Transition Towards Carbon Free Electricity - Developing CO_2 Emission Assessment Software For Corporate Use

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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October 2021

Acknowledgements

First, I would like to thank Simone Accornero, the CEO of FlexiDAO who enabled this work to happen, provided me with the topic of the work and introduced me to the important topic of real-time emission accounting. Second, I would like to thank Emanuele Rossi who was supervising my thesis during the time I have spent at FlexiDAO. I am thankful for his help, for discussing all the difficult parts with me and for being there for all the questions and doubts I had. Next, I would like to thank my academic supervisors: prof. Wojciech Adamczyk (Silesian University of Technology) and prof. Carlos Santos Silva (Instituto Superior Tecnico), for contributing to this thesis with their specialistic knowledge and expertise, and for all the ideas and suggestions they had during the time of my work. Lastly, I would like to say thank you to my friends and family that were supporting me during the time of working on my thesis, which happened to occur in the very difficult period of the global pandemic. Everything is easier with the right people around you.

Abstract

The development of renewable energy technologies has enabled the increment of the industrial scale renewable energy generation around the world. Currently in most of the countries electricity users are able to choose the origin of the electricity provided to their houses. However, since after the electricity enters the grid it cannot be tracked down, there emerged the need for tools enabling the transparency of the electricity sourcing and its traceability, especially for the non-domestic users who are obliged to account for their greenhouse gases emissions.

The purpose of this thesis was to empower industrial electricity users with the means of CO_2 emissions evaluation using different methods and an understanding of the differences between the methods. It was realized by creating software that will allow the corporates to assess their electricity-related CO_2 emissions in an easy and fast way, with the use of three different approaches. The software also addresses an important issue connected with the current emissions reporting system and introduces the practical implementation of the hourly-matching emissions estimation procedure. The hourly-matching procedure may soon become more present on the energy market, as the interest in the topic raises every year and more companies decide to commit to 100 percent renewable energy and search for ways to reliably prove it. The evaluation of the tool, which included the generation of results for different users located in different countries, shows that in the majority of the cases there exists a significant difference (up to 25%) between the CO_2 emissions value calculated using the hourly method and the CO_2 emissions value calculated using the annual average method. This indicates the need of reforming the emissions accounting market.

Keywords

CO_2 emissions, GHG accounting, transparency of electricity market, hourly emissions accounting, GHG protocol

Resumo

O desenvolvimento de tecnologias de energia renovável permitiu o incremento da geração de energia renovável em escala industrial em todo o mundo. Atualmente, na maioria dos países, os usuários de eletricidade podem escolher a origem da eletricidade fornecida às suas casas. Depois que a eletricidade entra na rede, ela não pode ser rastreada, portanto, surgiu a necessidade de ferramentas que possibilitem a transparência do abastecimento de eletricidade e a sua rastreabilidade, especialmente para os utilizadores industriais que são obrigados a contabilizar as suas emissões.

O objetivo desta tese foi capacitar os usuários industriais de eletricidade com os meios de avaliação das emissões de CO_2 usando diferentes métodos e entendendo as diferenças entre os métodos. Isso foi realizado com a criação de uma ferramenta que permitirá às empresas avaliarem suas emissões de CO_2 relacionadas à eletricidade de forma fácil e rápida, com o uso de três métodos diferentes. O software também aborda uma questão importante relacionada com o sistema de relatório de emissões atual e apresenta a implementação prática do procedimento de estimativa de emissões com correspondência horária. O procedimento de correspondência horária pode em breve se tornar mais presente no mercado de energia, uma vez que o interesse pelo tema aumenta a cada ano e mais empresas decidem se comprometer com a energia 100 por cento renovável e com a busca de maneiras de prová-lo de forma confiável. A avaliação da ferramenta, que incluiu a geração de resultados para diferentes usuários localizados em diferentes países, mostra que na maioria dos casos existe uma diferença significativa (até 25 %) entre o valor das emissões de CO_2 calculado usando método horário e o valor das emissões de CO_2 calculado usando o método da média anual. Isso indica a necessidade de reformar o mercado de contabilização de emissões.

Palavras-chave

Emissões de CO_2, contabilidade de GEE, transparência de mercado de eletricidade, contabilidade de emissões por hora, protocolo de GHG

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List of Abbreviations

PV	Photovoltaics
EU	European Union
GO	Guarantee of Origin
PPA	Power Purchase Agreement
EAC	Energy Attribute Certificate
EEA	European Environment Agency
IEA	International Energy Agency
PPA	Power Purchase Agreement
GUI	Graphical User Interface
LCA	Life Cycle Assessment
GHG	Greenhouse Gases
CDP	Carbon Disclosure Project
ISO	International Organization of Standardization
AIB	Association of Issuing Bodies
API	Application Programming Interface
ENTSOE	European Network of Transmission System Operators for Electricity

Chapter 1

Introduction

There was a point in the recent history of humanity, when the environment became progressively damaged by the consumerism of the human race and the increase of demographic growth, and it started to send us warnings about the consequences of our destructive activity. The current state of matter is already described as a climate crisis. Warming seas, the retreat of glaciers, shrinking ice sheets, sea-level rise, animal species extinction, droughts, bushfires and other extreme events are only a few examples of the changes happening around the world. Earth's average temperature has risen 1.1 Celsius degree since 1880 [1], and while it can appear not to be a significant increase, it is actually quite an unusual event in the history of humanity. Moreover, small temperature changes are related to enormous changes in the ecosystem. Climate change and related environmental degradation are an existential threat to the whole world. Scientists around the world are unanimously agreeing, that soon we will have to face a so-called tipping point, when climate changes reach such a scale and level, that it will not be possible to reverse them. However, since we haven't reached this point yet, we can still act and prevent the irreversibility of climate change.

One of the most solid arguments proving the human impact on climate change is the historical level of CO_2, measurements of which are available up to 800 000 years ago. In Figure 1.1 it can be observed that before modern times, the ecosystem could perfectly balance itself. At the moment, where human activities started to have a significant impact on the environment, the balance has been disrupted. The pace of changes happening since the beginning of industrialization can be defined as exponential. This change is visible in the form of CO_2 level anomaly in Figure 1.1 in the point of most recent history, where the CO_2 level surges over 400 CO_2 ppm, almost doubling

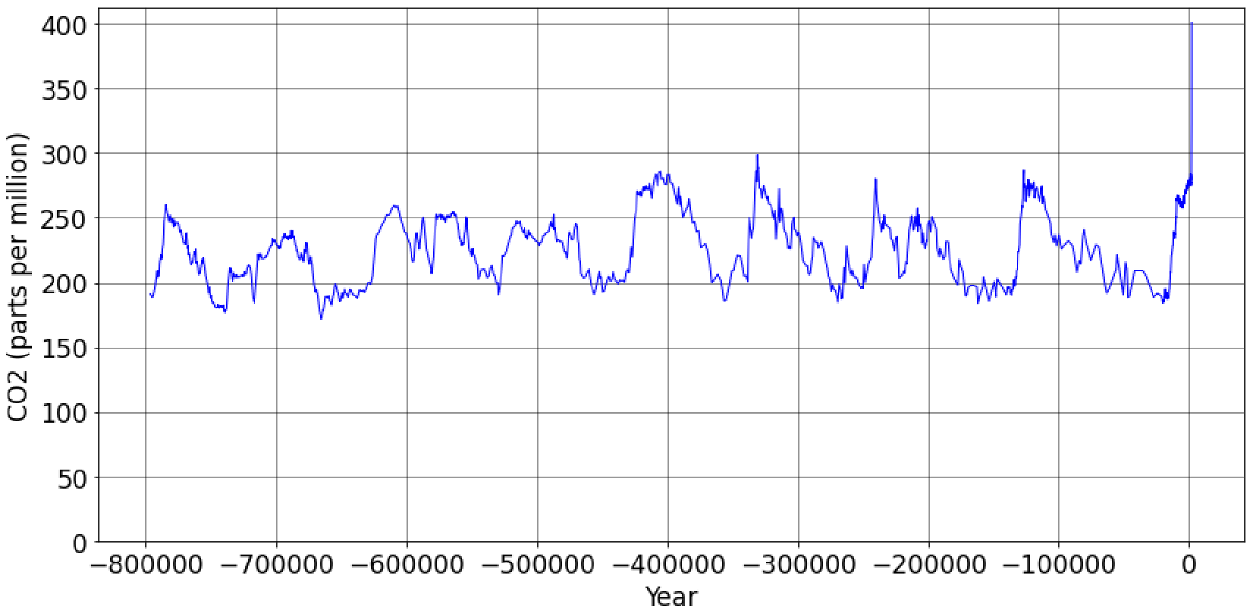

Figure 1.1: Carbon dioxide level from 800 000 years before year 0 until today [1]

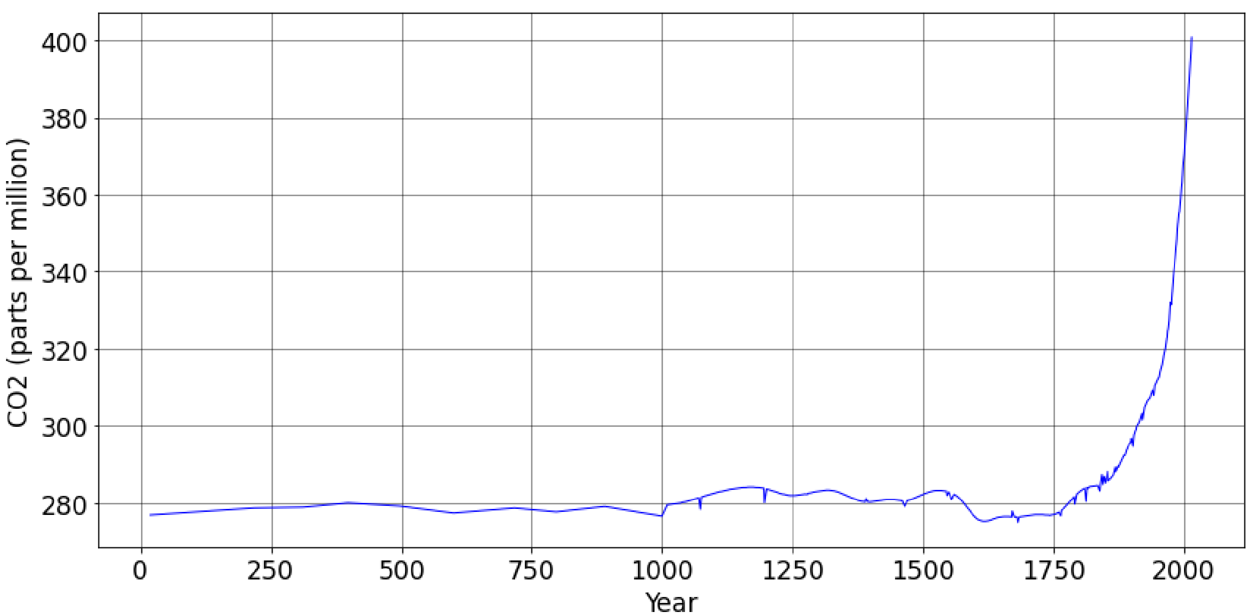

Figure 1.2: A closer look at carbon dioxide level from the year 0 until today [1]

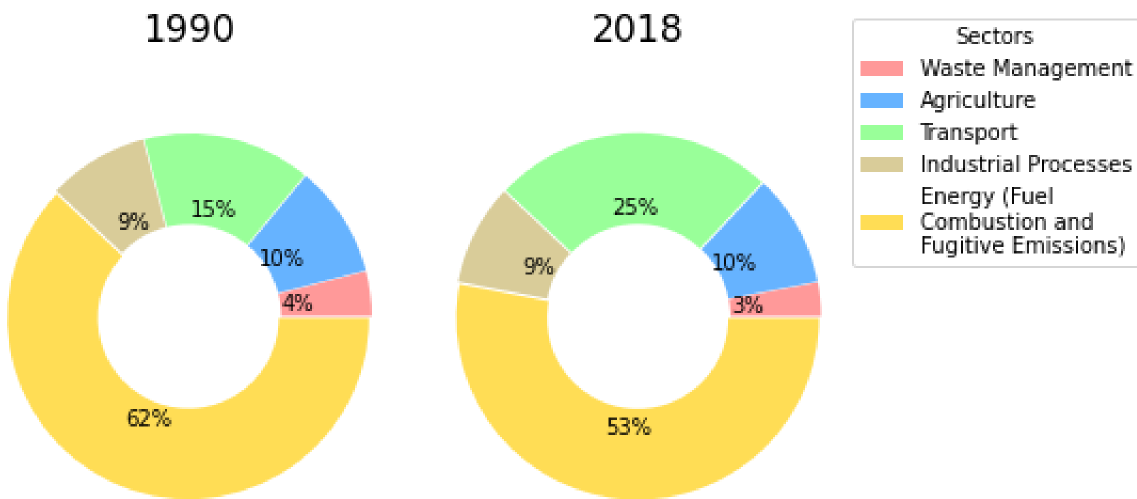

Figure 1.3: Greenhouse gas emissions by source sector in EU-27 [2].

its mean historical value. Currently, the CO_2 level reached the value of 418 ppm [1], which is the record highest value in history.

It has been noticed that the beginning of global warming can be closely related to rapidly processing industrialization, which begun in the late XVIII century. This point is very well captured in Figure 1.2, where around the year 1800 the sudden exponential growth can be noticed.

The largest driver of global warming is the emission of greenhouse gases, of which over 90% is carbon dioxide (CO_2) and methane (CH_4). The majority of anthropogenic CO_2 is caused by the combustion of fossil fuels, such as coal, petroleum and natural gas. In Figure 1.3 [2], the division of the CO_2 emission by sector is presented for the years 1990 and 2018. In the year 1990, the sector which contributed most to the global greenhouse gases emission is the energy sector. Almost 30 years later, the sector producing the largest amount of greenhouse gases is still the energy sector, but it is also the sector that changes most dynamically. Between the year 1990 and 2018, total emissions from the energy sector decreased by 15%, whereas all the other sectors remained more or less constant or increased, as in the case of the transportation sector. Many factors contributed to the rise of the greenhouse gases emission caused by the transportation sector, the main being progressing globalization and easy access to cheap transportation means (mostly individual cars).

Even though Europe has made significant progress towards the reduction of emissions, it is still responsible for around 10% of global emissions [3] and there is a lot of space for improvement. Depending on the strategy that we will follow, there are a few scenarios on how the world's CO_2 emissions can look in future. The actions that we will take are meaningful and really impactful on the pace of the progression of global warming. Until the year 2100, in the case where no climate policies will be followed, the mean earth's temperature may rise up to 4.8 Celsius degrees. Following the current climate policies, the mean temperature should not exceed 3.2 Celsius degrees and in the case where the Paris pledges are respected, we can expect the temperature rise in the range of 2.5 - 2.8 Celsius degrees [4]. It becomes obvious that in order to avoid severe climate changes connected with global warming, current restrictions are not enough and more actions need to be taken.

In Europe, the electricity generation sector is responsible for around 30% of the EU's greenhouse gases emission [5], and since it has been proven to be the main reason for the emission of greenhouse gases, a range of legislations have been released in order to regulate the scale of the emissions.

European Climate Policy was first introduced in the early 1990s, following the formation of the International Panel of Climate Change [6] and ever since a range of directives that update the regulations and tailor them accordingly to the progress made is being released [7]. One of the latest major updates of the EU energy policy framework was released in 2018. It recasts the Renewable Energy Directive (2009/28/EC) and formulates the target of at least 32% electricity generation coming from the renewable energy sources [5]. Other goals include increasing energy efficiency to 32.5% and reducing GHG emissions by at least 40% (below 1990 levels). The European Union climate policy changes very dynamically. In July 2018 a resolution on EU climate diplomacy was introduced. It emphasises the EU's responsibility to be the leader on climate action and conflict prevention [8]. On November 28 2019 the climate emergency has been declared by the EU Parliament, which has initiated the consideration of more ambitious targets. The urge to commit to net-zero greenhouse gases emission by 2050 appeared. It has been formulated in December 2019, in a form of a political commitment, named the European Green Deal. It states, in line with the Paris Agreement, that Europe will become the first carbon-neutral continent by 2050. The actions to turn this political commitment into a legal obligation are being currently taken [5].

1.1 Aim and Scope of the Thesis

In the actions preventing global warming and climate changes, imposing emission limitations determines a very important part of the strategy. CO_2 emissions are the main metrics to evaluate the environmental impacts of corporates' activities. The key action in gaining control over climate change issues is to systematically document the CO_2 emissions on each level of human activities.

The main objective of this thesis is to empower industrial electricity users with the means of CO_2 emissions evaluation using different methods and to understand the differences between the methods. It was realized by developing software that could be used by industrial corporates in accounting for CO_2 emissions originating from electricity consumption in their annual reports. The software also provides them with a constructive insight on the sustainability strategies and contractual instruments available on the market that lead to the reduction of the corporates' CO_2 emissions. Another purpose of the software is to raise awareness among energy procurement managers about the different environmental impact of various electricity contracts. The software also addresses an important issue connected with the current emissions reporting system and introduces the practical implementation of the hourly-matching emissions estimation procedure. The hourly-matching procedure may soon become more present on the energy market, as the interest in the topic raises every year and more companies decide to commit to 100 percent renewable energy and search for ways to reliably prove it.

The CO_2 estimation software has been created in cooperation with FlexiDAO company [9]. It may prove useful to all kind of industrial electricity consumers. Its target customer groups are energy managers, sustainability managers, environmental managers, innovation managers and energy consultants from corporates with strong sustainability agenda.

Chapter 2

Renewable Energy Market

2.1 Current State of the Market

2.1.1 Emissions reporting

In order to meet the goals dictated by the directives, a certain level of control over the industry and domestic users is needed. The attention focuses especially on the industrial and commercial users since the residential sector accounts only for 26% of the total final electricity consumption [10] and is far more difficult to control. Detailed instructions and restrictions are defined by each country's government individually. In most countries, the companies have to report their energy use and related CO_2 emissions in their annual reports. While all the corporates need to follow the obligatory regulations, many companies are voluntarily setting ambitious targets for themselves and are joining initiatives such as re100 (a global initiative bringing together the world's most influential businesses commited to 100% renewable electricity) [11].

Although the range of legislation has been introduced to the energy market since the 1990s, there existed no uniform guide providing instructions on the procedure of the emissions reporting routine. In 2004, the first important position, called the Corporate Standart, has been published by the Greenhouse Gas Protocol - an organization established in 1998. It was the result of the cooperation of various businesses, non-governmental organizations and other parties associated with the World Resources Institute and World Business Council for Sustainable Development [12]. The International Organization of Standardization introduced it's ISO 14064 two years later, in the year 2006 [13]. Like all the other standards issued by ISO, the ISO 14064 is protected by copyrights and in order to be used it not only has to be purchased by the company, but also implemented, audited and certified. Unlike ISO 14064, the Corporate Standard has been released under a free licence. Currently, more than 90% of the Fortune 500 companies are using Greenhouse Gas Protocol standards according to the CDP reports. It is the most widely used standard in the world, recognized by many authorities as an independent standard for reporting greenhouse gases. The Corporate Standard categorized the emissions into three main categories, based on their origin [12]:

Scope 1

All emissions released directly from the activities of an organisation or a party under their control. They represent emissions such as fuel combustion on-site (gas boilers, furnaces, vehicles).

Scope 2

This term describes indirect emissions connected with the purchase of electricity, steam, heating and cooling. Those emissions are a consequence of an organization's activities that occur at the sources it does not own or control. For most of the companies, Scope 2 emissions represent the majority of emission sources and operational costs.

Scope 3

All the other indirect emissions from activities of the organization, which occur from sources that are out of the company's control. They represent emissions such as business travels, waste, water or procurement.

This division, however, was not fully effective since it would not take into account the choices of contracts that companies are making. Scope 2 Guidance, an amendment to the Corporate Standard, has been released in January 2015. It was the first major revision to the Corporate Standard [12]. The main change that it introduced, was the creation of two ways of Scope 2 emissions reporting - the allocation methods, that assign emissions to end-users. Companies were strongly encouraged to publish numbers resulting from calculations based on both new methods.

The first method is called the location-based method, and it reflects the average emission intensity of grids that provide electricity (mostly using grid-average emission factor data) in the location where the consumption occurs. The second method, called the market-based method takes into account the electricity contract that the user has signed. It reflects emissions that companies have purposefully chosen. In this method, emissions are estimated based on any type of contract between two parties for the sale and purchase of electricity unbundled or bundled with certificates of energy generation.

However, there exists an important problem with the way that the CO_2 accounting system works, which has not been addressed yet. In both cases of location-based and market-based methods, values used in calculations are yearly averages. This means that insight on what exactly happens during the whole year of electricity consumption is not included.

The current way of calculating emissions in the case of both methods relies on yearly average grid carbon intensity, which does not account for any patterns in users' electricity consumption and does not take into consideration the time of consumption. In reality, the grid carbon intensity changes every hour, depending on the electricity generation mix in a given location, the import of electricity between countries and the demand on the market. Without accounting for those changes a good representation of reality cannot be achieved, which is however how the current reporting system works. For example, a company that owns an on-site photovoltaic installation that generates 10 MWh per year of electricity - the company's yearly amount of electricity consumption - can claim to be '100% renewable' and report their market-based yearly emissions as zero. But in reality, if this company happens to consume electricity at night, when no solar irradiation occurs, it is impossible for the photovoltaic installation to produce any electricity. Therefore the company is physically consuming electricity coming from the grid, which in many cases comes from the local fossil fuel power plant, and then it returns to the grid the amount of electricity produced by the PV installation at different time. But by consuming their electricity at night, the company contributes to the increased demand in the time when the emission intensity of the grid is high and should be responsible for the related emissions.

2.1.2 Hourly certification system

The concept of real-time emissions tracking or hourly emissions accounting has emerged as a response to the problem described in the previous section. The concept is relatively new and there are not many sources that describe it or make an analysis on this topic. However, some companies such as Google [14] or Microsoft [15] are already implementing it in their strategy, as they see the importance of such practice on the energy market.

The hourly emission accounting is about matching the user's consumption with electricity generation with an accuracy of 1 hour. This means that for every hour in a year, the energy source, electricity from which a user has contracted, produces enough energy to cover the user's electricity consumption. General rules for the hourly emission accounting are the same as in yearly accounting - when we need to match 10 MWh of yearly consumption with contracts that state the purchase of 10 MWh of energy in this year - but now the period is refined to hours. Therefore, for every hour, during which we consumed 5 kWh in average, we need to provide a certificate from the source, that produced the electricity at this specific hour.

European Union has been urged that changes in the way how energy certification system works are needed. Many experts in the renewable energy field are criticising the current system and are forecasting the imminent appearance of the hourly certification on the market [16]. Gillenwater et al point out the vulnerabilities of the market-based emission reporting method and recommend that the only method used to calculate and report Scope 2 emissions should be the location-based method. Moreover, they highlight that the location-based method is not perfect either and ideally, CO_2 emission factors should be specific to the time at which consumption takes place. Some of the problems with the market-based method include the incapability to provide accurate or relevant information and creating unfair situations for the companies in the Scope 2 reporting market. If one company purchases contractual instruments that allow them to report their Scope 2 emissions as 0 kg of CO_2, and the second company does not purchase any contractual instruments but implements an energy efficiency programme that reduces their physical electricity use, the first company is seen as far more environmentally friendly. In the reality, the first company's action has no impact on the environment but it is made seen as if it had a huge one. In addition to the first company's appearance being favoured, this action has a negative influence on the second company's image, as by claiming a part of renewable energy in the grid, it causes an increase of the CO_2 emission intensity of the residual grid mix, which the second company will have to use in calculating emission values in their reports.

The current accounting system is no longer sufficient to meet the climate goals that have been set. The use of best practices, such as electricity consumption curve shaping and shifting or any procedure that aims at energy efficiency improvement should be encouraged. But most importantly, we need to change the way how companies report their emissions and define on what basis they can claim to be emission-free.

2.2 Contractual instruments available on the market

For the companies that want to reduce their emissions originating from electricity consumption, there are several options currently available on the market, each of them having different features and environmental impact.

2.2.1 Guarantees of Origin

The Guarantee of Origin (GO) is an Energy Attribute Certificate regulated in the European Directive 2009/28/EC, Article 15 [5]. The GO is a certificate that proves that 1 MWh of electricity was generated by a renewable energy source. The European certifications system has been developed and is under the control of the Association of Issuing Bodies. Besides, within each country there exist national trading arrangements. A Guarantee of Origin does not represent energy itself. Energy traders are selling GO separately from the underlying renewable energy output to the third party - it is delivered separately from electricity. One GO allows the buyer to prove the origin of 1MWh of the electricity that he consumed. The certificate is valid for 1 year after it's was issued and can be cancelled (used) or resold on the market at any moment. After a year the certificate expires and can no longer be used.

There is no fixed price for a GO, and their value depends on market demand. The GO price is the premium to the wholesale price of electricity that the user is willing to pay for obtaining a legal document proving the origin of their electricity. The GO system's main goal is to create a transparent electricity market and give consumers the possibility to choose the origin of the electricity they purchase. And while giving disclosure to the electricity market was necessary and the idea of Guarantees of Origin was a good response to the challenges emerging on the energy market, they are not enough to face the needs of the energy transition phase to create a sustainable future.

The question of whether Guarantees of Origin have a positive environmental effect is a topic of many discussions in the academic literature, where they receive mostly bad critiques[17]. As for today, the average price of a Guarantee of Origin (offsetting emissions from 1MWh of electricity) in Europe is 0.30 EUR [18], whereas the average wholesale electricity price is 30 EUR/MWh [19]. Such a little price premium, that can provide you with the basis to offset your CO_2 emissions, cannot possibly stimulate the development of renewable energy. According to Gillenwater et al. [16] there exists empirical evidence proving that the amount of renewable electricity generated is the same in the absence of renewable energy certification markets. In many cases, consumers may be misled and convinced that the certificates they are buying are a contribution to renewable energy development. However, Guarantees of Origin fail to reliably prove additionality and transparency regarding their value drivers, and therefore the awareness about the characteristics of GOs should be spread among the customers to avoid (unintentional) greenwashing.

Another issue connected with the European GOs market is that it allows for buying certificates from sources that are completely detached from the consumer's location. In 2020, 43% [20] of the Guarantees of Origin export was coming from Norway. Nordic Hydro are the most competitive certificates because of their extremely low price, which attracts energy managers as they see the possibility of offsetting their company's emissions for a very small amount of money. However, electricity produced in Norway cannot be transferred to the corporate's arbitrary location. Because electricity usage in a corporate's physical location causes an increased demand for electricity at plants located in its proximity, supporting the national renewable generation is a much better practice and the big scale European Guarantees of Origin trade should be limited to the countries which are at least connected through the grid, meaning importing electricity from each other.

2.2.2 Power Purchase Agreements

Renewable Power Purchase Agreements (PPA) allow corporates to purchase renewable energy directly from a producer. A contract with an energy supplier is signed for several years, usually between 10 and 15. Even though a decision about signing such a contract needs a lot of preparation and planning, signing a PPA for a long period allows to avoid the risk and price volatility and helps in future budgeting since the customer knows in advance exactly how much he will pay. PPAs have been gaining lots of attention in the past few years since they are an excellent choice for bigger companies with secure finances and position on the market. Companies like Google, Facebook, Microsoft, Adobe, IKEA are among many others that have signed a PPA in recent years. Two main types of PPA can be distinguished:

On-site PPA

It is a type of contract where a renewable installation is mounted at the client's site. The client has certainty about the origin of his electricity that no other contract can provide. If the client is not the installation owner, he has no installation nor maintenance costs. If the client owns the installation, he can benefit from the return on investment and profits from selling electricity overproduction at peak hours. Because the installation is created specifically for the customer's needs, the project is considered to have a high rate of additionality. Additionality is the term used regarding the renewable energy projects and it describes whether the project has the direct effect of adding new amount of renewable energy to the grid. If a renewable energy contract comes from a plant which already functions for many years (for example hydro power plants in most of the countries) and it would function anyways, without us signing a PPA with this plant, then such a contract is not considered to cause any additionality.

Off-site PPA

Off-site PPA, also called a virtual PPA is considered to be an easier option for electricity purchase. The installation does not have to be located at the company's site. A developer sells renewable energy to an end customer directly or through an energy retailer. They agree on the price of the energy. The customer pays the wholesale electricity price and the developer covers the differences between the wholesale and the agreed price. The off-site PPA usually covers large amounts of energy and possesses clients before the power plant is created in order to secure the financing of the project. Off-site PPAs are an important part of nowaday's market and with every year their popularity increases. In 2020 a record 3 GWh of renewable PPA has been contracted in Europe, which adds up to a cumulative 11.1 GWh as an opposite to 2.2 GWh of cumulative capacity installed by 2016 [21]. The majority, 75% of the European PPAs are photovoltaic projects. The other 25% are wind projects. The countries with the highest proportion of PPA offers are Spain and the United Kingdom [22].

2.2.3 Green Tariffs

A green tariff is an optional tariff offered by utilities in regulated electricity markets, which refers to the energy mix that was used to produce electricity. It allows customers to buy renewable electricity bundled with a certificate of origin from specific projects. Either a supplier promises to match a customer's electricity usage with the generation from renewable energy sources or will contribute towards environmental schemes on the customer's behalf. Green tariffs work just like standard tariffs that energy retailers offer, but in addition, a Guarantee of Origin is bundled with each MWh of procured electricity. In most cases, the price paid for a green tariff is higher than the one paid for a standard tariff. The price per MWh varies a lot depending on the amount of electricity purchased. The details of an offer and the electricity price depend on the agreement made with the retailer.

Generally, green tariffs are considered a good option for industrial consumers. Via green tariffs, energy suppliers are promoting renewable energy. Additionally, increasing renewable electricity demand indicates the need for increased renewable power generation capacity which helps to make decisions about investing in new renewable installations. That contributes to the increased share of renewable energy in the national grid, which also proves the additionality of such contracts. The transparency of a contract's terms and the price is provided, which empowers the customer with more control. Fixed payments and price stability is another advantage.

2.2.4 Comparison of contractual instruments

Contractual instruments have different features that influence the decision of which contract to choose. The main features are quantitative features such as unit price, contract's length, contract's capacity, but also qualitative features such as additionality, transparency and complexity of the project.

Unit Price

The comparison between different contract's prices is a difficult thing because in each case we are getting something different out of it. The cost analysis would be different for each country, which is however out of the scope of this thesis, where European average prices are considered. The price of Guarantees of Origin does not include the price of electricity, unlike PPAs or Green Tariffs.

Contract's Length

An important factor affecting the decision-making process is the length of a contract. Companies with secure finances and position on the market may be more likely to decide on signing long term contracts, which will additionally limit the company's risk factors, whereas smaller companies may not want to enter a long term commitment and would prefer short term obligations. The length of different contracts' types is within the wide range of 1 - 30 years.

Contract's Capacity

Contracts are typically signed for the round amount of MWh, in the case of GOs and PPAs. Therefore the smallest capacity of the contract that we can acquire would be 1 MWh. Green Tariffs details depend on a retailer and specific agreements. In the case of an on-site installation owned by a client, the installed power should be calculated in such a way, to meet the electricity demand, taking into consideration the local conditions.

Additionality

Additionality has often been referred to as 'surplus', meaning public good benefits that are surplus to what would be the state of matters under baseline conditions. An activity is additional if its policy interventions are causing the activity to take place [23]. Different energy contracts are said to have a different impact on the environment. Contracts that promote the development of renewable energy assets are said to be additional.

Transparency

Transparency refers to the state of known value and value drivers. It means, that a customer knows what exactly he is buying and all characteristics of a contract must be disclosed, such as electricity origin etc. All provided information should be addressed in a factual manner and be based on a clear audit trail. Transparency of the contract highly contributes to the possibility of comparison of different energy contracts.

Complexity

Some contracts are easy to acquire, and others demand more time and planning. It is easier to obtain contracts unbundled from the electricity, but in such a case electricity needs to be contracted separately. In the case of Green Tariffs, the electricity price and corresponding certificate may be slightly costlier but save the time of buying those two things separately. Far more complex projects are PPAs, which demand lots of planning, cost and risk assessment, negotiating the details of the contract etc.

In Figure 2.1 a table containing the main features of renewable energy contracts is shown. The introduction of different colour field serves the simplification in distinguishing between the desirable and undesirable features. The colour scale is explained next to the table. It is important that sustainability or energy procurement managers are aware of the differences between the contracts. Knowing a contract's features helps in choosing the type of contract that is the most suitable for a corporate's needs. In addition to the contract's features, it is important to choose the electricity production source that will correspond the best with the corporate's electricity consumption habits.

Contract / Criteria	Unbundled Guarantees of Origin:		Guarantees of Origin bundled in:		
	EU GO	National GO	Retailer green tariff	On-site PPA	Off-site PPA
Contract length [years]	1	1	Min. 1 year	N/A	10-25
Capacity [MWh]	1	1	Any (Retailer dependent)	Any	Min. 1
Cost, time and complexity of implementation	Low	Low	Medium	Very High	Medium / High
Transparency	Unknown value drivers	Unknown value drivers	Known value drivers	Known value drivers and components	Known value drivers and components
Additionality	No proven stimulation of new projects	No proven stimulation of new projects	Helps to install new renewable generation capacity	Contribution towards increase of decentralized renewable energy production. Profit usually not reinvested.	Critical contribution to the decision about establishing new projects. Profit reinvested into new projects.
Recommended corporate size	Small / Medium	Small / Medium	Any	Solar: Any Wind: Medium / Big	Big
Price	0.3 EUR / GO + 30 EUR / MWh (EU avg wholesale price)	0.3 EUR / GO + 30 EUR / MWh (EU avg wholesale price)	40 – 120 EUR / MWh (Wholesale – Retail difference)	1500 – 3000 EUR/ kW 0.85 – 1.5 mln EUR / MW	47.88 EUR / MWh

Neutral feature ☐ Desirable feature ■ ■ ■ ■ Undesirable feature

Figure 2.1: Comparison of the different renewable energy contracts

Different sources have different production patterns and therefore can affect at what times the green electricity is produced at your proximity. The average patterns of electricity production from different energy sources are presented in Figure 2.2.

The most popular renewable energy sources are wind and hydro. Wind constitutes 36% of the total European, hydro - 33%. The next largest source is solar with 12% of the contribution in the renewable mix, biofuels with 10% and the remaining 9% are other sources. In the year 2020, all renewable energy sources represented 32% of the EU total electricity mix [24].

Most of the renewable electricity sources characterize by intermittent electricity production due to their fluctuating nature and are highly dependant on external conditions. The sources, which suffer the highest changes in electricity production during the day are solar and wind. However, taking a look in a larger period, wind on average remains stable over the course of a day. Photovoltaic electricity supply, on the other hand, always changes during the day. The biggest drawback of solar systems is that they are not able to operate at night, since there is no sun. It is an important thing to remember, as solar systems are becoming the cheapest and most competitive renewable electricity source, but a sustainable future cannot be built with solar as a dominating electricity source. The lack of electricity production in the nighttime is a serious limitation. Hydro, in the case of energy originating from the river run, is a very stable electricity source and can be controlled in order to meet the market's demand. Pumped hydropower plants that use water reservoirs are excellent renewable electricity source because of their ability to work as a storage plant. It is widely used for load balancing, which is visible in its production pattern - during a day where renewable energy is abundant in the grid (because of the energy from PV) hydro plants are consuming electricity for pumping the water into the upper reservoir. In the early daytime and evening, when the peak hours occur, the plants are producing electricity. Unfortunately, hydropower plants are subject to serious geographical limitations. Other renewable sources, such as geothermal or biomass are easily controllable and are not subject to issues with intermittent electricity production. The electricity generation profiles are important indicators in the decision-making process which determines the choice of the proper electricity source.

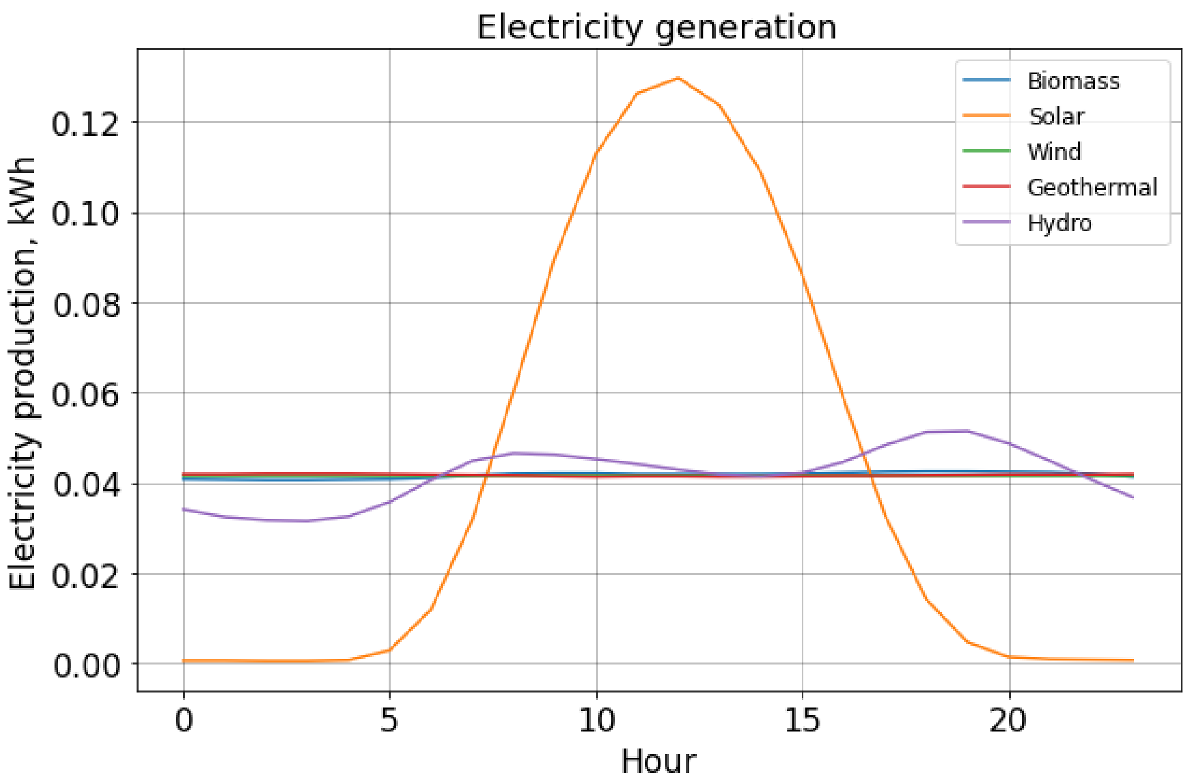

Figure 2.2: Daily electricity generation profiles from different renewable electricity sources. Average of all European countries available in ENTSOE database [25].

Chapter 3

Software design

The software has been designed in such a way that it eliminates the need for providing specific hourly electricity consumption data and at the same time requires minimum input from the user. The software uses hourly time series data in its calculations, but since accessing the user's hourly consumption data is impossible if he does not have smart meters installed, which would severely limit the group of users that can use the tool, the approximated time-series are created by the software based on a short survey. The software consists of 4 tabs: the first tab introducing the user to how to use the software, the second one where the user has to input his data, the third one returning CO_2 emission calculations to the user and the fourth one that allows for the selection of a contractual instrument in order to see its details generated by the software. The complete user's guide is located in this document in Appendix A.

The flowchart presented in Figure 3.1 shows the dependencies between the input data and the results that are the output of the software. The input data are the electricity generation and imports from the ENTSOE database [25], the CO_2 emission factors of different energy sources [26], electricity consumption profiles of typical industrial consumers [27], the input data provided by users and the yearly grid carbon intensity in European countries from EEA [28] and IEA [29] in order to provide the reference point for program's calculations. The input data is used for computing the final results, which are yearly CO_2 emission values calculated in 3 different ways. The data computed in the process are user's daily electricity consumption profile, hourly grid carbon intensity for all countries for the considered period of time, average yearly grid carbon intensity for all countries and hourly amount of CO_2 emission in kg.

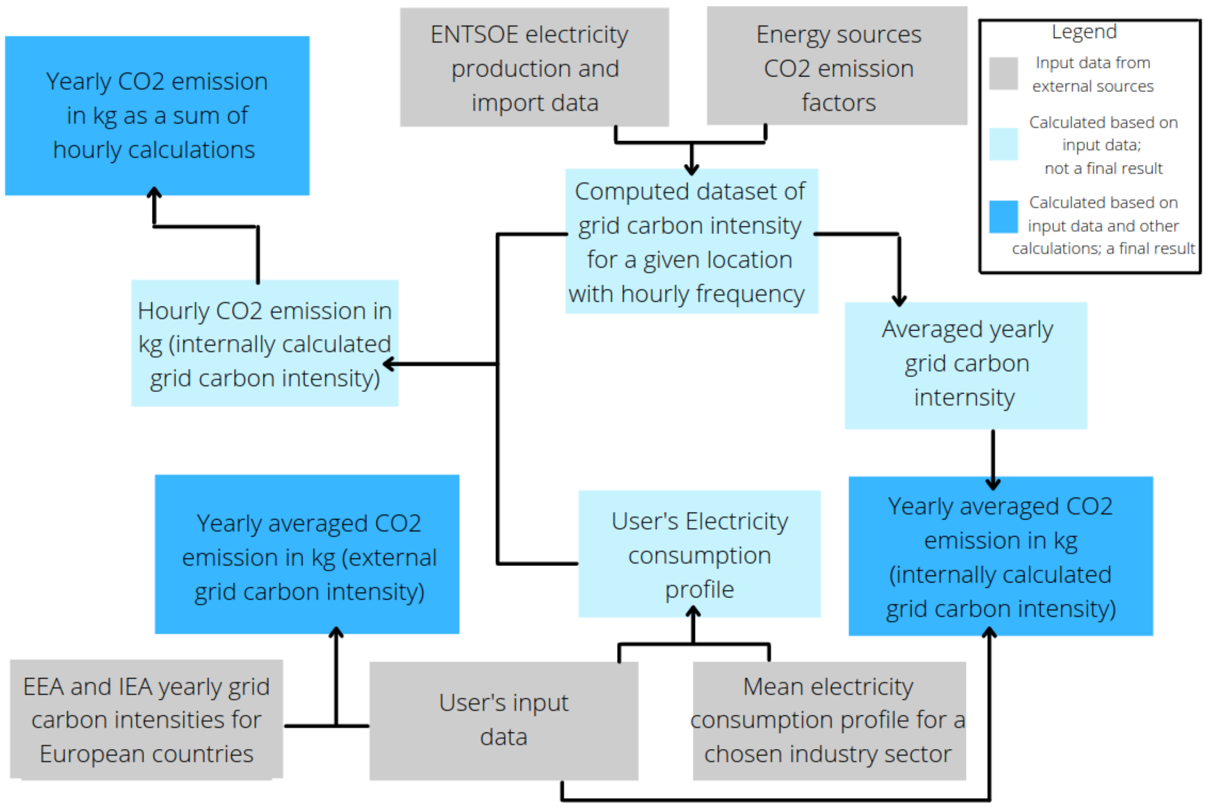

Figure 3.1: Dependencies between the input data and results

3.1 Input Data Tab

1. Country – The user chooses a country from the list. The country should be the physical location of the place where the user's corporate is located. The software allows the user to choose among 39 European countries, out of all 44 European countries with the exclusion of countries that occupy an area of fewer than 1 km^2.

2. Electricity consumption – The user needs to provide the amount of electricity in kWh that his corporate consumes in a period of the chosen year. The electricity consumption should be given for a full-year period, January – December of the chosen year.

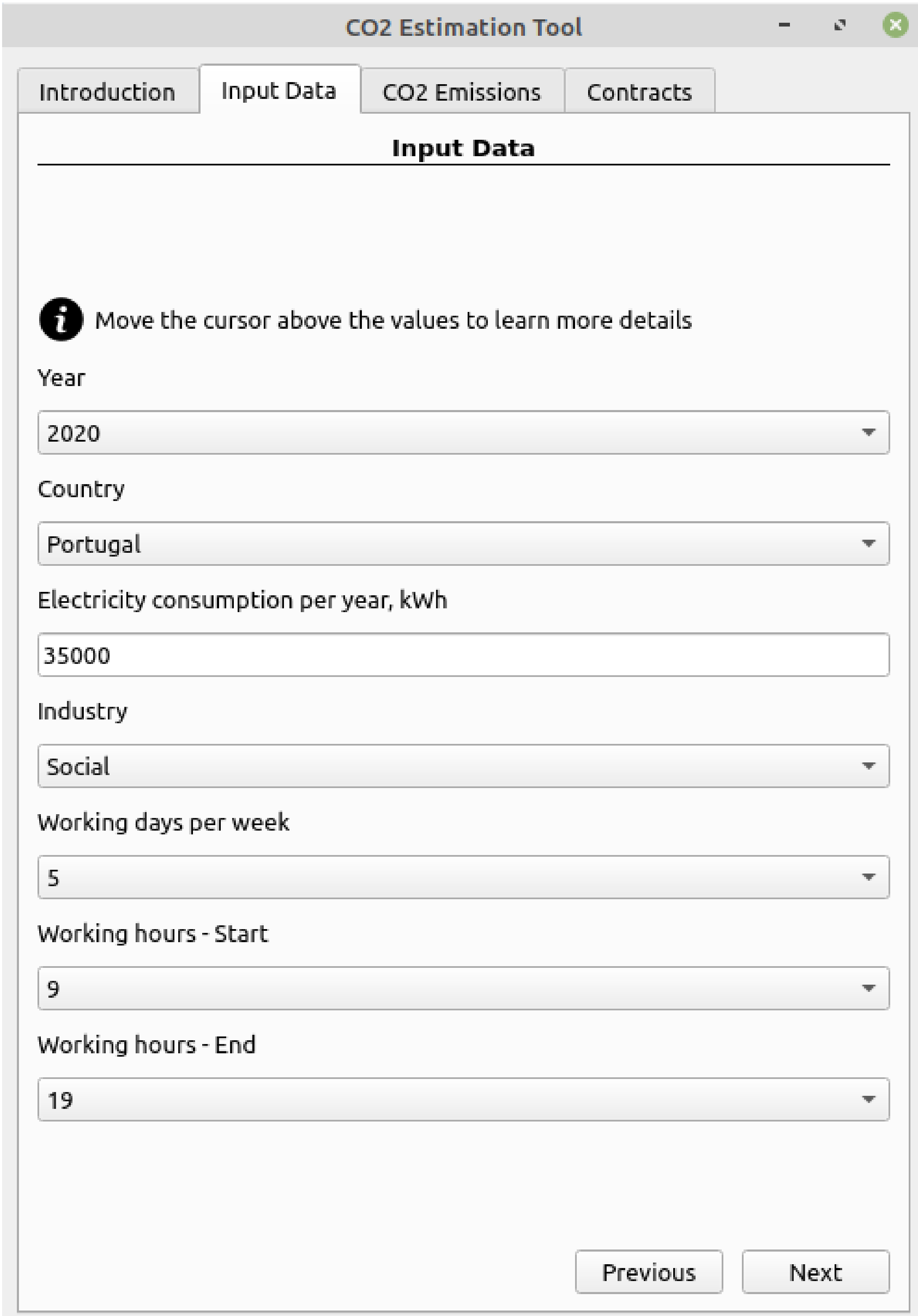

Figure 3.2: GUI Input Data Tab

3. Type of industry – The user chooses the type of industry, that corresponds the best to his company's activity, from the list. Six main groups have been distinguished to match different electricity consumption profiles. The shapes of default electricity profiles for different industry groups are presented in Figure 4.2. Each of the group characterizes with different curve shape, peak values and ratio between the peak and off-hours consumption. The groups have been determined based on external sources [27], [30]. The description and examples of different industry types are presented below:

   - Entertainment - Places that provide widely understood leisure time activities (Restaurants, Cinemas, Bars, Sport facilities),
   - Industry (Permanent use) - Factories and Manufactures that characterize with a constant .roduction and 3-shift working system (Power Plants, Mines, Environmental Facilities, Smelters, Food production, Production & Processing),
   - Industry (Modulated use) - Factories and Manufactures that characterize with mostly 1- or 2- shift working system, usually not operating in the nights (Construction, Agriculture, Assembling goods, Production & Processing),
   - Retail - Places providing various kind of services (Offices, Commercial and Business facilities),
   - Social - Other public and private organizations (Schools, Administrative offices, Universities, Government facilities),
   - Other - To be selected if the user's company does not fit any of the groups above.

4. The number of operating days in a week – The user chooses the number between 1 – 7 days of the week during which the corporate is actively operating (consuming electricity). E.g. if the company is operating from Monday to Friday, the number 5 should be selected. If the user's industry type is Industry (Permanent use), the number of operating days will automatically be set to 7.

5. The start hour of the active operation during the single-day period – The user chooses the number between 0 – 23 which corresponds to the hour at which the user's company typically starts operating (consuming the electricity). In the case of Permanent Use Industry the hours are fixed and cannot be changed (assumed constant operation 24/7). In the special case when

the company operates in different hour range, the user should choose Modulate Use Industry and manually input the hours.

6. The end hour of the active operation during the single-day period – The user chooses the number between 0 – 23 which corresponds to the hour at which the user's company typically ends operating (consuming the electricity). In the case of Permanent Use Industry the hours are fixed and cannot be changed (assumed constant operation 24/7). In the special case when the company operates in different hour range, the user should choose Modulate Use Industry and manually input the hours.

7. Year – The year for which the user introduced his data and wants to obtain the calculated amount of CO_2 emission and contractual instruments recommendation.

3.2 CO_2 Emissions Tab

The software is returning the following values:

- The grid carbon intensity for the chosen country given in $kgCO_2/kWh$. Its value is used to calculate the user's total CO_2 emission in a year. It is evaluated by independent organizations and reassessed on the yearly basis. The values used in this tool are taken from the EEA (European Environmental Agency) and IEA (International Energy Agency),
- The total CO_2 emission in $kgCO_2$ calculated based on the yearly grid carbon intensity and yearly electricity consumption given in kWh provided by the user,
- The yearly averaged FlexiDAO grid carbon intensity given in $kgCO_2/kWh$. It is calculated using purely the generation mix in a given location, assessed separately for each hour in a year. The final value is the sum of all the hourly grid carbon intensities in a full year,
- The total CO_2 emission in $kgCO_2$ calculated based on the yearly averaged FlexiDAO grid carbon intensity and the electricity consumption in kWh from the user's input (specified in the input tab and passed as a variable to the results tab),

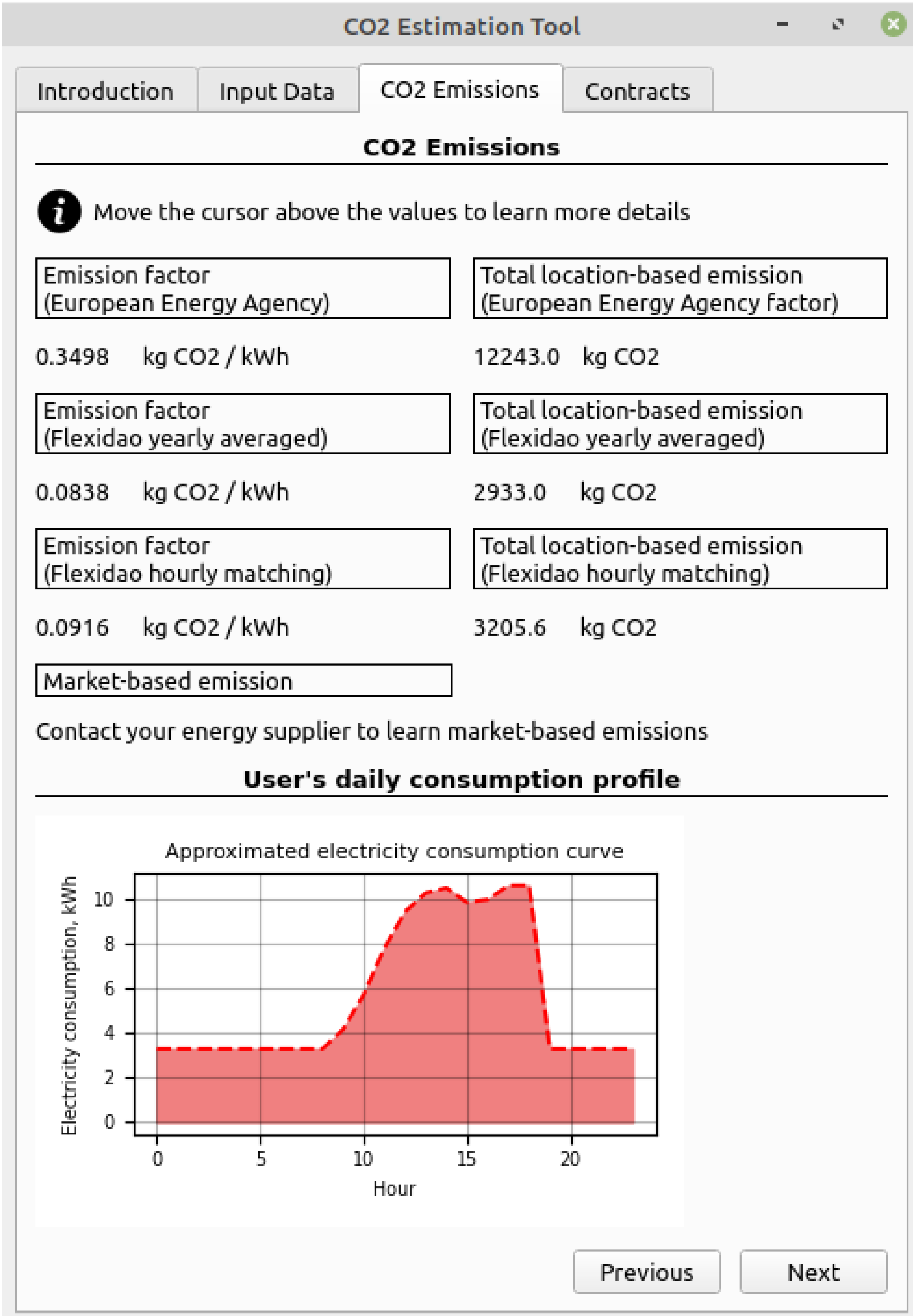

Figure 3.3: GUI CO_2 Emissions Tab

- The average hourly emission factor calculated from the total CO_2 emission in kg estimated based on hourly matching procedure,
- The total CO_2 emission in kgCO_2 estimated with the use of the hourly matching procedure. The user's electricity consumption gets split into hourly values (based on the daily consumption profile generated inside the tool) and based on the electricity mix in the grid and corresponding emissions CO_2 emission in kg is calculated for every single hour in a year. The total CO_2 emission is the sum of all the hourly values.

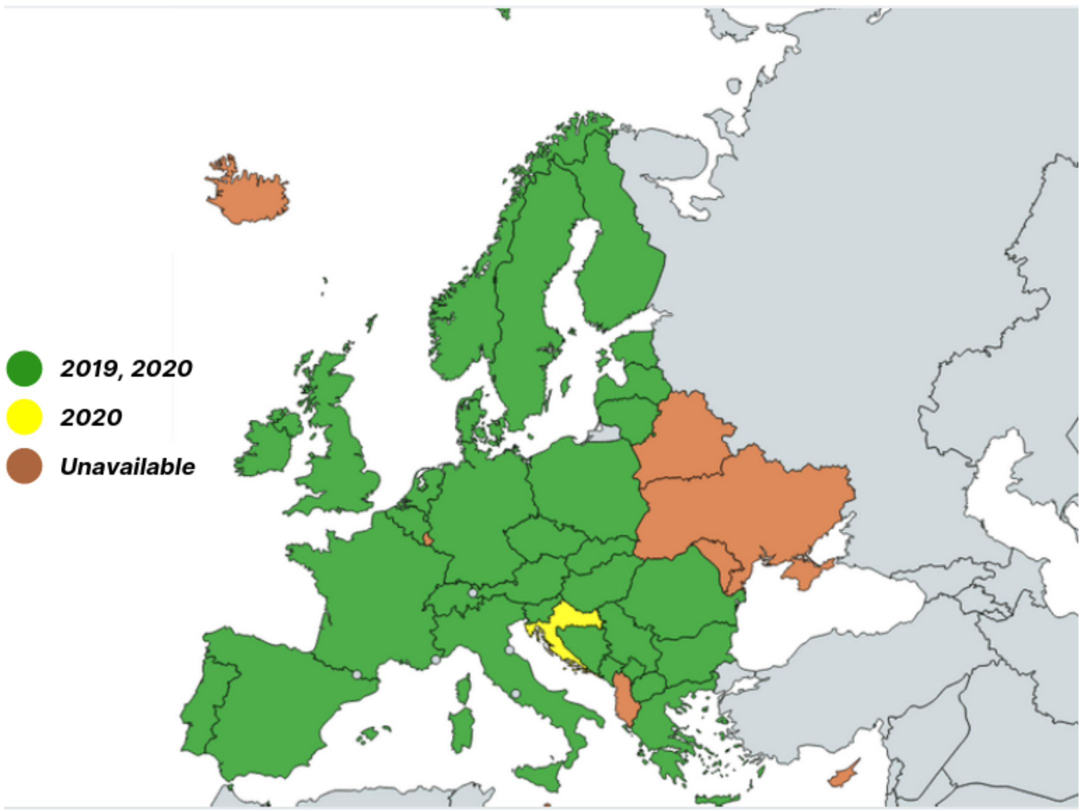

Figure 3.4: The availability of the calculations & results presented in this thesis

Together with the results, the user's electricity consumption plot is generated. The plot is a representation of the major trends in the industry chosen by the user and is scaled to the rest of the user's input and the total electricity consumption. The electricity consumption plot is vital for the hourly-matching procedure for emissions assessment. It is displayed together with the results in order for the user to check if, according to his best knowledge, the electricity consumption plot represents reality well.

It needs to be pointed out, that due to the lack of data from some countries that are not members of the EU, the CO_2 emission value based on hourly calculations may currently not be available. The data availability is shown on the map presented in Figure 3.4.

3.3 Contractual Instruments Tab

After calculating the CO_2 emission with the use of different methods, the software will generate details of the possible renewable energy contractual instruments that the user can acquire, with the aim of reducing his Scope 2 emissions. Contractual instruments are any type of contract between two parties for the sale and purchase of energy bundled with attributes about the energy generation, or for unbundled attribute claims [12]. There are 7 types of contractual instruments taken into consideration in this thesis:

- European Guarantees of Origin
- National Guarantees of Origin
- Off-site Solar Power Purchase Agreement
- Off-site Wind Power Purchase Agreement
- On-site Solar Power Purchase Agreement
- On-site Wind Power Purchase Agreement
- Green Tariffs

All of the contractual instruments will result in reducing the market-based emissions to 0. Each of the instruments has different features. The software will display a window containing the specifications of the instruments, which are:

1. Contractual instrument's description,
2. The number of units that the user has to purchase to offset his market-based emissions,
3. The user's market-based emission,
4. The user's location-based emission after acquiring the contractual instrument,
5. The amount of the avoided CO_2 emission,

6. The unit price of the contractual instrument and the total cost that the user will have to cover to purchase the contractual instruments that will completely offset his market-based emissions,
7. The source of the price,
8. Advantages and disadvantages of the contractual instrument,
9. The chart showing at what hours the renewable energy produced from the chosen contractual instrument's energy source covers the user's electricity consumption and when it doesn't,
10. The summary of the contractual instrument, containing the assessed real impact, the recommended company's size and the contractual instrument's capacity,
11. The comparison of contractual instruments, available in this document in Figure 2.1.

In Figure 3.6 the details of one chosen contractual instrument with the example data are shown. All contractual instruments overview is included in this thesis in Appendix B, Figures B.1 to B.7. The user, by accessing the contractual instrument's details is able to compare between different contractual instruments' features (discussed in this thesis in Chapter 2), but also between the energy source that the contractual instrument is mentioning (European Mix, National Mix, Solar, Wind). The energy mix depends on the percentage content of specific sources. Electricity production patterns for different renewable energy sources are presented in this thesis in Figure 2.2. In the case of the European mix, a strong influence of a high percentage of wind and hydro is visible (respectively 36 and 33% of the European mix as discussed in Chapter 2). For a specific country, one source (most of the time Solar, Wind or Hydro) usually will be dominating in the national energy mix and its influence will be visible in Figure 1 inside the contractual instrument details window.

The user will decide to choose a contractual instrument based on his needs. The most important indicator is CO_2 avoidance, which is visualized in Figure 1 inside the contractual instrument details window presented in Figures B.1 to B.7. It is a clear signal to the user, which sources should remain under his consideration and which should not. It is mostly useful for making a choice between solar-based or wind-based contractual instruments. If the user's company is consuming electricity at night, a contractual instrument based on solar power will indicate low CO_2 avoidance. In such a case, choosing wind as the electricity production source will result in a much higher CO_2 avoidance value. The described situation is presented in Figures B.5 and B.6.

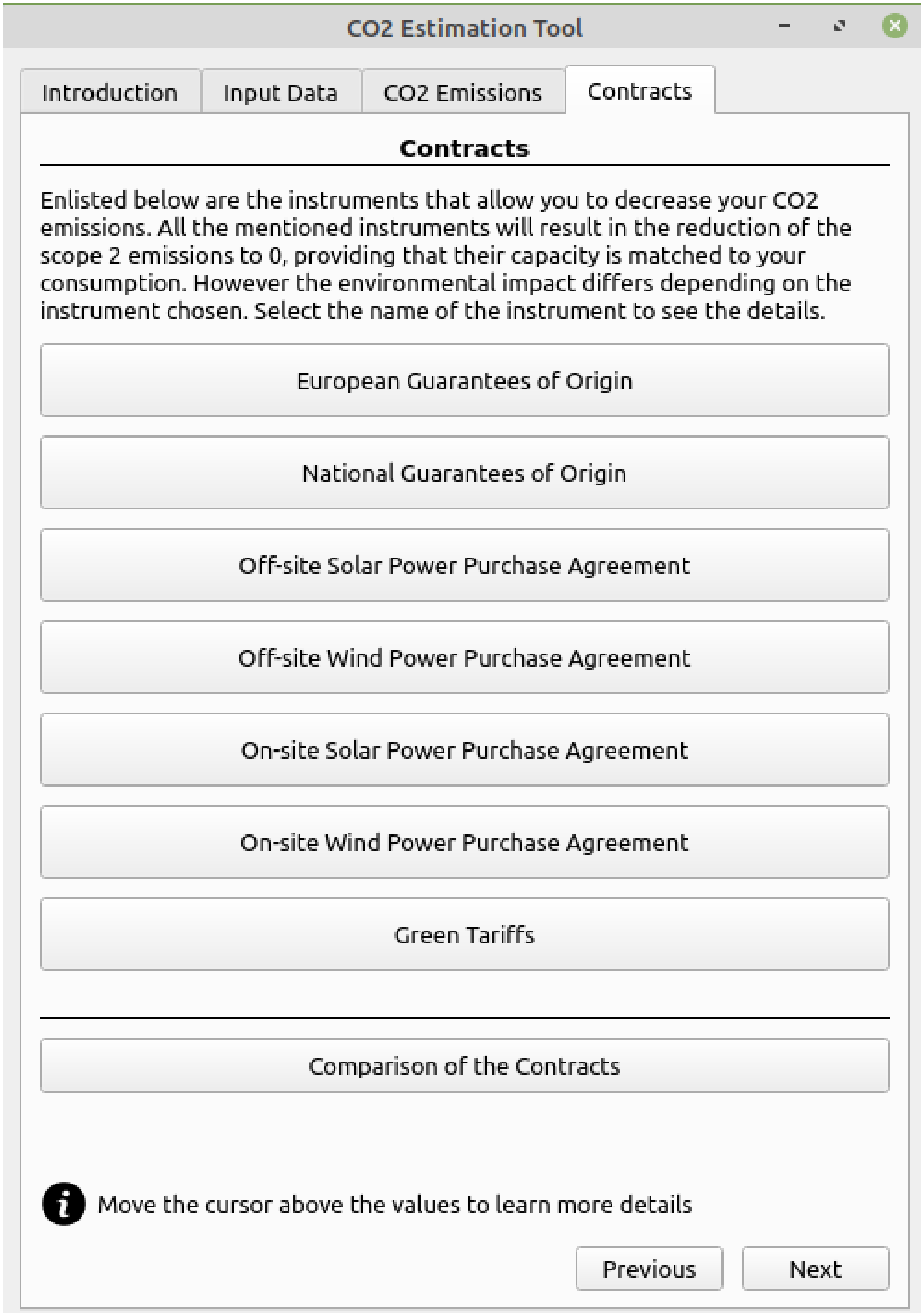

Figure 3.5: GUI Contracts Tab

However, comparing the CO_2 avoidance shouldn't be the only factor deciding about the contractual instrument choice, as the level of the real impact will differ depending on the contractual instrument's type. In order to better understand the differences between specific renewable energy contractual instruments, the user can access the comparison of the table, that is presented in this thesis in Figure 2.1.

In almost all cases the user will not be able to achieve 0kg of total location-based emission unless his electricity consumption pattern will match the one of green electricity production. However, in all the cases where the user owns contractual instruments that prove renewable energy sourcing his market-based emission will be equal to 0 no matter the consumption time or location. The user is informed about it via a tooltip.

Because of the great differences between different energy contractual instruments the user is given a recommendation which contractual instrument he may be more likely to choose depending on his company size. The size is distinguished based on electricity consumption. A general division is (electricity consumption given for a year):

- Small: X <= 30 000kWh
- Medium: 30 000 kWh >= X <= 50 000kWh
- Large: X >= 50 000 kWh

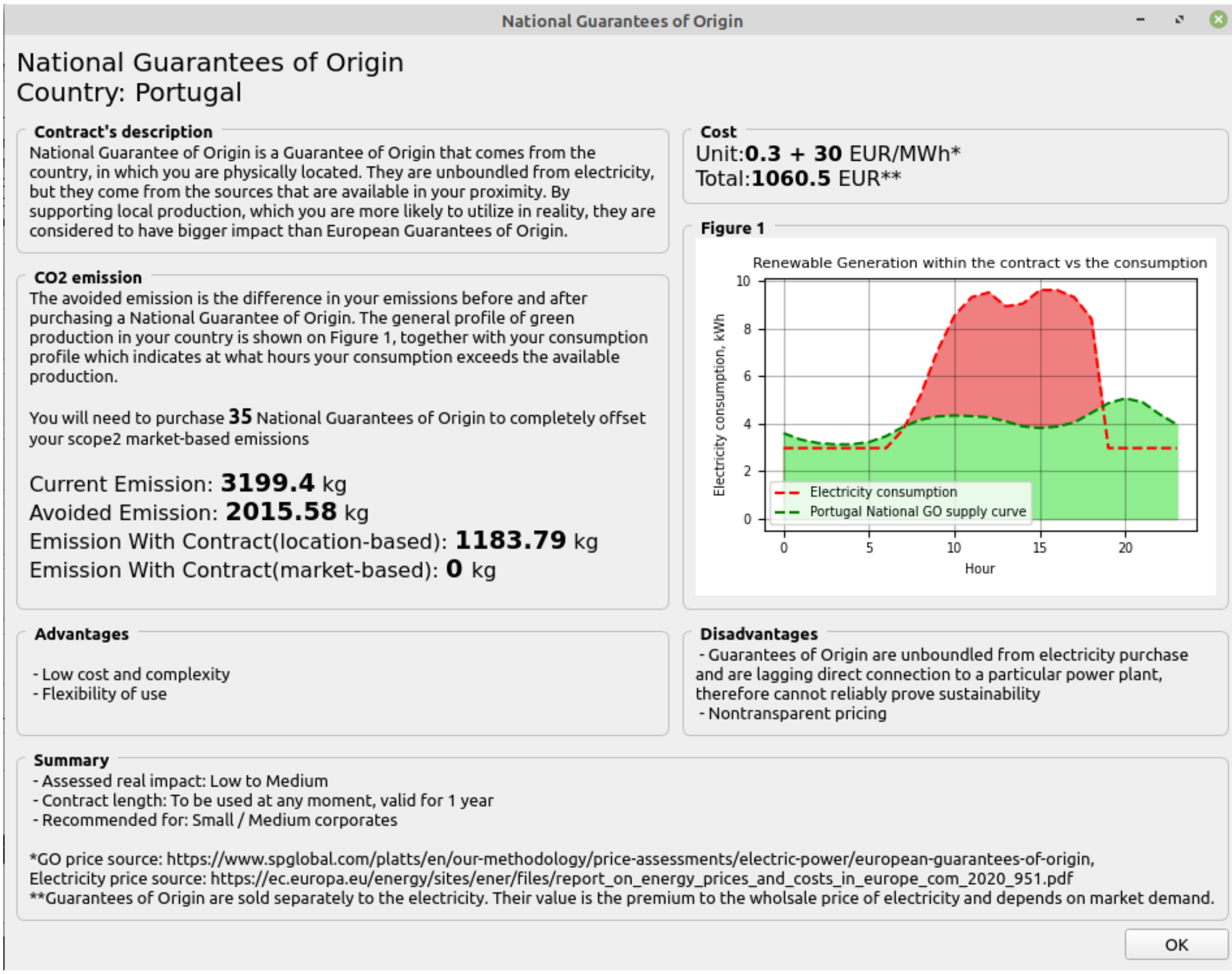

Figure 3.6: GUI Contracts Details - National GO

Chapter 4

Methodology and Calculations

The software consists of 4 components:

1. The file that sets up the database
2. The file containing the functions used for calculations
3. The file containing the text that is inside the GUI
4. The file which derives from all the other files and constructs the GUI

The first file (database_create.py) is placed in the database directory, the rest of the files are placed in the main directory. The file descriptions.py contains all the text that is visible inside the GUI. The text was moved to a separate file in order to make the code more clear and readable and it's editing easier. The GUI is built with the use of the PyQt toolkit. It consists of an introductory tab and 3 main tabs: Input Data Tab, CO_2 Emissions Tab and Contractual Instruments Tab. The detailed information about the input data and results can be accessed by a user via tooltips, that are displayed after pointing at a value with a cursor.

4.1 Setting up the database

The database is the main component needed for the program to work. In order to set up the database, run the database_create.py file and type the year for which you want to create the database. Setting up the database is an automatic process, and can take up to an hour, depending on your internet speed and computational power. Creating the database consists of 4 steps:

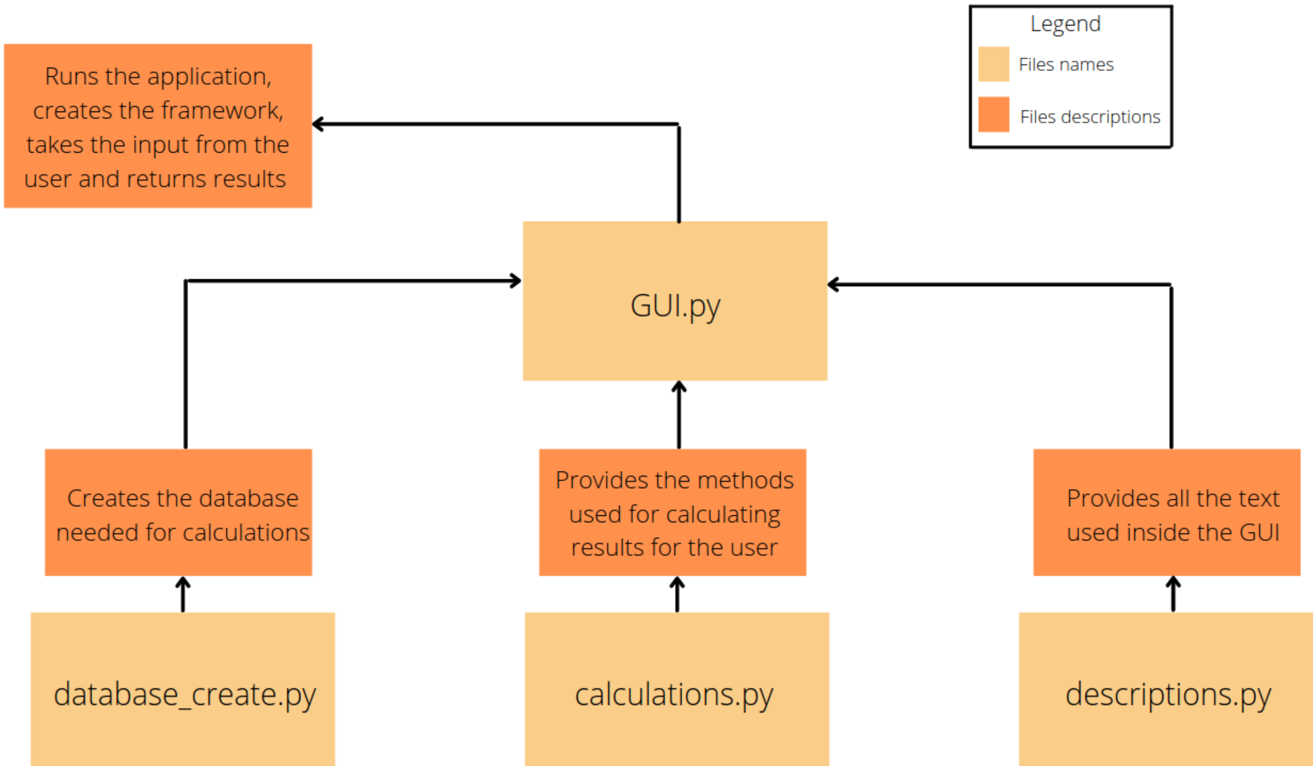

Figure 4.1: Relations between the software's internal files

1. Downloading the electricity generation mix data for all the available European countries via API request call from ENTSOE (European Network of Transmission System Operators for Electricity) [25]. The list of the countries is specified inside the database_create.py file and differs based on the year for which we want to create the database (the database is expanding and new countries are added every year). Because the data acquired from the ENTSOE database is raw, data cleaning needs to be applied. Linear interpolation is used to fill the entries with missing data. Because the data have different sampling frequency, all of them are resampled to full hours. Data is written in a separate file for each country. The format of the name of the downloaded data is 'year'+'country code'. The extension of the files is .csv. Country codes are commonly used abbreviations (e.g. DE for Germany) and are specified in a dictionary inside the database_create.py file. Additionally, the data containing electricity imports and exports between the countries is downloaded. The data is written into one file – imports.csv

2. Calculating grid carbon intensity for every hour for all the files. In this step, we want to calculate the CO_2 emission in kg/kWh based on the mix of the sources generating the electricity.

In order to do that, we need to know how much kg of CO_2 is emitted by generating 1 kWh of electricity from a given source. Only direct emissions are considered when performing the calculations, indirect emissions (Life Cycle Assessment) is not within the scope of the program. All the values that are used for the calculations are presented in Table 4.1. The CO_2 emission factor of total electricity production in each hour in a given country is a weighted average of the CO_2 emission factors of the individual electricity sources. After performing the calculations, the information about the total generation in MW, emission factor in kg/kWh and imports to and from the countries are put together into one file – generation_emission_import.csv, that will be needed for the next step.

3. Because of the constant exchange of electricity between the countries, the grid carbon intensity depends not only on the CO_2 emission factor of generated electricity but also on the emission factor of imported electricity. Therefore, it is needed to account for the electricity imports between the countries. In order to include the CO_2 emission factor of electricity flow into and out of the country, a set of energy balance equations needs to be written, where each equation represents a single country. For the country 'i' [31]:

$$C_i = \Sigma_m P_{i,m} + \Sigma_j I_{i,j} \tag{4.1}$$

Where C_i is the electricity consumption in kWh for the country 'i', $\Sigma_m P_{i,m}$ is the sum of electricity production in kWh originating from the source 'm' in the country 'i' and $\Sigma_j I_{i,j}$ is the sum of electricity imported from country 'j' to country 'i' in kWh.

We assume that the transmission cost is negligible. In a country, that exports more electricity than it imports, the import component will have a negative sign. In Equation 4.1, the final amount of energy physically consumed in a given country should be equal to the whole energy generated within the country from the number of sources 'm' plus the energy that was imported to the country from the number of other countries 'j'. Adding to Equation 4.1 the CO_2 emission intensity ($kgCO_2/kWh$) component (χ), we obtain the following:

$$\chi_i \cdot C_i = \Sigma_m \chi_m \cdot P_{i,m} + \Sigma_j \chi_j \cdot I_{i,j} \tag{4.2}$$

In Equation 4.2, the emission intensity of the consumption in the given country is equal to the emission intensity of the generation + emission intensity of the imported energy (associated with different intensities depending on the country of origin). Balance equations for all available locations will create a set of linear equations, that can be represented in a form of a matrix (Equation 4.3).

$$\begin{bmatrix} P_1 + I_1 & -I_{1,2} & \cdots & -I_{1,n} \\ -I_{2,1} & P_2 + I_2 & \cdots & -I_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ -I_{n,1} & -I_{n,2} & \cdots & P_n + I_n \end{bmatrix} \begin{bmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{bmatrix} = \begin{bmatrix} \sum_m (\varepsilon_{1,m}) \cdot P_1 \\ \sum_m (\varepsilon_{2,m}) \cdot P_2 \\ \vdots \\ \sum_m (\varepsilon_{n,m}) \cdot P_n \end{bmatrix} \tag{4.3}$$

4. Inside the matrix, each country's value has an index containing their country code (1 to n). In the case of electricity import component 'I', there are 2 numbers in the index, denoting the direction of the electricity flow - the first number is the country which exports electricity and the second number is the country that imports electricity. χ_1 to χ_n are unknown CO_2 intensity values. The CO_2 emission intensity of different energy sources within a country are denoted with $\varepsilon_{i,m}$ to $\varepsilon_{n,m}$ and are known values. The electricity sources are denoted with the index 'm'. The sum of the generation of the electricity from 'm' sources of a related emission intensity 'ε' is equal to the total country's electricity generation. Solving this linear system gives us the grid carbon intensity 'χ' for each of the locations. The values being the result of solving the import matrix are called 'consumption emissions' since they are the CO_2 emission intensity of the electricity that is consumed (not only generated) in the given location. The consumption emission values are computed for every hour in the database and written in a new file - consumption_emissions.csv - containing data for all the countries. The values from this file are then used in the CO_2 emission calculations made by the program.

Table 4.1: Direct CO_2 emission factor in $kgCO_2/kWh$ by the generation source [26].

Fuel	CO_2 Emissions Factor ($kgCO_2/kWh$)
Biofuels	0
Biomass	0
Brown coal / lignite	0.33
Coal-derived gas	0.25

Coke oven gas	0.14
Coke and semi-coke	0.34
Hard coal	0.33
Fossil gas	0.21
Fossil peat	0.25
Fossil oil	0.27
Fossil oil shale	0.26
Gas oil	0.25
Geothermal	0
Hydrogen	0
Hydro pumped storage	0
Hydro run-of-river and poundage	0
Hydro Water Reservoir	0
Marine	0
Nuclear	0
Natural gas	0.18
Other	0.18
Other renewable	0
Solar	0
Waste	0.25
Wind	0

4.2 Calculations

The file calculations.py contains all the functions that are used for calculating the values that appear in the GUI. The sources and methodology are discussed below.

4.2.1 Input data

Provided by the user

1. Year,
2. Country,
3. Amount of yearly electricity consumption in kWh for a full year (January-December),
4. Type of industry,
5. The number of days in a week during which the user's company is actively operating (consuming electricity),
6. The beginning and end hour of the company's operation in a day.

The aforementioned data is used in generating an individual consumption profile that will reflect the amount of electricity that is consumed during every single hour of a year.

Provided by the program

1. Electricity consumption profiles within the industrial users

   The profiles are presented in Figure 4.2. They represent general trends in the electricity consumption of non-domestic users. The profiles were generated based on the external research paper 'Power-use profile analysis of non-domestic consumers for electricity tariff switching' [27]. Based on the electricity consumption habits of different groups of industrial users, several lists containing normalized datapoints have been generated. The lists are stored inside the software's source code. They are used to distribute user's yearly consumption throughout a year and to get estimated values for every hour, which is needed for the hourly-matching procedure. The lists have been visualized and are presented in Figure 4.2 in order to better understand the impact of the electricity consumption patterns on CO_2 emissions. Most of the groups, such as Retail or Social characterize with the active electricity consumption between 6 a.m. and 8 p.m. The groups such as Permanent Use Industry or Entertainment tend to have big part of their electricity consumption between 8 p.m. and 6 a.m., which contributes to the fact that their CO_2 emissions from the unit electricity consumption will be on average higher than that of Retail or other groups that tend to consume their electricity during the daytime, especially in the coutries where fluctuating renewable energy sources are a big part of the country's electricity generation mix.

2. Direct emission intensity of the electricity generation in $kgCO_2$ / kWh

   The direct emission intensity for different energy sources is presented in this document in the

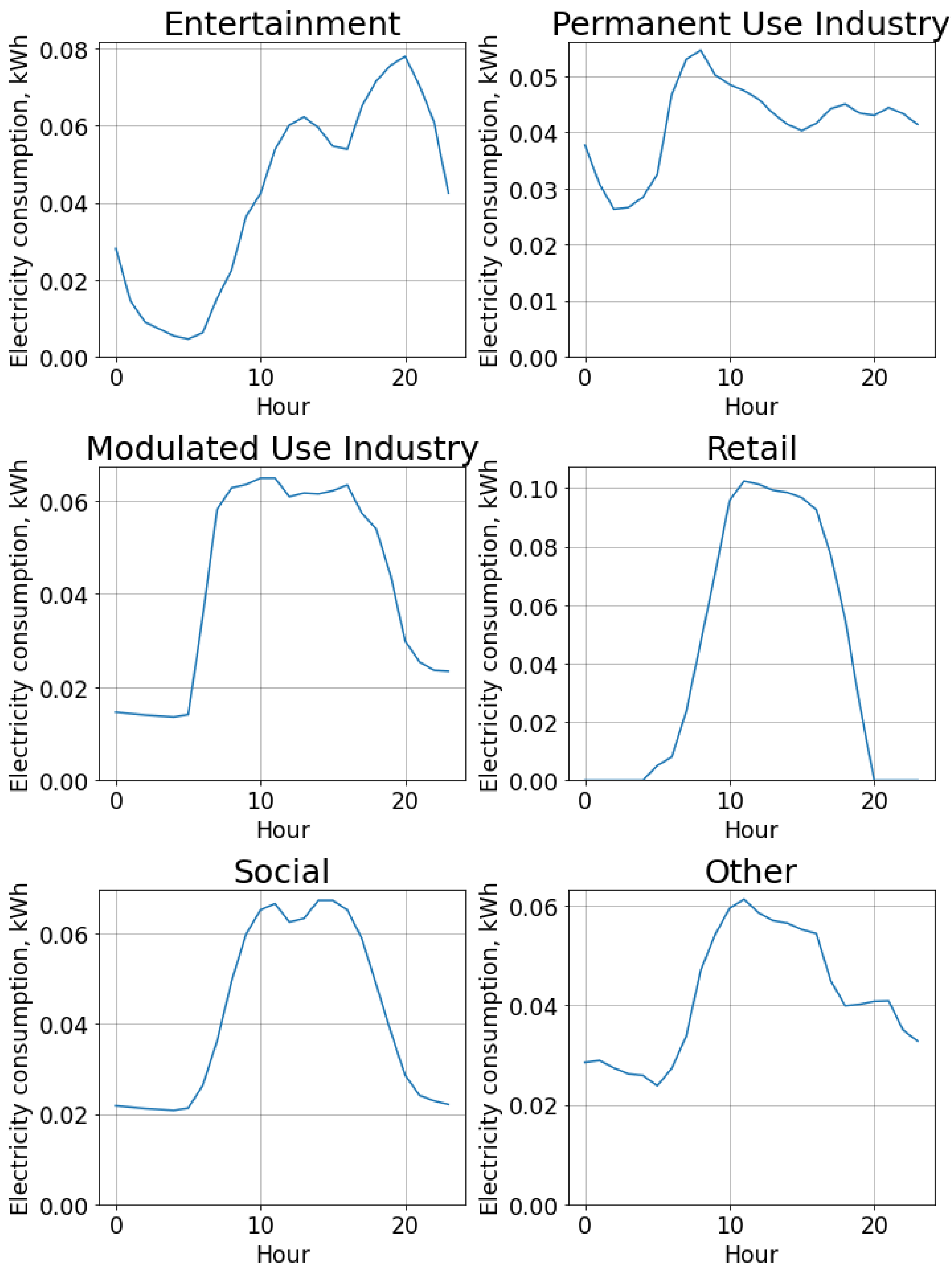

Figure 4.2: Electricity consumption proiles for different industry groups [27].

Table 4.1. The aforementioned data is used to calculate a grid carbon intensity for the chosen country in every single hour of the chosen year using the generation mix.

3. Location-based yearly grid carbon intensity for all the countries in kgCO_2 / kWh

   The grid carbon intensity data for specific countries is presented in Table 4.2 and has been provided by the European Environment Agency in the case of EU countries and by the International Energy Agency for several countries from outside the EU. The data is used to calculate the location-based yearly average emission of a user, in the way that is currently calculated in the companies' annual reports.

4. Generation mix for the specific locations

   The generation mix of a country is provided by ENTSOE transparency platform [25] and contains information about the amount of electricity delivered to the grid every hour in a given country. The generation data is given separately for each generation source (hard coal, natural gas, solar etc.). The generation mix is needed for calculating the grid carbon intensity, and for creating renewable electricity generation profiles.

5. Electricity transfer between different locations (countries importing and exporting electricity from each other)

   The electricity transfer between countries is provided by ENTSOE transparency platform [25] and contains information about the amount of import between 2 countries at every hour of the year. The information about the electricity transfer between the countries is needed for calculating the grid's intensity.

6. Grid carbon intensity at every single hour of the year based on the location

   The grid carbon intensity is calculated by the program and is stored in the program's internal database. It is calculated with the use of the data specified in points 1, 3 and 4. The grid carbon intensity is used to assess the user's total yearly emissions using the hourly matching method.

7. Prices of different green energy contracts

   The prices of contracts are presented in Tables 4.3 - 4.7. They are estimated prices of:

   - Certificates unbundled from the electricity purchase (Guarantees of Origin), which value is a premium to the wholesale price of a unit of electricity that a counterpart is willing to pay when compared to undisclosed electricity. The electricity needs to be contracted separately, aside from the certificate.

- Certificates bundled with the electricity purchase (Power Purchase Agreements, Green Tariffs). In the case of Green Tariffs and off-site Power Purchase Agreements the price is the total cost of a unit of electricity and the corresponding certificate that comes with it. In the case of on-site Power Purchase Agreements the price is the investment cost that is likely to provide an investor with the return on investment. The price per kW or price per MW represents the total cost of creating the installation. If a customer owns the installation, he will not have to pay for the electricity, moreover, he may sell any excess to the grid for the additional profit.

The program is returning to a user the assessed cost of offsetting user's total market-based CO_2 emissions. The contractual instruments' prices have an informative role. They are true as of February 2021 and may change over time as the market constantly evolves and changes.

Table 4.2: Grid carbon intensity by country [28] [29]. The values used as a reference point.

Country	CO_2 Emissions Factor ($kgCO_2/kWh$)
Austria	0.1040
Albania	0.3780 (IEA)
Belarus	0.4409 (IEA)
Belgium	0.1761
Bulgaria	0.4862
Bosnia and Herzegovina	0.9739 (IEA)
Croatia	0.1880
Cyprus	0.6607
Czech Republic	0.4379
Denmark	0.1477
Estonia	0.9224
Finland	0.0828
France	0.0672

Germany	0.4188
Greece	0.6573
Hungary	0.2530
Iceland	0.00001
Ireland	0.3930
Italy	0.2588
Latvia	0.0492
Lithuania	0.0637
Luxembourg	0.0652
Malta	0.4418
Moldova	0.4858 (IEA)
Montenegro	0.6532 (IEA)
Netherlands	0.4526
North Macedonia	0.8110 (IEA)
Norway	0.0189
Poland	0.7557
Portugal	0.3498
Romania	0.2625
Serbia	0.7838 (IEA)
Slovakia	0.1073
Slovenia	0.2483
Spain	0.3043
Sweden	0.0092
Switzerland	0.0140
Ukraine	0.2685 (IEA)
United Kingdom	0.2510

The direct emission factors for different energy sources has been provided by 2019 Government Greenhouse Gas Conversion Factors for Company Reporting and are presented in this document in Table 4.1. The aforementioned data is used to calculate the grid carbon intensity for a chosen country in every single hour of the chosen year.

4.2.2 Cost sources discussion

There are many good services offered by the leaders on the market that provide real-time Guarantees of Origin and Power Purchase Agreement pricing. All of them however are paid services that will not be used for this program's purposes. Instead, the available free sources have been taken into the consideration. Level10 has been chosen for providing PPA prices for this program. Level10 is a company with many years of experience in PPA performance and prices tracking. They are the largest industry's renewable PPA marketplace. Initially, they were present only in the Northern American market. In the year 2020, they have expanded the scope of their analysis with Europe. They are releasing their reports every quarter. Until now, Level10 Q2 2020, Level10 Q3 2020 and Level10 Q4 2020 have been released for the European market. Their database is expanding with each report, which is very promising regarding future reports and their scope. The methodology they are using assumes that the prices that are given are aggregated and reported in percentile buckets – the prices shown in the reports are mostly P25, which refers to the most competitive 25th percentile offer price. The sources that they are using include an online survey directed to project developers, custom requests for proposals received via Level10 Marketplace and offers posted in the Level10 Marketplace that are available to all Level10 partners and customers. In addition to PPA prices, Level10 reports offer other information about the PPA market, such as projects sizes, markets with the highest % of offers from developers, future year's price targets, term lengths and the main factors that have an impact on PPA development. Level10 reports are available free of charge. Unlike other sources that have been considered in this documentation, no monthly subscription is needed. Moreover, considering the purpose of this tool, the daily update of the prices is not necessary, as the prices given in the tool have an informative character. For future purposes, if the tool is developed to showing more accurate pricing and possibly the CO_2 emissions forecasting, a paid service such as Pexapark's PPA Price Reference may be found useful. Guarantee of Origin prices are sourced from S&P Global. They offer a paid service of real-time GO's price assessment based on the market data collected from active market participants. The free of charge information they are providing is the average daily-updated price of EU Nordic Hydro and EU Wind Guarantees of Origin. It is hardly possible to find a source that would provide both Guarantees of Origin and Power Purchase Agreement prices. Usually, the services are offered separately.

Table 4.3: Price of Guarantees of Origin [32].

Country	Guarantees of Origin Price, EUR	Wholesale Electricity Price, EUR
EU average	0.27	30

Table 4.4: Price of off-site PPA [22].

Country	Solar off-site PPA - Price, EUR	Wind on-site PPA - Price, EUR
Finland	-	30
Sweden	35	30
Denmark	31	-
United Kingdom	49	53
Spain	35	36
France	45	91
Ireland	64	57.38
Italy	42	-
Poland	49	-
Germany	49	55
Netherlands	39	-
Hungary	50	-
Austria	62	-
Czech Republic	-	69
Romania	-	44
Lithuana	-	34
EU average	45.83	49.94

Table 4.5: Price of on-site PPA, domestic scale [33].

	Solar on-site PPA	Wind on-site PPA
Investment cost [EUR / kW]	1500 - 2500	2000 - 3000

Table 4.6: Price of on-site PPA, industrial scale [33].

	Solar on-site PPA	Wind on-site PPA
Investment cost [mln EUR / MW]	0.85 - 1.20	1 - 1.50

Table 4.7: Price of Green Tariffs [34].

	Green Tariff
Retail cost [EUR/MWh]	120
Wholesale cost [EUR/MWh]	40

4.2.3 Electricity consumption profiles

In order to proceed with the hourly matching procedure, we need to know exactly how much electricity the corporate is consuming. Because many companies do not have access to smart meters or more detailed reporting, an approximation needs to be introduced. Based on general trends present in the existing non-domestic market, 6 different categories of industrial electricity consumers have been distinguished. The profiles are presented in Figure 4.2 and are placed inside the calculations.py file as lists of 24 points. The user chooses the industry group that his company belongs to. Then, based on the hours, that the company is operating within in the day, the electricity consumption curve is adjusted to fit the company's operation habits – the profile is moved and stretched to fit the user's input hours. Next, the electricity consumption curve is scaled to match the amount of electricity consumed in a year. All the days in the year can be divided into 2 categories – operating or non-operating days. During an operating day, the user's company is assumed to consume electricity accordingly to the electricity consumption curve from the corresponding industry type. During the non-operating day, a flat profile (no electricity consumption) is accordant. The user can choose, how many days in a week are operating days, and how many are non-operating days. For example, if the user chooses 5 operating days per week, the program, during the hourly-matching procedure will assume, that the company operates from Monday to Friday (the program counts days starting from Monday – for more information look into assumptions, discussed at the end of this chapter. User's total yearly consumption is evenly distributed between all the operating days in a year. The assumption, that the user consumes exactly the same amount during all the operating days is leading to minor errors in the total emission value, which is however the best approximation possible without having the exact hourly data from the user's company.

4.2.4 Calculating location-based CO_2 emissions

CO_2 emissions are calculated in 3 different ways:

1. **Using grid carbon intensity from external sources**

   Using the formula:

   $$m = C_{el} \cdot E \tag{4.4}$$

   Where m stands for total CO_2 emission in kg, C_{el} defines electricity consumption in kWh and E is the CO_2 intensity in kg/kWh.

   We can calculate the total CO_2 emission in kg based on the user's electricity consumption and the country's grid CO_2 intensity. The CO_2 intensity is taken for a country from Table 4.2.

2. **Using yearly averaged grid carbon intensity calculated from the program's database**

   Using the program's database, we calculate the average CO_2 grid carbon intensity as a simple average of grid carbon intensities every hour for the corresponding country. The equation has a similar form to the equation 4.4 with the difference in the CO_2 emission intensity component.

   $$m = C_{el} \cdot \sum_h \chi_h / 8760 \tag{4.5}$$

Where C_{el} stands for electricity consumption in kWh, χ stands for grid carbon intensity in kg/kWh and h defines an hour.

The methodology of estimating the χ component is described in this thesis in the beginning of this chapter, with the use of Equations 4.1, 4.2 and 4.3. The values used for assessing the hourly χ component are presented in this thesis in Table 4.1 The grid carbon intensity component is calculated separately for each hour, therefore in order to use it in yearly estimation we use a simple yearly average of all hourly values.

3. **Using hourly – matching procedure and values from the program's database**
In order to calculate the total CO_2 emission, we introduce generated by the program electricity consumption profile to the database containing grid carbon intensity. The consumption profile is a list of 24 points. Each value in the list corresponds to the amount of electricity in kWh that a user is consuming during a specific hour. Based on the number of operating days that we take from the user's input data, we assign the list containing points from the operating day to the number of the operating days and we assign the list containing zeros (no consumption, flat profile) to the non-operating days. Now that the amount of electricity consumption in kWh is specified for each hour of the year, we can calculate the total CO_2 emission in kg using the Equation 4.6. The hourly-matching assessed grid carbon intensity is then calculated by dividing the total CO_2 emission in kg by the user's electricity consumption. It is just an informative value shown in order to notify the user how much CO_2 emission on average 1 kWh of his electricity consumption is causing.

$$m = \sum_h C_{el,h} \cdot \chi_h \tag{4.6}$$

Where $C_{el,h}$ stands for the electricity consumption in one hour period in kWh and χ_h is the grid cabron intensity in one hour period in kg/kWh. The final value m sums up 8760 hourly values for a year period.

4.2.5 Contractual instruments' details

1. Contractual instruments green electricity generation
The general rule for matching the available renewable electricity production with the user's electricity consumption is as follows: Depending on the contract, different renewable electricity

sources are taken into the consideration. The program takes the average of each hour's electricity production and creates a list, which is then normalized. Next, based on the user's electricity consumption the program calculates how many contracts (in case of Guarantees of Origin) or what amount of electricity needs to be purchased to offset the total emission (min capacity is 1MWh for GOs). Then, the amount of produced green electricity is distributed to all days in the year accordingly to the electricity production profile. In the end, it is scaled based on the needed amount of contracts. The green electricity production is shown together with the user's consumption so that the user can see at what hours his company's electricity consumption exceeds the available green electricity production. In the case of GOs, because of the time that is needed to compute the electricity profile of the renewable generation from all the European countries, the file containing the profile for the given year is computed when setting up the database and is called 'year'+renewable_curve.csv. The program is using the curve from this file.

2. Contractual instruments CO_2 offset

   By purchasing green energy contractual instruments equal to the user's electricity consumption amount, a user can declare his market-based emissions as 0, in case of any contract. Using location-based emissions, we are able to calculate the avoided emission based on the hourly-matching procedure. It is done by simply taking time-series data of the user's electricity consumption and the time-series data of the renewable electricity generation available to the user via the contract, and subtracting the available renewable electricity amount from the user's consumption. If the result is the negative value, we will mark it as 0 (since the emission during this hour will be equal to 0, we cannot have negative emissions). If the result will be a positive value (there is electricity consumption that our green generation does not cover), we will multiply it by the grid carbon intensity for this hour, and the result will be the location-based emission that the user caused during this hour. This operation will be done for all the hours in the time series. Finally, we will sum up all the emissions from the single hours – it is the new location-based total emission for the year. By subtracting this value from the user's total hourly matched location-based emission from the CO_2 Emission Tab we will obtain the avoided emission.

3. Contractual instruments' capacity

   In the case of most contracts, the capacity that you need to acquire is based only on your consumption. In the case of Guarantees of Origin and off-site PPA, your consumption is rounded up to the full MWh since the lowest capacity you can purchase is 1 MWh. In the case of Green Tariffs, the capacity you need to acquire is equal exactly to your consumption in kWh – the possible capacity limitations may arise from the retailer side but they need to be evaluated separately for each situation between the contract's sides. In the case of on-site PPA, the capacity that the customer needs to install is calculated with the use of the following formula:

- On-site Solar PPA

  The general formula for calculating the energy production from the installed power in a year time [35]:

$$P_{EL} = n \cdot P_N \cdot I \cdot \eta \cdot A \cdot h \cdot 365 \tag{4.7}$$

Table 4.8: Solar PPA values used for capacity calculations [35].

Description	Symbol	Value
Electric output	P_{EL}	Provided by the user. kWh
Nominal power of 1 PV panel	P_N	250W
Number of PV panels	n	To be calculated
Solar irradiation at the STC	I	1000 W
Peak hours per day	h	4
Efficiency of electricity production	η	10%
Area of 1 PV panel	A	1.6 m^2

The symbols used in Equation 4.7 are explained in Table 4.8. After transforming the formula we are able to obtain the power that we need to install in order to produce the amount of electricity that we need. Assuming that each solar panel has the nominal power of 250 W we will obtain the nominal power of the whole installation by multiplying the number of panels by 250 W. It has to be mentioned, that the solar irradiation is variable over the course of the day and varies a lot between different geographic locations. In this case, the value of 1000 W is being used, as it is the value suggested by the Standard Test Conditions. The real values may differ significantly, depending on many factors, such as location, daytime, season, atmospheric conditions etc. Assessing the exact electricity generation for each user would require including a historical solar irradiation values to the database of the software, which is out of the scope of this thesis. Including the estimated electricity generation from PV installation serves the purpose of providing the user with the expected scale of electricity generation.

- On-site Wind PPA

  The general formula for calculating the energy production from the installed power in a year time [36]:

$$P_{EL} = P_N \cdot Cp \cdot 24 \cdot 365 \tag{4.8}$$

Table 4.9: Wind PPA values used for capacity calculations [36].

Description	Symbol	Value
Electric output	P_{EL}	Provided by the user. kWh
Nominal power of a turbine	P_N	To be calculated
Power coefficient	Cp	0.25

The symbols used in Equation 4.8 are explained in Table 4.9. After transforming the formula we are able to obtain the power that we need to install in order to produce the amount of electricity that we need. The number is a rough estimation and only takes into account the wind turbine's power coefficient Cp that for different locations and conditions might vary as much as 0.06 - 0.40. In ideal conditions the power coefficient has it's maximum in 0.593, which however cannot be achieved with the current technology [36].

4.3 Assumptions

The program operates under a few assumptions, that make the calculation process fast and requires a minimum data input from the user. The main assumptions are:

1. Even distribution of the consumed electricity between the operating days
2. The chosen amount of the operational days starts on Monday. If the user chooses 3 operational days, the program will assume that those days are Monday, Tuesday and Wednesday
3. The electricity consumption profiles are generated based on the general trends within the chosen industry. In some cases, they may not perfectly match the user's electricity consumption habits.
4. In the situation when some country lacks some specific kind of data (e.g. Solar generation), the European averages will be shown.
5. In the case of missing entries in the specific country's electricity generation data, interpolation is used for filling in the empty spaces. In the cases when interpolation can not be performed, the empty entries are filled with zeros.
6. In the capacity calculations for the on-site Power Purchase Agreements, the numbers like: efficiency, area, solar irradiation, wind speed, power coefficients are predetermined values. In different locations, the weather conditions may differ which may affect the potential power production. The details and the assumed values are included in the technical documentation.
7. In on-site PPA we assume that the user is the owner of the installation and therefore the cost of the investment is shown.

Chapter 5

Results

The most important application of the software is showing the difference between the amount of CO_2 emission calculated with the use of yearly averages and calculated using the hourly values. In order to examine the effect of using hourly data instead of yearly averaged, a study on the differences between the values has been conducted. The study involved calculating CO_2 emission with the use of hourly values for 3 different users:

1. A permanent use industry sector user, consuming electricity in a constant manner,
2. A retail sector user, consuming electricity during the daytime,
3. A entertainment sector user, consuming electricity at night.

The study has been performed separately for each country available in the database. For all three users, it has been assumed that the amount of 30 000 kWh of electricity is consumed annually. The only difference in the input parameters was the type of industry and consumption hours, which has affected how the user's electricity consumption profile looked. First, the reference value of yearly averaged CO_2 emission was estimated. This value does not take into account the user's electricity consumption pattern. Because all the cases had the same input annual electricity consumption, the yearly CO_2 emission values are the same. Then, the values of CO_2 emission based on hourly calculations have been calculated for all three cases separately.

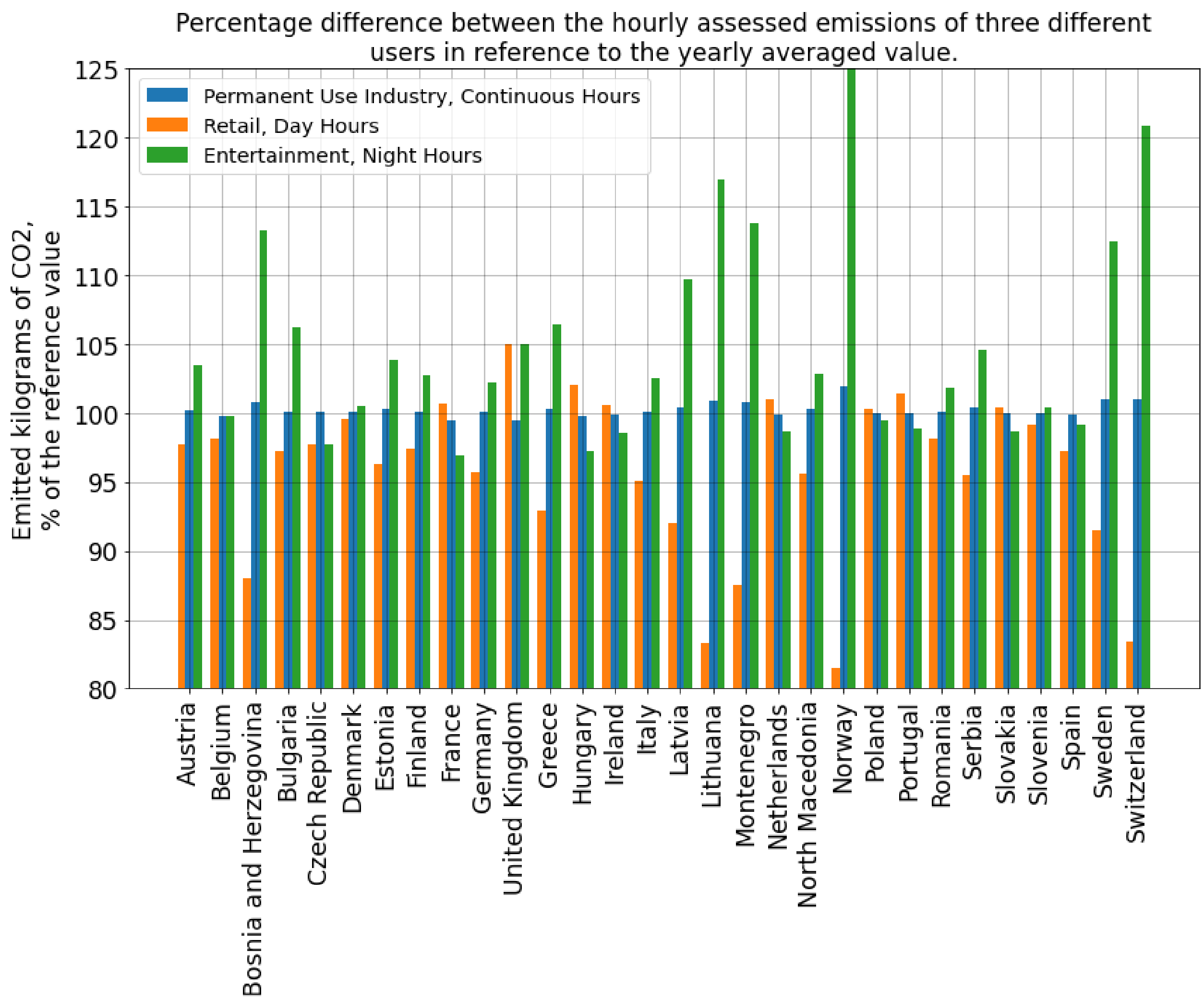

Figure 5.1: Comparison of the CO_2 emission for different electricity consumption patterns, hourly calculations. Yearly average as a reference point, marked by 100% value.

The study results are visualised in Figure 5, in the form of a bar chart. For each country, three bars having different colours correspond to different users. The values on the y-axis are expressed as percentage values, showing the difference between the current and the reference value of 100%. The value of 100% in the case of each country corresponds to the yearly averaged CO_2 emission value, which is the same for all three cases. The CO_2 emission values calculated with the use of hourly values are presented as a percentage of the reference value.

As expected, the first user characterised by the constant electricity consumption is the closest to the reference value of 100%. For this type of users, the deviation from the reference value does not exceed 2%. The mean value of the results for all countries almost perfectly matches the reference value, as it is equal to 100.2%. The standard deviation of the results is equal to 0.5%.

In the case of the second user, characterised by the electricity consumption during the daytime hours, the values tend to be much lower than the reference value, as low as almost 20%. There are big differences between individual countries, however, the general pattern can quickly be spotted: the user consuming electricity during daytime has on average the lowest CO_2 emission values. The mean value of the results for all countries equals 95%, which shows that on average, the electricity consumer in an arbitrary location is expected to be responsible for 5% lower emissions than the ones reported with the use of annual averages. The standard deviation of the results is equal to 5.9%.

In the case of the third user, characterised by the electricity consumption at night, the values seem to be higher than the reference value, as much as 25% higher. The mean value of the results for all countries equals 105%, so it can be concluded, that on average, the user consuming electricity at night in an arbitrary location will be responsible for 5% higher emissions than the ones reported with the use of annual averages. The standard deviation of the results is equal to 7.4%.

There are several countries that exhibit the CO_2 emission levels for the second (daytime) user that are higher than the reference value, and at the same time, the emission levels for the third (nighttime) user are lower than the reference value. It can be concluded, that in these countries the electricity generated at night has a lower CO_2 emission intensity than the electricity generated at night. These countries are France, United Kingdom, Hungary, Ireland, Netherlands, Poland, Portugal and Slovakia. There are many factors that can contribute to a country having a higher grid carbon intensity in the daytime hours. In order to determine the source of such behaviour, as well as learn what influences the differences between daytime and nighttime emissions, the factor that should be investigated is the countries' electricity consumption mix.

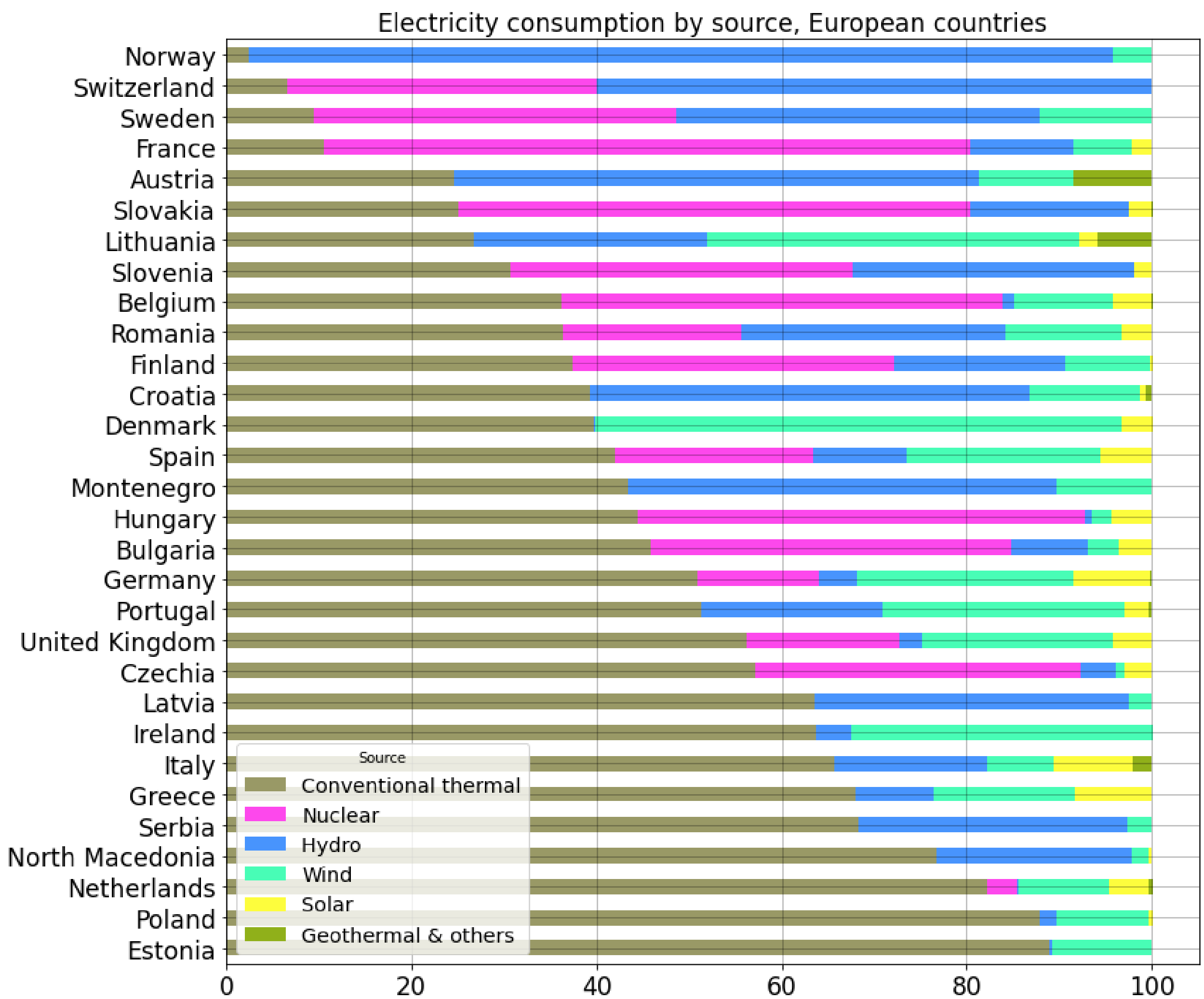

Figure 5.2: Electricity consumption by source [37].

In Figure 5 the electricity consumption mix has been shown [37]. The countries have been organized in an ascending order starting from the countries with the lowest share of conventional, fossil fuels, and finishing with the country having the highest share of conventional, fossil fuels. The countries that exhibit lower grid carbon intensity at night, as opposit to lower grid carbon intensity during the day, characterize with very high percentage content of conventional fossil fuels and nuclear energy, that are known for being independent on any external conditions. Therefore, the grid carbon intensity is expected to be more stable throught the course of the day. The fact, that in those countries the grid carbon intensity can be higher during the daytime, may be caused by the peak demand hours occuring in the morning and late afternoon. During the peak hours, more conventional energy sources may be engaged in the electricity production, in order to meet the required level of electricity production. Another thing is that sometimes measurement errors occur, there are missing series of data or different types of anomalies can happen due to random events, which can possibly impact the final results, especially of a dataset that consists of values of a period of 1 year.

To sum up the study, there definitely exists a difference in the CO_2 values emitted by the users with different electricity consumption patterns, which indicates the need of reforming the emissions reporting sector and introducing hourly emmisions accounting as opposite to the yearly emissions accounting that is currently commonly used. It can be noticed, that the countries with the higher percentage content of renewable energy sources in the grid are experiencing higher fluctuations of the grid carbon intensity values between different hours. As the share of renewable energy sources in the countries' electricity mix is only expected to rise in the next years, the differences between the CO_2 emitted from electricity use at different hours will also increase.

The CO_2 emission estimation software may have more applications. Because it is very easy to update the program's database with another year - the database is built automatically for a whole year period after initializing the update - its maintenance becomes very easy. One of the additional applications is tracking changes in the energy infrastructure in countries. In Figure 5 the grid carbon factors by country and year are shown. In most cases, there is an improvement between the year 2019 and 2020. The software provides a tracking tool that may help in determining the dynamism of the changes in each country.

There is a significant difference between CO_2 emission results calculated by the program with the use of external database grid intensity and other methods. There are several factors that can contribute to that. In the program, pure grid mix is used for assessing the grid's intensity - indirect emissions (LCA - Life Cycle Assessment) were not included and market instruments were not taken into the consideration (no residual mix). External databases may be using either direct emissions assessment or LCA in their calculations, which often is not clearly stated in the report containing the values. The values they are publishing may or may not be national residual mixes, which causes further differences between various databases. Finally, the big role in assessing a national grid intensity is energy source CO_2 emission factor values - the values used in external databases are most often not disclosed, so it becomes difficult to objectively compare the results from different databases. The energy source CO_2 emission factors used in this thesis are in Table 4.1.

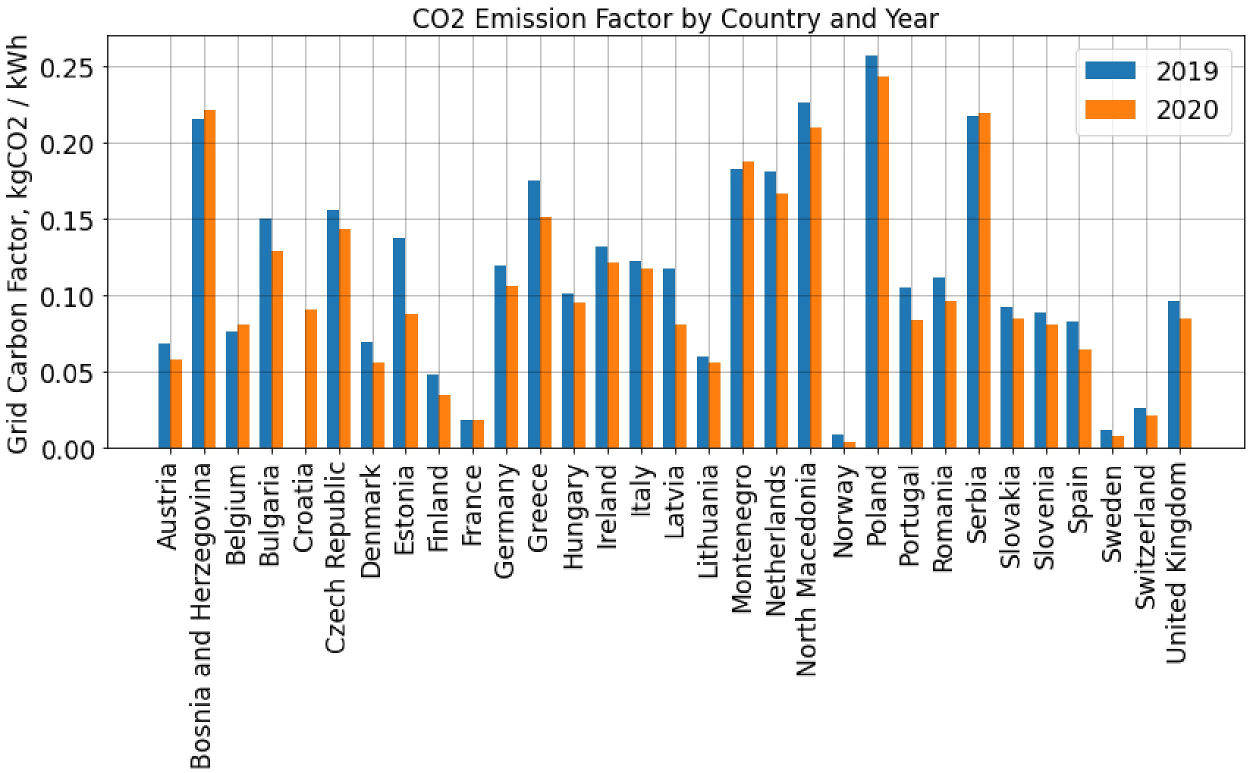

Figure 5.3: CO_2 Emission Factors by Country and Year

Another information useful to the users is the contracts' comparison and contracts' details. It is very important that the user, knowing his current environmental impact, is advised about what to do next in order to cut them down. Depending the electricity consumption habits, different contracts will be suitable for different users. The main indicator of which contract is the best should be the avoided CO_2 emission, but more details are provided in order for the user to be able to make the best decision for him. The contract details are presented in Figure 5. Contracts' details for different users are attached in the Appendix B.

From both the chart and the numbers we can draw the conclusion about which contract is better for a specific user. For the user presented in the Figure 5, the solar PPA performs better than other contracts (see Appendix B). However, if we changed the user to one with more stable electricity consumption pattern, then it would rather be recommended that the user chooses a wind energy based contract, as wind energy production curve would better match the user's electricity consumption curve. The comparison of the contracts' features helps to understand the influence of each contract on the environment, which are quite significant.

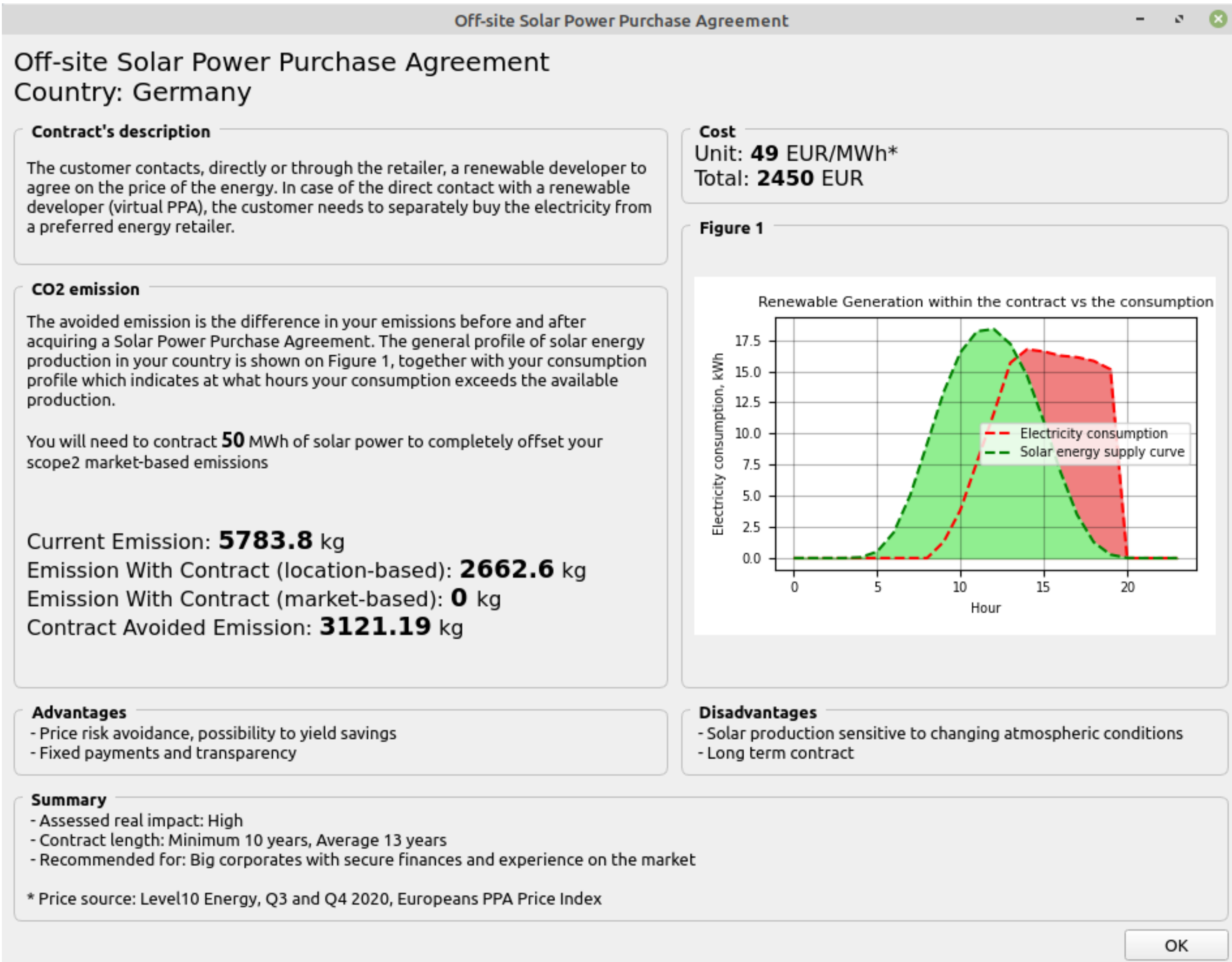

Figure 5.4: Contracts details - On-site Solar PPA

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis presented software for CO_2 emission estimation dedicated for corporate use, specifically for energy and sustainability managers. The program offers 3 different types of yearly CO_2 emission calculations, and generates estimated details of green electricity contracts based on the user's input data.

In order to create the software, a significant amount of energy market research had to be done. As the market changes very rapidly, most of the resources available are quickly becoming obsolete. It has to be stressed, that the most recent information are very difficult to obtain, especially the financial data. There exist services that offer this kind of information but it is not free of charge. The same problem exists in the case of electricity generation data. The only easily available solution is using ENTSOE platform, which however offers access to a limited number of countries. Performing the analysis and obtaining the data was followed by a range of data manipulation and data cleaning. In order to produce the desired results, the electricity database, the renewable electricity production profiles, the energy contracts' details, the CO_2 emission factors and all the calculations linking them together had to be combined in the graphical user interface to provide easy access to the results. A qualitative analysis of the green energy contracts is available to the users, based on which they can make a decision about their next steps towards cutting down their emissions.

An important thing introduced by CO_2 emission assessment software is the hourly-matching emission estimation procedure. This procedure is becoming more and more present in the reporting schemes and is expected to soon become a norm in the reporting standards. It is built on assumption that emissions should be accounted for in real-time, which also imposes the use of the hourly grid intensity factor. There are more and more large companies on the world's market that voluntarily are implementing the hourly scheme in reporting their emissions as a way to achieve 0 net carbon and be able to reliably prove it.

There does not exist one solution for a company to achieve 0 net carbon emissions. The market and norms are still not perfect and some changes and rapid progress is needed in order to meet the climate goals determined for the next 30 years. It is very difficult to assess the exact emissions, direct and indirect and limit them. The best approach, as described in GHG protocol is to divide the emissions by their origin, identify the sources of the emission in each company and implement programs that will eventually lead to the reduction of these emissions to 0. In the case of Scope 2 emissions, it is not so difficult anymore since nowadays we can easily choose the origin of the electricity we purchase. What we need to remember about is that different energy contracts may have various environmental impacts, and before signing a contract or buying a contractual instrument with intention of offsetting the emissions one needs to be aware of the features of such a contract. Achieving carbon neutrality as a whole will not be possible as long as there is any fraction of electricity in the grid that is not produced by sustainable energy sources. Companies should not only be subject to implementing green programs in order to fit in imposed restrictions but also should be encouraged and rewarded by taking voluntary actions towards environmentally-friendly schemes. Limitations on the domestic market may not happen for a long time, if ever. Because of this, the industrial market should be the main driver in the energy transition process.

6.2 Future Work

The current state of the program provides the users with the results of CO_2 emissions calculated with the use of a few different approaches, it generates the user's approximated electricity consumption curve and generates a recommendation regarding the possible contracts for emission offsets. However, it is possible to extend the scope of the program and improve the existing features. The main features that can be developed in order to improve the program's functionality are enlisted below.

1. Extend the database with the missing countries data – this can be realized in 2 ways:

- In the following years to extend the countries database as the ENTSOE database is growing – this solution will require the minimum amount of work – appending a new country name to the existing dictionary inside the 'database_create' file. The rest of the process is automatic

- Search for the data of the missing countries in different sources. ENTSOE is the biggest and most reliable web page containing electricity data from multiple countries. It is actively being developed when new, verified data is available. In a case, when a given country does not exist in the ENTSOE database, it may mean that the data is not easily available, usually, it is needed to search in the local country's web page, which rarely offers an English framework. If the data can be acquired, they need to be integrated with the existing database, which means the necessity of interfering with the code. Because of this reason, this solution may be time-consuming.

2. For the majority of countries, the prices of contracts are the average European prices. The prices of off-site Power Purchase Agreements and Guarantees of Origins are available through services like Pexapark or Bloomberg. However, they provide pricing on a regular basis only for a few major European countries. The mentioned pages do not offer free access to the data via using an API call, which means, that the contract's prices won't be updated with the time elapsed. This functionality of the program could be improved into displaying real-time prices. Additionally, the prices should ideally be specified separately for each country, instead of giving European averages.

3. The electricity consumption curve that is generated by the program is a rough estimation. It is generated based on only 5 inputs:

   - Type of the industry,
   - Number of operating days in a week,
   - Start hour of the operation during a day,
   - End hour of the operation during a day,
   - Amount of electricity consumption in a year time.

   In some cases, the chart may not be the best representation of reality. The ideal situation is the scenario when the user has a smart-meter installed that can note the electricity consumption with an hourly frequency. The data from the smart-meter can then be forwarded to the program, which would calculate the corresponding CO_2 emissions with great accuracy. In most cases, however, our users will not have smart meters installed. In this case, in order to increase the accuracy of the calculations, a more detailed questionnaire can be introduced.

4. Currently there exist no ideal solution in the case of dealing with the missing electricity generation data. The missing entries are independent of any party since they are mostly a result of an interruption of the measuring process, weather conditions, or failure of the measuring devices. When having a database containing a couple of years of data for the individual countries, it would be possible to predict what the missing data could be, based on the time and weather conditions, using machine learning algorithms.

5. Using machine learning algorithms and forecasting methods can also allow us to add important functionality to the program – based on our historical data, what are the forecasted CO_2 emissions for the following years. Adding this feature definitely would increase the attractiveness of the program.

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Appendix A

User's Guide

1. Choose the country from the list. The country should be the physical location of where your company is situated.

2. Introduce the amount of the electricity consumed by your company. The value should be in kWh. Please keep in mind, that the provided value should cover the electricity consumption in a full-year period (e.g. 1st January 2019 - 31st December 2019). Don't use spaces.

3. From the list of different industry types, choose the one that best describes your company's activity. The examples for different types of industries are:

- Entertainment – Places that provide widely understood leisure time activities: (Restaurants, Cinemas, Bars, Sport facilities)

- Industry (Permanent use) – Factories and Manufactures that characterize with a constant production and 3-shift working system (Power Plants, Mines, Environmental Facilities, Smelters, Food production, Production & Processing)

- Industry (Modulated use) – Factories and Manufactures that characterize with mostly 1- or 2- shift working system, usually not operating in the nights (Construction, Agriculture, Assembling goods, Production & Processing)

- Retail – Places providing various kind of services (Offices, Commercial and Business facilities)

- Social – Other public and private organizations (Schools, Administrative offices, Universities, Government facilities)

- Other – Select if your company does not fit any of the aforementioned groups

4. Choose the number of the days per week, during which your company is actively operating. E.g. if the company is operating from Monday to Friday, please select 5.In the case of chosen 'Industry (Permanent use) type of electricity consumer, the value will be automatically set to 7.

5. Choose the hour at which your company starts operation during the day. The European hour notation applies. If the company opens at 6 am, please choose 6. If it opens at 3 pm, please choose 15. In the case of chosen 'Industry (Permanent use) type of electricity consumer, the value will be automatically set to 0.

6. Choose the hour at which your company finishes operation during the day. The European hour notation applies. If the company closes at 8 pm, please choose 20. If it closes at 1 am, please choose 1. In the case of chosen 'Industry (Permanent use) type of electricity consumer, the value will be automatically set to 0.

7. Set the year for which you want to obtain the results. Keep in mind, that the year should be the year for which the yearly consumption in kWh was introduced.

8. In order to generate the results, use the buttons on the right side of the window. The results will appear on the bottom of the window.

Appendix B

Graphical User Interface - Contractual Instruments

The details of contractual instruments presented below has been generated for the following input:

- Country - Germany
- Annual electricity consumption - 50 000 kWh
- Industry - Retail
- Working days per week - 7
- Working hours, start - 9
- Working hours, end - 20

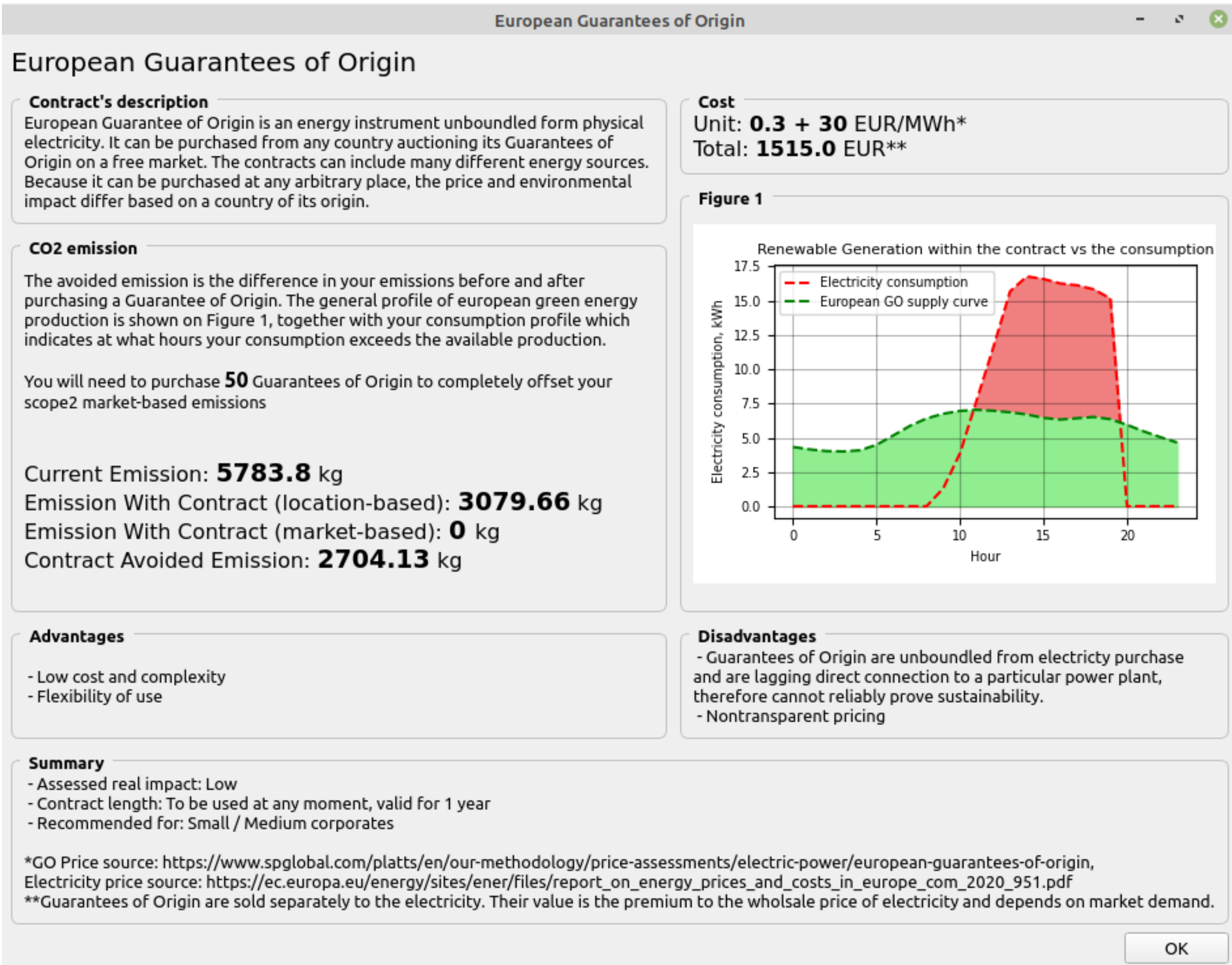

Figure B.1: GUI Contracts Details - European GO

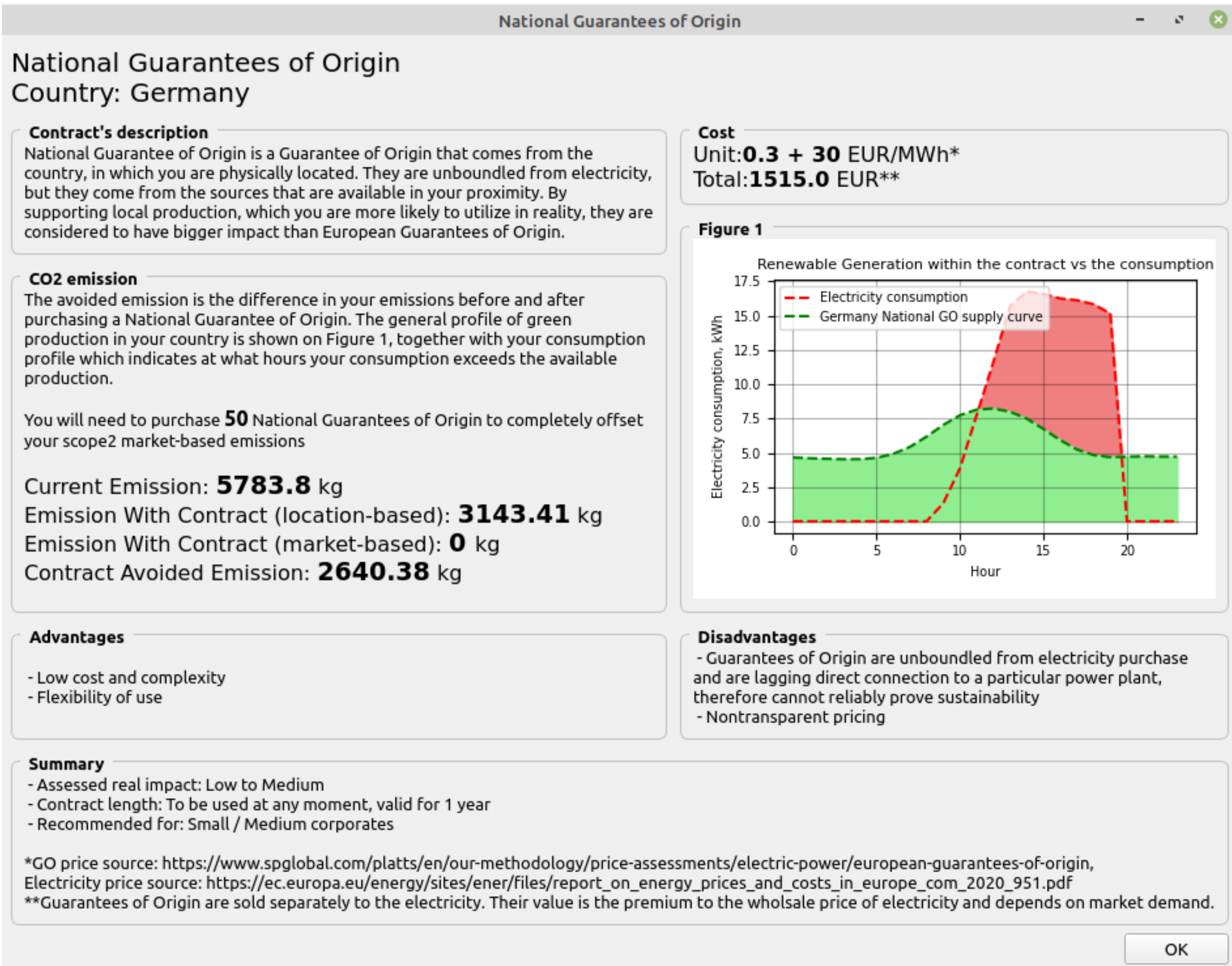

Figure B.2: GUI Contracts Details - National GO

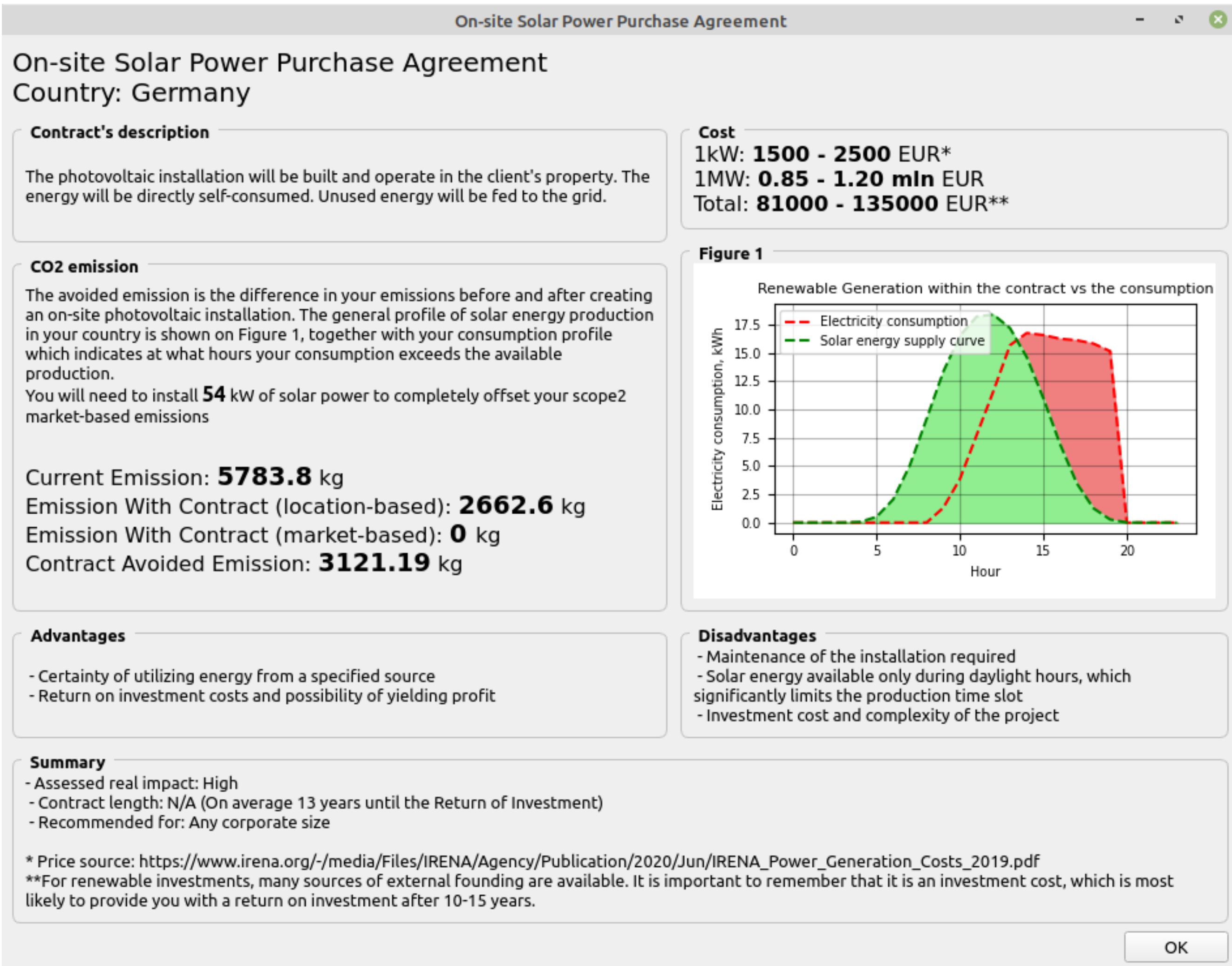

Figure B.3: GUI Contracts Details - On-site Solar PPA

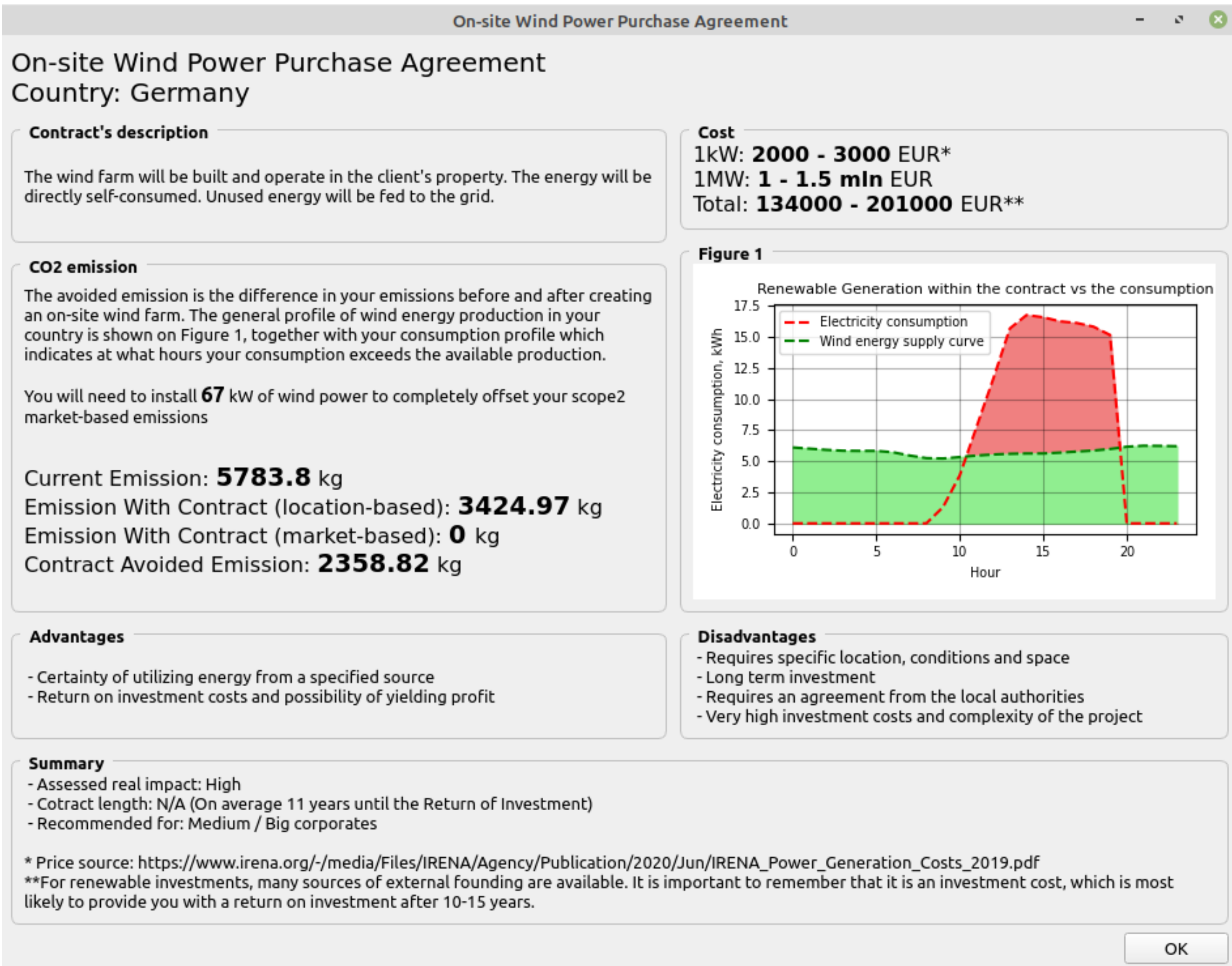

Figure B.4: GUI Contracts Details - On-site Wind PPA

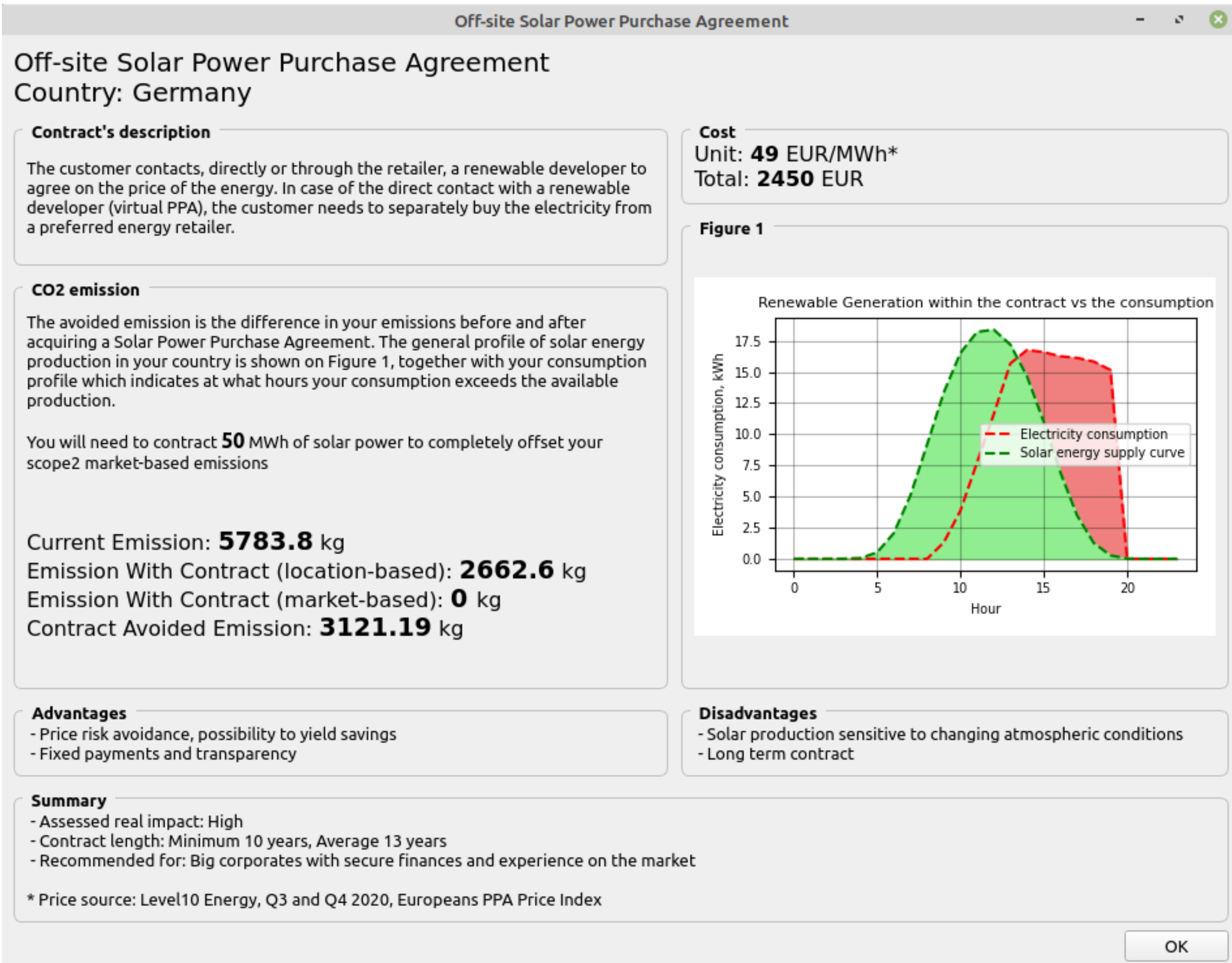

Figure B.5: GUI Contracts Details - Off-site Solar PPA

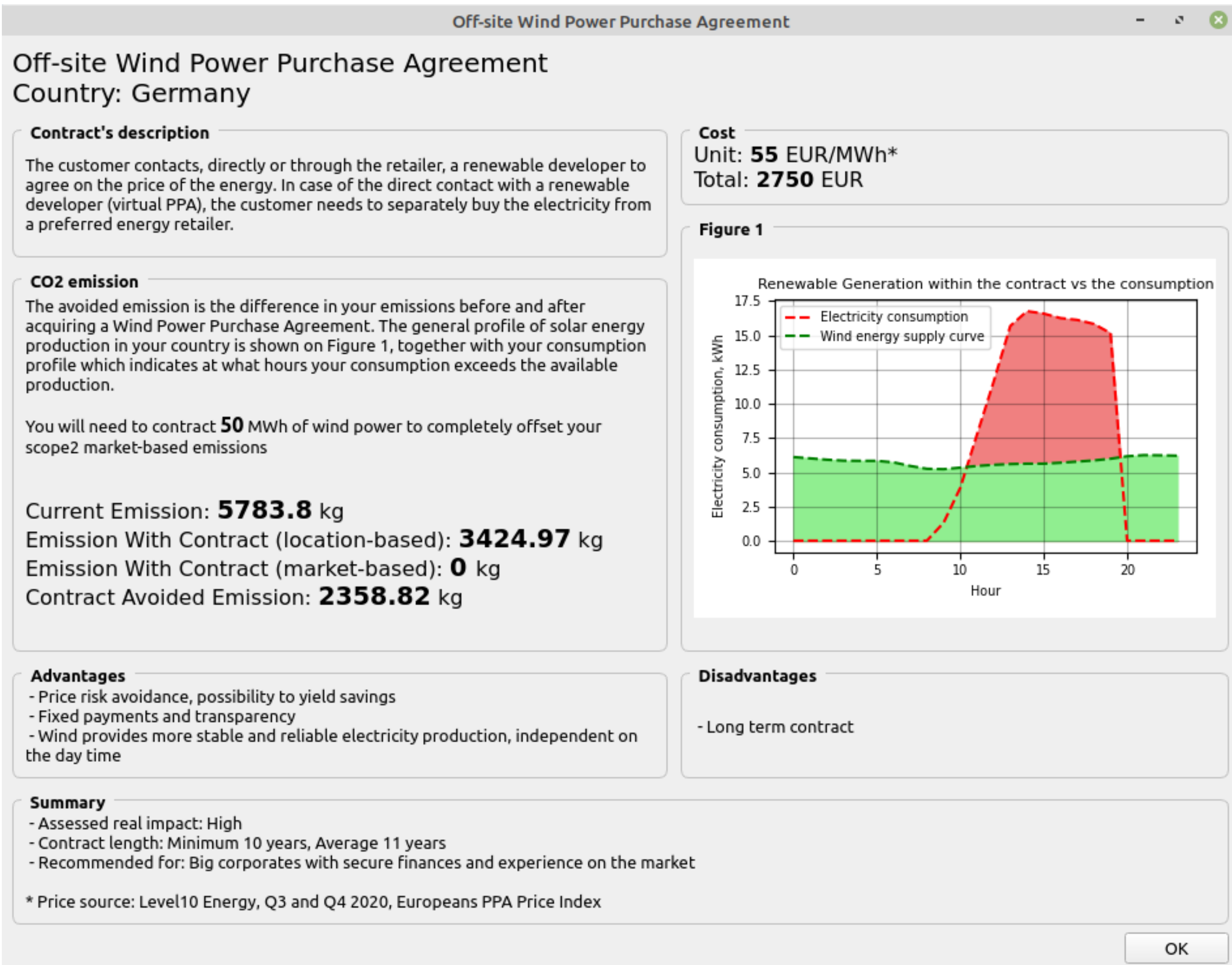

Figure B.6: GUI Contracts Details - Off-site Wind PPA

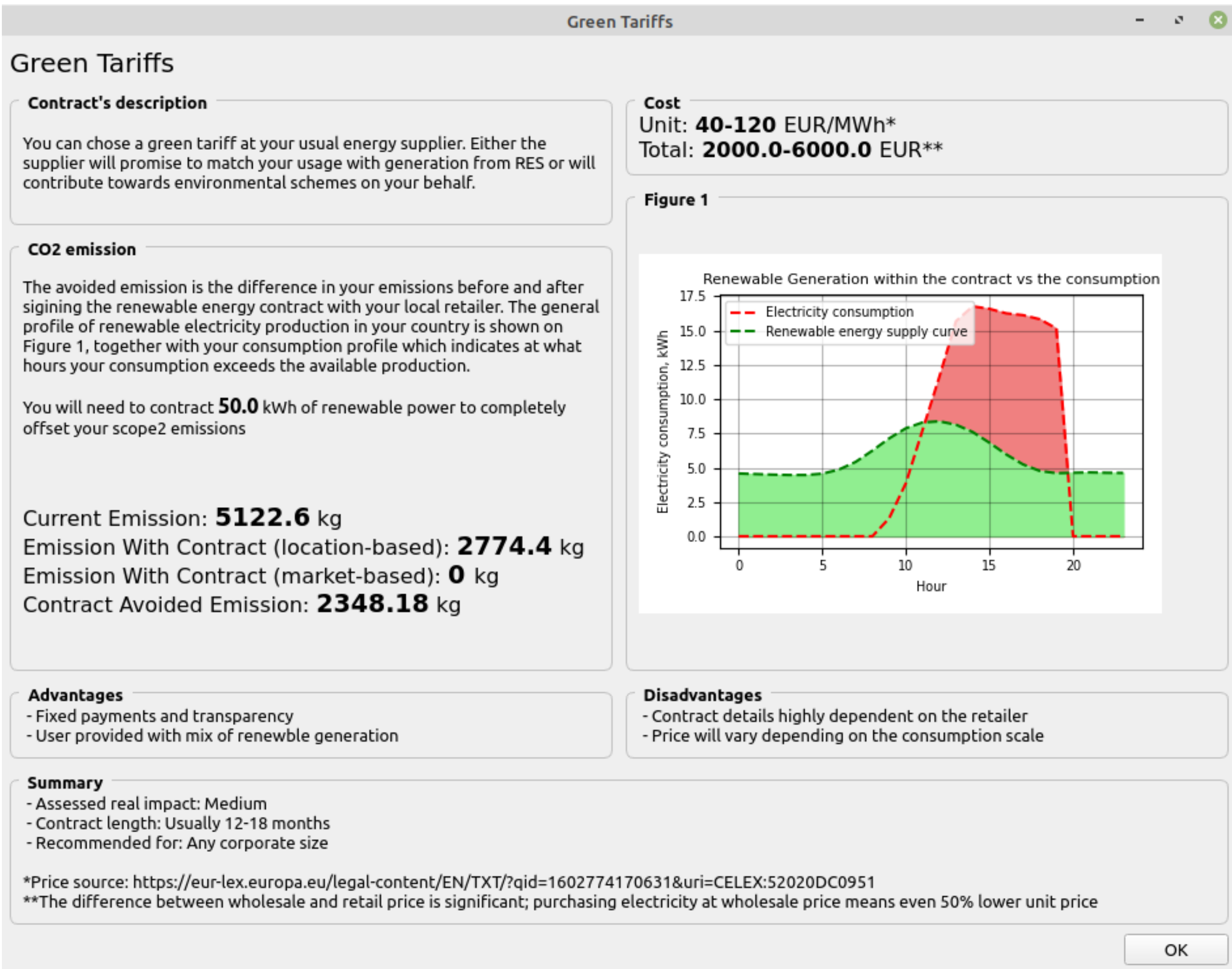

Figure B.7: GUI Contracts Details - Green Tariff