RECOMMENDATIONS FOR THE FURTHER DEVELOPMENT OF THE GERMAN SYSTEM OF GUARANTEES OF ORIGIN

Severin Sylla, FfE[1], +49 89 158121 85, ssylla@ffe.de
Michael Hinterstocker, FfE, +49 89 158121 53, mhinterstocker@ffe.de
Alexander Bogensperger, FfE, +49 158121 38, abogensperger@ffe.de
Louisa Wasmeier, FfE, +49 158121 57, lwasmeier@ffe.de
Amanda Pleier, FfE, +49 89 158121 80, apleier@ffe.de
Simon Koderer, FfE, +49 89 158121 86, skoderer@ffe.de
Kristin Wagner, FfE, +49 89 158121 85, krwagner@ffe.de

1. Introduction

The energy transition and the associated departure from fossil energy sources is an ambitious transformation project that requires the interaction of many components of the energy system. It is not only the expansion of renewable energies (RE) or the grid that are crucial, but also adequate markets, digital control options, and the participation and acceptance of individuals and companies. Above all, existing components and regulations must be adapted to meet the current state of the energy transition and future developments without thwarting them. An example of such a component is the Guarantee of Origin (GoO), which forms the basis for green electricity tariffs. Green electricity tariffs suggest to customers that they contribute actively to the energy transition. However, due to many factors, this is only very limitedly the case. For example, the term "green electricity" is not clearly defined legally in Germany. However, it can be derived from § 42 of the *Energiewirtschaftsgesetz* (Energy Industry Act, “EnWG”) [1] as a minimum requirement that a green electricity product is an electricity product whose electricity labeling exclusively indicates renewable energy (RE) sources that must be backed up with corresponding GoOs in terms of quantity [2].

Clear labeling of the origin of electricity is of great importance for various energy-related application areas (Figure 1). It should not only facilitate the marketing of certain electricity products as green electricity, but also, for example, facilitate action against fraud and greenwashing, provide an incentive for the expansion of electricity generation plants from RE sources, and have a steering effect on user behavior.

More and more households and companies are signing up for green electricity tariffs. The underlying goal behind this decision is often to actively support the energy transition and reduce one’s own ecological footprint. To demonstrate the connection between the decision to purchase a green electricity tariff and its environmental impact, according to § 42 EnWG, the electricity mix and the associated greenhouse gas emissions must be disclosed in all electricity supply contracts. Electricity suppliers demonstrate the origin of electricity from RE sources through GoOs, which are issued and managed in Germany by the *Herkunftsnachweisregister* (Guarantee of Origin Register, “GoOR”). This is necessary because in market trading, electricity loses information about its origin which must thus be exchanged separately. For this purpose, renewable electricity producers apply for GoOs for the electricity generated by their facilities and subsequently market them to suppliers, who in turn provide proof to their end consumers. If a supplier can demonstrate that GoOs from RE sources have been acquired and canceled for the total consumption of their customers, they can advertise a green electricity tariff.

To convey to consumers that green electricity products possess added value which exceeds the legal minimum requirements, various green electricity labels (e.g., "Grüner Strom" [3], "OK Power" [4], TÜV Süd "EE01" [5] and "EE02" [6], TÜV Nord "Geprüfter Ökostrom" [7], "EKOEnergie" [8], "RenewablePLUS" [9]) play an important role today in Germany. They are intended to demonstrate that green electricity products certified with such a label significantly advance the energy transition. The criteria for certifying green electricity products are not legally prescribed but are individually determined by independent label providers. Therefore, the effect of green electricity products strongly varies, even if certified by a green electricity label [10]. While in general it can be understood by customers to what extent different green electricity products, for example, create added value for the energy transition through investments in new RE power plants, the large number of labels and criteria requires considerable research effort and knowledge of the energy industry.

The physical delivery through the grid, the trading of electricity on the markets, and the transfer of GoOs through the GoOR take place separately from each other. During physical delivery, generation and consumption must

[1] Forschungsstelle für Energiewirtschaft e.V. (FfE), Am Blütenanger 71, 80995 Munich, Germany

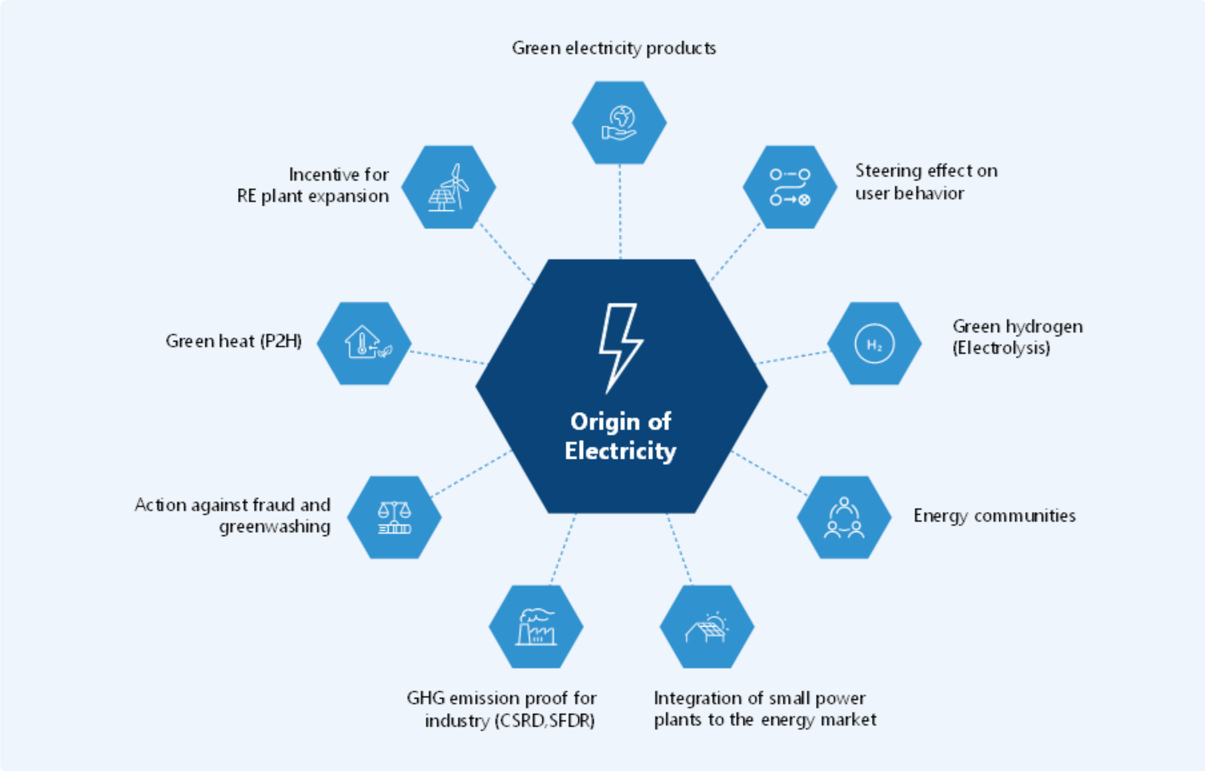

Figure 1: Application areas of electricity labeling

always be balanced to keep the energy system stable. This is indirectly taken into account in trading, as all balancing groups for which electricity is procured from generators (usually through markets) must be balanced within 15 minutes. As a result, electricity prices on the markets adequately reflect both supply and demand, as well as the current availability of generation and consumption.

However, GoOs are temporally decoupled from generation and consumption. Their accounting period is one year, which means that generation and consumption do not have to occur simultaneously, but only within the same calendar year. Additionally, GoOs can be imported from abroad independently of physical delivery. Due to this strong temporal and spatial decoupling between generation and consumption, the weather-dependent and seasonal availability of renewable generation is not reflected. Moreover, the majority of GoOs which are canceled in Germany comes from Scandinavian hydropower. Far more GoOs than physical electricity are imported from these countries [2].

This temporal and spatial decoupling, as well as the integration of European markets, leads to an oversupply of GoOs and correspondingly low prices. Their purchase is inexpensive, allowing suppliers to cheaply "green" their electricity products without actively contributing to the energy transition. As a result, the impact of green electricity tariffs on the expansion of RE is very limited [2].

Furthermore, the processes in the GoO system are currently oriented towards large generation facilities and have limited capability to accommodate small-scale power plants such as PV modules on residential rooftops which are increasing due to the decentralization of the generation structures [11]. In particular, the GoO granularity of 1 MWh and the high registration and account fees make it uneconomical for small-scale power plants to participate in the GoO system. The phase-out of numerous facilities from subsidies under the *Erneuerbare-Energien-Gesetz* (Renewable Energies Act, “EEG”) [12] in the coming years exacerbates this situation [10], making these facilities eligible for using the GoOR. This is expected to lead to a significant increase in the number of managed facilities and GoO transactions, for which the current system is not equipped.

The GoO system in Germany is formed on one hand by the requirements of German and European regulations, and on the other hand by the concrete implementation of processes from the issuance and transfer of GoOs to their cancellation for electricity labeling. In Germany, the implementation is currently carried out through the GoOR, which is managed by the *Umweltbundesamt* (Federal Environment Agency, “UBA”).

The German GoOR is part of the European Association of Issuing Bodies (AIB). A total of 35 members [as of end 2022] have standardized their requirements for certification and trading of GoOs via the European Energy Certificate System (EECS). This enables the international trade of GoOs as required by EU Directive 2018/2001 on the promotion of the use of energy from renewable sources (also known as Renewable Energy Directive II, “RED II”) [13]. The AIB provides an inter-registry platform, the AIB HUB, to ensure a fair and transparent trading of GoOs within Europe [14].

As mentioned above, the majority of GoOs which are canceled in Germany come from Scandinavian hydropower, which is the primary source of renewable GoOs, accounting for 60 % of the volumes issued in Europe in 2020 [15]. Norway is the largest supplier of hydro GoOs, followed by Sweden, France, Switzerland, Austria, and Italy. Germany, Sweden, and the Netherlands lead in GoO cancellations for hydro generation. Norway holds the largest market share in total supply of GoOs in Europe, accounting for approximately 20 %. The primary reason for this is that 95 % of the country’s energy production comes from hydropower, resulting in a high proportion of RE sources in Norway [15]. Germany has a significantly lower market share in the supply of GoOs, standing at 2 %. This is mainly due to the ban on double marketing in Germany, which prevents the issuance of GoOs for subsidized power plants.

However, this is likely to change, because as part of the European Green Deal and the "Fit for 55" climate and energy package, RED II is set to be amended. One significant proposal which is currently being discussed is the removal of the option to withhold GoOs from subsidized RE power plants. This revision would lift the prohibition of double marketing of electricity from such power plants in Germany and result in an increase in the issuance of GoOs. The increased availability of GoOs is expected to lead to lower prices. The legislative reform process is ongoing and the lifting of the ban on double marketing is projected to take effect around 2024/2025 [16]. In general, the market-based concept leads to different prices for GoOs depending on their local supply. For countries with low GoO prices, arbitrage opportunities arise between them and other countries, mostly Central European power markets. Unsubsidized renewable power plants are thereby incentivized to export GoOs elsewhere in Europe, where market prices are high, thus limiting local GoO supply. Although the GoO system was standardized with the EECS, members have freedom in implementation, thus fragmenting the market. All in all, the international trade of GoOs leads to lack of transparency for consumers, as they cannot retrace the origin of their purchased electricity.

The current regulatory framework fails to ensure reliable information for final consumers due to unlimited trading of GoOs regardless of physical reality, leading to discrepancies between disclosure information and official statistics. In fact, the international trade of GoOs exceeds the actual international physical flows, and the traded quantities of electricity attributes are much higher than what can be realized in physical flows given the present interconnector capacities [17]. An example that recently attracted some media attention is the case of GoOs generated in Iceland. During recent years, most of the GoOs which were issued in the country were exported to continental Europe although there is no physical connection between the two electricity grids. Controversially, Icelandic companies also claimed large quantities of electricity consumption to come from RE sources based on the location-based electricity mix in Iceland. This obvious double marketing of Icelandic green electricity led AIB to a compliance assessment against its Icelandic member Landsnet. Based on the assessment, AIB suspended all exports of Icelandic GoOs [18].

The GoO system has been designed as a tool to merely label electricity from RE sources, as indicated in RED II. The GoO system does neither have a large effect on the progress of the energy transition, nor is it suited to fulfill the requirements of certain energy economical applications that arise with the steadily advancing energy transition, such as the supply of detailed high-resolution data for corporate sustainability reporting or for green hydrogen. This study aims to highlight conflicting issues and potential solutions. One focus is placed on the crucial role that GoOs play in the energy transition. Demands on GoOs and major challenges are identified based on present and future energy-economical applications. Solutions are proposed such that the GoO system can fulfill the current and future requirements that arise from these applications. The proposed solutions are presented in a roadmap for the further development of the German GoOR which suggests a step-by-step evolution starting from the status quo, without the need to overturn the whole GoO system. Additionally, the analysis is put into an international context, discussing the synergies and challenges when adjusting not only the German GoO system to the demands, but also transferring our results to the European level.

2. Methods

Solutions are proposed based on requirements expressed by stakeholders, our own experience from building an energy data platform for electricity labeling in the research project InDEED, and investigation of external conditions and other developments in research, businesses and the regulatory framework. The methodology and results in this work partly follow our recent study "*Zukunftsfähige Herkunftsnachweise – Roadmap zur Weiterentwicklung*" [10].

In order to identify the requirements for an improved labelling process, the current and future applications of a GoO system are analyzed. To this end, stakeholder interviews were conducted. When selecting the interview partners, particular attention was paid to existing personal or indirect experience with the GoOR. This includes the trading of GoOs in day-to-day business as well as expertise on electricity labelling built up elsewhere. Most of the interviewees work in energy supply companies. Employees of conventional energy suppliers as well as of energy suppliers with a distinct green power product portfolio were approached in order to capture different perspectives on the electricity labeling system. A total of eight interviews were conducted in a digital format, each lasting one hour. In the interview, a previously prepared questionnaire was filled out together, covering the topics of user experience, the importance of the GoO system certificates for the energy transition, and suggestions for further development of the GoO system. The format of filling out a questionnaire together was chosen in order to be able to carry out both a quantitative evaluation of the answered questions and to allow for oral elaboration and explanations on certain main topics. The statements of the interviewees were analyzed based on categories and sub-categories derived from these topics.

Based on the current and future demands on GoOs which we identified by the methodology described above, we analyze the status quo of the German GoO system and identify improvements to the system which are critical in order to fulfill those demands. We then summarize our proposed path from the status quo to a future-proof GoO system in a roadmap which allows a step-by-step development of the German GoO system.

3. Results

In this section, the economic framework and requirements for electricity labeling and thus for the GoO system are initially examined from the application side, based on current developments in research, energy industry, and the regulatory framework. Subsequently, the results of the stakeholder interviews are summarized. Then, we present our roadmap for the further development of the German GoO system, followed by a brief description of the InDEED data platform as an example of fully digitized high-resolution electricity labeling. Finally, we extend our examination to the international perspective.

3.1. Economic framework and requirements

In this section, the economic framework and requirements for a revised GoO system are presented from various perspectives. The aim is to derive the implications and requirements for the GoO system from these perspectives. Individual aspects related to the GoO system are briefly explained, and the resulting implications are elaborated upon. This includes the following topics:

- The smart meter rollout,
- Corporate finance and sustainability reporting,
- the prohibition of double marketing for subsidized energy quantities in Germany,
- sector coupling,
- other developments such as energy communities, local markets, and power purchase agreements (PPAs).

3.1.1. The smart meter rollout

Intelligent metering systems, also known as smart meters, are part of the fundamental infrastructure for the digitalization of the energy system, including the GoO system. They enable the automated collection and transmission of high-resolution measurement data, which can be used for real-time billing and balancing. In the future, this data could also be used for real-time electricity labeling.

The German smart meter architecture consists of a digital meter and a smart meter gateway (SMGW), with the latter serving as the central communication unit for receiving, storing, processing, and communicating measurement data with other market participants [19]. The SMGW ensures a high level of information security based on the technical guideline TR-03109 issued by the Federal Office for Information Security (BSI). It utilizes a public key infrastructure (PKI) to prevent unauthorized data access. Energy suppliers, network operators, and metering point operators can act as active or passive market participants with different data access rights.

According to the *Messstellenbetriebsgesetz* (Metering Point Operation Act, "MsbG") [20] regulations, mandatory installation of smart meters is planned by 2032 for at least 95 % of all end consumers with an annual electricity consumption of over 6,000 kWh. End consumers using controllable consumption devices according to § 14a EnWG, as well as operators of RE systems or combined heat and power systems with an installed capacity over 7 kW, are also required to have a smart meter. However, the rollout was initially suspended due to issues with interoperability, but a provision was later made to allow voluntary installation of previously BSI-certified SMGWs. A recent amendment to the MsbG aims to accelerate and streamline the smart meter rollout, enhance its legal certainty, and adjust the distribution of metering operation costs. The rollout plan in this *Gesetz zum Neustart der Digitalisierung der Energiewende* (Act for the Restart of the Digitalization of the Energy Transition, “GNDEW”) [21] primarily aligns with the target year 2030, aiming to establish the necessary digital infrastructure for a largely climate-neutral energy system by that date [22]. As of today, Germany is lagging behind other European countries in the smart meter rollout, with only a small percentage of the total metering points equipped with smart meters [23].

The German SMGW architecture enables automated data collection from meters through various communication channels, eliminating the need for manual readings. It can be connected to electricity, gas, and potentially water meters in households. It also allows communication with a Home Area Network (HAN) for controlling electrical devices and facilitates communication with external market participants through the Wide-Area Network (WAN) interface. The SMGW administrator, typically the metering point operator or a designated third party, is responsible for its secure operation. The digital infrastructure, with the SMGW as a central component, enables automated and time-resolved metering, providing real-time visualization of energy consumption and potential savings. It allows for the detection and correction of measurement errors, as well as the development of new pricing models based on variable tariffs. The high-resolution data supports energy-related processes such as billing, balancing, and grid management. Network operators can benefit from access to detailed data for forecasting and managing critical grid conditions, while also having the ability to control and steer grid-connected assets.

Overall, smart meters provide a basis for the GoO system to obtain generation values from RE power plants in an automated, direct, and significantly higher temporal resolution than before. This allows for the gradual reduction of the previous balancing period of the GoO system from one year (status quo) to quarters, months, weeks, days, and down to 15-minute intervals. In our roadmap (see below), smart meters play a central role in the revision of the GoO system.

3.1.2. Corporate finance and sustainability reporting

Sustainability criteria are increasingly becoming the focus of European industry. Important political influences in recent years include the UN’s Agenda 2030 "Transforming our world" with its 17 Sustainable Development Goals [24] and the Paris Climate Agreement [25]. At the European level, the European Green Deal aims to make the EU climate-neutral by 2050. In the context of the European Green Deal [26] and the Sustainable Finance Strategy [27], new regulations are being introduced for corporate reporting, including the Corporate Sustainability Reporting Directive (CSRD) [28], Sustainable Finance Disclosure Regulation (SFDR) [29], and EU Taxonomy [30]. These regulations place greater emphasis on sustainability in corporate strategy, management, performance assessment, and financing.

Companies above a certain size are required to disclose the sustainability of their business operations, in addition to financial aspects. The emissions considered can be divided into three categories: Scope 1 (direct emissions), Scope 2 (indirect emissions from purchased energy), and Scope 3 (indirect emissions within the value chain). Key indicators such as Scope 2 greenhouse gas (GHG) emissions become mandatory in the sustainability reporting requirements of the CSRD [31] and SFDR [32]. To determine these Scope 2 GHG emissions, companies need data on their electricity consumption and the corresponding electricity mix. The indirect GHG footprint of the different sources of electricity generation can be determined via emission factors [33], [34].

For the increasing demand for data on sustainability aspects, precise data on energy consumption such as the specific electricity mix or knowledge of the origin of the energy used play a crucial role. In [35], the authors conclude in the context of the CSRD that aspects such as country of origin, technologies and age of plants, or the criterion of additionality can become increasingly important. The planned key indicator in the sustainability reporting requirements of the CSRD [31] is also the energy consumption differentiated between different sources, for which data on the origin of the energy is needed. This applies not only to electricity but also to other energy carriers such as heat, gas, and prospectively to hydrogen.

In general, it can be observed that the consideration of the entire value chain and the life cycle of products and business activities is gaining importance in the new regulations. According to the CSRD proposal, for example, a description should be provided of "the principal actual or potential adverse impacts connected with the undertaking’s value chain" [28]. The EU Taxonomy explicitly states that the assessment criteria should be based on life cycle assessments [30]. The method of life cycle assessment plays an increasing role in sustainability reporting and management. It is used, among other things, to determine cumulative energy consumption, carbon footprints, or broader environmental footprints of products or organizations. Important standards referred to in the EU Taxonomy include ISO 14067:2018 for the carbon footprint [36], [37], [38], and the "Recommendation 2013/179/EU" of the European Commission for the development of product or organization environmental footprints (PEF/OEF) [39], [37], [38]. However, the "Recommendation 2013/179/EU" for PEF/OEF is currently being revised in a new version [40]. Precise energy origin data and data on the energy mix of usage play a crucial role in determining a carbon or environmental footprint through life cycle assessment. With the help of emission factors, they quantify the environmental impacts of energy consumption in business activities. Both in the old and the revised PEF/OEF recommendation by the European Commission [39], [40], it is stated, for example, that the electricity used from the grid should be modeled as accurately as possible with a preference for supplier-specific data. The energy supplier should guarantee, for example, that the energy used from renewable sources is not simultaneously attributed to others. Similar requirements also exist in ISO 14067:2018 [36].

Environmental management systems aim to collect environmental key indicators of the company, such as those of the European Eco-Management and Audit Scheme (EMAS) [41], [42], which is based on ISO 14001 [43]. Core indicators of EMAS include, for example, energy consumption and GHG emissions [41]. It is not mandatory but plausible to further disaggregate energy consumption by energy sources and include corresponding indirect GHG emissions through electricity consumption. For this, data on the origin of electricity or energy is needed – the more precise, the better. This could also be potentially applicable for the energy management system ISO 150001.

The origin of the energy used or supplied also matters when companies have set goals for RE use, sell “green products” with corresponding promises, or (e.g., in supply or framework contracts) assure customers that no electricity from fossil generation plants is used. In such cases, individual energy consumption data can be used for internal control to fulfill certain external (marketing) promises.

In the GHG Protocol [34], two methods to quantify indirect emissions from purchased energy are specified. These methods serve as the basis for carbon accounting standards in the CSRD. The first method, market-based emissions, focuses on emissions that companies can influence through their choice of electricity product or supplier. GoOs play a significant role in reducing these emissions. Companies can procure GoOs through their electricity supplier, directly on markets, or through brokers. PPAs can be signed, ensuring a physical supply of RE for a longer period. Electricity not covered by GoOs is accounted for using an average emission factor from the grid [34]. The options for reducing a company’s market-based emissions include energy consumption reduction, procurement of RE from specific providers, direct purchasing from wholesale markets, self-procurement and retirement of GoOs, off-site or financial PPAs, and investing in off-site RE facilities.

The second method, location-based emissions, reflects the average emissions intensity of local grids, including locally generated RE and directly connected RE systems. Individual consumers cannot directly influence location-based emissions. However, increased demand for products that reduce market-based emissions is expected to contribute to long-term reduction in location-based emissions [34]. Strategies to decrease a company’s location-based emissions include energy consumption reduction, flexible adjustment of electricity consumption based on real-time carbon intensity of the grid (given a high-resolution emission intensity), own investment or on-site PPAs with RE systems.

It is intentionally limited for companies to influence location-based emissions. The division between market-based and location-based emissions assumes that increasing demand for GoOs to reduce market-based emissions will have an impact on the energy transition and thereby on location-based emissions. However, the UBA stated that guarantees of origin currently have a limited impact on the energy transition. According to them, GoOs act solely as a balancing instrument that takes existing generation capacities into account without adding new ones. They mentioned that the construction of new RE plants through direct marketing will only occur if the market price for renewable electricity exceeds the revenue secured by the EEG. The UBA also noted that a higher demand for GoOs would result in a shortage, leading to an increase in price. They stated that this price increase could serve as an incentive for the electricity industry to invest in new power plants. However, they highlighted that the European green electricity market is currently far from reaching such a scenario, as the supply of electricity from renewable sources exceeds the demand for green electricity tariffs throughout Europe [44].

The European integration of GoOs currently leads to inexpensive imports from Scandinavia. However, debates in countries like Norway about leaving the GoO market could lead to significant price increases in the future [35], potentially impacting the attractiveness of green energy products. Furthermore, the majority of German RE production is supported through the EEG during the first 20 years after their installation and is therefore not eligible for GoOs due to the double marketing prohibition. As an increasing number of power plants reach the end of their EEG subsidy in the coming years, the supply of GoO will increase, which can have a downward effect on GoO prices. If efforts of the EU commission to abolish the double marketing prohibition [16], [35] are successful, further price declines for GoOs can be expected, weakening or offsetting the potential incentive effect described earlier. Low GoO prices benefit companies wishing to "green" their Scope 2 emissions, but they do not have an impact on the energy transition and location-based emissions.

According to the GHG Protocol, both market-based and location-based emissions should be reported. Market-based emissions are calculated based on the energy mix provided by the European Network of Transmission

System Operators for Electricity (ENTSO-E). The ENTSO-E energy mix for Germany is adjusted by removing the amounts subsidized by the EEG and those accounted for through GoOs. Unretired GoOs are reported by the UBA to the *Bundesverband der Energie- und Wasserwirtschaft* (German Association of Energy and Water Industries, "BDEW") and included in the mix. The BDEW provides an annual average for Germany, which can be used to disclose emissions for non-green electricity on utility bills. Location-based emissions are also calculated by ENTSO-E, considering the use of fossil fuels in power plants, including all RE power plants. The resulting data is available from both ENTSO-E and BDEW.

There is currently criticism from the industry that the calculation method and the provision of annual averages are insufficient. In particular, the active load shifting for CO_2 optimization is not possible with these methods. Although various service providers already offer dat with higher temporal resolution (e.g., opendata.ffe.de [45]), there is a lack of a unified method or common standard to ensure cross-company comparability of data. Without standardization, there is a risk that company data will not be comparable, verification becomes more challenging, and data in supply chains is incorrectly calculated. Even a "race to the bottom" in calculating CO_2 values may occur within legal limits, meaning that it may not be the methodologically most sensible calculation method that prevails, but the one that results in the lowest GHG emissions.

The requirements for companies to conduct data-based and verifiable sustainability reporting are increasing. The number of companies that need to comply with these requirements will also rise. By the year 2026, approximately 15,000 companies in Germany will be subject to reporting obligations [46].

Sustainability reporting, like financial reporting, is also audited by auditors. Similarly, an auditor may issue a qualified or adverse opinion if the financial statements [and sustainability report] have such significant deficiencies that the auditor cannot form a reliable assessment [47]. This applies even if the information provided is insufficient [47]. Consequently, it is likely that in the future, robust, credible, and transparent data will be required, particularly for Scope 2 emissions, in order to obtain an audit opinion. This includes monitoring electricity consumption, proper procurement and retirement of GoOs, as well as monitoring the resulting GHG emissions. The latter depends on the sources of electricity and whether GoOs were procured and correctly retired for these quantities. Furthermore, many companies are increasingly setting their own goals or need to demonstrate and prove the sustainability of their operations to themselves, their customers, clients, or shareholders. Voluntary initiatives such as EnergyTag, which aim to achieve "24/7 clean power," are at the forefront of this new trend [48], [49].

In addition, the intended effect of high GoO prices, which is expected to have a positive impact on the energy transition, is not realized in Germany. A large volume of GOs imported from Scandinavia leads to an oversupply of certificates of origin compared to the relatively low demand for green electricity products. As a result, guarantee of origin prices have been low in recent years [2]. While an increase in demand (e.g., through the CSRD) could potentially lead to price increases, the elimination of the double marketing prohibition (see below) could offset the effect of the CSRD by causing a price decline. Therefore, it is necessary to establish an effective mechanism between GoOs and the energy transition. This could be achieved through adjustments to the GoO system or through the implementation of the CSRD in Germany.

3.1.3. The prohibition of double marketing for subsidized energy quantities in Germany

Currently, in Germany, the double marketing prohibition states that GoOs cannot be issued for energy quantities subsidized via the EEG. However, the future of this prohibition is uncertain, as it may be abandoned in the upcoming RED III legislation [16], [35]. If the double marketing prohibition is lifted for all new and existing power plants, it would lead to a significant increase in the supply of GoOs, potentially causing a price decline. If GoOs were issued for the entire renewable electricity production in Germany, the country would become a net exporter of GoOs [15]. This could allow energy suppliers and large industrial companies to acquire cheap GoOs and label their electricity consumption, or that of their customers, as "green" and GHG-neutral. However, this would not contribute to the energy transition as the power plants generating the additional GoOs already exist and do not depend on the volatility and seasonal availability of RE sources. To prevent the devaluation of GoOs, it was suggested to limit the focus to newly supported power plants subsidized according to the EEG [35].

In our recent study [10], we conducted an analysis based on the *Marktstammdatenregister* (Master Data Register, "MaStR") [50], load factors for different RE generation types [51], and the *Herkunfts- und Regionalnachweis-Gebührenverordnung* (GoO and regional certificate fee regulation, "HkRNGebV") [52], estimating the amortization of costs for different types of power generation facilities participating in the GoO market. The analysis shows an increasing number of potential market participants in the coming years, with a significant increase if the double marketing prohibition is removed. Regardless of the possible end of this double marketing prohibition, the number of GoOs issued in Germany is expected to be much higher than today, by 2040 reaching over 80 % of the total electricity generation from RE sources generated in 2021. Correspondingly, this would result to roughly 200 million GoOs per year issued in Germany by 2040, which is more than ten times of the approximately 18 million GoOs issued in 2021.

The analysis also indicates that low GoO market prices make it economically challenging for small-scale power plants, such as rooftop PV systems, to participate in the GoO market. However, for many operators of such power plants, GoOs could provide an opportunity to market their produced electricity as green power after the expiration of EEG subsidies. The unpredictable price development poses an economic barrier for small-scale power plants. Regardless, the annual number of GoOs issued in Germany could reach a nine-digit range by the 2030s, similar to the total electricity generation from renewable sources. If the double marketing prohibition is lifted, this situation could occur as early as 2025. In such a scenario, the issuance, transfer, and retirement of additional GoOs would require an automated solution to reduce the significant manual effort involved in the current system.

Overall, it is crucial to consider the implications and challenges associated with the GoO system, particularly in terms of scalability and automation, to handle the potential increase in GoO issuance and market participation.

3.1.4. Sector coupling

The coupling of different sectors is becoming increasingly important for a successful energy transition. This document focuses on the electricity-based generation of green hydrogen and heat, as well as the implications of current developments in these areas for the GoO system for electricity. GoOs for green hydrogen and heat are not the main focus here.

Green hydrogen plays a crucial role in decarbonization efforts, and its production methods vary, including steam reforming, methane pyrolysis, and electrolysis. The climate impact of hydrogen production depends on the source and method used. Two key challenges for the GoO system are ensuring proof of green electricity for hydrogen electrolysis and tracking the origin of hydrogen through different transportation methods.

The "Delegated Act" to Article 27 of RED II [53] sets conditions for attributing RE to hydrogen production for the transport sector, which may also serve as a basis for regulations in other sectors. The Delegated Act outlines four criteria for classifying hydrogen as green, such as direct connection to RE sources, a high share of renewable electricity in a specific country, power purchase agreements with specific requirements regarding the additionality of power plants and the simultaneity of electricity generation and consumption, or reduced need for redispatching due to electrolysis.

For heat, which contributes significantly to emissions, similar challenges arise in terms of proving green electricity for heat generation and tracking the origin of heat when production and consumption are spatially separated. The existing GoO system for electricity can serve as a basis for issuing GoOs for heat, but the increasing demand for heat pumps is expected to raise the need for GoOs for electricity. However, the current system does not provide sufficient transparency or incentives for load shifting to reduce emissions, limiting the full potential of electricity-based heat generation.

From the EU directives and the current plans of the EU in the form of the "Delegated Act" or through the drafts of RED III, higher requirements for the GoO system are indicated. An important requirement is the coupling of generation facilities with individual consumers and the proof of simultaneity of generation and consumption. Solutions have already been developed in Germany that allow for the proof of simultaneity, for example, through environmental assessors. However, this leads to additional bureaucratic hurdles and costs, which particularly affect the economic viability of the end product (e.g., green heat or hydrogen), especially for smaller facilities. A fully digital solution that does not require environmental assessors or similar entities and can demonstrate simultaneity with high temporal resolution and at low cost is therefore a necessary next step for the GoO system. Furthermore, the lessons learned from the implementation of the GoO system for electricity and possible improvements should also be taken into account when establishing registers for heat and hydrogen/gas.

3.1.5. Other developments

In recent years, new possibilities have emerged on the basis of digitalization, which can interact either directly or indirectly with the GoO system. These opportunities include energy communities, local markets, and PPAs and are briefly described below.

Energy communities can be described as a group of individual actors (citizens, businesses, public institutions) who voluntarily accept certain rules to act together in the energy sector to pursue a common goal [54]. The EU has defined two terms in the context of energy communities within the framework of two directives. Firstly, "citizen energy communities" were regulated in the EU internal market for electricity directive 2019/944 in 2019 [55]. In citizen energy communities, a community consisting of citizens, small and medium-sized enterprises, and public institutions can allocate, share, or trade electricity, participate in the energy market, aggregate, or provide various energy services. The community may also potentially operate the local grid (the design is optional for EU members). Secondly, "renewable energy communities" were introduced in RED II in 2018. They are similar to citizen energy communities but are not limited to electricity and can also utilize other RE sources. Additionally, the members of a renewable energy community are located in close proximity to the facilities they operate.

Renewable self-consumers, also introduced in RED II, aim to “empower renewables self-consumers to generate, consume, store, and sell electricity without facing disproportionate burdens”.

The goal of these three concepts is to provide equal and fair access to the energy market for the mentioned legal entities. Disproportionate costs and administrative barriers should be reduced. In Germany, as of the time of this study, these provisions were not specified further. However, the actions mentioned in the concepts are not prohibited at present but the current implementation of the GoO system poses challenges and bureaucratic hurdles, particularly for small-scale power plants, in demonstrating the simultaneity of generation and consumption.

Local markets enable small RE producers, prosumers, and consumers to trade electricity, usually through an automated platform. Transparent exchange and trading of electricity are essential in these markets, and participants need to know the origin of the electricity for their actions. However, the formal requirements of the GoO system, such as application, transfer, and cancellation of certificates, create difficulties, especially for smaller power plants, which may hinder the operation of local green electricity markets.

PPAs are long-term electricity supply contracts. There is currently no clear regulation of the term PPA but it is rather a collective name for various distinct kinds of contracts in energy jurisdiction [56]. They can be divided into utility-PPAs and corporate-PPAs based on the parties involved, and into physical and financial PPAs based on their implementation. PPAs aim to provide long-term marketing and procurement of RE with price security and assurance of green characteristics and origin. However, the current process of proving the renewable origin of electricity generated, delivered, and consumed through a PPA requires environmental assessments, which could be simplified through digital solutions.

In conclusion, to facilitate the integration of energy communities, local markets, and PPAs into the GoO system, it is necessary to reduce costs, administrative burdens, and regulatory barriers. Simplifying and digitizing the process of proving the origin of electricity within these contexts would enable a more efficient and transparent energy market while supporting sustainability goals and the energy transition.

3.2.Stakeholder interviews

The interviews revealed a clear trend among stakeholders who regularly use the GoO system, expressing dissatisfaction with its complexity and the associated effort. Most respondents identified simplification, automation, and improved user-friendliness as the most crucial areas for improvement in the GoO system. They suggested creating an Application Programming Interface (API), improving the interface’s clarity and usability, and implementing overarching user profiles for service providers. Figure 2 shows a selection of results from the interviews.

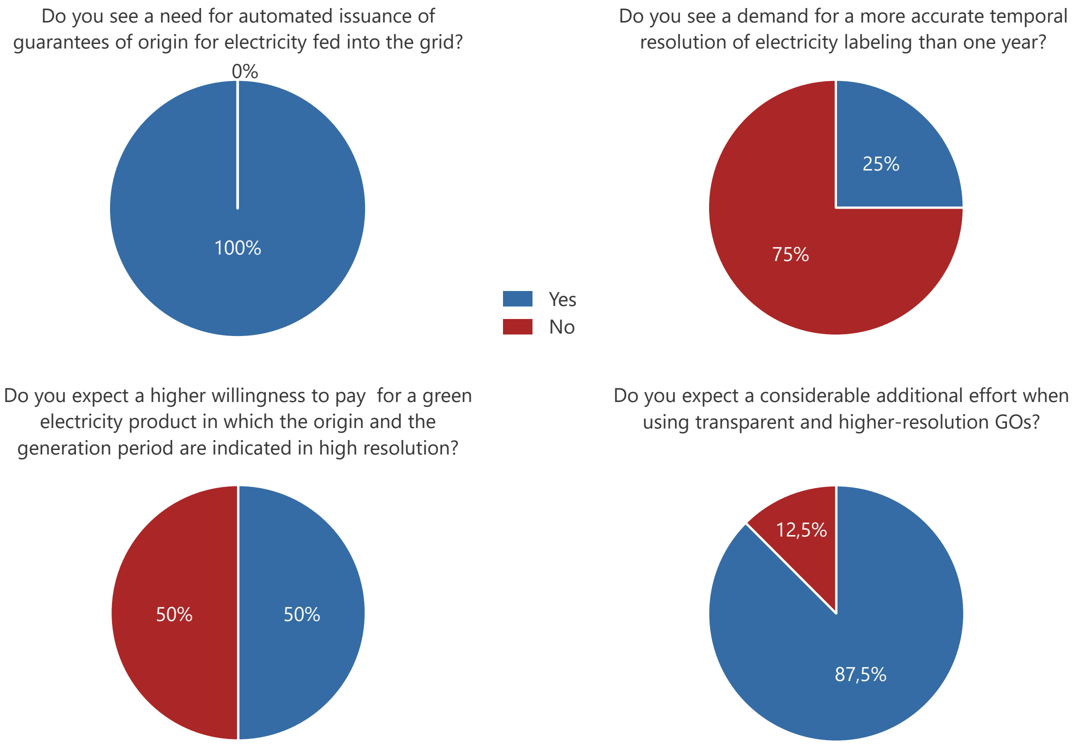

Figure 2: Selected Results from Stakeholder interviews

Regarding the significance of the GoO system for the energy transition, the majority of respondents acknowledged the importance of transparency in labeling of green electricity. However, they felt that the current system provided little added value to accelerate the transition due to factors such as the lack of incentives for new power plant investments and the practice of "greenwashing" electricity from unknown sources using GoO certificates from Norwegian hydropower plants. While some respondents criticized limiting GoO trading to German certificates, they doubted customers' willingness to pay a premium for such a product. Even providers offering certified green electricity products expressed difficulties in conveying the added value of regional marketing through the GoO system.

Concerning potential developments in the GoO system, the majority of respondents considered additional issuance of GoO certificates for EEG-subsidized power plants as reasonable. However, some expressed concerns about the administrative burden associated with the large number of small-scale, EEG-supported power plants. While most respondents saw an increase in temporal resolution as theoretically beneficial from an energy economics perspective, those with practical experience using GoOs opposed it due to the anticipated increase in complexity and lack of digital infrastructure. Similar concerns were raised regarding a certificate size smaller than 1 MWh. However, some respondents suggested reducing the certificate size to facilitate access for operators of small-scale power plants. Other key improvement suggestions included reducing fees for small-scale power plants, additional labeling for electricity from fossil sources, eliminating the "preliminary cancellation" process, and improving transparency in electricity labeling.

In conclusion, the stakeholders had mixed opinions on the development of a high-resolution and transparent GoO system. Those with personal experience of using the system were concerned about the increased effort, as they believed the current system already allowed for many improvements. Furthermore, there were doubts about customer demand and willingness to pay higher costs for associated electricity tariffs. Challenges such as corporate sustainability reporting have yet to fully reach energy providers, as increased demand is expected in the coming years.

Overall, it is evident that the multifaceted challenges highlighted in this work are slowly reaching energy suppliers. However, the resulting pressure for change is still insufficient to drive fundamental modifications to the current system. This poses a problem as requirements, such as sustainability reporting from 15,000 companies, will rapidly increase, and adjustments to supplier processes and the GoO system can take years. Therefore, it is crucial to redesign the GoO system to quickly accommodate future demands. Additionally, there are immediate improvement opportunities within the current system to simplify present and future usage.

3.3.Roadmap for the further development of the German guarantees of origin system

As already explained in the previous sections, the current and future requirements exceed the functional scope of the current design of the GoO system. Figure 3 summarizes the requirements that the German GoO system meets or does not meet in the status quo. It is evident that the GoO system, as currently designed, has little impact on the energy transition. Moreover, new technical possibilities have emerged since the initial implementation of the registry, which can be taken into account in a redesign. For this reason, a roadmap is described below on how the GoO system can be successively developed. The roadmap is oriented towards the availability of technologies, for example, and relies as much as possible on digitalization and automation. The individual steps of the roadmap are shown in Figure 4.

3.3.1. Creation of digital interfaces

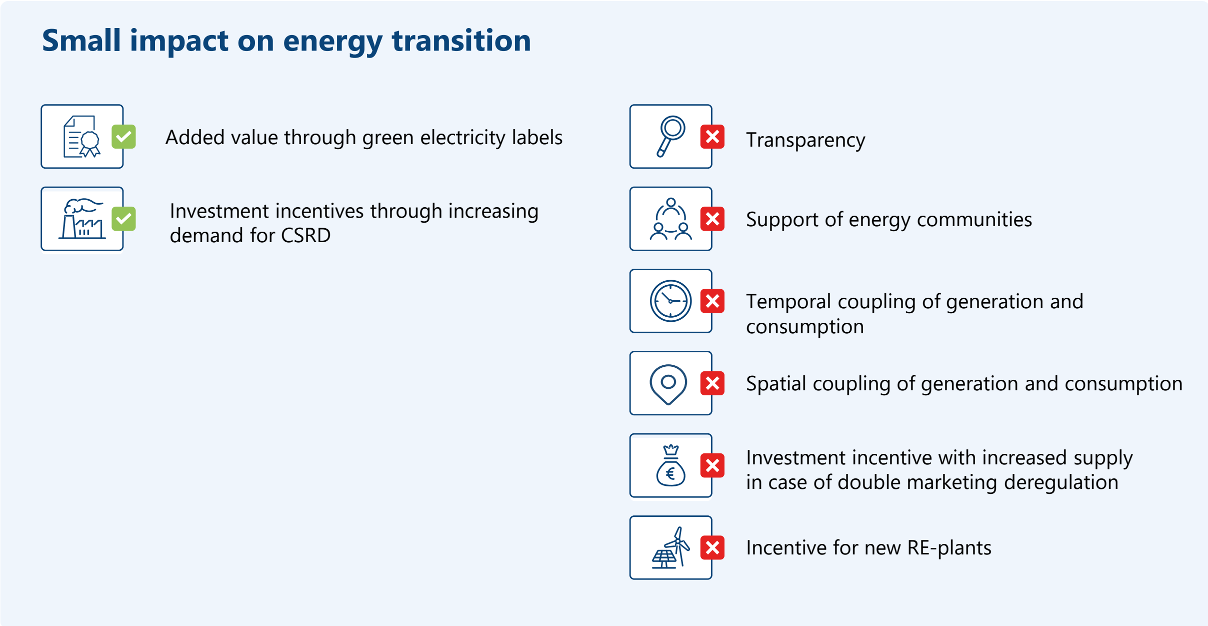

Figure 3: Impact of electrity labeling on the energy transition in the status quo

The German GoOR currently provides only a web interface for the registration, application, transfer, cancellation, etc., of GoOs. However, it is particularly time-consuming for companies that manage a large number of facilities to manually handle these processes. Additionally, this approach leads to the allocation of significant resources.

To enable efficient and automated handling of GoO processes, it is necessary to offer corresponding interfaces, as is typically done on digital platforms. This is especially relevant given the increasing number of small-scale power plants and transactions, as well as a higher temporal resolution in the future. Digital interfaces provide users with more freedom in automating their processes, allow for automated data exchange, and offer prospective new functionalities. This proposed solution was also suggested by respondents of our stakeholder interviews and in [35].

The challenges involve an IT transition and the creation of an Application Programming Interface (API). All existing and planned functionalities should be accessible via the API. Assessing the challenges for integrating an API into the existing system architecture of the GoOR can only be done by the UBA. One of the most commonly used architectures for these interfaces is based on the REST and HTTP standards. An alternative is the Simple

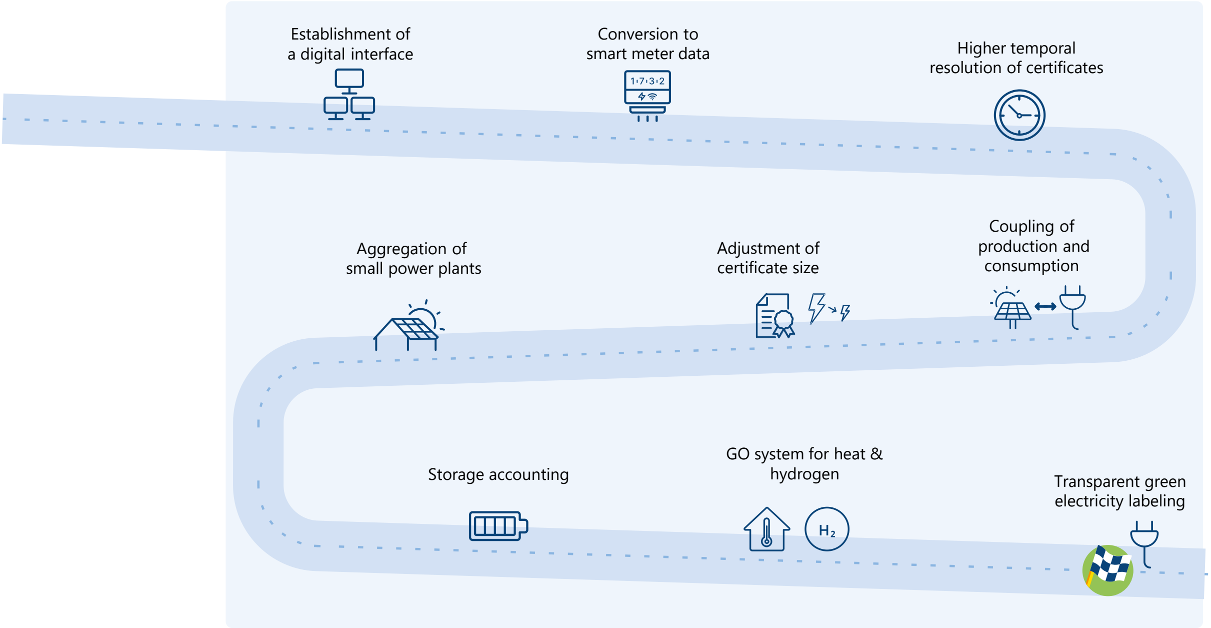

Figure 4: Roadmap for the further development of the German GoOR

Object Access Protocol (SOAP) managed by the World Wide Web Consortium (W3C). However, REST APIs are easier to scale and implement in websites and services [57].

3.3.2. Transition to smart meter data for data collection

In the current GoO system, energy quantities from which GoOs are derived are requested from the metering point operator (MPO). This exchange relies on the EDIFACT standard for exchanging energy quantity data with metering point operators. The data is requested by the UBA and sent via encrypted emails (S/MIME). For RE power plants above 100 kW, the necessary data, especially electricity generation per year, is already available in 15-minute resolution from the MPO (§ 9 EEG). This is because such data is required for balancing purposes. Generation values are sent to network operators and energy marketers by the MPO. For smaller power plants, manual meter reading is necessary.

Although EDIFACT is an older standard, it is commonly used for communication in the energy sector. The main challenge lies in the underlying process of meter data collection and transmission through the network operator. Increasing the frequency of data retrieval is difficult because high-resolution meter values are typically not read directly after measurement. Therefore, with this process, it is only possible to achieve a limited increase in the temporal resolution of the proof of electricity origin. A process that involves active querying by the UBA to the MPO and is conducted via email or one that includes too many intermediaries is not sufficiently efficient to automate and scale the frequency of data transmission or the number of facilities.

The smart meter infrastructure will provide a unified, standardized, secure, and reliable means for the GoOR to directly obtain generation data from the facilities themselves, or automated through the responsible MPO. By law, 95 % of RE power plants over 7 kW will be equipped with an SMGW by 2032, which enables access to the measured data. The transmission of data through the standardized and certified smart meter infrastructure is recommended as a suitable solution and should be utilized wherever available. Alternatively, a separate metering and data transmission system specifically for participation in the GoO system is conceivable. However, utilizing the already deployed smart meter infrastructure is associated with lower overall costs, imposes lower entry barriers on market participants due to established processes and access channels, and ensures defined data quality with high temporal resolution (potentially with substitute value creation). The required functionality for the GoO system is already fulfilled by Generation 1 of SMGW. Alternatively, data retrieval can also be automated by the MPO. However, it should also be considered to utilize an appropriate interface that is sufficiently scalable for high-resolution data transmission in the long term.

Smart meters are gradually rolled out, and this also provides an opportunity for the GoO system to undergo a step-by-step transition. Parallel operation is possible, allowing the necessary hardware and software to be acquired and the processes to be tested on individual power plants. If this testing is successful, a mandatory transition can be implemented for all RE power plants equipped with an SMGW within a transition period. Alternatively, it is also conceivable to define the SMGW as a mandatory requirement for participation in the GoO system, indirectly accelerating the rollout. By 2032, all power plants over 7 kW should already be equipped with an SMGW according to existing requirements.

The advantage of this solution is that communication with the MPO via EDIFACT is no longer necessary. However, according to § 49 MsbG, it is necessary for the GoOR to obtain the consent of the connection user in the corresponding market role in order to access the data.

3.3.3. Increase of temporal resolution of Guarantee of Origin certificates

According to the *Durchführungsverordnung über Herkunfts- und Regionalnachweise für Strom aus erneuerbaren Energien* (Regulation on Proof of Origin and Regional Proof for Electricity from Renewable Energies, "HkRNDV") [58], the generation period of a GoO is defined as the month in which the generation of a quantity of electricity of 1 MWh is completed. A GoO can be transferred to the account of another account holder within the trading period, which extends up to twelve months after the end of the generation period. It expires if it is not canceled within 18 calendar months after the end of the generation period. However, in Germany, a GoO can only be used to label electricity quantities that have been supplied by an energy supply company to consumers in the same calendar year as the generation period of the electricity quantity for which the GoO was issued (§ 30 HkRNDV). GoOs can fulfill their intended purpose of labeling green electricity to consumers for a maximum of 12 months.

The low temporal resolution of GoOs does not reflect the actual availability of RE, which leads to the overestimation of greenhouse gas reduction by many companies through the purchase of GoOs [59]. This issue is also reflected in the requirements for "green" hydrogen, for example. The current GoO system is not sufficient for its classification. Higher temporal resolution evidence becomes increasingly relevant for many new business models and contractual arrangements. For example, it is possible for a company to cover its relatively constant consumption over a year with the GoOs of a large solar power plant in Southern Europe, even though the power plant does not generate any electricity at night and may not frequently import electricity to Germany.

This decoupling of generation and consumption results in consistently low GoO prices, as it allows the labeling of green electricity from periods of high RE supply to be shifted to periods of low RE share. The lower the temporal resolution, the less influence the seasonal and weather-related volatility of RE supply has on the certificate price. Due to these low prices, the impact of high demand for green electricity products on the incentives for the system-friendly expansion of RE is severely limited. In case the issuance of GoOs to subsidized power plants will be legally enabled in the future, the supply increases significantly, further lowering the price of GoOs.

A higher temporal resolution of GoOs could counteract a potential price decline resulting from GoOs from subsidized power plants and the resulting low incentive for RE expansion. For example, a quarterly or monthly issuance and cancellation of GoOs would at least capture seasonality. Only higher resolutions (e.g., daily) would capture weather-induced fluctuations. However, the daily volatility associated with solar and wind power generation would only be reflected if GoOs were cancelled within a few hours for the respective consumers. The trading of GoOs and the processing (issuance and cancellation of GoOs) do not necessarily have to occur during the window in which the electricity is generated or consumed. They can also take place before or after this period. The crucial factor is to increase the temporal connection between the generation and consumption of green electricity.

The prerequisite for transitioning to a higher temporal resolution is data collection through smart meters. This enables automated data retrieval, with negligible time delay. Transitioning to quarterly or monthly resolution appears to be generally feasible within the current system. However, smaller time intervals would increase administrative and communication efforts. Additionally, the number of transactions would increase proportionally. Determining the temporal resolution always involves a trade-off between effort and added value.

The transition can be carried out gradually. The temporal resolution can evolve from annual to semi-annual, then quarterly, and finally monthly. GoOs can still be traded within the familiar time periods. However, a certificate can only be canceled for consumption that occurred within the same time period (e.g., 15 minutes). In principle, a parallel operation is possible for a certain period, where high-resolution GoOs are traded for those plants that already have smart meter data available, while GoOs for other plants are still traded at a lower resolution.

Limiting GoOs to quarters or months allows for the representation of seasonality in certificate availability. This will also be reflected in prices, as the supply of solar generation, for example, is significantly lower in winter months compared to summer. This is particularly advantageous for generation units that can produce electricity or store it long-term independent of seasonality.

Increasing the temporal resolution to at least one hour brings additional benefits. At this resolution, it is no longer possible to cover the entire electricity demand with PV-GoOs alone. This creates incentives to build renewable generation facilities that can provide electricity precisely when existing power plants can only do so in limited quantities and when certificate prices are high. Thus, it promotes the system-oriented expansion of RE. Another advantage of hourly GoOs is the creation of incentives for load flexibility. However, the prices of green electricity increase as a result, which may result in lower demand.

3.3.4. Coupling of generation and consumption

In the current GoO system, there is the option of "optional coupling" between generation and consumption. This is intended to ensure that there is an actual supply relationship between renewable electricity generation in Germany and electricity consumption, thereby excluding purely virtual shifting of the green attribute [60], [61]. Only a fraction of 0.9 % of all GoOs, but 7.4 % of domestic GoOs are coupled GoOs [60].

The GoO system only covers the part of electricity supply from the generation facility to the supplier. The supply to the end customer is currently not part of the GoO system. However, during the process of GoO cancellation, the energy supplier can specify a specific electricity customer or product for which the GoOs are canceled. In the current GoO system, when opting for coupling, an environmental auditor must verify that the announced renewable electricity generation corresponds to the coupled delivery quantity. The auditor needs to review the balance sheet transactions and schedules to rule out counteractive bookings. Furthermore, evidence must be provided to demonstrate that an actual delivery from the RE facility has been recorded in 15-minute intervals within the balance sheet and without counteractive bookings.

The requirement for verification of the coupling between GoOs and physical generation or consumption through an environmental auditor leads to unnecessary costs and effort. Additionally, it raises questions about whether an analogue audit in practice provides the desired level of assurance that the supply has actually been carried out properly. The automated verification of a delivery contract underlying a trading transaction without counteractive bookings cannot be covered by the InDEED labeling solution (see below). However, with a quarter-hourly resolution, it could be ensured that the generation and consumption of green electricity match for every quarter-hour. This would significantly mitigate the incentive for counteractive bookings which could only persist for regional resolution. Therefore, this presents another important argument for increasing the temporal resolution to quarter-hourly intervals.

3.3.5. Adjustment of certificate size and handling of small-scale energy production

In the current GoO system, there is no differentiation between different types of facilities or their capacity in terms of processes. However, the procedural effort involved in registering a facility, applying for and transferring GoOs, the GoO size of 1 MWh, and the associated fees make it particularly challenging for small-scale power plants to participate. Additionally, low prices for GoOs due to competition from abroad further reduce profitability. This becomes especially challenging when owners of small-scale power plants, for example, want to sell or share electricity locally as part of energy communities or local energy markets. Currently, it is generally required for RE facilities to use the GoO system to market their generated electricity as "green electricity." This poses a barrier for small-scale power plants.

Two proposed solutions aim to address these challenges. The first solution proposes simplifying participation in the GoO system, reducing costs and effort for producers through better digitalization, the use of smart meters, and digital interfaces for streamlined administration. Reducing the GoO size from 1 MWh to 1 Wh would also be beneficial, offsetting the additional effort through digitalization. The second solution suggests introducing an opt-out option for small-scale power plants up to a defined threshold. These power plants engaged in electricity trading or exchange within energy communities or local markets would be allowed to market their electricity as green within those contexts, without regular GoOs. To avoid double marketing, the opt-out would be digitally indicated and confirmed once. Energy service providers would indicate the local share of green electricity to consumers. Practical implementation of this opt-out has been developed in the InDEED research project [10], [62].

Prerequisites for both solutions include adjusting the existing legal framework, establishing mechanisms for participation, and implementing digital procedures. Smart meters would play a crucial role, and a register could regulate each power plant’s chosen path to prevent double marketing. The transition should be tested using real energy communities, developing and testing digital interfaces and cryptographic methods for compliance. The transition would allow small-scale power plants to participate in energy communities and local markets without excessive bureaucracy, reducing administrative and technical barriers.

Determining an appropriate threshold for small-scale power plants in the second solution proposal requires analysis. In addition to the share of small-scale plants in the total German RE plant park, Figure 5 shows an estimate of the amount of electricity generated annually by these plants (as a percentage of total RE electricity generation per year). The estimation is based on the MaStR and with load factors fixed to the mean of the historical and forecasted values from 2009 to 2026 [51] for PV, wind, hydro and biogas power plants, respectively. The load factors of wind power plants were estimated as a weighted average of the values for offshore and onshore plants, with weights corresponding to the (forecasted) average power in the years 2009 to 2026 [51].

Kinks at 10 kW, 30 kW, and 100 kW are observed in Figure 5, influenced by technical, fiscal, and regulatory requirements. For example, power plants up to 10 kW were exempt from the EEG levy for own consumption until the end of 2020 and from income tax until the end of 2021. From 30 kW, a ripple control receiver was required until the end of 2020 (from 25 kW from 2021). From 100 kW, a system operator does not receive a fixed feed-in tariff but must market the electricity generated directly and can benefit from the EEG subsidy via the market premium model.

A threshold of 10 kW would exempt 61 % of all RE power plants from the GoO system, but they would generate only 3 % of the annual renewable electricity generation. The RE power plants up to 10 kW, which by large parts are operated by PV prosumers, could generate around 8 million GoOs per year through, for example, aggregation. It should be noted that a significant portion of the electricity generated by these power plants, about 10-50 % [63], [64] can be directly used by the prosumer and is therefore not available for GoO certificates. A threshold of 30 kW would exempt 88 % of power plants, covering 8 % of the annual renewable electricity generation. The RE power plants up to 30 kW could generate approximately 17 million GoOs per year. A threshold of 100 kW would exempt 95 % of power plants, representing 11 % of the annual renewable electricity generation. These power plants could generate approximately 26 million GoOs per year.

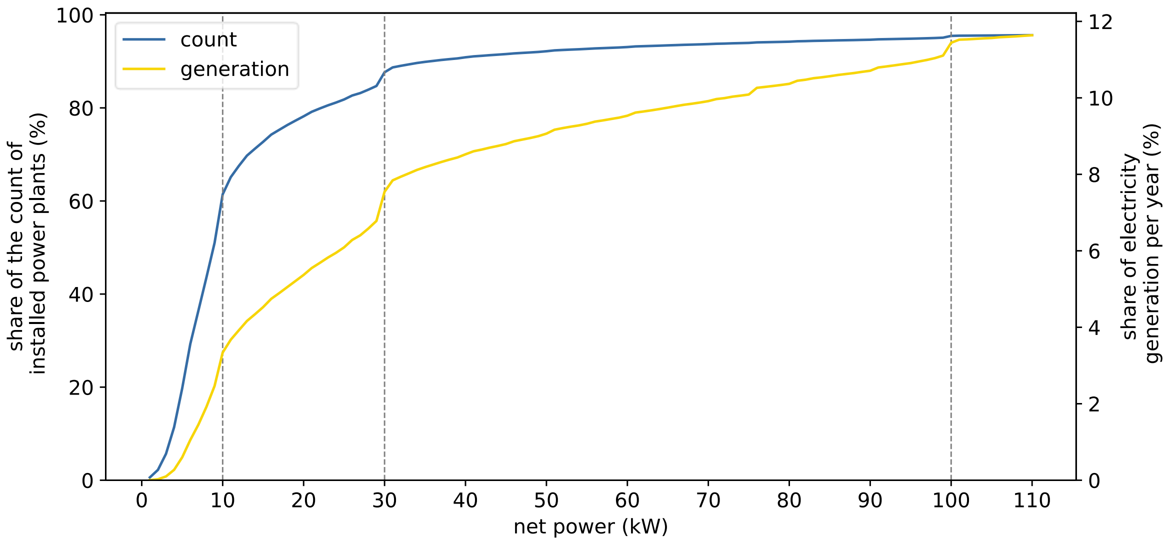

Figure 5: Cumulative number of small-scale power plants in Germany as well as the amount of electricity generated by these plants per year, as a function of the net power. The number of plants is given as a percentage of the RE plants installed throughout Germany and the amount of electricity per year as a percentage of the total amount of electricity produced by RE plants per year. Vertical lines are drawn for orientation at 10 kW, 30 kW and 100 kW.

3.3.6. Aggregation of small-scale energy production

Currently, individual registration of power plants with the UBA is required. This prevents the aggregation of many small-scale power plants due to the associated administrative burden. While the registration process can potentially be significantly reduced using APIs, the costs and time required for registration and transactions act as entry barriers for many small-scale power plants.

Apart from the certificate size of 1 MWh, the main challenges for participating in the GoO system are the costs and efforts involved. Additionally, for small prosumer power plants, data privacy is a concern. For example, if the RE generation of a small power plant can be traced on a daily or hourly basis through the GoO system, and the data can be attributed to individual households, it potentially violates the General Data Protection Regulation (GDPR) [65].

To address these issues, a proposed solution involves using cryptographic methods and smart meters to assign power plants to aggregators. This assignment would be publicly visible through registers or a blockchain. Aggregators would receive surplus energy from decentralized generators and use Zero-Knowledge Proofs (ZKPs) to demonstrate the total amount of GoO certificates without revealing individual power plant data. This solution requires small-scale power plants to have smart meter gateways and the establishment of registers and rules for ZKPs.

Implementing this solution would enable aggregators to include small-scale power plants in the GoO system, eliminating barriers such as certificate size, costs, and administrative efforts. This would increase the availability of aggregated power plants and facilitate participation in the GoO system, particularly for local markets and energy communities. The use of Zero-Knowledge Proofs as evidence has been practically tested in the InDEED project. This demonstrates the possibility of trusting the data and processes of an aggregator without needing to access them directly.

3.3.7. Accounting for energy storage systems

To successfully implement the energy transition and achieve a fully renewable electricity supply, a significant expansion of storage capacities is necessary. However, the current design of the GoO system does not include the integration of storage. This is currently not practical due to the low temporal resolution of GoOs, as the storage duration is typically much shorter than one year.

When integrating storage, it must be ensured that the storage systems do not generate GoOs themselves or shift them in a way that disconnects them from the actual electricity consumption. Additionally, storage and efficiency losses need to be appropriately accounted for, which can be particularly challenging for continuously operating storage systems.

Our proposed solution to integrate storage facilities into the GoO system is based on the definition of a separate asset class for storage within the GoO system, allowing storage operators to register their assets. When charging, the storage operator covers the energy quantities drawn from the grid by canceling GoOs. The storage operator reports the information about the stored energy quantity covered by GoOs to the GoO system. When discharging the storage, the system issues GoOs to the operator if they have previously reported sufficient charging of the storage. A similar solution proposal is also made by the Energy Tag initiative in their guide on use cases for high-resolution certificates [49].

A fundamental requirement for integrating storage into the GoO system is a higher temporal resolution of GoOs. Only with a high temporal resolution (e.g., 15 minutes) can the integration of storage provide added value. There are still technical challenges to address regarding the accounting of storage losses before integrating storage into the GoO system. This includes dealing with efficiency losses and self-discharge.

The integration of storage into the GoO system enables differentiated pricing of green electricity. This can create new financial incentives for storage operators to store excess RE during periods of high availability and discharge it during periods of low availability. This can have positive effects on the expansion of new storage capacities.

3.3.8. Implications for a guarantee of origin system for heat and hydrogen

Currently, there is no standardized Guarantee of Origin (GoO) system for heat or hydrogen as there is for electricity. According to the *Herkunftsnachweisregistergesetz* (Guarantees of Origin Act, “HkNRG”) [78], a GoO system is being established for both gas and hydrogen and for heat and cold. The Delegated Act [53] which was issued by the European Commission in February 2023 sets criteria for green hydrogen to be considered fully renewable for the climate goal in the transport sector in the RED II.

The establishment of a GoO system for gas and hydrogen, as well as for heat and cold, faces two central challenges. Firstly, the respective GoO system itself faces similar challenges to the current GoO system for electricity. It is advisable to establish a system that addresses the current challenges to avoid complex transition processes like those currently required for the electricity GoO system. Secondly, the electricity-based generation of heat and cold, as well as hydrogen, requires the coupling of GoO systems to avoid inefficiencies and high susceptibility to errors. The implications drawn from the current challenges faced by the electricity GoO system for the development of other GoO systems include the implementation of digital metering, transmission of metering data to the GoO registry, and the digital and automated execution of processes.

For the establishment of a GoO system for heat and cold, handling small generation and consumption facilities is also an important issue. Similar solution proposals to those presented previously for small-scale power plants in the electricity sector can be applied here. In the case of heat, the transport inertia (e.g., latencies of up to one hour in district heating networks) does not allow for direct simultaneous matching of generation and consumption as proposed for electricity GoOs. Despite these latencies, a temporal resolution should be pursued in the heat sector that captures at least seasonality and ideally daily variations in generation capacity, in order to promote demand flexibility (e.g., flexible heat pump operation [66]) and encourage the deployment of storage in this sector. The improved storage capabilities, especially hydrogen, also increase the importance of storage accounting.

One of the crucial challenges of a future-proof GoO system is the second point mentioned above, which is the representation of various energy conversion processes within a coupled GoO system in the context of sector coupling. Failure to address this could result in significant additional effort and high potential for errors in GoO transfers. This applies, on one hand, to the electricity-based production of green hydrogen or green heat and cold, as described in the HkNRG. On the other hand, it is also relevant to couple the systems for the potential reconversion of green hydrogen into electricity or the use of green hydrogen for heat production.

The creation of digital interfaces, the transition to smart meter data, and the increase of the temporal resolution of GoO certificates are three fundamental requirements for the implementation of a coupled GoO system. This applies for both the current electricity GoO system and the planned GoO systems for gas, hydrogen, heat, and cold. If a GoO system for gas, hydrogen, heat, and cold is established taking these points into account from the beginning, significant additional effort can be avoided. Moreover, this approach could ensure that the GoO system can effectively contribute to the expansion of RE and the reduction of greenhouse gas emissions right from its introduction. Coupling a GoO system for hydrogen with a high-temporal-resolution GoO system for electricity, for example, could enable clear classification of hydrogen without requiring environmental auditors, resulting in substantial savings in effort from an energy economics perspective.

3.4.The InDEED labeling solution

The research project InDEED focuses on the conception, implementation, and evaluation of an energy labeling system. The term "labeling" here refers to the clear, transparent, and tamper-evident digital representation of feed-in, withdrawal, and storage of electricity, as well as their temporal and spatial correlation, taking into account physical boundary conditions. The project aimed to enable automated and user-friendly labeling of green electricity for RE systems. This is particularly challenging for small-scale power plants. Currently, GoO certificates are limited to 1 MWh, and the effort and costs of participating in the GoO system are not viable for small-scale power plants.

To address this issue, a system was developed to be used in the context of local energy markets, energy communities, or local electricity products. It aims to combine the newly developed labeling system with the existing, usually annual, electricity labeling. In this system, the responsibility for GoOs is transferred to the respective suppliers. However, ensuring compliance with rules and the accuracy of the evidence has been a challenge [62]. InDEED utilizes the smart meter infrastructure and combines it with new digital technologies such as Self-Sovereign Identity and Zero-Knowledge Proofs to develop a solution that provides transparent, tamper-evident, and privacy-compliant evidence of accuracy. The solution allows for the demonstration of high-resolution GoOs in real-time, considering individual contract structures and innovative business models. Figure 6 provides an overview of the design, benefits, and applications of the InDEED labeling solution.

The electricity generation data is collected through smart meters and transferred to the assigned supplier for the labeling process. Simultaneously, the electricity consumption data that the supplier needs to cover is also collected through smart meters. If sufficient electricity volumes are available, an automatic matching process is performed to allocate a certain share of the generated electricity to each consumer. This allocation can also consider individual generators and consumers, spatial proximity, consumer prioritization, contractual structures, and specific electricity products.

To prove the correctness of the allocation and adherence to other rules, a ZKP is used. The ZKP cryptographically demonstrates that all predefined rules have been followed without revealing generation and consumption data. This validation process allows for data privacy compliant evidence for public inspection of electricity labeling, even though it is performed by suppliers. The ZKP is stored on a blockchain and verified through a smart contract.

Finally, both consumers and an overarching verification authority (e.g., the UBA) receive notifications of the correctly performed electricity labeling.

This system ensures compliance with electricity labeling rules, even though small-scale power plants do not obtain, trade, transfer, or cancel GoOs through the GoO system. The system is user-friendly for end consumers and generators and only requires the use of smart meters. The prerequisites for this solution include fully end-to-end digitized and secure data transmission. Additionally, corresponding systems (e.g., digital identities, verifiable credentials, or registers) are required to verify the correctness of participants' master data, the suppliers' authorization to include specific RE power plants and consumers in their GoO system, and whether the RE power plants are subsidized or not.

An additional aspect of the presented process is the traceability and tamper-evident proof of any local surplus from small RE power plants using ZKP. It would be technically feasible to issue GoOs for these energy volumes through the existing GoO system and distribute them in the GoO market to prevent the local surpluses from being wasted.

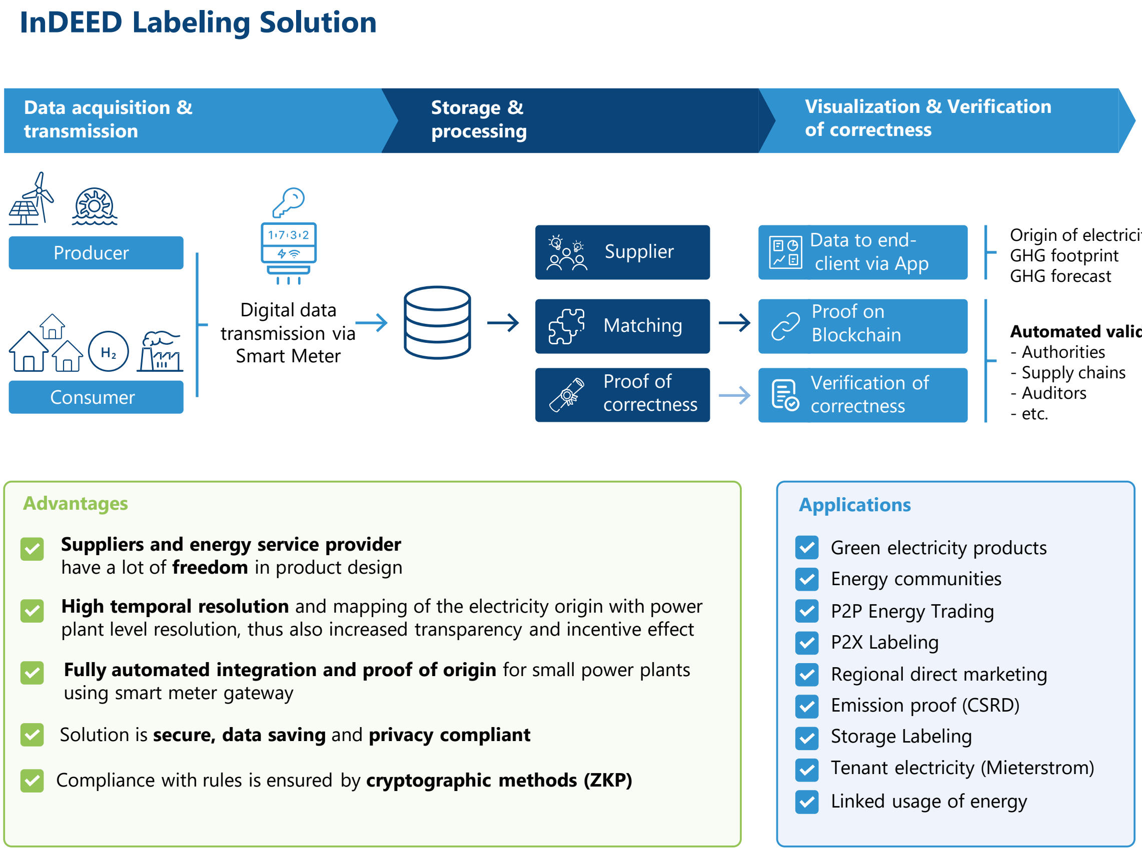

Figure 6: Design, advantages, and possible applications of the InDEED labeling solution

Conversely, if there is a shortage of electricity volumes, their regularly issued GoO certificates must be transferred to the supplier and canceled within the electricity labeling process. Given the existence of an appropriate interface, this enables suppliers to use the GoOs they acquired through the GoO system in the InDEED solution.

The InDEED project practically and conceptually demonstrated the technical feasibility of this solution. To make the solution legally viable, some changes to the current GoO system are required, as presented in this work. An earlier legal assessment analyzed potential barriers to implementation in the current state of affairs [67].

In addition to the further developments of the GoO system mentioned in the previous sections, additional improvement suggestions by other authors are briefly summarized below.

- Companies require the authority to cancel proof of origin certificates [35], [68] for sustainability reporting. If the necessary interfaces are available, this step can be significantly easier to implement.
- The abolition of the double marketing prohibition, as proposed in [35] and [68] can be best achieved after the integration of small-scale power plants and processes in the GoOR system has been optimized.

Otherwise, there is a risk of unnecessary cost increase for the UBA due to increased utilization of the GoOR.

- An adjustment of the CEN EN 1632 standard to include additional information and allow for more flexibility and the integration of the "energy transition benefit" (see [68]) is possible independently of the development steps proposed in this work.
- Self-consumption within the GoO system is currently relatively difficult to implement [35]. The integration of smart meter data, higher temporal resolution, and the coupling of generation and consumption serve as the technical basis to fulfill this requirement. This could also be achieved through the InDEED solution without the need to disclose data.
- Currently, a separate registration process and redundant data storage are required for the GoOR and many other (system) services [69]. By implementing digital machine identities or utilizing the MaStR, synergies can be created, and data quality as well as registration processes can be harmonized and simplified. However, this requires at least digital interfaces and the unique identification of facilities, such as through digital identity or metering point numbers.

3.5.International developments

Most European countries are in the process of a full deployment of intelligent metering. In Denmark and Sweden, 100 % of households are equipped with smart metering systems. Estonia, Spain, Finland, Italy, Luxembourg and Norway have reached at least 98% coverage [23]. Especially for those countries, the synchronization of GoO disclosure and energy demand are technically possible. This would also go in line with hourly market price billing, as already offered in some of the EU member states [70].

Within several projects coordinated by the industry-led, global initiative EnergyTag, a more granular issuance of GoOs as well as the interoperability with AIB, and therefore pan-European trading, was tested and evaluated. EnergyTag was initiated in 2020 with the goal to accelerate the energy transformation by defining and building a framework for hourly energy certificates [71]. The Dutch energy supplier Eneco together with Microsoft and FlexiDAO investigated the issuance and cancellation of guarantees of origin marked with the precise time of energy production. The Dutch Issuing Body CertiQ B.V stated that they see many potential benefits for the current GoO system in this innovation [70]. A similar project took place in Norway. After successfully providing the Mercedes-Benz Group in Germany with hourly certified RE, Statkraft started a pilot project in 2021 together with Unicorn, the software developer of the AIB HUB and Tibber, a Norwegian electricity supplier. The aim was to demonstrate the feasibility of issuing GoOs with hourly granularity, matching them to the consumption profile of all Tibber customers in Norway [72]. That was realized by Unicorn developing a certificate registry that allows daily and hourly issuance of GoOs. The platform is based on the EECS rules of GoOs and works within the AIB HUB. [71].

Parallelly, pan-European Spot auctions for GoOs started in September 2022 at the European Energy Exchange AG (EEX) through the French GoO registry. The market concept is a monthly multilateral auction for GoOs in European countries that are part of the EECS. Buyers and sellers can specify preferences for specific assets or regions within a pay-as-bid auction or access generic GoOs, optimizing market liquidity and transparency. Several choices are provided within three dimensions: land, technology, and subsidy regimes. The indices are published after each auction. Starting exclusively with GoOs from subsidized renewable production plants, the auctions have been extended to facilitate also non-subsidized energy. In January 2023, spot auctions reached 116 GWh of GoOs traded with 45 participants from seven countries. The majority of these GoOs were from RE under a subsidy scheme [73].

The above-described projects as well as the monthly auctioning of GoOs indicate the international ambitions for a more transparent market of GoOs which accurately reflects production and consumption of renewable energies. Finally, the European association for the cooperation of transmission system operators (TSOs) for electricity (ENTSO-E) also advocates for changes in the existing GoO mechanism to effectively support the transition to a completely decarbonized electricity system. ENTSO-E appreciates the extensive and recent discussions initiated by market participants regarding innovative GoO schemes. However, they found that the majority of these discussions indicate support for transitioning towards hourly granularity for GoOs. ENTSO-E believes that the granularity goal should in fact be set at 15 minutes to align with Europe’s target for imbalance settlement periods [74]. The proposed adaptions of the GoO system should be made possible for all AIB members to further harmonize pan-European GoO trading.

4. Conclusions

The importance of GoOs is continuously increasing. Companies require them for their sustainability reporting, as well as for green hydrogen and heat through sector coupling. The demand for higher-resolution GoOs is also rising due to energy communities, local markets, and PPAs. At the same time, digitalization offers opportunities to make the process more efficient, cost-effective, and, above all, sustainable for the energy transition. There is also a growing awareness of sustainability among both the general population and industry. Several stakeholders have already expressed the need to adjust the GoOR and the associated regulatory requirements.

The current system is struggling to keep up with the increased demands. The processes are inefficient and heavily reliant on manual inputs, and the GoOR lacks the necessary interfaces to simplify or automate them. As a result, high operating costs are incurred, making it impossible or uneconomical for small-scale power plants to participate. Moreover, the low temporal resolution and integration into European trading without considering physical boundary conditions (e.g., actual electricity flows between countries) mean that GoOs have no impact on the energy transition in Germany or Europe without the requirements of green electricity labels such as “Grüner Strom”.

This allows any supplier who procures and cancels enough GoOs to match their consumption to offer a green electricity tariff or make their market-based emissions appear green. Consumers then pay a higher price for presumably purchasing green electricity, while they physically receive their local energy mix [74], [17]. Considering that the system is relatively difficult for outsiders to understand, it can be understood why GoOs (similar to CO_2 offsetting) are associated with the perception of ecological indulgence trading [75], [76], [77]. It is therefore important to modernize the system and create real value when marketing and purchasing renewable electricity or GoOs. This value is created when GoOs have an impact on the energy transition. This can be achieved by increasing their prices and making them particularly valuable for new power plants. Renewable electricity and any resulting additional costs due to increasing GoO prices should remain optional.

There are numerous possibilities to further develop the GoO system. These include the creation of digital interfaces for better and more cost-effective processing and automation of processes, the utilization of smart metering infrastructure (if available), and the increase in temporal and spatial resolution of GoOs. The coupling of generation and consumption, necessary, for example, for green hydrogen or PPAs, can be greatly simplified through digitalization and the preceding steps. A challenge today is the certificate size of 1 MWh and the handling of small-scale power plants, which practically cannot participate in the GoO system. However, this complicates the labeling of green electricity in local markets or energy communities. Consistent digitization allows for cost reduction, administrative burden reduction, and the inclusion of small-scale power plants. Modern cryptographic methods like ZKPs also allow for the inclusion or aggregation of power plants outside the GoOR for GoOs. Compliance with rules (e.g., avoiding double counting) is ensured in the process. When establishing GoOR for heat and gas/hydrogen, the criticisms of the GoO system for electricity should be taken into account. In particular, digital interfaces and the utilization of modern measurement infrastructure, if available, would be desirable.

Some European countries already have better prerequisites and are willing to make the GoO market more transparent and consumer-oriented. A stepwise transition of the entire AIB Hub would be highly beneficial, especially because the software and processes could be initially tested in individual countries and then gradually be expanded to the EU. To truly depict physical flows, the actual cross-border transmission capacities, i. e., how much can be physically delivered, should be taken into consideration.

Overall, there are various optimization opportunities for the GoO system, enabling more efficient processes, automated handling, greater sustainability, and more room for innovation among users. It also allows the UBA to handle a higher number of power plants with fewer personnel and costs. As described in Section 3, it can be expected that the requirements will quickly increase. The described development steps entail increased personnel effort, costs, and, in some cases, regulatory adjustments.

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