converting aero-derivative gas turbine engines (GTEs). Gas turbines are more energy-efficient, compact, and lightweight compared to other sources of power at various types of power plants, making them a promising option to be implemented in power generation, industry, and transport [2].

The most common application of gas turbines in the power industry is to fuel electric generators. These are used as part of simple cycle gas turbine (SCGT) power plants and combined cycle gas turbine (CCGT) condensing power plants. They are also used in combined heat and power plants, which produce both electrical and thermal energy [3]. A gas turbine installation can be set up at a place of business as a main, secondary, or backup source of electricity. The main advantages of gas turbine installations include lower costs to produce heat and electricity, significantly reduced electrical and thermal energy loss thanks to closer proximity to the consumers, autonomous operation, short construction time, and lower fuel consumption.

Most of the existing gas turbine installations can operate as-is on a fuel mixture (hydrogen-containing fuel) with a hydrogen content of up to 20%. This makes it possible to increase gas use efficiency by 20–25% and reduce fuel consumption by up to 35% while at the same time reducing NOx emissions by a factor of 4 and emissions of CO_2 and CO by a factor of 1.5 [4,5]. According to serial manufacturers of gas turbines, such as GE Gas Power, Baker Hughes, Siemens Energy, Mitsubishi Power, Ansaldo Energia, and Kawasaki Heavy Industries, gas turbines can indeed operate on fuel gas mixtures with an H_2 content of up to 20% [6]. Ansaldo Energia is carrying out a series of projects on existing GTIs to modify the combustion chamber and partially replace a number of required materials in order to use fuel with up to 40% hydrogen. New GTIs are equipped with two-zone low-emission combustion chambers (LECC), which allow the combustion of gas mixtures with a hydrogen content of 50% [7]. General Electric produces gas turbines (LM2500 with an output of 22 MW, based on CF6-6) that can operate on fuels with a hydrogen content of up to 85% [8]. In 2020, Siemens Energy tested gas turbines capable of running on up to 100% hydrogen (SGT-A35, 35 MW capacity) [9].

Compared to solid oxide fuel cells (SOFCs), gas turbines today have tremendous potential for electricity generation. SOFCs are limited in their output power (up to 100 kW) [10]. Furthermore, they have high fuel quality requirements, a shorter service life, and a fuel cell startup time, which is much longer than that of a GTI [11]. They also have a high cost per kW of energy produced—$1875 (SOFC with a power of 5 kW) and $1215 (SOFC with a power of 10 kW), for example [12].

When assessing the carbon footprint of fuel used in power plants, the life cycle chains of both the fuel itself and the power plants need to be taken into account. The carbon footprint of the fuel itself (especially fossil and hydrogen fuels) is often substantially larger than the contribution of the equipment (gas turbines, combined cycle power plants, etc.) to GHG emissions per unit of energy obtained or unit of work performed. However, an assessment of the carbon footprint of any installation is necessary to understand each aspect's contribution to the total greenhouse gas emissions, as well as to compare alternative energy installations with each other and with installations that do not use fuels for energy production (e.g., solar panels and wind turbines).

Due to the fact that many studies have been devoted to the assessment of GHG emissions from fuel combustion in power plants, this study is instead focused on the life cycle stages associated with the receipt of materials, the production of components for gas turbine installations and their recycling and disposal after the component reaches its end of life.

In most studies dealing with LCAs of GTIs and which consider GTIs as part of carbon-capture storage power plants (CCSPPs) [13–19], the equipment is divided into 4–8 materials. Material processing technologies in the production of equipment components are not taken into account, and neither is the transportation of materials (parts) and structures or the maintenance and repair of equipment during the operational stage.

It is quite difficult to assess the carbon footprint of GTIs due to several factors, including the use of a large number of materials for production, multi-stage processing technology, and long-term development of GTI components. A gas turbine installation is a complex technical device, so it is extremely difficult to carry out an LCA at all life cycle stages; one must, therefore, introduce limitations and assumptions. Nonetheless, it is necessary to identify which stages (processes, materials, resources, etc.) should be included in or omitted from the LCA.

This can be achieved by analyzing the LCA results of other complex technical devices. Complex technical devices were selected for the LCA as analogs to GTIs. These were structurally similar installations (turbines), along with fuel-using and "fuel-free" installations for electricity generation. To date, a number of studies have been published on LCAs of the following technically complex equipment: wind turbines [13,20–28], electric vehicles [29,30], buses [13], power plants [31], aircraft [13,32,33], aircraft engines [34], gas turbines and combined cycle power plants [13–19]. Wind turbines are similar to GTIs, using turbines and rotors to generate energy. Electric vehicles convert energy via an electric motor, which is as complex in design as a GTI. Power plants generate energy using fuel cells and, like GTIs, are examples of fuel-consuming installations (including those using hydrogen). Aircraft engines have the same design as the land-based gas turbine engines included in GTIs. Combined cycle power plants were considered due to the fact that they incorporate gas turbine units.

The study analyzed accepted system boundaries, functional units, and other aspects of life cycle assessment. The features of the selected stages and resources used in assessing the life cycle of complex technical devices were evaluated, as was the amount of material used for production and construction. An analysis of the categories considered was carried out to assess the environmental impact of complex technical devices, taking into account the selected calculation methods, software, and information sources.

With the results of the analyses, an approach to assess the life cycle of a gas turbine installation was established, and an environmental impact analysis was completed based on the carbon footprint of GTIs.

2. Materials and Methods

2.1. General Principles of LCA

LCA is a methodological framework for analyzing and evaluating the environmental impacts associated with a product's life cycle, including raw material extraction, manufacturing, distribution, transportation, and end-of-life disposal. General requirements for life cycle assessment are contained in ISO 14040-2022 "Environmental management–Life cycle assessment–Principles and framework" [35]. An LCA study consists of four stages: goal and scope definition, inventory analysis, impact assessment, and interpretation.

At the inventory analysis stage, the data collected on the quantities of resources consumed (e.g., metals and electricity) are first converted into elementary flows. At the impact assessment stage, the elementary flows are converted into environmental impact indicators. This means that the contribution of individual substances to a particular impact is taken into account. Further data for the LCA can be taken from primary data obtained by direct measurement (inventory data of the main processes—quantities of fuels and materials) or by calculations based on direct measurement and from secondary data obtained by any means other than primary data (e.g., data on electricity consumed in the production of a material).

The inventory analysis was carried out using open data published in scientific articles, books, electronic resources, and the electronic database Ecoinvent 3.8 (Ecoinvent Association, Zürich, Switzerland). The LCA was performed using OpenLCA 1.10.3 software for the LCA of products and materials (GreenDelta GmbH, Berlin, Germany). This study focused solely on life cycle GHG emissions.

2.2. Functional Unit

The functional unit for energy-generating equipment or engines, including those that consume fuel, is a unit of energy produced, and in the case of electricity production, heat production (kWh, MW) [13–18,20–28,31] or work performed, this can be a kilometer of car travel [29,30], or a passenger kilometer (PKM) of air travel, for example [32,33].

To estimate the carbon footprint of fuel-consuming equipment, the carbon emissions of the fuel are often taken into account. As a functional unit for fuel, mass values are used—kg CO_2-eq./t, kg CO_2-eq./m^3, or taking the heat of the fuel combustion into account—kg CO_2-eq./MJ.

When assessing the carbon footprint of complex technical devices, the following functional units are among those used: for wind turbines—CO_2-eq./kW [20,25], kg CO_2-eq./kW [23], t CO_2-eq./MW [24], for power generating plants and combined cycle power plants—kg CO_2-eq./kW·h [15,16], g CO_2-eq./kW·h [17], kg CO_2-eq./GW [14], for cars—g CO_2-eq./km [29,30]. Based on an analysis of the current scientific literature, g CO_2-eq./kW·h was taken as the functional unit for assessing the carbon footprint of a land-based gas turbine installation used for electricity generation.

2.3. Limitations of LCA

The definition of system boundaries plays an important role in the LCA process since incorrectly chosen system boundaries can significantly affect the results of the assessment. Traditionally, LCA starts with the extraction of raw materials and ends with the disposal of the components. Within the considered system boundaries, the main production process can be subdivided into additional processes based on the level of detail.

The life cycles of fuels and fuel-consuming equipment intersect at the stage of equipment operation in the form of energy received or work performed, which together contribute to the carbon footprint (Figure 1).

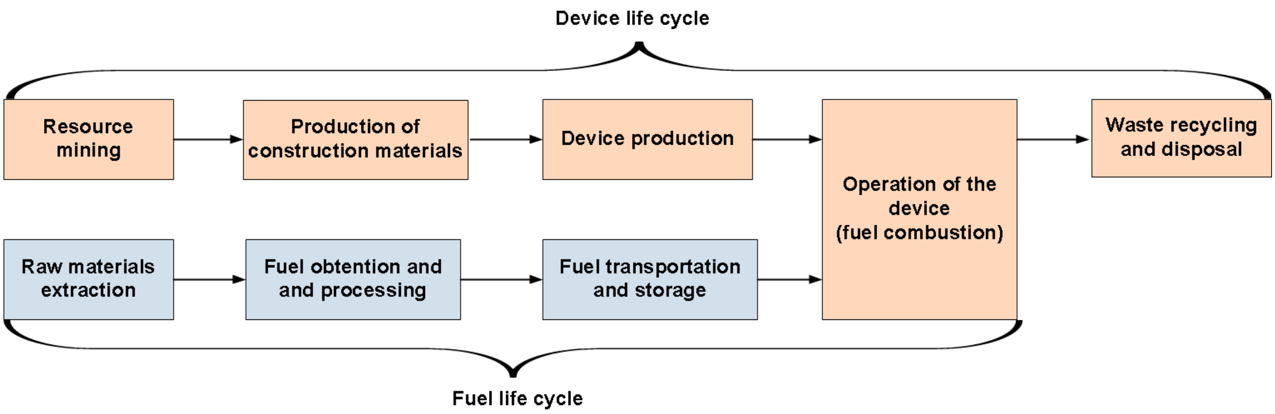

Figure 1. The life cycle of fuel/energy and fuel-consuming devices.

In the case of electricity generation, for example, research [18] has shown that 410 g CO_2-eq./kWh is associated with the life cycle of the fuel (natural gas), and 1.1 g CO_2-eq./kWh is linked with the life cycle of the combustion plant (gas turbine power plant). For technically complex equipment, such as wind turbines and solar panels, the carbon footprint of the electricity they generate is only determined by the life cycle of the equipment itself since the energy sources (sun or wind) do not have a carbon footprint. When assessing the life cycle of a gas turbine installation, the life cycle of the fuel (hydrogen) is not taken into account.

When performing an LCA of a technically complex piece of equipment such as a gas turbine, the following stages must be considered:

- The production stage, which includes the processes of obtaining structural materials, processing said materials, production of components, assembly and installation, and production of operating materials and spare parts;
- The stage of producing fuel and electrical energy;
- The operational stage, which includes the use of the device in the field, as well as maintenance and repair procedures (e.g., replacement of failed components);
- The disposal stage, with processes including decomposition, processing (recycling), and disposal of materials at the end of their useful life.

Examples of the coverage of individual stages and processes of technically complex equipment in LCA studies are shown in Table S1 (Please see the Supplementary Materials for Table S1).

Analyzing the LCA studies of technically complex equipment has made it possible to identify the parameters to be considered at each stage of the life cycle.

An LCA of wind turbines compared to other technically complex equipment is considered in more detail. At the production stage of wind turbines, the materials used are divided according to the main elements produced: nacelles, rotors, blades, or tower and mooring systems for offshore wind turbines [13,20–24,27]. With regard to material processing, the following methods are considered: injection molding for composite materials in the manufacture of rotors, rolling (steel or aluminum), welding, and copper wire drawing [13]. According to research [25], when a category such as steel is chosen for the LCA in the SimaPro program, the steel production processes take into account the extraction and production of raw materials according to the type of steel (low alloy, chrome, etc.). The foundation, electronics, substation, and electrical cabling were considered as auxiliary structures [13,22–29]. Other resources included lubricating oil [21–23,27], paints, varnishes [13,23,25], adhesives, sealants [23,25], and zinc coating [13].

At the installation and assembly stage, researchers considered land acquisition, site and access road preparation, and fuel consumption of the construction equipment [13,23,25,26]. The structures were transported from the production site to the building site by sea and road [20–26]. The operation phase of the wind turbines involved the following: repair of the turbine in case of failure, as well as maintenance, including the replacement of oils in the gearbox, generator, and cooling system; replacement of the brake system; and lubrication of mechanical parts [20,22,23,25–27]. Disposal at the end of the life cycle included recycling up to 81% of recyclable materials (metals—98%, polymers—90%, and electronics—50%) [23,25,26] and incinerating or disposing of non-recyclable components (concrete, composites, oils, paints, etc.).

The LCA of electric vehicles considered three main components: the vehicle frame, the electric axle drive, and the battery system. Other resources used in the production of an electric vehicle included textiles [30], as well as paints and coatings for the body of the vehicle [29]. Shipping and freight were used to transport materials and parts to the manufacturing plant [29]. During the operation phase of electric vehicles, maintenance was considered, including tire and brake pad replacement. The main stages in the end-of-life phase were vehicle dismantling, crushing, sorting, waste treatment, and recycling of materials [30].

When assessing the life cycle of electric motors for electric vehicles [13], rolling (for steel or aluminum), copper wire drawing, and nickel plating were considered as material processing methods during production. Electronics were considered as auxiliary structures [13].

The LCA studies of passenger aircraft [14,32,33] considered the production of five materials (excluding engine materials). The processing of these materials was only discussed in one of the studies [13], and it included the injection molding of composites. In the case of aircraft production, heat and water supply were among the resources considered [13]. Air and road transport was used to deliver materials, parts, and structures to the manufacturing plant [29]. Due to a lack of data in the Ecoinvent database [13], titanium and nickel were replaced by copper scrap at the end of the aircraft life cycle since all three metals are classified as first-row transition metals. At the end of the aircraft's life, composites (carbon fiber-reinforced plastics) were represented in the model by a stream of mixed plastic waste.

The LCA of a bus, based on data from the Ecoinvent database [13], considered 13 types of materials as they underwent various processes: steel rolling, glass tempering, and copper wire drawing. The production building for bus assembly was considered an auxiliary structure. Other resources included heat supply, diesel, lubricating oil, acids, and paint (alkyd). The production and disposal stages of the power plants used to operate the bus included the components and materials needed for the production of batteries and the maintenance, repair, and replacement of failed components throughout the life cycle [31].

When assessing the life cycle of gas turbine installations and power plants, 4–8 materials were taken into account [13,14], as is processing, including sheet steel rolling, steel metalworking, welding, injection molding for polymers, and construction work [13]. The foundation and industrial buildings were used as auxiliary structures [13,14]. Other resources involved in the production of the gas turbine installations were heat supply, water, organic chemicals, etc. [13,14]. Materials, parts, and structures were transported to the production site by car [13] and by truck [14]. In one case [14], the main material flows during the operational phase of a gas turbine power plant (GTPP) were associated with the operation of the plant itself (fuel combustion) and its maintenance (oil, spare parts, etc.). Decommissioning of the GTPP included dismantling and waste management (incineration and disposal) [14].

It was found that most of the existing studies and databases used between 2 and 15 materials to assess the life cycle of technically complex equipment, while only a few studies took into account the material treatment processes (e.g., metalworking, injection molding, and welding). The main auxiliary structure for the production of technically complex equipment was the foundation, while the other main resources were heat supply, water, and lubricating oil. Electricity consumption in the production process was considered in almost all studies. The transport of materials, parts, and structures for the production and installation of technically complex equipment was mainly carried out by freight. Most studies considered land acquisition for the installation and assembly of the equipment, while a few studies considered site preparation. During the operation phase of technically complex equipment, the main consideration was the replacement of oils and consumables (e.g., spare parts, lubricants, tires, and brake pads). End-of-life waste management for technically complex equipment was mainly considered in terms of recycling and disposal.

By analyzing research on the LCA of gas turbine installations and combined cycle gas turbine plants, it was possible to identify the stages and resources that were included in or omitted from the LCA. In most cases, the LCA of a gas turbine installation considers the stages from extraction of raw materials to disposal of the installation. It takes into account the production of structural materials (mainly metals) according to their class (low alloy steel, stainless steel, etc.), as well as energy consumption and waste management at the end of operation. The LCA of a gas turbine rarely takes into account the technologies for processing structural materials (metalworking, casting, rolling, etc.), the construction of the foundation during assembly and installation, the transport of materials (structures), or the maintenance. Repairs are also excluded from the LCA of gas turbines. The same is true for scientific and technical research and development in the production of materials, parts, components, and more.

Figure 2 shows the life cycle of a gas turbine installation and outlines the LCA boundary used in this study.

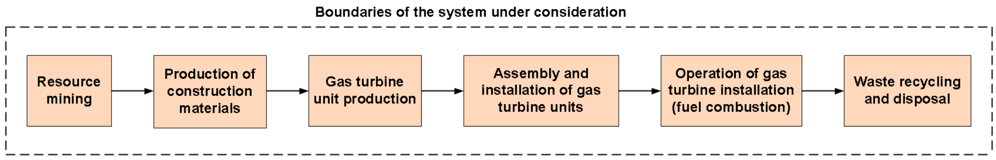

Figure 2. Gas turbine installation life cycle diagram.

In assessing the life cycle of a gas turbine installation, the authors considered the following processes: extraction of resources, production of structural materials (steel, aluminum, nickel, and titanium), technologies for processing the materials, energy consumption, production of the gas turbine unit (GTU), assembly and installation of the GTI, operation of GTIs on different types of fuel (natural gas, hydrogen-containing fuel, or hydrogen), and recycling of GTI components. The transportation phases, maintenance, and repair of the gas turbine installation were not included in the LCA.

In addition, technically complex equipment is characterized by a long period (up to several decades) of research and development (R&D), which is also associated with high resource consumption and environmental impact. R&D can lead to improved productivity, which increases profits and creates an advantage in identifying competitors. For example, it took 25 years to develop and invent a combined cycle gas turbine (CCGT) and 10 years to develop lithium-ion batteries [36]. In practice, however, this phase of research and development is almost never assessed as part of an LCA. The R&D phase is very important because its implementation requires the use of large amounts of resources (electricity, water, and heat), as well as labor, time, and more, with corresponding greenhouse gas emissions. R&D is not considered in this study due to the insufficiency of open data on production processes in the gas turbine life cycle stages.

2.4. Level of Detail in the Material Data

Complex technical devices consist of numerous materials (more than 30), including various alloys and composites. For example, about 35 different types of materials were used to produce the Vestas V110-2.0 MW wind generator [37], and more than 40 materials were needed to produce the Mitsubishi i-MiEV electric vehicle [29].

A large number of materials are also used in the production of gas turbine equipment. The production of a GTE (PS-90A) gas turbine engine [38], which is used as part of a land-based gas turbine installation, involves more than 50 different materials and alloys, which are selected for use in a GTI component based on specific temperatures and conditions for their use. However, because of the large amount of labor and time involved, it is almost impossible to assess the life cycle of a gas turbine installation on the basis of how much of each material is used. Therefore, as shown above, up to 15 types of materials are used in practice to assess the life cycle of technically complex equipment.

Even when assessing the construction or production life cycle of the same type of technically complex equipment (e.g., wind turbines), different studies consider different amounts of materials (see Table S2).

When assessing the manufacturing phase of wind turbines (whether offshore or onshore), 5–15 materials are identified. These are mainly metals (iron, steel, cast iron, aluminum and copper alloys, zinc, rare earth metals, etc.), non-metallic materials such as polymers (e.g., high-density polyethylene and polypropylene), composites (e.g., glass and carbon fiber), concrete, and epoxy resin [13,20–28].

Various materials are used to make various parts of wind turbine components. Steel is used in the manufacture of several components, including the tower, nacelle, rotors, and foundation [20–24,27,28]. Concrete and steel are important materials for the foundation and are used in different types of turbines depending on the location, the specific requirements of the manufacturer, or the foundation conditions at each site. Aluminum is used to produce strong yet lightweight turbine components. Copper is mainly used in generator stator and rotor coil windings, high-voltage power cable conductors, transformer coils, and earthing [28]. Zinc is used as a protective coating against corrosion when wind turbines are exposed to harsh climatic and mechanical influences [13]. Boron and rare earth elements (e.g., dysprosium and neodymium) are required for turbine structures that use permanent magnets [39]. Epoxy resin composites, combined with glass or carbon fiber, account for 8–12% of the weight of a turbine and 2–6% of the weight of the equipment. Polymers are another key material used in turbines, generally making up 20% [40].

The breakdown of an electric vehicle requires the use of 14 materials, including metals, polymers, textiles, and rubber. By weight, the main material used in the airframe of an electric vehicle is steel, while the main materials used in the body and the lithium-ion battery are nickel, cobalt, and manganese [30]. Lithium-ion batteries in electric vehicles use a cathode, an anode, and an electrolyte conductor. The cathode consists mainly of nickel (73%), cobalt (14%), lithium (11%), and aluminum (2%). The anode is usually made entirely of graphite. The electrolyte conductor consists of lithium salts (lithium hexafluorophosphate and $LiPF_6$) in an organic solvent [41].

When assessing aircraft production, approximately five materials are used [13,32,33], generally including steel, aluminum, titanium, nickel, and composites. A list of materials used in long-haul aircraft (>4000 km), as determined by the year of manufacture, is given in the study [42]. The approximate material content for passenger aircraft is 60% aluminum, 25% composites, and 12% steel, with the remainder made up of nickel and titanium.

When assessing the production stage of electric motors, electric power plants, and aircraft engines, 5–10 materials are used, consisting mainly of metals (iron, steel, cast iron, aluminum and copper alloys, nickel, titanium, etc.), composites (e.g., fiberglass), polymers, graphite and lithium titanate (LTO).

In modern aircraft engines, such as those manufactured by General Electric, the main materials are nickel alloys (46%), titanium alloys (25%), steel (16%), aluminum alloys (8%), and composites (4%). Titanium and composite materials make it possible to reduce the weight of engines, which leads to increased fuel efficiency [34].

There is currently little data on consumables used in the manufacture of gas turbines, combined cycle power plants, and power stations. When assessing the production stage of these types of technically complex equipment, 2–15 materials are used, including metals (iron, steel, aluminum and copper alloys, nickel, zinc, cobalt, chromium, etc.), non-metallic materials, such as polymers (e.g., HDPE), and concrete.

According to the Ecoinvent database, 5–8 materials (steel, copper, and aluminum alloys, concrete, polypropylene, etc.) are generally taken into account when evaluating the production of gas turbine units [13]. To assess the life cycle of a combined cycle power plant, only steel and cement are considered [17] since they are the main consumables during the construction phase and the main factors in the budget. In order to carry out the LCA of a mini thermal power plant with gas piston engines, the following components and their materials are considered for research purposes [19]: an engine (steel, cast iron, and aluminum), a generator (steel and copper) and a tank (steel).

An analysis of the studies conducted to assess the production and construction phases of technically complex equipment showed that 2–15 different materials were taken into account. These consisted mainly of metals and their alloys and non-metallic materials, including polymers, composites, and concrete (in the case of wind turbines). Therefore, technically complex equipment can be analyzed in terms of which materials generate the most greenhouse gas emissions during the production process. On average, 4–5 materials are identified when assessing the production phase of a gas turbine unit; usually, these are metals, such as steel, aluminum, titanium, and nickel.

2.5. Environmental Impact Assessment Categories

The LCA of technically complex equipment was carried out in various studies according to a range of environmental impact categories (see Table S3).

Based on the reviewed studies related to this topic, the number of categories assessed varied from 2 to 18, and it generally included global warming potential, greenhouse gas emissions, total energy demand, ozone depletion, ecotoxicity, depletion of fossil resources, and eutrophication. The software products SimaPro [14,22–25,30,32,33] and OpenLCA [15,16] were most often used to calculate the environmental impact of technically complex equipment, whereas the authors' approaches based on the well-known methods (ReCiPe 2008 [22] and Eco-Indicator 99 [33]) were very rarely used for calculations. Data from equipment manufacturers and databases (mainly Ecoinvent) were also used as sources of information for the calculations; only a handful of studies used the results of the authors' own research [15,16,32].

Calculations of the environmental impact of wind turbines [20,22–26] were carried out using SimaPro software (different versions), with information from the Ecoinvent database as well as data from wind turbine manufacturers and from publications by other researchers. The main categories assessed were global warming potential, total energy demand, and ozone depletion.

To assess the environmental impact of electric vehicles [29,30], the main category considered was global warming potential, with supporting information from manufacturers and various databases (Ecoinvent 3.6, BRUSA, 2019; European Energy Agency, 2016).

The environmental impact assessment of power plants [31] considered two impact categories: CO_2 emissions and energy costs. The developed methodology was used for the calculations, and information was also taken from the Ecoinvent v.3, GREET, and ELPICA databases.

The environmental impact of an aircraft [32,33] was assessed based on several categories, including global warming potential, greenhouse gas emissions, fuel consumption, and minerals. The Eco-Indicator 99 method, as well as versions 7.1.8 and 8 of the software program SimaPro, were used for the assessment [33], with further information drawn from manufacturers' data, scientific publications, and the Ecoinvent v.2 and Ecoinvent 3.1 databases.

The number of categories used ranged from 2 to 11 when it came to assessing the impact of gas turbines and combined cycle units [14–19], with greenhouse gas emissions being the most commonly selected category. Applicable software included OpenLCA versions 1.9–1.11 and SimaPro 5.1. Sources of information included the Ecoinvent database, manufacturers' data, the authors' own research, and other scientific publications.

To assess the environmental impact of gas turbines, GHG emissions were chosen as the main category because they have the greatest impact at all stages of the life cycle, and they depend on numerous factors, including the source of electricity, the type of production resources, and their consumption.

2.6. The GTI Considered

The subject of the study is the GTU-16P, which was created based on a gas generator from the PS-90A high-power aircraft engine and the GTU-12P gas turbine unit, which were both developed by Aviadvigatel JSC, Perm, Russia [43].

The GTU-16P has been produced in series by UEC-Perm Motors JSC (Perm, Russia) since 1999 and is used as a part of the Ural series gas pumping units during the reconstruction of existing gas pumping units and as a drive for the AC electric generators of the GTPP-16PA gas turbine power plants. Since 2021, all new GTU-16Ps have been equipped with a single-module low-emission combustion chamber (LECC), which reduces emissions of nitrogen oxides (NOx) and carbon monoxide (CO) [44].

Among the industrial energy companies that use the GTU-16P are PJSC Gazprom, OJSC NK Rosneft, PJSC T Plus (Russia), and the Botas Petroleum Pipeline Corporation (Turkey) [45]. As of 1 June 2023, a total of 404 gas turbine installations with a capacity of 16 MW are in operation at industrial sites, and their overall operating time has reached 13 million hours. The GTU-16P primarily uses natural gas as fuel. A gas turbine installation can be fueled by a mixture of natural gas and hydrogen-containing fuel (up to 20% hydrogen) without any need to change the design of the combustion chamber [46]. In order to operate a gas turbine power plant in the future using hydrogen fuel, it is necessary to make a number of technological improvements, such as modernizing the combustion chamber, changing the size of the fuel line, changing the fuel line system by replacing flanged connections with welded ones, installing safety sensors and leak detectors, and modernizing the gas turbine control system [47,48]. Possible types of fuel for use in gas turbine units (natural gas, hydrogen-containing fuel, and hydrogen) must be taken into account when assessing the carbon footprint of the operation phase.

The GTU-16P gas turbine unit is located in the power block of the turbo container. It is a complex setup, which is comprised of the following components:

- PS-90GP-2 gas turbine engine on a sub-engine frame (Figure 3), consisting of a gas generator (compressor, combustion chamber, and high-pressure turbine) and a power turbine [43]. It also features:
- a transmission with casings;
- an input device;
- noise-heat-insulating casing;
- an output device;
- a fuel unit cabinet;
- pipeline and electrical communications.

The main technical characteristics of the GTU-16P are presented in Table 1 [49].

Table 1. Main technical characteristics of a GTU-16P gas turbine installation.

Options	Designation	Value
Power turbine shaft power (performance)	MW	16.0
Efficiency of the power turbine shaft	%	35.2
Total efficiency	%	84.7
Gas temperature in front of the gas generator turbine	°C	1196
Exhaust gas consumption	kg/s	54.7
Gas temperature behind the gas generator turbine	°C	805
Temperature of gases behind the power turbine	°C	540
Fuel consumption	kg/h	3350
Overall dimensions (L × W × H)	mm	8250 × 3200 × 3200
Weight (dry)	kg	5150
Full installation resources	thous. h	100
Gas generator life before major overhaul	thous. h	25
Power turbine service life before major overhaul	thous. h	50

The components considered when assessing the life cycle of a gas turbine installation are a gas turbine engine (GTE); a gas turbine unit (GTU), including a GTE with a sub-engine frame; and a gas turbine installation (GTI), including GTUs with foundations, gas turbine power plant (GTPP) consists of GTI and auxiliary equipment (see Figure 3).

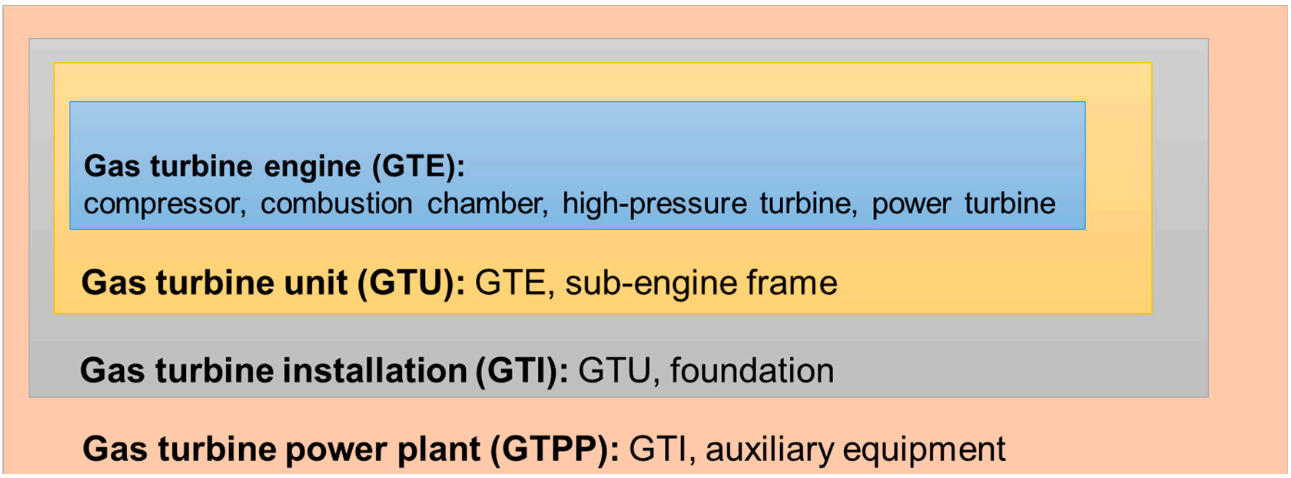

Figure 3. Elements of the gas turbine LCA.

3. Results

Carbon Footprint Assessment of the GTI

In accordance with the methodology described above, an assessment was made to determine the carbon footprint of the GTI during its production and use in Russia. The boundaries of the system were defined by the production of structural materials (e.g., material processing, production of the gas turbine unit, production and installation of the foundations for the gas turbine unit, and disposal at the GTU's end of the life). GTI operation, transportation of materials, and the use of other resources (e.g., raw materials) were not considered because these stages were not included in the objectives of the study.

The life cycle inventory of the GTU included the collection of both quantitative and qualitative data on the main flows of structural materials. In determining the material consumption for the GTU-16P, based on the PS-90GP-2 aircraft engine, the material content of the CF6 aircraft engine (General Electric, Boston, MA, USA) was used as an analog [50]. The sub-engine frame and other elements of the gas turbine unit were assumed to be made of structural steel. The materials used to make the GTU-16P and the manufacturing processes for these materials are shown in Table 2. The main materials used in the production of GTUs are steel (51%)—structural and stainless steel—and nickel alloys, which make up a relatively high percentage (about 30%) and are used in the combustor as well as in the turbines (Figure 4).

Table 2. Inventory analysis of gas turbine unit production.

Name	Value per 1 GTU	Calculation or Reference
Production of construction materials		
Structural alloy steel, kg	2150	Calculations based on [13,50]
Stainless steel (chromium), kg	480	
Titanium alloys, kg	750	
Nickel alloys, kg	1530	
Aluminum alloys, kg	240	
Material processing		
Structural steel casting, kg *	2150	Calculations based on [43]
Metalworking, average for the production of structural steel products	2150	
Rolled stainless steel, kg	480	
Metalworking, medium for the production of steel products **	480	
Metalworking, average for the production of titanium alloy products **	750	
Metalworking, average for the production of products from nickel alloys **	1530	
Aluminum casting, kg *	240	

* Includes mold making, alloy melting, casting, dewaxing, cutting, grinding, straightening, machining. ** Metalworking technology for titanium and nickel alloys is adopted for steel (chromium) due to the similar product production technologies and melting temperatures.

At the production and installation stages of the foundation for a gas turbine unit, researchers considered the costs of materials, land acquisition (including the transfer of land to another category), and site preparation, taking into account the energy resources needed for implementation, such as electricity, heat supply, and fuel for the construction equipment (Table 3). The data for the inventory analysis during the production and installation stages for the foundation were taken from information about a similar case (a 10 MW gas turbine unit) available in the Ecoinvent 3.8 database [13].

The gas turbine installation operation stage is associated with the production and use of fuel in the GTI (Table 4). Three fuel options were considered: natural gas, hydrogen-containing fuel (a natural gas and hydrogen mixture), and hydrogen. Fuel production is associated with the extraction of raw materials and the consumption of resources (e.g., electricity, water, and fuel). The carbon footprint of natural gas consumption was assessed based on fuel consumption per MW of energy produced in the GTI [49] and on the carbon footprint of natural gas production [13]. The carbon footprint of natural gas combustion in GTUs was calculated based on the composition and consumption of fuel per MWh [51] of energy produced [50]. The carbon footprint of hydrogen consumption was calculated based on the hydrogen consumption per MWh of energy produced [52] and on the carbon footprint of hydrogen produced by water electrolysis technology with renewable energy sources [53]. Hydrogen-containing fuel is a mixture of 80% methane and 20% hydrogen. Thus, the data needed to calculate the carbon footprint of hydrogen-containing fuel was used relative to data on natural gas and hydrogen production. Data for the inventory analysis of fuel production were taken from the Ecoinvent 3.8 database. Information on fuel consumption for these calculations was taken from Table 1.

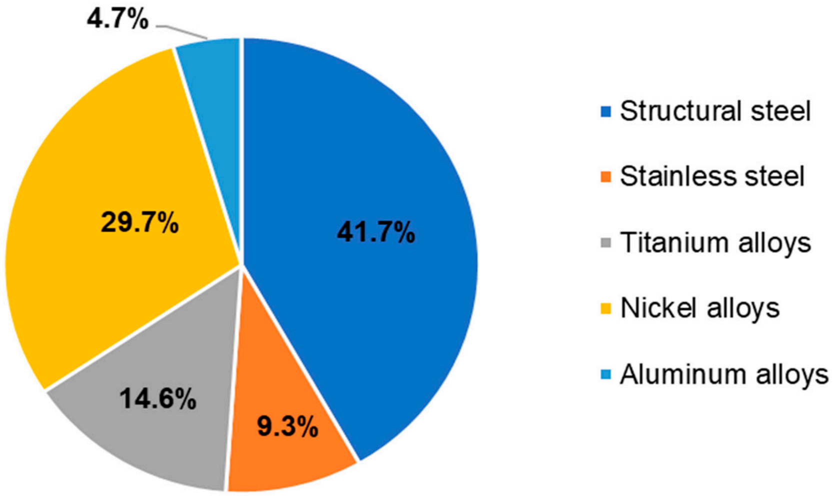

Figure 4. Distribution of materials used in the production of gas turbine units (% by weight).

Table 3. Inventory analysis during the production and installation of foundations for gas turbine units.

Name	Value per 1 GTU [13]
Concrete, m^3	50.0
Copper (cathode), kg	5000
Low-pressure polyethylene, kg	15,000
Reinforcing steel, kg	47,500
Diesel fuel (for operation of construction equipment), MJ	759,000
Electricity, kW	46,900
Heat supply, MJ	721,050
Land allocation (industrial zone), m^2/year	15,000
Conversion of land of undetermined purpose, m^2	1000
Transfer of land to an industrial zone, m^2	1000

Table 4. Inventory analysis during the operation stage of a gas turbine installation.

Name	Value per 1 GTI per MWh	Calculation or References
In the case of natural gas combustion		
Natural gas consumption, kg $CO_{2\text{-eq.}}$	60.6	[13,49]
$CO_{2\text{-eq.}}$ from natural gas combustion, kg	543.4	Calculation based on natural gas composition [49,51]
In the case of hydrogen combustion		
Hydrogen consumption, kg $CO_{2\text{-eq.}}$	197.7	[52,53]
$CO_{2\text{-eq.}}$ from hydrogen combustion, kg	0	-

The waste management phase at the end of the life of a GTI involves dismantling, sorting, and recycling the construction materials (Table 5). Approximately 80% of materials used in the manufacture of gas turbine units can be recycled in accordance with the manufacturers' recommendations. The calculations are based on data confirming that the materials generated at the end of a gas turbine unit's service life are indeed waste.

Table 5. Inventory list for end-of-life management of a gas turbine installation.

Name	Value per 1 GTI	Calculation or References
End-of-life gas turbine unit		
Steel waste (steel scrap), kg	2630	Calculation based on [13,50]
Titanium waste (titanium scrap), kg *	750	
Nickel waste (nickel scrap), kg *	1530	
Aluminum waste (aluminum scrap), kg	240	
End-of-life foundation		
Reinforced concrete waste, kg	167,500	[13]
Copper waste (copper scrap), kg	5000	
Low-pressure polyethylene waste, kg	15,000	

* Due to the lack of information in the database for the carbon footprint of titanium and nickel at the end of the life of a gas turbine unit, data for copper scraps were used since all three metals are considered first-row transition metals.

The results obtained present the carbon footprint of the GTI life cycle stages (without taking the operation stage into account) and the carbon footprint of operating a GTI using various types of fuel.

Figure 5 shows the carbon footprint of the life cycle stages of a gas turbine installation (excluding the operation stage).

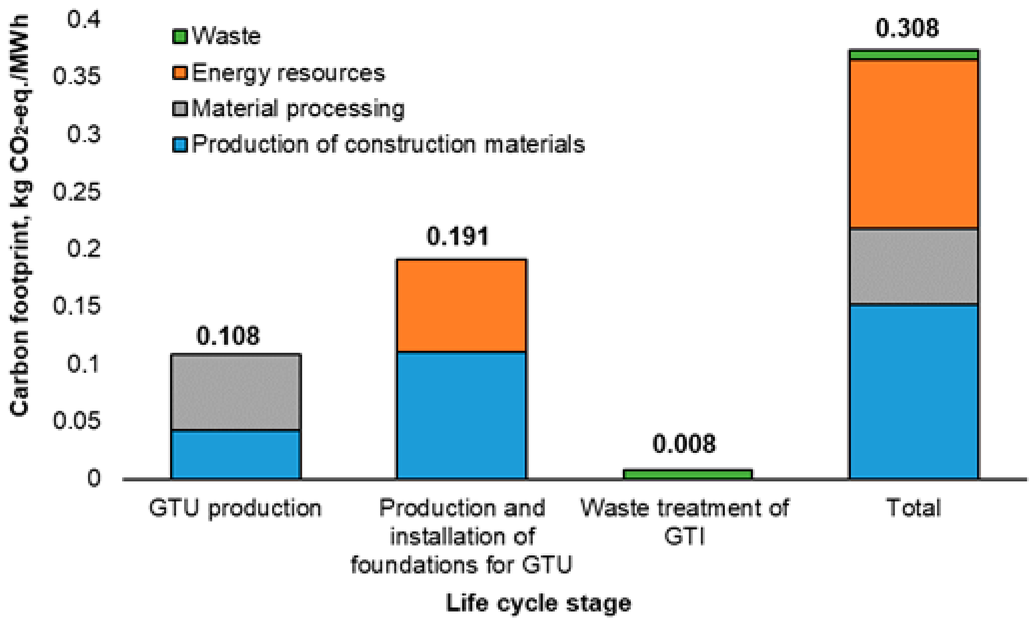

Figure 5. The carbon footprint of the life cycle stages of a gas turbine installation (excluding the operation stage).

Based on the data obtained regarding the carbon footprint (per MWh of electricity produced) of the GTI life cycle stages (excluding the operation stage), it was determined that the main contribution came from manufacturing and installing the foundation for the gas turbine unit. This number includes the carbon footprint of materials production (0.110 kg CO_2-eq./MWh) and that of energy resource consumption (0.080 kg CO_2-eq./MWh). The carbon footprint of the overall construction of the GTI was 0.108 kg CO_2-eq/MWh, with the majority of emissions coming from the processing of materials (0.066 kg CO_2-eq/MWh).

Recycling the gas turbine unit and the foundation for the GTI left the smallest carbon footprint—0.008 kg CO_2-eq/MWh. The largest carbon footprint among the processes, resources, and other work considered was 0.153 kg CO_2-eq/MWh from the production of materials, which represented half of the total emissions from the GTI life cycle stages (excluding the operation stage).

For comparison, the carbon footprint of the 10 MW GTI [13] was 0.374 kg CO_2-eq/MWh, and it included the production of the gas turbine unit (only steel was considered) as well as the production of the GTU foundation, but it excluded the processing of materials during the production and disposal stages of the GTI.

Figure 6 shows the carbon footprint from operating a gas turbine installation using various types of fuel.

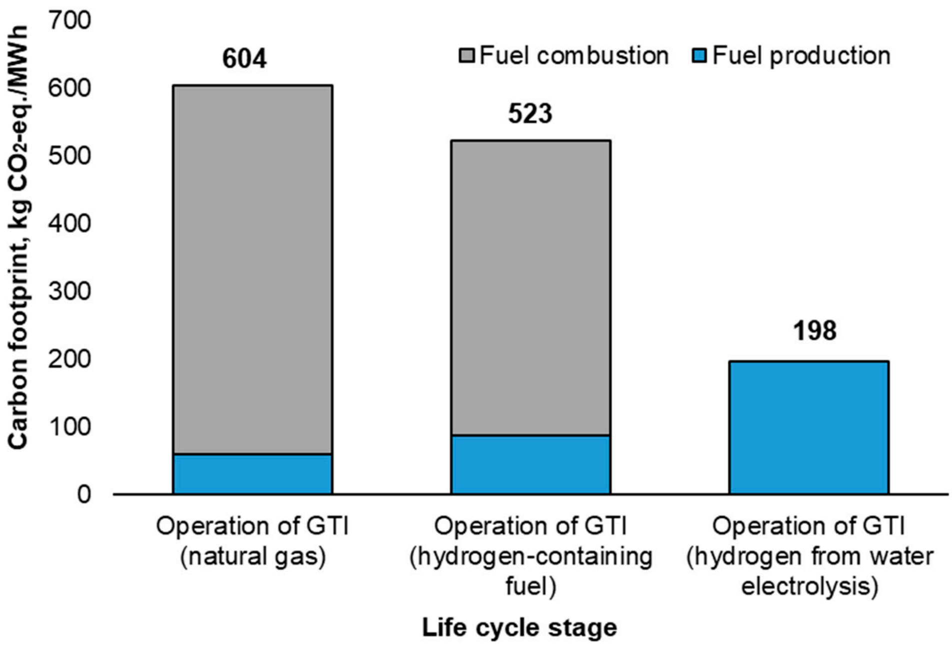

Figure 6. Carbon footprint from operating a gas turbine installation using various types of fuel.

Based on the data obtained regarding the carbon footprint (per MW of electricity produced) at the operation stage of a gas turbine installation, it was determined that the largest carbon footprint was left by the production and use of natural gas in the GTI (608 kg CO_2-eq./MWh). When using hydrogen-containing fuel (with 20% H_2 and 80% natural gas) in a GTI, fuel consumption and CO_2 emissions are reduced by 20% compared to those of natural gas during combustion. The largest carbon footprint in fuel production was found to be for hydrogen obtained through water electrolysis (198 CO_2-eq./MWh); however, the use of hydrogen in a gas turbine installation does not generate CO_2 emissions. Hydrogen content in the fuel mixture can be up to 20% in a GTI without requiring any design changes. Thus, to increase the percentage of hydrogen in the fuel mixture to more than 20%, it is necessary to first complete a set of modifications in order to alter the combustion chamber and partially replace several materials used in GTIs.

Based on the results obtained from the carbon footprint analysis of the GTI life cycle stages, it was determined that the largest carbon footprint per MWh of energy produced (more than 99% of the total carbon footprint) came from the operation stage of the GTI. Hence, to reduce the carbon footprint, it is important to know the amount of CO_2 emissions generated during the production and use of fuel in a GTI. Moreover, determining the carbon footprint of the production and disposal stages of a GTI is crucial for comparing alternative energy installations with each other and with installations that do not use fuel for energy production (e.g., wind turbines).

The carbon footprint of a gas turbine installation is highly dependent on that of the individual materials. The carbon footprint of producing basic metals depends on numerous factors, including the technology and production method (e.g., blast furnace or electric arc furnace for steel), the raw materials (virgin or recycled), the electricity source (thermal, nuclear, renewable, etc.), and the alloy type. Table 6 shows the total emissions of the main metals used to produce technically complex equipment. The carbon footprint values of the metals used for the calculations (taken from the Ecoinvent 3.8 database) are between the minimum and maximum values shown in Table 6.

Table 6. The carbon footprint of producing basic metals.

Metal (Alloy)	Carbon Footprint, t CO_2-eq./t Metal					
	Accepted Values	Average Value		Based on Production Method/Type	Based on Energy Source	Using Recycled Materials
		Global	Russia			
Steel	1.89 (structural steel) 5.07 (stainless steel)	1.4–1.85 [54,55]	1.4 [55]	2.32 (BF-BOF) 0.67 (EAF) 1.65 (DRI-EAF) [56]/ 6.15 (stainless steel) [57] 1.8–5.5 (stainless steel) [58]	1.9 (coal) [59] 1.4 (renewable energy sources and natural gas) [59,60] 0.76 (renewable energy sources and hydrogen) [59,60]	0.4 [59]
Aluminum	5.51	12.5 [61,62]	4.0 [63]	4.28 (alumina electrolysis) [64] 0.01 (inert anode technology) [61]	16.5 (coal) 7.5 (natural gas) 2.4 (hydroelectric power station) [61]	0.6 [62]
Titanium	46.06	18.5 [57,65]	no data	16.9 (titanium 6–4 alloy) [66] 35.6 (Kroll process) [67] 55.0 (6Al-4V alloy) [68]	no data	3.2 (titanium 6–4 alloy) [66] 7.8 [69]
Nickel	16.67	13.0 [70,71]	8.1 [72]	7.2 (class 1 sulphide ore) [73] 27.5 (class 1 laterite ore) [74] 45.0 (class 2 laterite ore) [75] 8.5 (Inconel 718 alloy) [66]	16.0 (coal) 14.0 (grid mix) 7.0 (hydroelectric power station) 6.0 (natural gas) [76]	1.6 (Inconel 718 alloy) [66]

BF-BOF—Blast furnace and basic oxygen furnaces. EAF—electric arc furnace. DRI-EAF—production in an electric arc furnace based on direct reduced iron (DRI).

The global contribution of the metallurgical sector to overall greenhouse gas emissions is about 9% [77].

Steel is one of the main metals used to produce a land-based GTI. According to the International Energy Agency (IEA), the carbon footprint of steel is 1.4 tons of CO_2-eq./t, whereas according to the World Steel Association (WSA), it is 1.85 tons of CO_2-eq./t [54,55]. The intensity of CO_2 emissions from steel production is influenced by the given country's industrial structure, technology, fuel choice, emissions factor, steel plant capacity utilization, and materials (e.g., the availability of steel scrap) [77]. Each ton of scrap used to make steel eliminates 1.5 tons of potential CO_2 emissions and allows the world to forgo the consumption of 1.4 tons of iron ore, 740 kg of coal, and 120 kg of limestone [78]. When steel is produced from recycled materials, the CO_2 emissions are 0.4 CO_2-eq./t [56].

To produce steel, there are two main technological chains: blast furnace (BF) steelmaking, which is based on the process of reducing iron ore in a blast furnace (BF), followed by the combustion of carbon from pig iron in a basic oxygen furnace (BOF); and electric arc furnace (EAF) steelmaking, in which steel is remelted, either with scrap or with direct reduced iron (DRI). According to the WSA, BF-BOF uses 13.8% scrap with emissions of 2.32 t CO_2-eq./t, while EAF uses 105% of steel scrap with emissions of 0.67 t CO_2-eq./t. [56]. China is the world's largest steel producer, with a higher amount of CO_2 emissions per ton of steel compared to other countries. This is because almost all steel in China is produced in blast furnaces. Steel production in Europe is less polluting because 40% of it is produced in electric arc furnaces [79].

CO_2 emissions are influenced by the source of electricity, and this is the case for steel produced using electricity. According to the updated IEA report "Net Zero by 2050: A Roadmap for the Global Energy Sector", the share of energy from renewable sources (e.g., solar, wind, and hydro power engineering) is expected to increase from its current level of about 10% to reach over 60% by 2030. The share of fossil fuels will hopefully be reduced from 80% to about 20% [80]. As of now, coal still provides about 75% of the steel sector's energy and raw material needs, which is comparable to its share in the last decade. Another aim, according to the Net Zero Emissions (NZE) Scenario, is to reduce the share of emissions-intensive blast furnaces used in steel production by approximately 10% by 2030 through the phase-out of existing plants [54].

The aluminum industry is responsible for more than 1% of global anthropogenic greenhouse gas emissions [81]. Over the past decade, the overall global direct emissions intensity of aluminum production has declined moderately (by an average of 2% per year). However, the NZE Scenario anticipates that this decline will accelerate significantly to reach 4% per year by 2030 thanks to reductions in alumina refining and decreases in primary and secondary aluminum production [81]. According to the International Aluminum Institute (IAI), the global average carbon footprint of primary aluminum production is 12.5 t CO_2-eq./t, whereas it is only 0.6 t CO_2-eq./t when using recycled materials. [59]. The energy cost of aluminum remelting is only 5% of the total energy costs of primary aluminum production [82].

Currently, almost all primary aluminum smelting processes use carbon anodes, which release CO_2 during the electrolysis process. The use of inert anodes and increased scrap production could help replace existing emissions-intensive industries. By 2030, inert anodes are expected to be used in about 7% of primary aluminum production [81]. A division of TÜV AUSTRIA Standards & Compliance conducted an independent verification of greenhouse gas emissions in the aluminum production process at RUSAL's Krasnoyarsk aluminum plant in Russia and confirmed that aluminum produced using inert anode technology and hydroelectric power has specific emissions measured at 0.01 t CO_2-eq./t [83].

Non-renewable energy sources (e.g., coal and natural gas) are used to produce 68% of the world's primary aluminum [84]. Since 2010, the share of coal in the aluminum industry has increased, and the share of hydropower has also decreased, mainly due to the growing significance of aluminum in China, where more than 80% of production is coal-fired. In Europe, North America, and South America, more than 80% of aluminum production is hydroelectric. By 2030, the emissions intensity of the entire power generation infrastructure will hopefully be reduced by around 60% compared to today's levels through the use of renewable energy sources. China has announced that, as part of its plan to synergize efforts toward mitigating pollution and reducing carbon emissions, the production of recycled aluminum will reach 11.5 million tons by 2025 and that the share of renewable energy sources used in the aluminum industry will increase by more than 30% by 2030 [81].

The carbon footprint of titanium production ranges from 1.0 to 36.0 t CO_2-eq. depending on several factors, such as primary raw materials, production technology, and electricity sources [57,65]. Up to 2.8 t CO_2-eq. per ton can be saved by using natural rutile rather than upgrading ilmenite via smelting and chemical processes to produce high-quality titanium raw materials, such as titanium dioxide slag and synthetic rutile [69].

An LCA conducted by EarthShift Global found that recycled titanium powders produced by IperionX using its proprietary technology at the company's demonstration plant (Virginia, USA) could potentially have a carbon footprint of only 7.8 t CO_2-eq./t [69]. That would be more than 90% lower than traditional titanium powders produced by plasma atomization and 80% lower than powders with a titanium ingot obtained by the Kroll process (35.58 t CO_2-eq./t) [67]. However, using only recycled titanium alloys for the manufacture of new parts for GTI components is not possible due to a decrease in the metal's strength properties and its corresponding inability to withstand certain temperatures.

According to data from the Nickel Institute, the global average carbon footprint of class 1 nickel is 13.0 t CO_2-eq./t of the finished product [70,71]. China is responsible for about 31%

of global nickel production [70], with coal serving as its main energy source. According to research [76], nickel produced using mixed energy sources (grid mix) emits 14.0 t CO_2-eq./t, hydropower emits 7.0 t CO_2-eq./t, and natural gas energy emits 6.0 t CO_2-eq./t. The main producer of nickel in Russia is Norilsk Nickel, which has one of the highest shares of renewable energy use (hydropower plant) at 47% in 2021 [72].

Nickel and its alloys, including corrosion-resistant and high-temperature alloys (which are used in the combustion chamber, the high-pressure turbine, and the power turbine of a GTI), are almost 100% recyclable and can be recycled indefinitely without losing any of their quality. Nickel keeps most of its original value, with high-grade scrap typically retaining at least 95% of the primary metal value. Recycling nickel requires only about 20% of the energy required to extract and process the primary form of the metal [82]. For example, the estimated carbon footprint of 1 ton of the primary nickel alloy Inconel 718 is 8.507 t CO_2-eq./t, whereas the greenhouse gas emissions reduction observed with recycled Inconel 718 nickel alloy is 6.940 t CO_2-eq. /t [66].

Thus, the carbon footprint of individual materials used in the production of a GTI can affect its final carbon footprint. The total carbon emission values of metal production are also influenced by country-specific fuel conversions, CO_2 emission factors from the country's electrical grid, and reasons related to auxiliary materials. Depending on the source of electricity production, the carbon footprint of producing 1 kWh of electricity may differ. Here are some examples: coal—820 g CO_2-eq., natural gas—490 g CO_2-eq., biomass—230 g CO_2-eq., solar energy—41–48 g CO_2-eq., hydropower—24.0 g CO_2-eq., nuclear energy—12.0 g CO_2-eq., wind energy (offshore)—12.0 g CO_2-eq., wind energy (onshore)—11.0 g CO_2-eq. [85].

When assessing the life cycle of technically complex equipment, the amount and type of primary energy consumed in the production of electrical energy is of great importance. The extent of energy generation capacities in different countries and in different regions within the same country can vary significantly and depends on several factors, including climatic and geographical conditions, the availability of hydrocarbon fuels and natural resources, and the level of technological development [31].

Currently, it is difficult to assess the carbon footprint of electricity generation in Russia due to a lack of uniform and widely accepted regional coefficients for electricity generation. When calculating emissions factors for the energy system, emissions of all types of energy production (thermal, nuclear, hydroelectric, renewable, etc.) are averaged and "evenly distributed" among all consumers. Specifics of electricity production are not taken into account, and no adjustment is made for the import or export of electricity within the boundaries of a given territory (region).

It is clear that the carbon footprint of the electricity used to produce materials has a large impact, which in turn affects the carbon footprint of the GTI itself. The use of renewable electricity to produce metals (e.g., green steel) will lead to a much lower carbon footprint than there is today, given the use of fossil fuel energy.

4. Discussion

In order to compare the results obtained in assessing the carbon footprint of a gas turbine installation when excluding fuel consumption versus when including fuel consumption, it was necessary to use research results for other technically complex electricity-generating plants–in this case, a wind turbine, a fuel cell and a gas turbine installation (see Table 7).

Analysis of greenhouse gas emissions over the life cycle of wind energy systems allowed the authors to determine the carbon footprint values, which ranged from 3.0 to 45 kg CO_2-eq./MWh–the average value was 11.0 kg CO_2-eq./MWh [23,25,86–91]. The main carbon footprint (87.2%) came from the stage of producing materials and components for the wind turbine [20].

Table 7. The carbon footprint of technically complex electricity-generating plants.

Object	Carbon Footprint (without Fuel Combustion) (kg CO_2-eq./MWh)	Carbon Footprint (Fuel Combustion Included) (kg CO_2-eq./MWh)
Wind turbine	3.0–45.0 [23,25,86–91]	-
Fuel cell	30 [92]	176–372 * [93] 410–530 [94]
Gas turbine installation	0.374 [13] 0.98–4.72 [17]	47.0–54.3 ** [17] 353–575 (natural gas) [95] 402–500 (natural gas) [18] 481–757 (light fuel oil) 629 (heavy fuel oil) [95]
Gas turbine installation (authors' own research)	0.308	198 (hydrogen) 523 (hydrogen-containing fuel) 604 (natural gas)

* Without taking the production stage into account. ** Taking into account hydrogen fuel production and electricity production.

Research [93] has been carried out to estimate the greenhouse gas emissions of a 1-kW polymer electrolyte membrane fuel cell (PEMFC) without taking the production stage into account. In the case of a PEMFC fed with hydrogen from natural gas reforming, the GHG emissions total was 372 kg CO_2-eq/MWh, and for the PEMFC fed with hydrogen from a photovoltaic-water electrolyzer, the GHG emissions total was 176 kg CO_2-eq/MWh.

The carbon footprint of solid oxide fuel cells (SOFCs) depends on how powerful they are. Building a "typical" 1-kW SOFC battery results in emissions of 410–530 kg CO_2-eq./MWh and requires 7.1–9.9 GJ of primary energy, 60% of which is spent on sintering cells. Other research [94] determined that the carbon intensity of electricity production from an average SOFC is approximately 355 kg CO_2-eq./MWh, and accounting for the construction of chimneys and an exhaust gas purification system, it increases to 391 kg CO_2-eq./MWh. The carbon footprint of SOFC production is 3–25% [96]. For a 1 MW SOFC, the GHG emissions at the production stage are about 30 kg CO_2-eq. /MWh [92], which is equal to 29% of the total greenhouse gas emissions. The remaining 71% of CO_2 emissions come from the operation stage of the SOFC.

During the production stage, the carbon footprint of a gas turbine installation was 47.0–54.3 g CO_2-eq./kWh. This took into account the stages of production and storage of hydrogen fuel, as well as electricity production via wind energy. At the same time, the carbon footprint during the construction stage of a gas turbine installation, taking the production of steel and concrete into account, amounted to 0.98–4.72 g CO_2-eq./kWh [17]. The overall carbon footprint of gas turbine installations, taking emissions from fuel combustion into account, increased significantly–emissions were at 353–575 t CO_2-eq./GW when using natural gas, at 481–757 t CO_2-eq./GW when using diesel fuel, and at 629 t CO_2-eq./GW when using fuel oil [95].

Upon comparing the gas turbine and the fuel cell in terms of their carbon footprint at the production stages, it can be said that the GHG emissions for the fuel cell are higher (about 20% of total emissions) than for the gas turbine (less than 1% of total emissions). This may be due to the fact that gas turbines have a fairly long operating period (about 20 years) and can produce higher electrical power. Therefore, greenhouse gas emissions per 1 MWh are very low compared to the emissions from fuel cells, which have a shorter service life (10 years maximum) and generate less output power.

Based on the authors' own research, it can be said that the carbon footprint at the stages of the GTI life cycle is relatively comparable to the carbon footprint of other complex technical devices. The results indicate that the carbon footprint value of the gas turbine installation is lower with greater consideration of input parameters, which supports the idea that using GTIs for electricity production is an effective strategy to help reduce greenhouse gas emissions.

5. Conclusions

Hydrogen is a promising energy resource for industrial decarbonization and can be used for energy and transportation in energy carriers, such as fuel cells, combustion engines, gas turbines, and hydrogen power plants. Gas turbines are widely used to generate electrical and thermal energy. Nowadays, there is a great deal of interest surrounding the use of GTIs to burn hydrogen as part of the development of hydrogen energy. To assess the prospects of this trend towards GTIs, it is necessary to understand the carbon footprint of GTIs as part of the overall carbon footprint of the hydrogen life cycle as a whole.

The assessment of greenhouse gas emissions (per MWh of electricity produced) at different stages of the GTI life cycle made it clear that the largest carbon footprint (more than 99% of the total) comes from the GTI operation stage. Of the four GTI fuels under consideration, it was determined that the largest carbon footprint was left by the production and use of natural gas in the GTI (608 kg CO_2-eq./MWh). The largest carbon footprint in terms of fuel production was found to be caused by hydrogen obtained through water electrolysis (198 CO_2-eq./MWh); it should be noted, however, that the use of hydrogen in a gas turbine installation does not generate CO_2 emissions. The hydrogen content of the fuel mixture in a GTI can be up to 20% without requiring any design changes. Thus, to reduce the carbon footprint of GTIs, it is essential to know the amount of CO_2 emissions generated during the production and use of fuel in a GTI.

Moreover, determining the carbon footprint of the production and disposal stages of GTIs is necessary in order to compare alternative energy installations with each other and with installations that do not use fuel for energy production. Data obtained regarding the carbon footprint (per MWh of electricity produced) of the GTI life cycle stages (excluding the operation stage) indicated that the main contribution came from the manufacturing and installation of the foundation for the gas turbine units, which consisted of the combined carbon footprint of materials production (0.110 kg CO_2-eq./MWh) and energy resource consumption (0.080 kg CO_2-eq./MWh). The carbon footprint of the GTI production stage was 0.108 kg CO_2-eq/MWh, with the majority of the emissions coming from material processing (0.066 kg CO_2-eq/MWh). Recycling the gas turbine unit and the foundation for the GTI had the smallest carbon footprint of 0.008 kg CO_2-eq/MWh. The largest carbon footprint among the considered processes, resources, and other work was the production of materials (0.153 kg CO_2-eq/MWh), which represented half of the total emissions from the life cycle stages of the GTI (excluding the operation stage).

After comparing the gas turbine and the fuel cell in terms of their carbon footprint at the production stages, it can be said that the GHG emissions of the fuel cell are higher (about 20% of total emissions) than those of the gas turbine (less than 1% of total emissions). This may be due to the fact that the gas turbine has a fairly long operating period (about 20 years) and can produce higher electrical power. Consequently, greenhouse gas emissions per 1 MWh are much lower compared to the emissions from fuel cells, which have a shorter service life (10 years maximum) and generate less output power. Thus, the construction of a GTI and its further use for the production of electricity has the smallest carbon footprint compared to other complex technical devices.

The reliability of the carbon footprint assessment results for GTIs in Russia is, in most cases, directly tied to the quality of the initial data, so the absence or low quality of open data on production processes at the stages of the GTI life cycle has a significant effect on the results. To try and solve these issues, it is necessary to create a clear methodology for assessing the carbon footprint at all stages of the GTI life cycle, taking into account the specifics of the technologies used (e.g., processes of obtaining and converting materials, use of resources, and auxiliary production processes). For the sake of calculating greenhouse gas emissions, it is also important to develop a methodology and information database with verified data on relevant materials, energy sources, and technologies.

Supplementary Materials: The following supplementary information can be downloaded at https://www.mdpi.com/article/10.3390/en17020345/s1, Table S1: Stages and resources taken into account when assessing the life cycle of technically complex devices; Table S2: Materials used for the production/construction of technically complex devices; Table S3: Impact categories used when assessing technically complex devices.

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