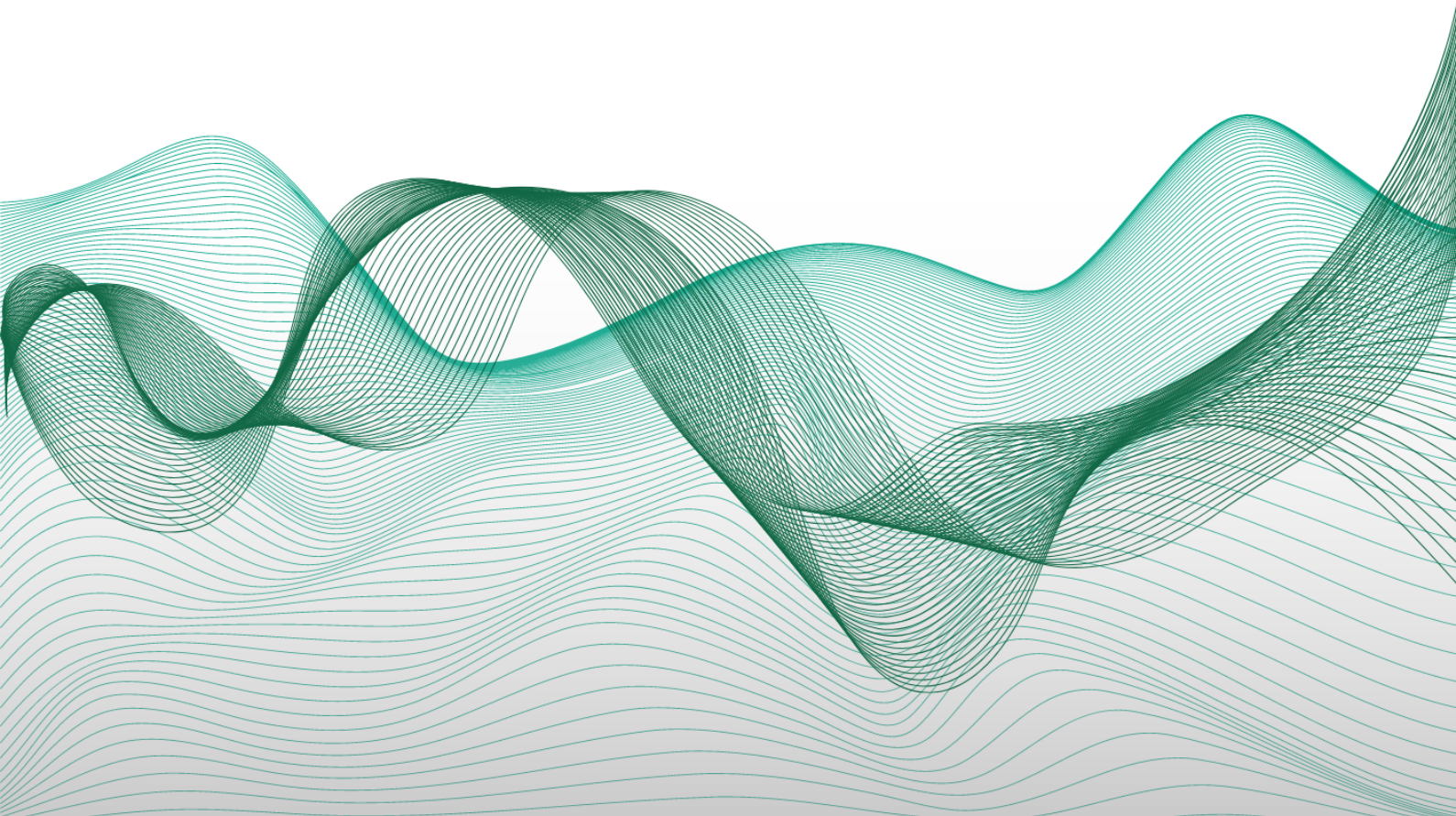


HOURLY RESIDUAL MIX

Granularity Matters: Filling the Data Gap for Granular Carbon Accounting

A Methodology for the European Certificate Region



Impressum



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Abstract

This paper proposes a methodology to calculate an hourly residual mix for the AIB region, aiming to fill the data availability gap for a more granular accounting approach. The methodology proposed in this paper is based on publicly available certificate data published by AIB and power system data provided by Electricity Maps. Overall, it highlights the limitations of the current EAC system by analysing certificate claims at an hourly level, proposes a calculation for an hourly residual mix and assesses the impact of using hourly residual mix emissions data in granular market-based Scope 2 carbon accounting.

By increasing the temporal granularity of certificates from annual to hourly, this work highlights the mismatch between renewable electricity consumption claims and actual renewable generation patterns, which the current annual certificate system omits. A Scope 2 carbon accounting case study shows that replacing hourly grid averages with hourly residual mix emission factors leads to higher market-based GHG inventories.

The purpose of this work is to propose a first iteration of an hourly residual mix methodology for the AIB region. Moreover, it should provide a foundation for further collaboration on initiatives around granular accounting between different organisations and stakeholders active within the corporate sustainability and carbon accounting space.

Executive Summary

Energy attribute certificates (EACs) have been a cornerstone of corporate renewable energy procurement and an essential instrument for companies to claim the consumption of renewable electricity. Despite their widespread use, renewable energy claims based on EACs do not properly represent the physical reality of the electricity grid and thus can be misleading. This is due to the fact that electricity consumption claims do not match generation patterns of technologies both in time and space, especially with the expansion of intermittent renewable sources like solar and wind. To increase the accuracy and credibility of these claims, a more granular market-based Scope 2 accounting system has been proposed to align corporate renewable consumption claims with actual generation patterns. Accounting with granular certificates would not only enhance transparency, but also drive more impactful corporate action towards grid decarbonization - yet a more granular approach would require refining the residual mix calculation to an hourly level.

The presented paper proposes a methodology to calculate an hourly residual mix for the Association of Issuing Bodies (AIB) region, aiming to fill the data availability gap for a more granular accounting approach. The methodology proposed in this paper is based on publicly available certificate data published by AIB and power system data provided by Electricity Maps. The paper discusses the limitations of the current EAC system and shows the potential of granular certificates to more accurately represent the physical flow of electricity. The purpose of this work is to propose a first iteration of an hourly residual mix methodology for the AIB region and provide a foundation for further collaboration on initiatives around granular accounting between different organisations and stakeholders active within the corporate sustainability and carbon accounting space.

Top-line-findings

Insight 1: EAC (Energy Attribute Certificate) purchasing appetite for green electricity consumption claims differs significantly among AIB region countries. Although the technology to trace electricity flows between these countries is available, the lack of publicly available certificate data prevents a clear oversight of how certificates match with physical delivery of power on a geographical level..

Public certificate data allows AIB region countries to be categorised as net-importers or net-exporters of certificates. Net-importers buy certificates from other countries to satisfy local demand, while net-exporters sell surplus certificates to the European market. For instance, Ireland (a net-importer) consumes 8 times more certificates than issued locally. In some situations, satisfying local demand is only possible by sourcing EACs from the European market. The following figure represents the proportion of cancellations over issuances in the countries analysed in this study to identify net-importers and net-exporters countries.

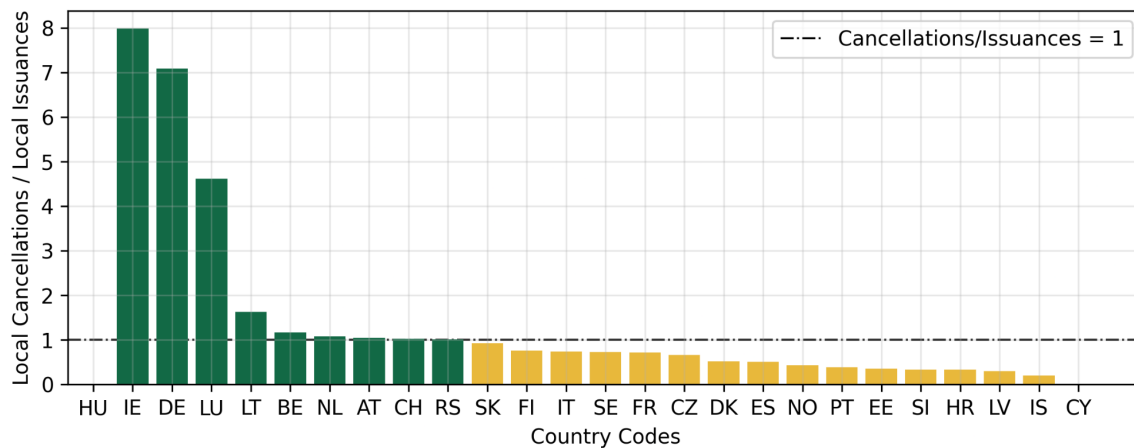


Figure 1. Net-Importers (green) and Net-Exporters of Certificates (orange)

Ideally, publicly available certificate data would enable following a certificate from where it is issued to where it is finally canceled so that the flow of electricity between countries can be compared with the flow of certificates, which would ultimately verify the physical deliverability of certificates. Since such comprehensive data is unavailable, it is not possible to follow a certificate from origin to sink. If such information were publicly available, it would be possible to use the flow-tracing methodology that Electricity Maps is using already today, to compare electricity flows with certificate flows. As a result, the methodology presented in this paper only focuses on an increased temporal granularity, relative to today's annual system.

Insight 2: Comparing certificate issuances with certificate cancellations on an hourly level highlights the mismatch between renewable electricity consumption claims and actual renewable generation, which the annual certificate system omits.

In today's annual certificate system, an organisation matches its electricity consumption with EACs on an annual basis. Therefore, it is possible to claim the consumption of green electricity, irrespective of when the corresponding electricity has been generated. In some cases, this means that an organisation can claim to supply 100% of its consumption with solar generation, even when consuming electricity during the night. By developing hourly certificate issuances and comparing them with hourly certificate cancellations, it is shown that a relevant portion of the certificates that are traded on an annual basis are non-deliverable at an hourly level, since the corresponding electricity is unavailable. When comparing the demand for certificate cancellations with available certificate issuances at each hour, it is found that only 90% of aggregated annual certificate volume can be serviced. It is important to note that the deliverability of certificates depends on generation profiles of different technologies and thus is different for all technologies. While dispatchable, fossil-fueled technologies such as oil, coal and gas, but also other dispatchable technologies such as nuclear show very high deliverability shares, technologies that show strong diurnal fluctuations perform much worse. This analysis shows that only 46% of all solar certificates claimed in today's annual system can be provided by corresponding available generation.

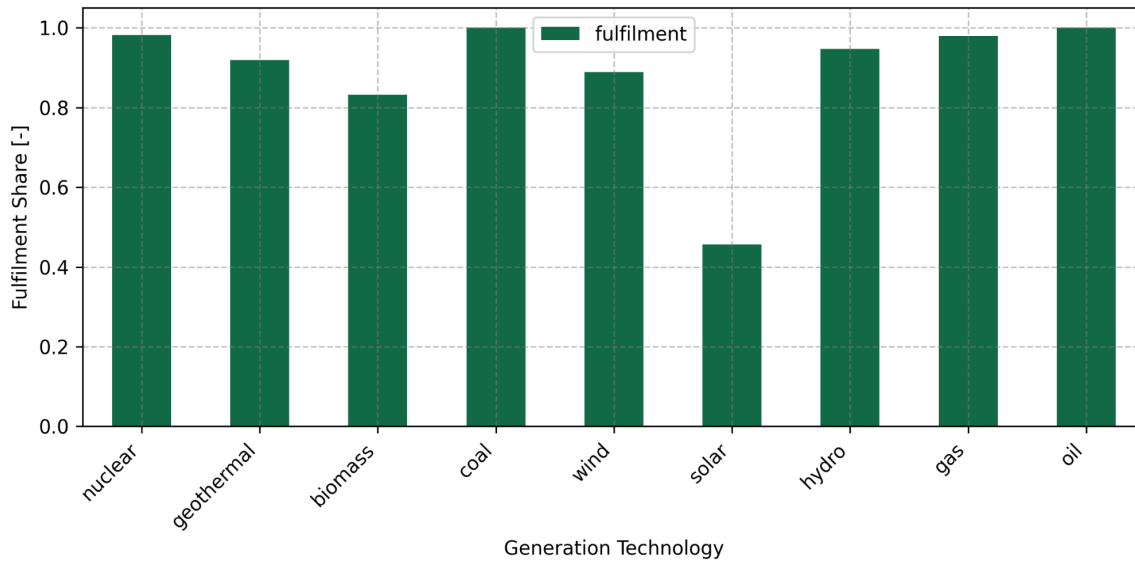


Figure 2. Share of Serviced Cancellations of Total Demanded Cancellations

Insight 3: While an increase in temporal granularity from annual to hourly certificates reduces the amount of tracked electricity that is deliverable, the effect on total residual generation volumes remains small.

Within the annual certificate system, around 29 % of the electricity generation volume within the AIB region is tracked through various instruments. As a result of this, the remaining 71 % are considered untracked generation and thus represent the residual generation volume. As highlighted above, increasing the temporal granularity from annual to hourly reduces the amount of tracked electricity and thus, increases the untracked share of electricity. This work shows that the residual generation volume at an hourly granularity amounts to 74 % of total generation, as opposed to 71 % using the current certificate system - which could be considered a minimal increase.

Insight 4: A use case analysis on Scope 2 carbon accounting shows a higher carbon emissions inventory when using hourly residual mix emission factors, relative to hourly grid average emission factors.

Without an hourly residual mix emission data set, organisations seeking detailed Scope 2 market-based inventories use hourly average grid emissions factors. Yet, average grid emissions factors include both tracked and untracked electricity, causing double-counting of renewable generation and thus an understatement of market-based Scope 2 emissions, if they are used in place of residual mix emission factors. A carbon accounting study across 4 countries reveals that substituting hourly average grid emission factors with hourly residual mix emission factors raises Scope 2 market-based emissions between 1.5% up to 152%, depending on the region.

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Peer Reviewers

A number of international professionals and sector experts reviewed preliminary drafts of this report and provided valuable feedback to improve this work. They are listed below in the alphabetical order:

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CONTENT

Abstract	2
Executive Summary	3
Acknowledgements	6
Definitions	8
Introduction	11
The Purpose of this Paper	15
A Common Baseline	19
Deriving the Methodology of Hourly Residual Mix	23
Hourly Residual Mix: Proposed Methodology	33
Results and Discussion	43
Use Case: Scope 2 Hourly Carbon Accounting	51
Future Work and Recommendations	58
References	62
Annex	66

Definitions

Definitions

Association of Issuing Bodies (AIB):

AIB is an organisation with the purpose of developing, using and promoting a standardised energy certificate system, namely the European Energy Certificate System - "EECS". To facilitate this, it acts as an inter-registry communications hub and publishes certificates and related data of the AIB region on a regular basis.

Concepts for Certificate Actions:

For this methodology, we introduce new concepts relating to certificate actions:

- **Certificate Issuance Supply:** Represents the amount of certificate issuances which result from production curves multiplied by the issuance coefficient for each technology. The issuance coefficient is derived from the actual issuance volumes published by AIB.
- **Certificate Cancellation Demand:** Represents the amount of certificate cancellations which result from the local load curve multiplied by the cancellation coefficient. The cancellation coefficient is derived from the actual cancellation volumes published by AIB.
- **Actual Certificate Cancellations:** Represents the certificate cancellation demand, that can be serviced by available certificate issuance supply. It is determined by comparing available certificate issuance supply with certificate cancellation demand and curtailing any surplus certificate demand.

Domain:

Domains represent independent markets within the AIB region. Usually, domains represent individual countries, however in special cases countries can be separated into sub-national markets. These sub-national markets are themselves considered individual domains. In our analysis, sub-national markets have been combined into countries. As a result, countries and domains can be used interchangeably in this paper.

Electricity Generation Technologies:

In this paper, we differentiate between different electricity sources using the term 'technologies'. The different technologies are taken into account in the proposed hourly residual mix methodology, following the same principles used in the current annual approach. Renewables are backed up by GOs systems, and other technologies might be tracked via other reliable tracking systems.

Energy Attribute Certificate (EAC):

An EAC is a certificate that provides information about the attributes of the underlying energy. Once issued, EACs become a tradable commodity that carry the environmental attribute of energy. This means that the underlying energy loses its environmental attributes and thus, when purchasing the underlying energy, the environmental benefits do not transfer to the buyer (unless they also purchase the corresponding EAC). Examples include Guarantees of Origin, or Renewable Energy Certificates.

European Certificate Pool (ECP):

The ECP represents the aggregation (pool) of issuances and cancellations at European level (AIB region) to be able to verify if the cancellation demand can be fulfilled with the issuances per technology.

European Residual Generation Pool (ERGP):

The ERGP collects the surplus residual generation from surplus domains and redistributes residual generation volumes to deficit domains that lack residual generation volumes.

Granular Certificate (GC):

Certificate relating to the characteristics of energy produced during a period of one hour or less. GCs are commonly referred to as time-based EACs.

Guarantee of Origin (GO):

The purpose of Guarantees of Origin (GOs) is to track the attributes of a given megawatt-hour (MWh) of renewable energy from production to consumption. A GO is a certificate under the Renewable Energy Directive (RED III) that attests the renewable origin of energy.

Tracked Energy Volumes:

Amount of energy that has been tracked using a certificate system. In the AIB region this is covered by The European Energy Certificate System (EECS).

Abbreviations

<i>AIB</i>	Association of Issuing Bodies
<i>CFE</i>	Carbon-free Energy
<i>DED</i>	Domestic Expiration Demand
<i>DEP</i>	Domestic Expiration Potential
<i>EAC</i>	Energy Attribute Certificate
<i>ECP</i>	European Certificate Pool
<i>ERGP</i>	European Residual Generation Pool
<i>GC</i>	Granular Certificates
<i>GHGP</i>	Greenhouse Gas Protocol
<i>GO</i>	Guarantee of Origin
<i>HRM</i>	Hourly Residual Mix
<i>Pre-GC HRM</i>	Pre-Granular Certificate Hourly Residual Mix
<i>Post-GC HRM</i>	Post-Granular Certificate Hourly Residual Mix

Introduction

Introduction

1.1. Sourcing Electricity

More than two decades ago, Energy Attribute Certificates (EACs) were established as a book and claim system to reliably track attributes linked to the generation of electricity. With the liberalisation of electricity markets, consumers were allowed to choose their electricity retailer based on their services and prices. Together with the rise of environmental policies and the interest of organisations to improve their sustainability performance, EACs became the way to certify the sourcing of renewable electricity. In Europe, Directive 2001/77/EC [1] of 27 September 2001 introduced the use of Guarantees of Origin (GOs) as a basis to inform consumers of the renewable energy source of electricity supplied to them. Subsequent versions of the Renewable Energy Directive in Europe ensured the robustness of the GO as the one and only EAC for EU countries, providing a single proof of the origin of supplied energy (electricity, gas including hydrogen, heating and cooling).

As electricity cannot be physically tracked once injected into the grid, it was extremely difficult for companies to increase consumption of green electricity beyond what was provided through the generation mix of the local grid. As a means to provide actionability to organisations, while at the same time helping connect green electricity providers with consumers willing to source clean electricity to reduce their environmental impact, EACs have been introduced. This not only provided organisations with a practical tool to reduce their environmental impact, but also supported the financing of renewable energy projects.

1.2. Two Commodities

Today, a generator (e.g. wind or solar power plant) can produce two commodities for each unit of electricity: the electricity it generates itself, as well as the Energy Attribute Certificate. They are both individual commodities that can be traded on their respective markets independently (unbundled) or as a package together (bundled).

The lifecycle of an EAC starts at its issuance, after which they can be traded among market participants with the help of registries. Throughout its lifetime, a certificate either needs to be cancelled, or it will expire. A consumer can cancel a certificate, to claim the underlying attributes (e.g. renewable electricity). An EAC can have a validity for transfer of 12 months up to 18 months after the end of the production period of the corresponding energy, meaning that if it is not cancelled in this period, it will expire. In this paper, this dynamic is referred to as the certificate balance, as an issued certificate can only have two outcomes - being cancelled or expired.

$$\text{Issuances} = \text{Cancellations} + \text{Expirations}$$

Figure 3. Certificates balance

1.3. Accounting for Emissions using Energy Attribute Certificates

Once EAC markets have been established in various countries, the Greenhouse Gas (GHG) Protocol introduced the Scope 2 market-based approach in 2015 [2], by amending the already existing corporate standard [3]. This accounting approach reflects the GHG emissions associated with consumer's choices in contracting or sourcing electricity. Companies can match their electricity consumption with EACs, effectively reducing their market-based emissions to zero, which is usually done on an annual basis. To avoid double-counting, a concept called residual mix was introduced, which represents the energy source of untracked and unclaimed energy in a given region, and the corresponding direct CO₂ emissions related to this. In Europe, the Association of Issuing Bodies publishes the annual residual mix for each registered domain. These are obtained with an issuance-based calculation methodology, as explained in a publication by AIB (contracted to Grexel) [4].

1.4. Increasing the Time Granularity

Over the past years, EACs have been a widely used instrument to promote and accelerate the development and growth of renewable energy technologies. On top of that, they provide energy consumers the ability to source electricity from renewables if so desired. Despite this, it is important to recognise that certificates today remain far from mirroring, or correctly representing the physical reality of electricity flows. This is due to the fact that the power mix changes with each hour, specifically when considering solar and wind generation variability. In other words, today's EAC system does not allow for the matching of electricity generation and consumption at an accurate temporal and spatial level.

The digitalisation of the energy sector, most notably on the power generation side, but also on the demand side through the deployment of smart meters, has improved not only the availability, but also the time granularity of energy data. This enables essential solutions for the energy transition, such as demand response programs, bidirectional charging, grid flexibility, energy communities, among others. The progress in digitalisation has also opened a window of opportunity for the next generation of electricity procurement and carbon accounting, namely granular energy procurement and granular carbon accounting.

Today, there are many different programs promoting the adoption of more granular energy procurement and carbon accounting, with the aim to match the generation of electricity with consumption at an hourly level. For instance, the United Nations defines 24/7 Carbon-Free Energy as a procurement strategy that guarantees "that every kilowatt-hour of electricity consumption is met with carbon-free electricity sources, every hour of every day, everywhere" [5]. In a similar vein, recently political agreement has been reached on the Renewable Energy Directive III (RED III), which could include and propose a wider implementation of granular certificates.

Granular certificates are an instrument that aim to better represent the physical flow of electricity and thus provide market signals for times when green electricity supply is insufficient and, thereby, incentivise new investments in carbon-free electricity generation or energy storage. Granular certificates also allow for more granular market-based Scope 2

accounting, increasing not only the transparency of electricity procurement, but also its accuracy. A market-based approach at an hourly granular level will not only need granular certificates, but also an hourly residual mix.

1.5. The GHG Protocol Revision Process

Recently, the GHG Protocol has initiated its revision process with the goal of ensuring that carbon accounting methodologies are effective in providing a rigorous and credible accounting foundation for businesses to measure, plan and track progress toward science-based and net-zero targets in line with the global 1.5°C goal [6]. The current Scope 2 Guidance is based on an annual accounting framework, though recent research suggests that moving toward more granular accounting practices is core for an effective decarbonisation of electricity grids [7, 8, 9]. As the GHG Protocol focuses both on effective, but also implementable accounting standards, the opportunity of adding more granularity to the standard will also depend on whether the necessary data and tools are available.

The Purpose of this Paper

2. The Purpose of this Paper

The purpose of this paper is to provide a first iteration of a methodology to calculate an hourly residual mix for the AIB region, aiming to fill the data availability gap for a more granular accounting approach. A main design criterion is that this hourly residual mix methodology shall not undermine the currently used annual residual mix methodology as maintained by AIB. The main reason for that is that the transition towards (sub)hourly Guarantees of Origin/Granular Certificates is not taking place overnight, and to maintain reliable claims, no method should undermine the credibility of the existing practices embedded in the EU legislative framework. Like the existing annual residual mix method, the new method shall ensure that renewable attributes are only accounted for once and thus avoid double counting.

The approach presented in this paper is based on publicly available certificate data published by AIB and is intended to be an approximation of hourly residual mix to highlight what is possible with today's data. The decision to focus on the AIB region was based on multiple reasons, which include the existence of a uniform regulatory landscape across European countries, as well as the availability of EAC data and an already established EAC-based residual mix methodology.

Despite the fact that some organisations are working on Granular Certificate Standards and pilot projects proving their feasibility, it is still unclear if and when Granular Certificates will become the primary market-based instrument available to organisations to source green electricity. It is therefore necessary to recognise the existence of two cases for an hourly residual mix methodology:

- Pre-Granular Certificates Hourly Residual Mix: In the absence of granular certificates on a wider scale, this methodology focuses on approximating an hourly residual mix based on the current EAC system of annual certificates and granular power system data. This approach should be valid for the duration of a transitional period from an annual to a more granular certificate system and is intended to be used with no changes to the current system.
- Post-Granular Certificates Hourly Residual Mix: Once GCs are broadly available, it is possible to calculate hourly residual mix using hourly transactions of certificates combined with granular power system data.

As this paper is based on today's certificate data, the proposed methodology will focus on an hourly residual mix methodology for a pre-granular certificate scenario. The whitepaper does not intend to replace the current annual residual mix based on the annual EAC system, but instead aims to illustrate what can be achieved with resources that are available today. It proposes a first iteration of an hourly residual mix methodology, which should serve as the foundation for future iterations and spur collaboration between different organisations and stakeholders active within the EAC and carbon accounting space.

This paper is structured as follows. First, it highlights a common baseline to provide the reader the necessary context. Next, it explains the main challenges encountered during the development of the methodology and provides an overview of the resulting methodology. To finalise, the whitepaper shows some of the results obtained and topics for discussion. For those readers who want to have a more in-depth view on the methodology, detailed information is provided in the Annex.

A Common Baseline

3. A Common Baseline

This section is intended to provide a basis for the further understanding of this paper.

3.1. What is Residual Mix

Before diving into further details, it is important to develop a common understanding of residual mix. As outlined above, EACs have become a common tool to not only trace the origin of electricity, but also claim the use of sustainable electricity. As a result of this, it is possible to break down electricity production into tracked electricity and untracked electricity.

$$\text{Total Generation} = \text{Tracked Generation} + \text{Untracked Generation}$$

Figure 4. Breakdown of generation into tracked and untracked

Tracked generation represents all electricity generation that is tracked and cancelled through the use of energy attribute certificates (e.g. Guarantees of Origin, Renewable Energy Certificates) and other tracking instruments. What remains after all tracked generation has been removed from the total power mix is the untracked generation, or the residual mix.

Today, the residual mix is calculated on an annual basis using annual generation and annual certificate data. Following the same approach, to calculate an hourly residual mix, one will need hourly generation as well as hourly certificate data. The formula for an hourly residual generation - in a very simplified manner - can thus be defined as:

$$\text{Hourly Residual Generation} = \text{Hourly Total Generation} - \text{Hourly Tracked Generation}$$

Figure 5. Definition of hourly residual generation

Similar to a generation mix, the residual mix represents the percentage composition of the residual generation differentiated by production technologies.

To conclude, the primary data required to calculate hourly residual generation are hourly generation data and hourly tracked generation in the form of hourly certificates. As hourly generation data is already available through data sources such as Electricity Maps, the final missing piece is hourly certificate data, of which the calculation will be at the core of this paper.

3.2. How it Works Today

Today's residual mix calculation in the AIB region is based on the issuance-based method calculated by Grexel [4] with results published by AIB in its statistics dataset [10]. This approach relies on the annual power system and certificate data for each country in the AIB region. The main steps of the current methodology are summarised below. To calculate residual mix, one needs to determine the amount of tracked electricity generation, tracked consumption and their overall balance. Surplus tracked generation is pooled in the European Attribute Mix, while a shortage of tracked generation (due to a tracked consumption surplus in a country) needs to be sourced from the European Attribute Mix:

1. **Determining the local untracked generation in each domain:** The local untracked generation, which is commonly referred to as Domestic Residual Mix, represents the generation of a domain that is not tracked through certificate issuances.

$$\text{Tracked Generation} = \text{Issuances} - \text{Expirations} \quad (\text{Eq. 1})$$

$$\text{Domestic Residual Mix} = \text{Generation} - \text{Tracked Generation} \quad (\text{Eq. 2})$$

2. **Determining the local untracked consumption in each domain:** This is the volume of consumption that has not been tracked with certificates in a region. It is determined by subtracting the electricity consumption that is tracked through cancellations from the electricity consumption.

$$\text{Untracked Consumption} = \text{Consumption} - \text{Cancellations} \quad (\text{Eq. 3})$$

3. **Determine whether a domain is a surplus or deficit domain and transfer certificates from the European Attribute Mix (EAM) accordingly:** Verify for each domain if untracked generation is larger than untracked consumption (Surplus) or if untracked generation is smaller than untracked consumption (Deficit). Once this has been determined, any surplus generation from surplus countries that is untracked in each country is combined in the EAM, making up the European Mix. Energy volumes that are required by deficit countries are allocated to them based on the power mix found in the EAM.
4. **Calculate the annual residual mix carbon intensity:** Once the annual residual power mix has been determined for each domain, the residual mix carbon intensity is calculated using emission factors.

3.3. Data Sources for Power System and Certificate Data

As outlined above, in order to calculate hourly residual mix, one needs access to the power system and certificate data. This methodology relies on two datasets:

- European certificate data provided by the Association of Issuing Bodies (AIB) [10]
- Power system data by Electricity Maps [11]

European Certificate Data

As mentioned, the geographical focus of this paper is the AIB region located in Europe. The primary certificate data source, therefore, are the certificate statistics published by AIB [10]. At the time of writing, the most recent complete certificate data set referred to the year of 2021, which lists 29 domains, of which only 25 domains provided certificate data. The reason for the delay is the fact that certificate datasets only have to be finalised up until 12 months later.

As a baseline, it is important to differentiate between 'Production' and 'Transaction' based EAC statistics:

- **Production:** Considers the time of production of the energy associated with the certificate. These figures include actions performed with the certificates having a Production Period belonging to the specific month (regardless of the time when the transaction was done).
- **Transaction:** Relate to the moment when the transaction with the certificate actually took place (action-based).

To develop an accurate representation of an hourly residual mix, it is necessary to focus on when electricity has been generated, and thus, on the production statistics dataset of the AIB.

As there are three different actions for certificates, it is important to clarify what information the data from AIB carries. Note that each certificate refers to 1 MWh of electricity:

- **Issuance:** The number of certificates issued by the reporting Domain.
- **Cancellation:** The number of certificates cancelled by the reporting Domain, including cancelled to other Domains (regardless of where the certificates were issued).
- **Expiration:** The quantity of certificates expired by the reporting Domain (regardless of where the certificates were issued) .

Certificate information is published by AIB on a monthly basis per technology per domain, which includes production-based issuance, production-based cancellations, and production-based expiration volumes per domain and per technology. It is important to note that the validity of monthly data should be approached with caution, as the data can change up to 12 months after. Because of this, the annual certificate data set has been deemed more accurate and reliable.

Table 1. Set of information available in AIB Statistics dataset

Variable	Description [Units]	Known (source) / To be Solved
$I_{prod - AIB}$	Certificate issuances per technology per domain monthly aggregated	Known (AIB Statistics)
$C_{prod - AIB}$	Certificate cancellations per technology per domain monthly aggregated	Known (AIB Statistics)

$E_{prod - AIB}$	Certificate expirations per technology per domain monthly aggregated	Known (AIB Statistics)
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The data of the following domains is shown in AIB Statistics: Austria (AT), Belgium (BE), Switzerland (CH), Cyprus (CY), Czech Republic (CZ), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Croatia (HR), Hungary (HU), Ireland (IE), Iceland (IS), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Netherlands (NL), Norway (NO), Portugal (PT), Serbia (RS), Sweden (SE), Slovenia (SL), and Slovakia (SK). Belgium's different domains have been combined into one domain. Luxembourg has been combined with Germany, due to data consolidations.

Power System Data

The power system data used in this analysis is obtained from Electricity Maps, which provides hourly power system data in more than 60 countries and 160 zones in real-time. Granular power system data is essential to determine the hourly generation of different technologies in different locations, as well as a domain's hourly load. Based on this data, a methodology that distributes annual certificate volumes at an hourly level, and thus approximates an hourly residual mix over all AIB domains, is developed.

Table 2. Power System Data used

Variable	Description [Units]	Known (source) / To be Solved
$G_{i,m}$	Hourly generation per technology, per country [MWh]	Known (Electricity Maps)
L_i	Hourly total load per country [MWh]	Known (Electricity Maps)
$EF_{i,m}$	Regional emission factor per technology, per country	Known (IPCC 2014 [12], in case more accurate regional emission factors do not exist [13])

Deriving the Methodology of Hourly Residual Mix

4. Deriving the Methodology of Hourly Residual Mix

This section elaborates on the key challenges that were encountered during the development of the hourly residual mix (HRM) methodology and how they were overcome. How these key challenges are tackled has a significant impact on the resulting methodology. The core barriers are related to the temporal mismatch of electricity and certificates, as well as the inability to trace certificate flows from origin (where they are issued) to sink (where they are cancelled or retired).

4.1. Temporal Mismatch of Electricity and Certificates

Today's annual certificate system relies on the assumption that any certificate of any technology can be used to cover any electricity consumed by an entity (within the market boundary). It is possible to cancel a certificate for any time period (within the year of validity), irrespective of when the certificate has been issued. This means that an entity can cancel a certificate for consumption in August, even though this particular certificate has been issued (and the corresponding electricity has been generated) in January. In an extreme case, if there are enough certificates available, an entity can purchase wind certificates from January, to cover its total annual electricity consumption. Alternatively, an entity is able to purchase solar certificates to cover all of its annual electricity consumption. In simpler terms, this means that in the case of solar, the entity is able to use solar electricity to cover its electricity consumption even during the night - which ignores the physical reality of electricity generation.

The issue of the temporal mismatch of electricity and certificates can be separated into three core problems:

- **Relating certificate issuances to hourly production curves**
This ensures that certificates are issued only if corresponding electricity has been generated at an hourly level.
- **Relating certificate cancellations to hourly consumption curves**
This ensures that certificates need to be cancelled for each hour of consumption and through this aligns hourly electricity consumption with hourly certificate cancellation demand.
- **Matching certificate issuances with cancellations at an hourly level and ensuring that cancellations can be matched with relevant issuance supply**
This ensures that certificates can only be cancelled if the corresponding certificates have been issued in the same hour. For instance, this prevents cases where solar certificates are cancelled during the night.

The above challenges are further explored below. Additionally, the approach of how they have been overcome will be highlighted.

4.1.1. Relating Certificate Issuances to Hourly Production Curves

In today's certificate system, certificate issuances are aggregated at a monthly and annual level and thereby do not consider any diurnal fluctuations in production. Since certificate issuances are not related to any specific hour, they are not representative of actual production curves of different technologies. Both solar and wind power are inherently fluctuating and thus, not accounting for diurnal fluctuations can lead to severe inaccuracies.

To overcome the challenge of the mismatch between actual electricity production and issuances, this work proposes to ensure that certificates are only issued when the corresponding electricity has been generated. To do this, a scaling factor that enables to derive hourly certificate issuances based on the hourly production curve of each technology is introduced. The scaling factor - also called the issuance coefficient α - is determined by relating annual certificate issuances to annual electricity generation:

$$\alpha = \frac{\text{Annual Certificate Issuances}}{\text{Annual Electricity Generation}} \quad (\text{Eq. 4})$$

In essence, α provides information on how many certificates are issued per MWh of generated electricity. For instance, if $\alpha = 0.3$, this means that for each 10 MWh of electricity, 3 certificates each representing 1 MWh are issued. Once α is determined, it is possible to calculate hourly certificate issuances using hourly generation.

$$\text{Hourly Issuances} = \alpha * \text{Hourly Generation} \quad (\text{Eq. 5})$$

For instance, the case of solar would yield the following issuance curve for an assumed issuance coefficient of $\alpha = 0.3$:

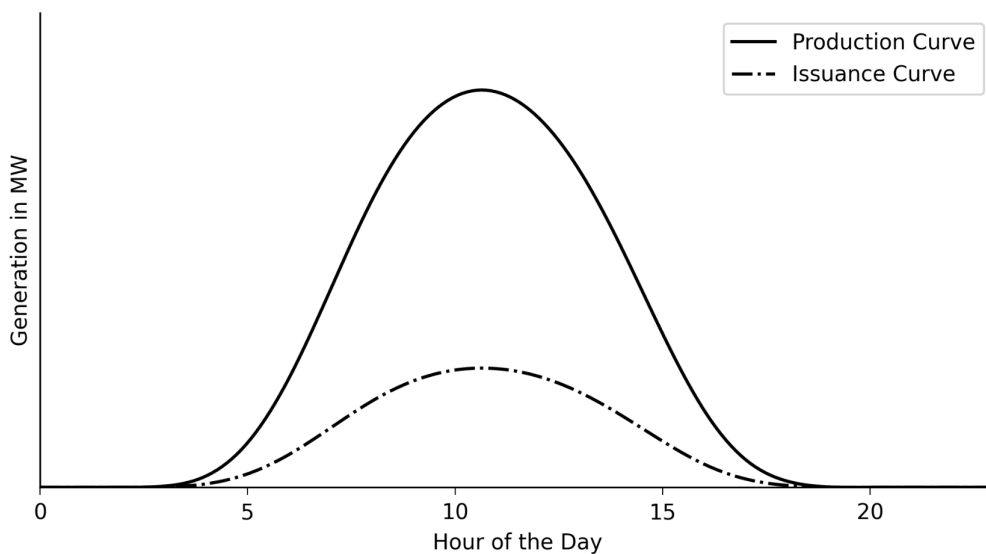


Figure 6. Hourly Solar Issuance Curve based on $\alpha = 0.3$

This is done for all generation technologies for each domain at an hourly level with their own respective issuance coefficients. Through this, it is possible to obtain hourly issuance curves for each technology in each domain that follow actual local production curves.

4.1.2. Relating Certificate Cancellations to Hourly Consumption Curves

In today's system, it is possible to cancel a certificate for any time period (within the year of validity), irrespective of when electricity has been consumed. The annual certificate and accounting system does not differentiate between entities that cancel certificates without considering time of production and time of consumption (business-as-usual behaviour) and entities that try to match cancellations of certificates with actual generation (strategic behaviour). When trying to associate certificate cancellations with hourly consumption, the following question appeared: **"How could one model the hourly demand for certificate cancellations using power system data?"**. Two main options of modelling hourly certificate cancellations were identified:

1. **Assume Business-as-Usual Behaviour:**

This assumes a behaviour that is equal to the general behaviour of today's annual system, whereby entities cancel certificates irrespective of their actual hourly consumption curves. To avoid assuming a certain certificate cancellation behaviour, one can decide to model hourly cancellations using the country-level hourly load curve of a domain. Similar to hourly issuance curves, a scaling factor - also called the cancellation coefficient - can be used to estimate the hourly cancellation curves within a domain, making certificate cancellations proportional to the hourly demand. In such an approach, solar cancellations would follow the hourly load curve, instead of the hourly production curve.

2. **Assume Strategic Behaviour:**

This option assumes that organisations show a strategic behaviour, whereby companies cancel certificates based on prevailing production curves. In other words, this would assume that companies cancel certificates under the consideration of when technologies are producing electricity - which is not the case today. For instance, in the case of solar cancellations, the hourly solar cancellation curve follows solar production curves.

Out of the two options above, the decision was made to go with option 1 where a business-as-usual behaviour is assumed. The primary reason for this is the fact that this option enables one to remain behaviour-agnostic and avoid assuming certain strategic patterns that are not present today. Additionally, there are technical reasons to decide against using production curves to model hourly certificate cancellations. For instance, take the example of a country that has no local hydropower production, but which in turn covers a significant portion of its consumption through hydro certificate cancellations. If one would use production curves to model hourly hydro certificate cancellations, the lack of local hydro production will result in estimated hydro cancellations to be zero - which would not align with today's hydro certificate demand.

To ensure that certificate cancellations are proportional to electricity consumption at an hourly level, hourly certificate cancellations for each technology are approximated by multiplying the hourly load curve for each domain with a scaling factor - the cancellation coefficient β . The cancellation coefficient β is determined by relating annual certificates cancellations to annual electricity consumption:

$$\beta = \frac{\text{Annual Certificate Cancellations}}{\text{Annual Electricity Consumption}} \quad (\text{Eq. 6})$$

In essence, it is assumed that certificates are cancelled according to local electricity consumption and thus, the demand for hourly cancellations scales in accordance with the hourly load. β provides information about how many certificate cancellations are demanded for each MWh of grid load. For instance, in the case of $\beta = 0.20$, an electricity consumption of 10 MWh indicates a local demand to cancel 2 certificates each representing 1 MWh.

Once β is determined, it is possible to calculate hourly certificate cancellation demand using hourly grid load.

$$\text{Hourly Cancellation Demand} = \beta * \text{Hourly Load} \quad (\text{Eq. 7})$$

For instance, the case of solar would yield the following cancellation demand curve for an assumed cancellation coefficient of $\beta = 0.2$:

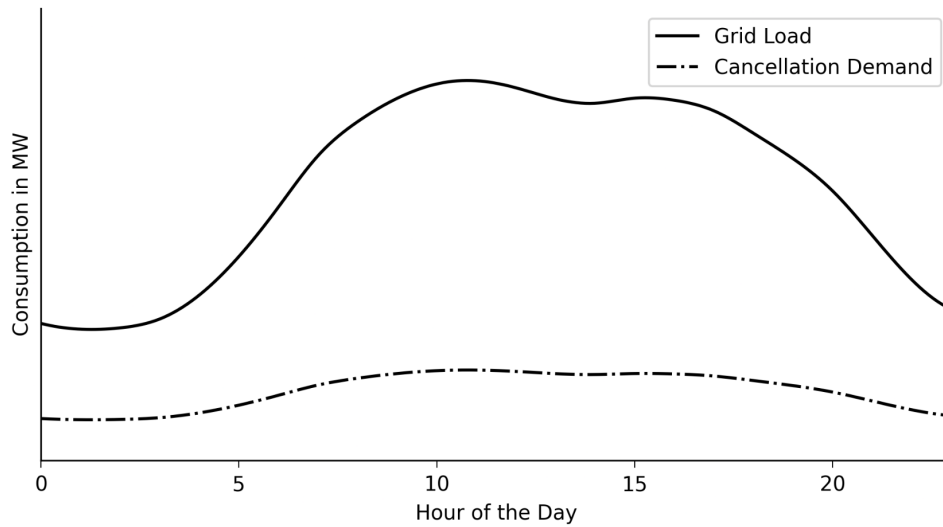


Figure 7. Hourly Solar Cancellation Curve based on $\beta=0.2$

This is done for all generation technologies for each domain at an hourly level with their own respective cancellation coefficients. Through this, it is possible to obtain hourly cancellation demand curves for each technology that follow actual prevailing consumption curves.

4.1.3. Matching Certificate Issuances with Cancellations at an Hourly Level and Ensuring that Cancellations can be Matched with Relevant Issuance Supply

As highlighted above, today's certificate system allows users to freely use certificates for issuances and cancellations, irrespective of when electricity has been produced and consumed. Figure 8 below illustrates a case whereby solar issuances are used to cover two different consumption profiles. Figure (a) shows a typical solar production curve. Figures (b) and (c) show two options of consumption curves, for which solar certificates can be purchased and cancelled.

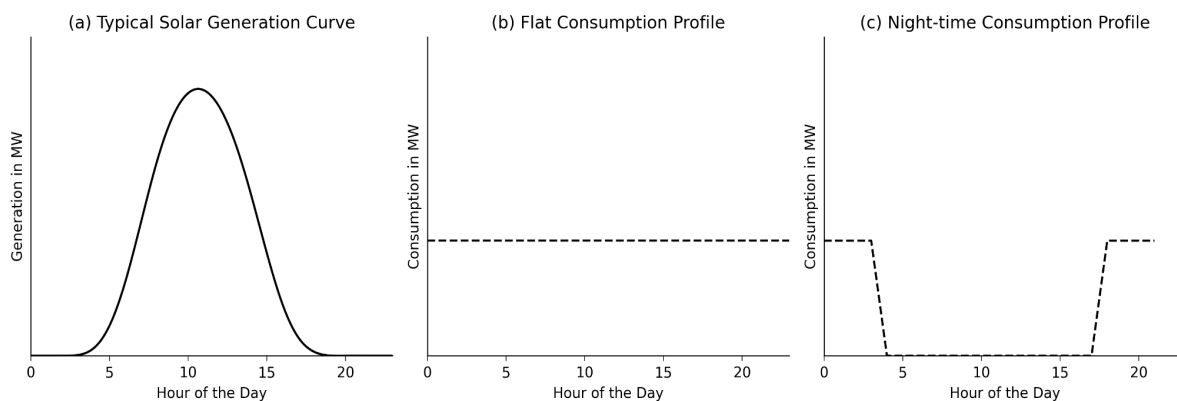


Figure 8. Typical solar generation curve (a) and example consumption profiles (b) and (c)

While the consumption curves do not match the production curve of solar, in today's annual system cancelling solar to cover consumption in both cases would be valid.

To prevent such a mismatch between electricity generation and electricity consumption, it is necessary to match certificate issuances and cancellations at an hourly level. This would allow verifying whether there issuance supply is large enough to satisfy the demand of certificate cancellations. Figure 9 below provides an example case of hourly curves for solar issuances and solar cancellations.

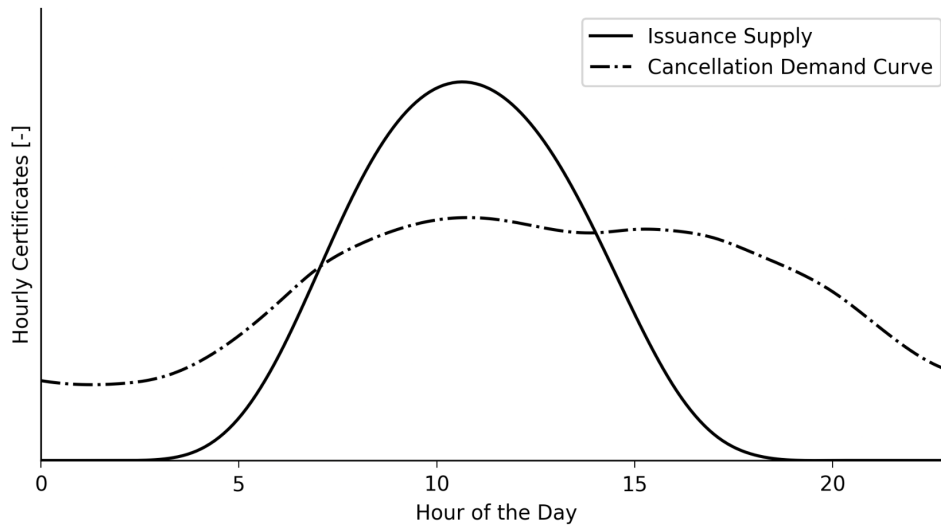


Figure 9. Comparison of hourly issuance and cancellation curves for Solar

The case of solar showcased above highlights the importance of modelling certificate issuances and cancellations at an hourly level while taking into account actual prevailing production curves. The hourly issuance and cancellation curves highlight two cases:

1. During some hours, the number of certificate issuances may exceed the number of demanded certificate cancellations. Any surplus issuances will turn into expirations, as there is not enough demand to consume them during that specific hour. For the case of solar, this is the case during the daytime. For the case of solar, this is during the daytime.
2. During some hours, the number of certificate issuances may be lower than the number of demanded certificate cancellations. In this case, any surplus certificate cancellation demand is curtailed to comply with the certificate balance. For any specific time period, if there are not enough certificate issuances for the existing certificate cancellation demand, the surplus demand is considered unserviceable. For the case of solar, this is during the nighttime.

Considering these two cases, the cancellation demand curve will need to be adapted to appropriately reflect the certificate cancellations that can actually be serviced by available certificate issuance supply. Any surplus cancellation demand that cannot be serviced will be curtailed to reflect this. This approach has considerable impact on the results of the hourly residual mix, since some cancellations that are reported today on an annual level will be disregarded as they are non-serviceable at an hourly level. Figure 10 below showcases the actual cancellation demand curve that results from matching issuance supply with certificate demand:

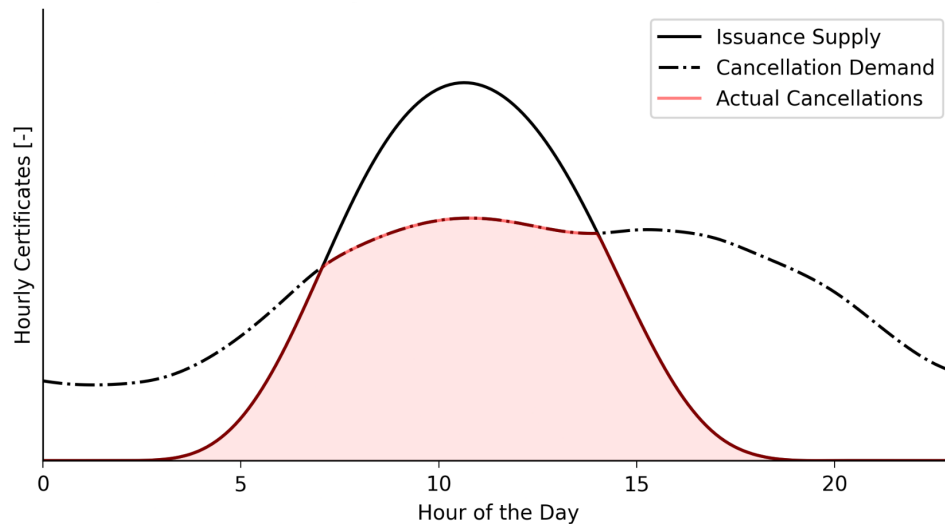


Figure 10. Comparison of hourly issuance and cancellation curves for solar

This verification is done for each technology in each domain, to determine the actual certificate cancellation curve that will feed into the residual mix calculation.

4.2. Inability of Tracing the Flow of Certificates from Origin to Sink

In an ideal case, it is possible to follow a certificate from where it is issued to where it is finally cancelled or expired. This would allow comparing the flow of certificates between countries with the flow of electricity and verify whether a certificate is physically deliverable or not. However, publicly available data does not provide such information. Figure 11 below shows the three actions a certificate is exposed to, as well as the data that is publicly available with respect to each transaction.

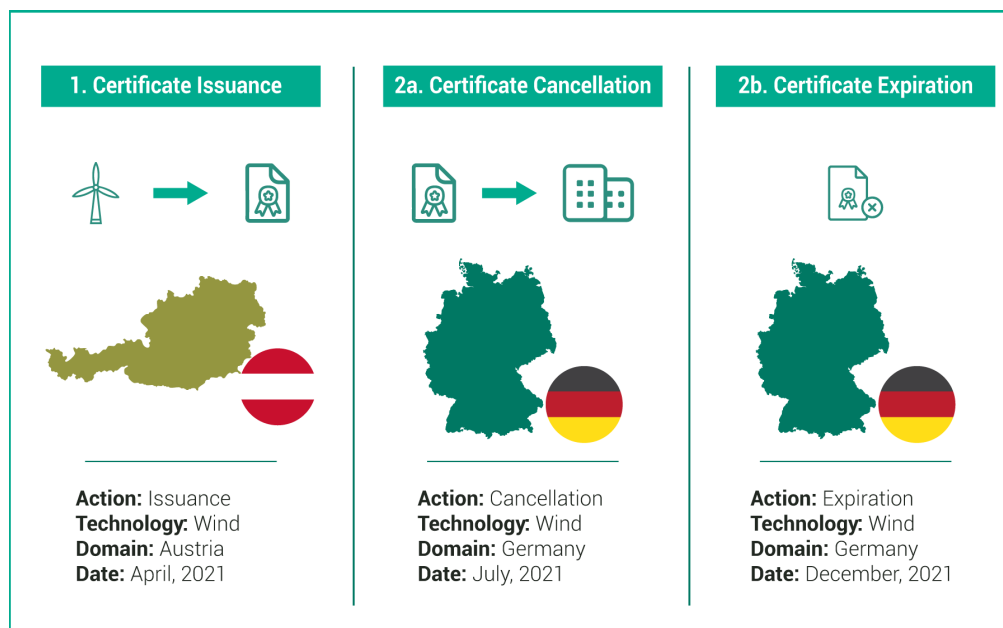


Figure 11. Representation of the different actions linked to EACs

As indicated in the figure, publicly available certificate data provides the following information:

- The certificate action (i.e. issuance, cancellation, expiration)
- The generation technology the certificate relates to
- The domain in which the certificate action has been performed
- The date or time period of when the action has been performed

For instance, it is possible to identify the country of origin of a solar certificate issuance as well as the month during which the certificate has been issued. Additionally, it is also possible to assess which countries cancel solar certificates for their own use. However, with the currently publicly available data, it is impossible to verify the flow of a certificate, i.e. where a cancelled certificate originally came from. In other words, it is impossible to say where a hydro certificate that was cancelled in Germany was originally issued. Since it is impossible to trace the flow of certificates from one country to another, it is also impossible to assess whether a locally produced certificate has been cancelled within the local domain, or traded away. This means that it is impossible to balance certificate issuances with cancellations and expirations on a country-level. This challenge was overcome by approaching the balancing and verification of certificates at a European level. To this end, issuances and cancellation demand from the country-level are collected and pooled together in a European Certificate Pool (ECP). This is represented as the Step 1 in Figure 12.

In essence this pool collects issuances and cancellations demand from all countries and verifies whether these cancellations can be fulfilled or not - this corresponds to the Step 2 in Figure 12. This enables matching available certificate issuances with cancellation demand for each technology. In case certificate issuances are in surplus of cancellation demand, issuances are expired. In case cancellation demand exceeds the available certificate issuances, surplus demand is curtailed. Once this verification step has been conducted at a European level, it is possible to reallocate actual or fulfilled cancellations and expiries to the respective domains - corresponding to the Step 3 in Figure 12.

The advantage of this approach is that it allows an efficient allocation of certificates across the AIB region and thereby ensures that the certificate balance holds. The approach taken is based on a non-discriminatory approach, whereby cancellations and expirations are based on the level of contribution from a domain towards the European Pool. For instance, for the above case, 20% of issuances expire (30 out of 150). Since it is impossible to verify with publicly available data, whether all Austrian or all German certificate issuances have been used to satisfy certificate demand, a fair allocation based on percentages was conducted. As Austria issued 100 certificates, the expiration share dictates that 20 of these certificates expire. In turn, out of the 50 issuances originating from Germany, 10 will expire. Overall, through this approach, it is possible to reconcile certificate actions across technologies and domains, without knowing the exact details on certificate flows.

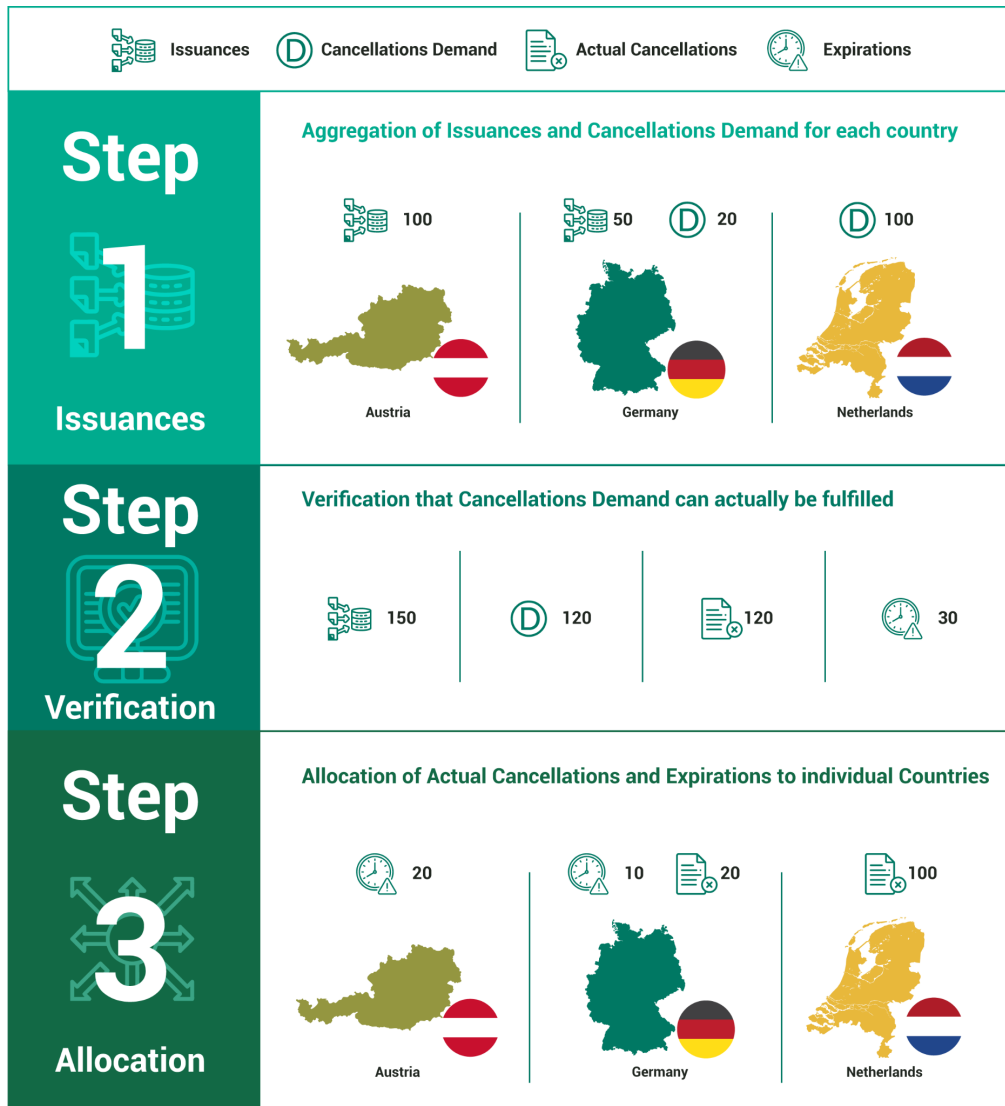


Figure 12. Simplified sequence of issuance, cancellations and expirations procedure at a domain-level

A core caveat of this approach is the fact that using a European Certificate Pool ignores any aspect of physical deliverability of electricity. While this matches the approach done today, it does not improve on the currently existing system in terms of tracing deliverability. As a result of this, this methodology improves on the current methodology purely on the temporal level. If information on certificate flows were publicly available, it would have been possible to include physical deliverability constraints using the flow-tracing methodology currently employed by Electricity Maps [14].

Hourly Residual Mix: Proposed Methodology

5. Hourly Residual Mix: Proposed Methodology

This section provides an illustrative overview of primary steps to calculate hourly residual mix for the regions considered in this paper. For interested readers, the detailed equations are provided in Annex A.

5.1. Core Assumptions

The methodology for hourly residual mix is based on the following core assumptions, based on the challenges and decision to overcome them highlighted in the previous chapter.

- **Hourly certificate actions, such as issuances and cancellations need to match what happens on the grid (production and consumption).** For this, a methodology that calculates hourly certificate issuances and cancellations using local power generation and power consumption curves was developed.
- **The certificate balance must hold for each hour.** As highlighted in the introduction, certificates that have been issued will either be cancelled or expire. This also means that there can never be more cancellations than issuances, which ensures that it is impossible to claim the consumption of green electricity, if it has not been produced. This balance is enforced for each hour. This can be described mathematically as:

$$\sum_i [I_{i,m,t} - C_{i,m,t} - E_{i,m,t}] \equiv 0 \quad \forall \quad m, t \quad (\text{Eq.8})$$

Where $I_{i,m}$, $C_{i,m}$ and $E_{i,m}$ represent issuances, cancellations, and expirations per technology m for each country i at each hour t .

- **Certificate issuances and cancellation demand are aggregated at the European level, since it is impossible to follow certificates from origin to sink.**

5.2. Stepwise Methodology

The methodology presented in this paper can be separated into three main sections and eight individual steps:

- A. Aligning production and load data with certificates data**
 - Step 1. Calculating hourly issuances per domain.
 - Step 2. Calculating hourly cancellation demand per domain.
- B. Balancing certificates across the European market**
 - Step 3. Calculating available certificate supply and cancellation demand in the European Pool.
 - Step 4. Computing actual serviceable cancellations for each generation technology at the European Certificate Pool level.

- Step 5. Distributing cancellations from the European Certificate Pool to domain-level.
- Step 6. Calculating hourly expirations at domain-level.

C. Residual mix calculation

- Step 7. Computing the residual mix.
- Step 8. Computing the residual mix carbon intensity.

A. Aligning Production and Load Data with Certificates Data

The first steps of the methodology relies on the calculation of hourly certificate issuances and cancellations demand using the available power system and certificate data. As mentioned before, hourly issuances and cancellations can be determined using the respective coefficients α and β for each technology in each country Eq. 4. Before obtaining the actual cancellations, the cancellation demand for each technology in the domain needs to be obtained.

Step 1. Calculating Hourly Issuances per Domain

The following figure provides a visual representation of how hourly issuances are calculated. This is obtained for each technology in each domain at an hourly level.

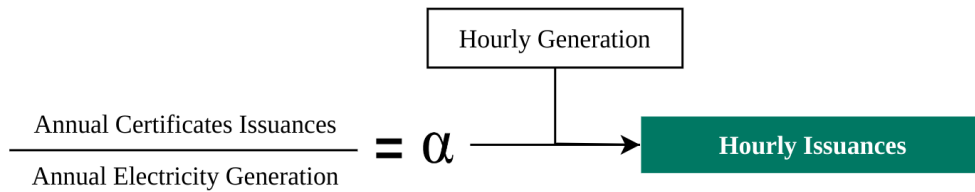


Figure 13. Determining hourly issuances using hourly generation and coefficient α .

Step 2. Calculating Hourly Cancellation Demand per Domain

The following figure provides a visual representation of how hourly cancellations demand is calculated. This is obtained for each technology in each domain at an hourly level.

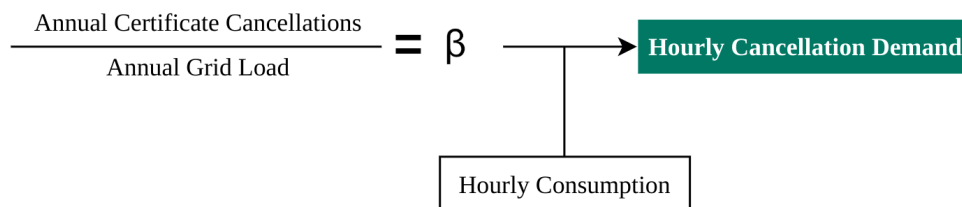


Figure 14. Determining hourly cancellation demand using the hourly consumption and coefficient β .

B. Balancing Certificates Across the European Market

Once hourly issuances and cancellation demand have been obtained per country, the next step relies on checking if the cancellation demand can be serviced by the available issuances for each specific hour at the European market level. As a reminder, certificates can be freely traded amongst AIB regions, therefore the certificate balance must hold at European market level, and not on country level. This section of the methodology contains the required steps to guarantee the certificate balance in the European market level and to obtain hourly actual cancellations and issuances at country level.

Step 3. Calculating Available Certificate Supply and Cancellation Demand in the European Certificate Pool

Once hourly certificate issuances and cancellation demand are known for each technology in each domain, they are aggregated in the European Certificate Pool. This pool is used to analyse how many certificate issuances and how much certificate cancellation demand are present across the AIB region. This is an essential verification step and is done for each hour and technology.

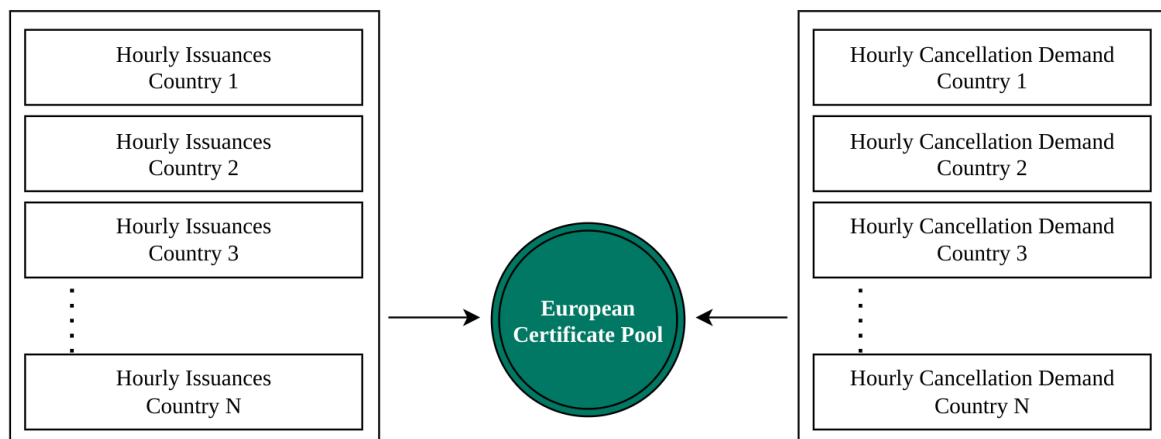


Figure 15. Collecting issuances and cancellation demand in the European Certificate Pool

Step 4. Computing Actual Serviceable Cancellations for Each Generation Technology at the European Pool level

Once hourly certificate issuances and cancellation demand have been aggregated from countries at the European Certificate Pool, it is possible to verify whether there are enough issuances to supply the certificate cancellation demand. In case more certificates issuances are available than cancellation demand, all cancellation demand can be serviced. In case there are less certificate issuances than cancellation demand, part of the cancellation demand is non-serviceable. In this case, any surplus demand is curtailed. This step is essential to ensure that cancellations don't exceed the available issuance supply and is done for each technology for each hour and yields actual hourly certificate cancellations.

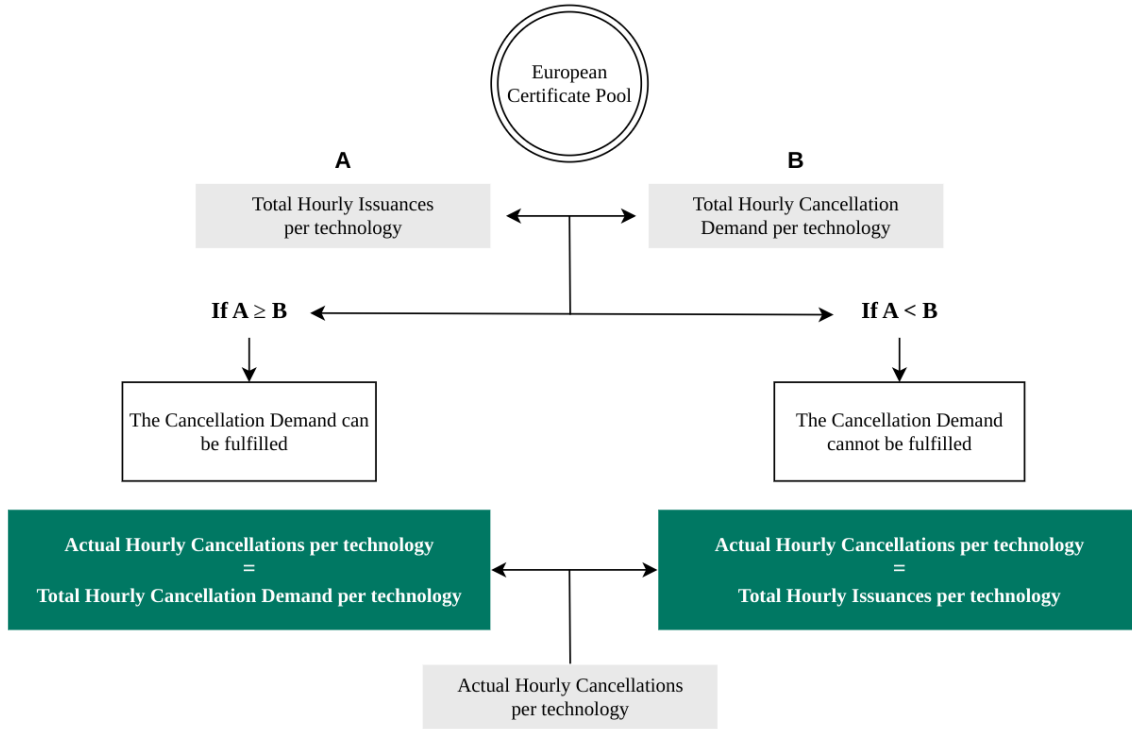


Figure 16. Determining actual serviceable cancellations at the European Certificate Pool

Step 5. Distributing Cancellations from the European Pool to Domains

Within this methodology, a “fair-share” allocation approach is taken. Since it is impossible to track where certificates flow, it is important to find an allocation method that is non-discriminatory against any domain or technology. Actual cancelled certificates are allocated to domains using a fulfilment coefficient $k_{Pool,m}$. This coefficient provides information about the share of certificate cancellation demand that can be serviced. For instance, a $k_{Pool,m} = 0.8$ indicates that only 80% of cancellation demand can be serviced through available issuances. Using the “fair-share” approach, the cancellation demand of each domain is multiplied with the fulfilment coefficient, and thus curtailed in equal shares, resulting in the actual cancellation demand for each domain and technology at an hourly level.

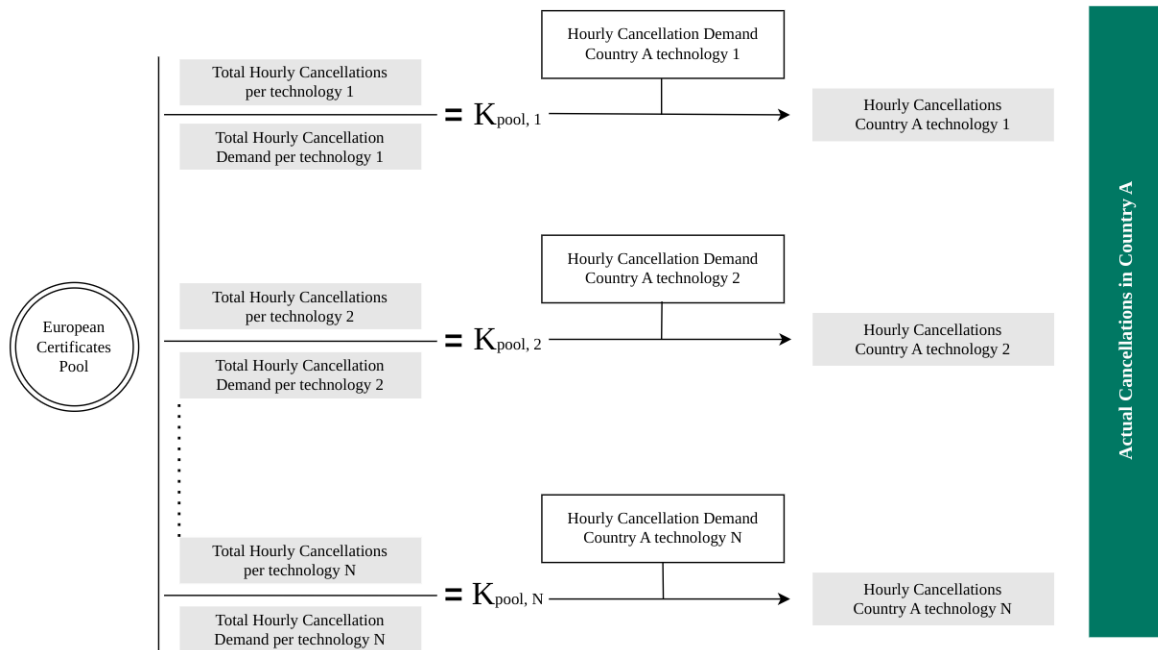


Figure 17. Allocation of actual cancellations from the European Certificate Pool to the domains

Step 6. Calculating Hourly Expirations at Domain-Level

This step follows a similar procedure as the two previous steps used to determine actual cancellations and their allocations to individual domains. Similar to actual cancellations, the expiration demand is determined at a European level for each technology, since the certificate balance is not valid at the domain level. Issuances can only expire, if they exceed the cancellation demand. If cancellation demand is higher than available issuances, all available issuances are used to service the demand resulting in no expirations

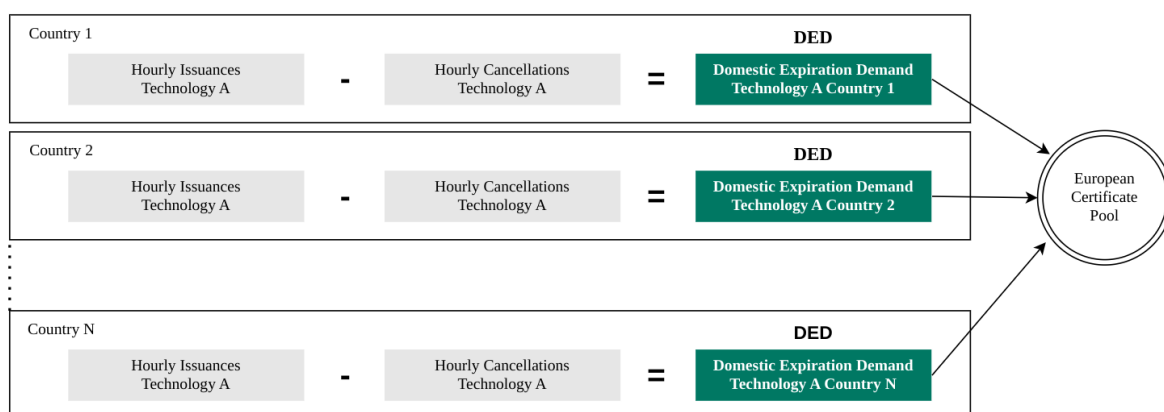


Figure 18. Determining the Domestic Expiration Demand

Similar to the cancellation allocation, a “fair-share” allocation approach is used to allocate expirations from the European Certificate Pool to domains. The key difference here is that there will be some domains with higher issuances than cancellations and others with lower

issuances than cancellations. The former domains are referred to as net-exporters of certificates, while the latter domains are referred to as net-importers of certificates. As the net-exporters are responsible for the oversupply of certificates, only net-exporters will receive expiration allocations from the certificate pool. This is done by making use of a so-called expiration coefficient. This approach is necessary, since it is impossible to determine whether a domain cancels certificates that have been issued locally or traded into the domain. As such, issuances that originate from net-importers cannot expire, since these issuances *might be used* to cover the cancellation demand of the domain.

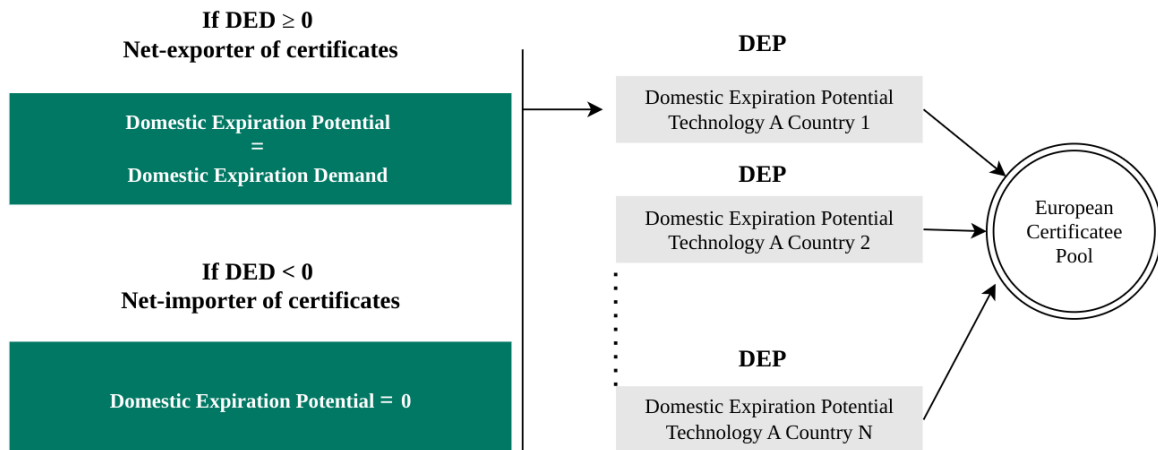


Figure 19. Determining the Domestic Expiration Potential

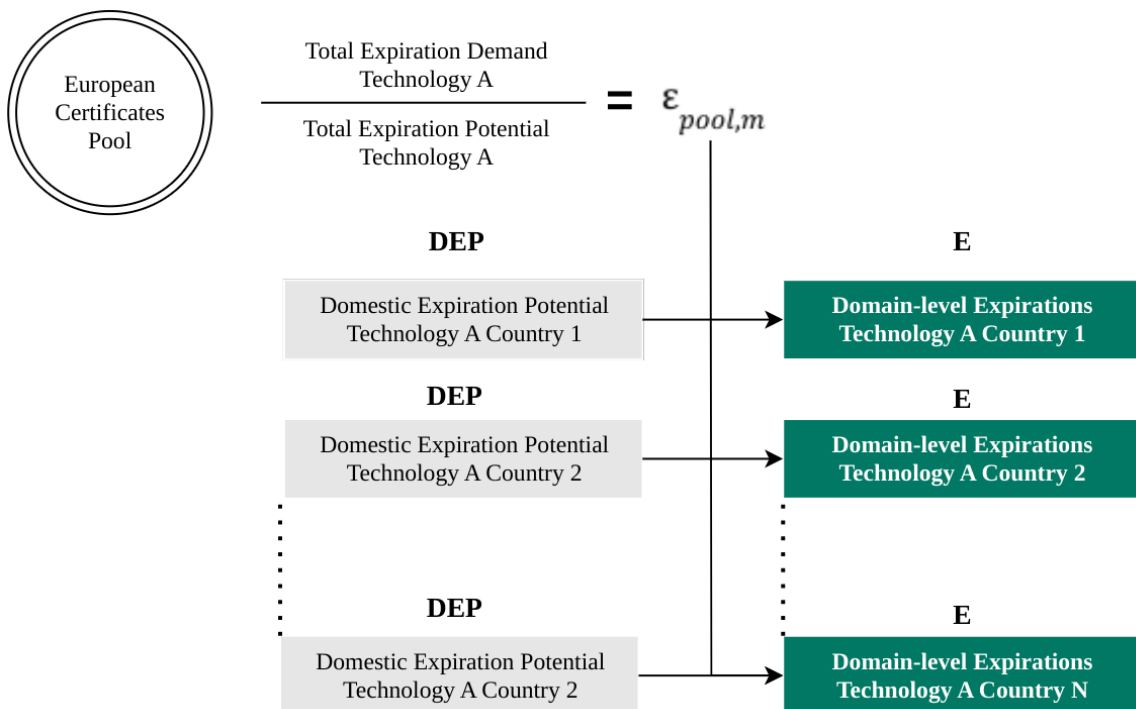


Figure 20. Determining Domain-level Expirations

C. Residual Mix Calculation

Up until this point, the methodology has been focusing on how to obtain issuances, cancellations and expirations on an hourly level. With that information, the residual mix and the corresponding carbon intensities can be obtained following a similar approach that is used by Grexel to obtain the annual residual mix (which has been introduced in [Chapter 3](#)).

Step 7. Computing the Residual Mix

Once hourly issuances, cancellations and expirations have been determined for each technology and domain, it is possible to calculate hourly residual generation for each domain. This last step follows a similar approach used in today's methodology by Grexel. First, the hourly domestic residual generation (local untracked generation) is determined per country and technology. This allows to determine the resulting domestic residual mix.

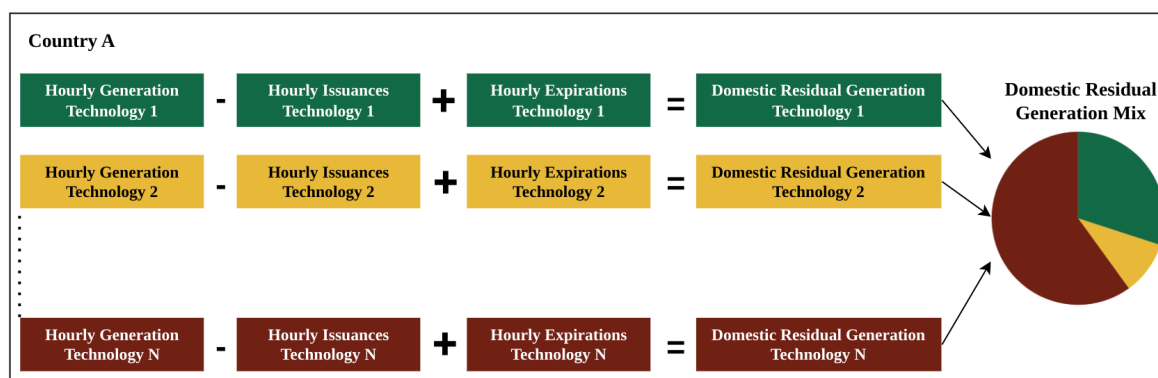


Figure 21. Calculating the Domestic Residual Generation and the corresponding Mix

The next step is to determine if the residual generation can satisfy the untracked consumption in each country per time interval. As in the current methodology, it is important to differentiate between two cases: if residual generation is higher than local untracked consumption the domain is referred to as a Surplus Domain. If residual generation is lower than local untracked consumption the domain is referred to as a Deficit Domain. Surplus domains supply their surplus residual generation to the European Residual Generation Pool, to make it available for deficit countries.

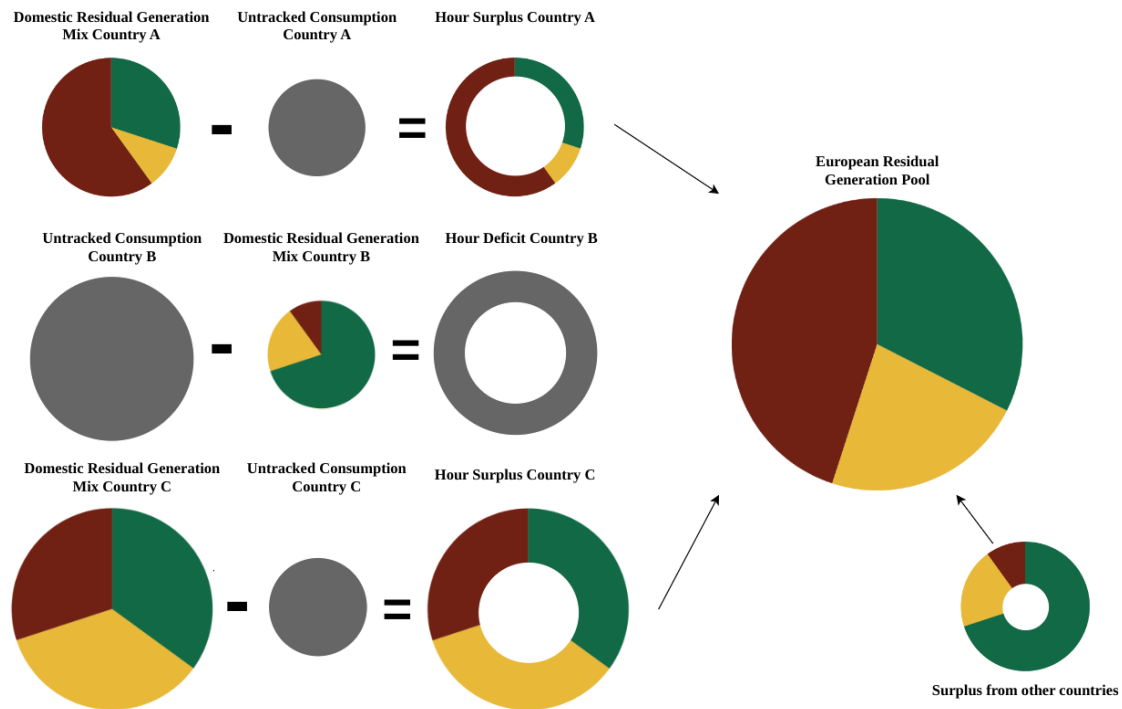


Figure 22. Surplus Countries supply their surplus residual generation to the European Residual Generation Pool

For surplus hours (where the untracked consumption can be satisfied with the domestic residual generation), the untracked consumption takes on the technology mix of domestic residual generation:

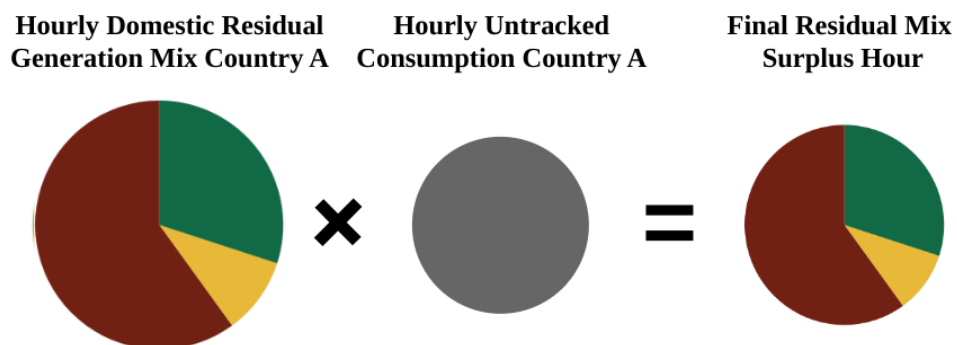


Figure 23. Determining the Final Residual Mix in Surplus Hours.

In turn, deficit hours (where the domestic residual mix cannot fulfill the untracked consumption) residual generation is drawn from the European Residual Generation Pool. Both the local domestic residual mix as well as this additional residual generation make up the final residual generation and thus the mix. The missing residual generation volume takes on the technology mix of the European Residual Generation Pool.

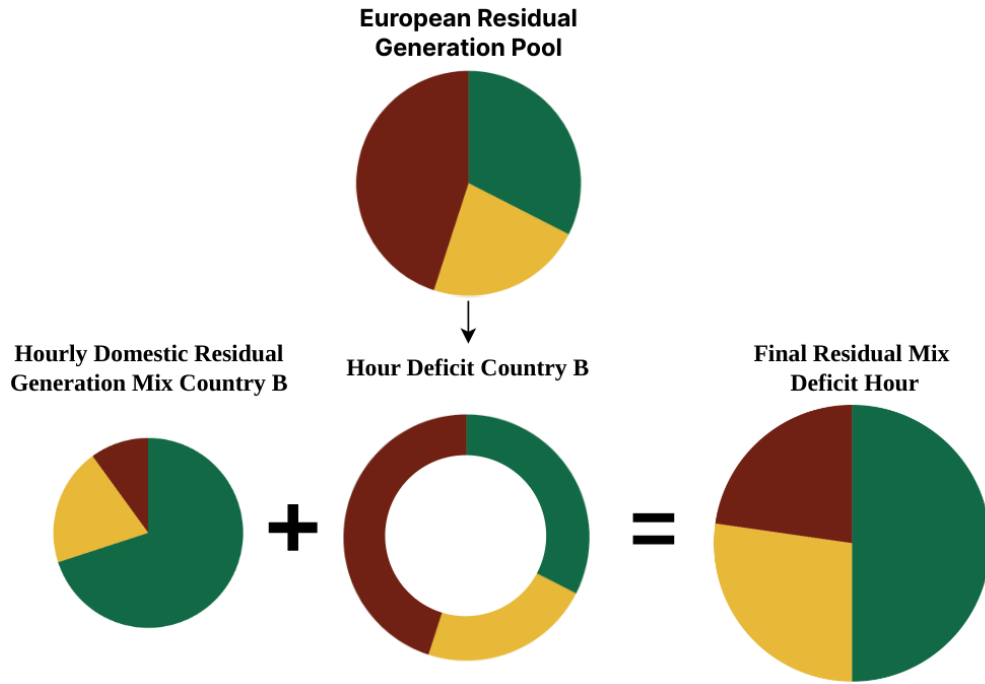


Figure 24. Determining the Final Residual Mix in Deficit Hours.

The above steps are conducted for each domain in each hour. Note that domains can change from being a surplus domain to being a deficit domain from one hour to the next, depending on its local generation and consumption profiles for each hourly interval.

Step 8. Computing the Residual Mix Carbon Intensity

Once the final residual mixes are determined for each domain in each hour, it is possible to calculate the residual carbon intensity on a country level, by multiplying technology specific emission factors with its residual generation, then divide it by the total residual generation volume. The residual carbon intensity (RCI) represents the average emission factor of a domain's residual generation mix:

$$RCI_i = \frac{\text{Residual Emissions of Country } i}{\text{Residual Generation Volume of Country } i} = \frac{\sum_m EF_{i,m} * RG_{i,m}}{\sum_m RG_{i,m}} \quad \forall \quad i \quad (\text{Eq.9})$$

Electricity Maps provides data on regional emission factors and thus, domain-specific emission factors can be used for calculating the RCI.

Results and Discussion

6. Results and Discussion

Overall, it is important to restate that this methodology is providing an approximation of an hourly residual mix using hourly power system data, as well as annual certificate data provided by AIB. This section presents the results and discusses their implications.

6.1. Hourly Matched Certificates

6.1.1. Consequences of Hourly Matching

While matching certificates on an hourly basis provides a more accurate view on the amount of certificates that are demanded versus the certificates that can actually be serviced, it ignores the opportunity to cancel certificates as flexibly as it is done today. Generally, this leads to two specific cases that only surface when matching certificate actions at an hourly level:

1. There will be times where demanded cancellations will not be able to be matched with available generation and thus available issuances. For instance, since all demanded solar cancellations are equally distributed across the year, a significant amount of solar cancellations are demanded during nighttime, which ultimately results in non-serviced cancellations, as the sun does not shine during the night.
2. Conversely, allocating cancellations according to load curves ignores opportunities to intelligently match consumption with available generation and thus available issuances.

Figure 25 showcases solar certificate actions as well as the demand for solar certificate cancellations on July 22nd 2021 at the European Certificate Pool. As highlighted in previous sections, hourly certificate cancellation demand is assumed to be proportional to the hourly electricity demand and, thus, fluctuates according to common electricity consumption patterns throughout the day. Similarly, hourly solar issuances follow typical solar generation patterns and are only available during daylight hours, as solar assets generate electricity exclusively during the day. Since consumption and generation patterns of specific technologies differ across the day, there will be times where the demand for certificate cancellations will exceed the available certificate issuances. In the case of solar, this is particularly relevant during the nighttime. Conversely, figure 25 shows that during the daytime, cancellation demand can be serviced by the available issuance supply, so much so that a large amount of issued certificates expire, as they exceed the prevailing demand. Indeed, following the hourly certificate approach presented in this paper yields 10 times higher solar certificate expirations, relative to the annual data from AIB. It is important to note that this procedure was performed for all technologies at the European Certificate Pool, in order to ensure that any demanded certificate cancellation will be supplied by an available certificate of the relevant technology. This also means that surplus certificate issuances of

one technology cannot be used to cover open certificate cancellation demand of another technology, as this would go against today's Business-as-Usual behaviour.

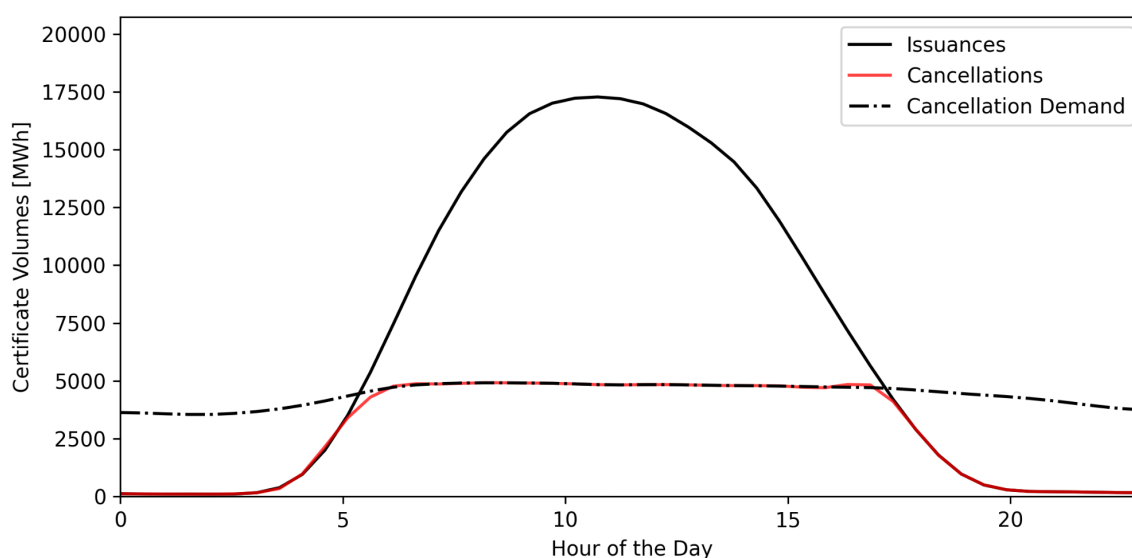


Figure 25. Solar Certificate Volumes for a typical July Day at the European Certificate Pool

6.1.2. Demanded vs. Realised Cancellations

Table 3 below provides an overview of the share of demanded cancellations that are ultimately serviced - also called the fulfilment share.

Table 3. Share of demanded cancellations that are serviced

Nuclear	Geothermal	Biomass	Coal	Wind	Solar	Hydro	Gas	Oil
0.98	0.92	0.83	1.00	0.89	0.46	0.95	0.98	0.99

While the fulfilment share is above 90 % for most technologies, it is important to highlight that only 46 % of all demanded solar cancellations can be serviced, once issuances and cancellations are matched at an hourly level. As discussed above, this can be attributed to the way cancellations are reallocated from an annual level to the hourly level and the subsequent mismatch with solar generation patterns. Overall however, around 90 % of the demanded cancellation volume (around 750 TWh) is serviced by available issuance supply and thus a large majority of demanded cancellations are serviceable using this methodology. The above results are depicted in Figure 26 below.

Ultimately, the certificate fulfilment share is a measure of how much of total certificates are allocated by the HRM methodology, relative to the currently used annual methodology by AIB/Grexel.

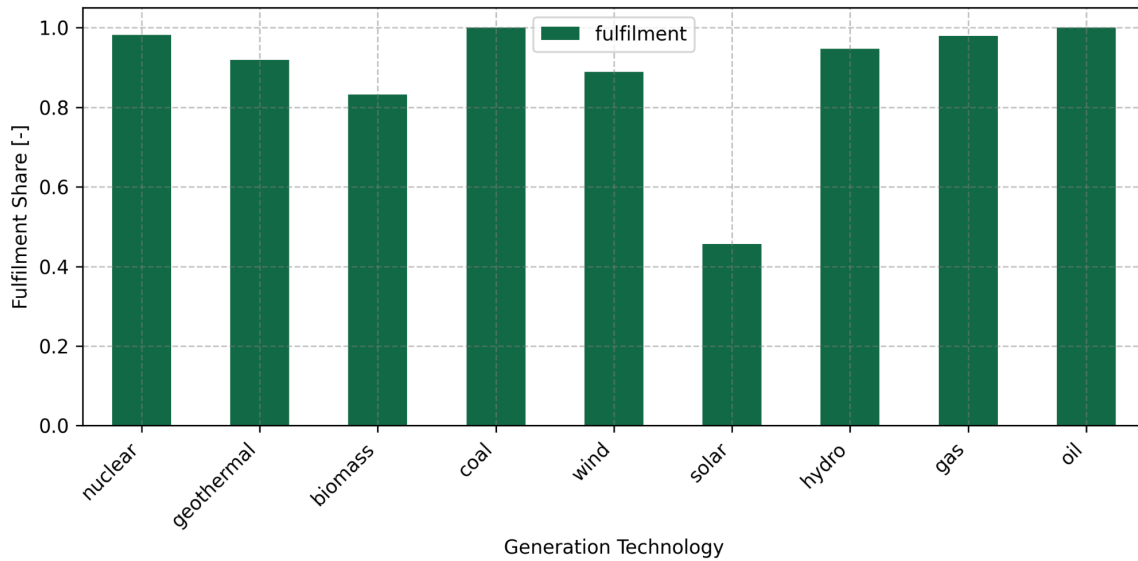


Figure 26. Share of Serviced Cancellations of Total Demanded Cancellations

6.2. Residual Generation

Figure 27 below highlights the monthly average residual generation as a result of applying the above methodology at the European Pool Level.

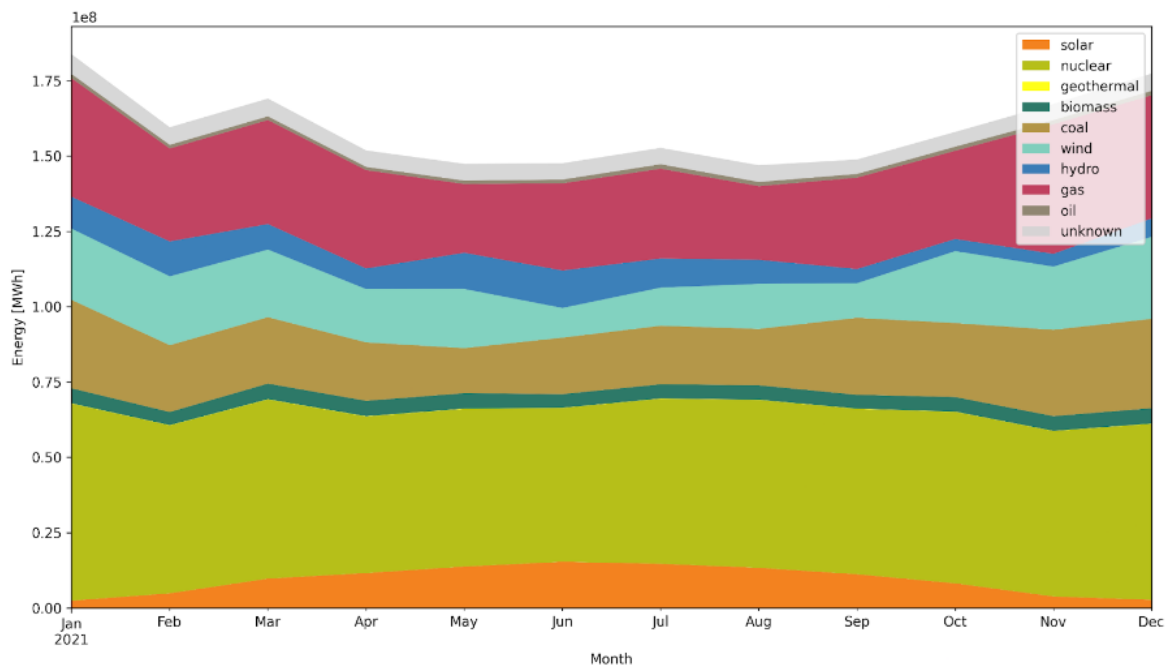


Figure 27. European Pool - Monthly Residual Generation

What can be observed is not only higher total residual generation during the winter months, but also seasonality of production technologies. For instance, seasonal changes for solar generation can be observed, with higher residual generation values over the summer

months. Moreover, the drop in residual generation during the summer months is also in line with the overall trend for monthly load patterns, with higher consumption prevailing during winter months.

When comparing both the actual annualised generation and the annualised residual generation, one can observe the technology specific differences. Aggregated across all AIB domains, around 73.9% of total generation ends up in the residual mix and thus untracked, as compared to around 71 % using AIBs annual numbers. Figure 28 showcases both annualised generation volumes and annualised residual generation volumes aggregated over all AIB domains for different technology. When comparing the discrepancies between both energy volumes, one can notice the different appetite levels for certificates for different production technologies. With 92 %, geothermal is leading the share of generation value that is tracked with certificates, before hydro with 80 % and biomass with 46 %. Not surprisingly, demand for tracking instruments for fossil fuels including coal, gas and oil, but also nuclear remains very low.

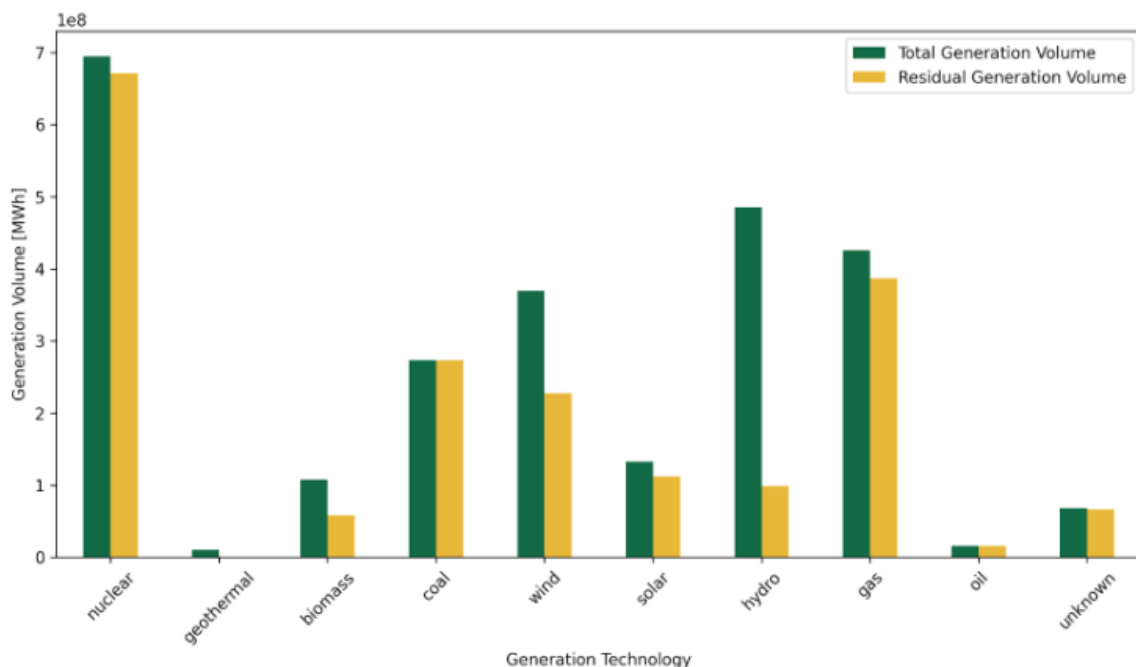


Figure 28. Annualised Hourly Generation and Residual Generation Volumes

6.3. Residual Carbon Intensity

Figure 29 provides an overview of the emission factors of the annual residual mix provided by AIB, the annualised hourly residual mix calculated using the methodology presented in this paper and the annualised hourly grid emissions provided by Electricity Maps.

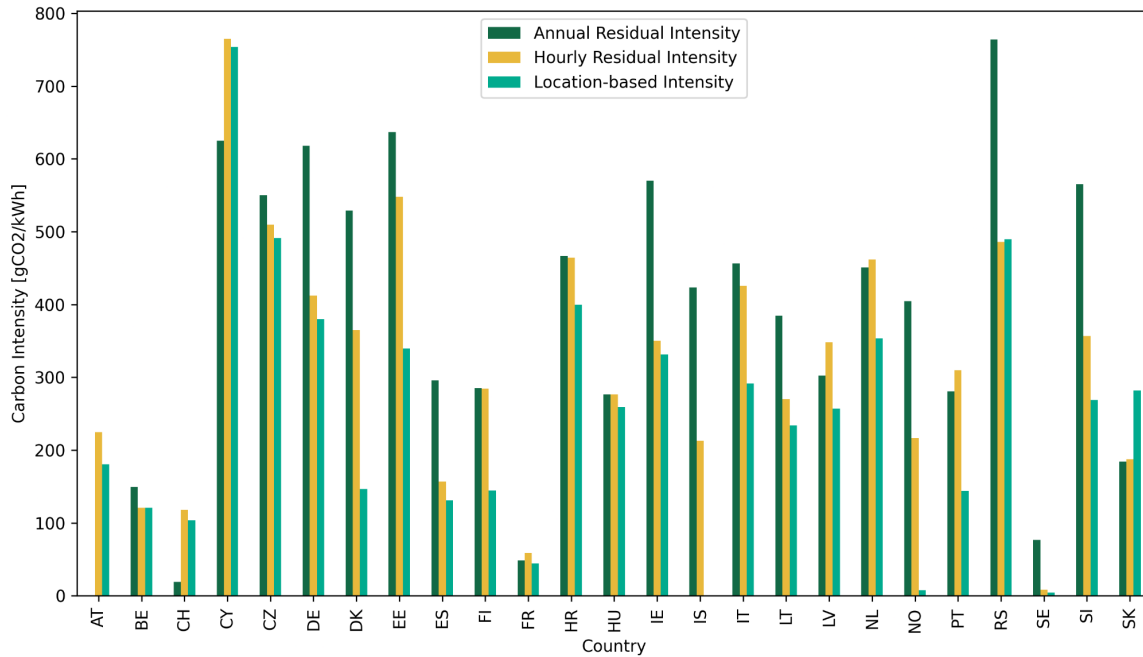


Figure 29. Comparison of Annualised Emissions Factors

As can be seen, most countries show the typical pattern where the residual carbon intensity calculated by the current annual residual mix methodology is the highest, followed by the hourly residual carbon intensity and the location-based carbon intensity of the grid. This is a sensible result as generally the residual mix will showcase higher carbon intensity values, as it does not include clean electricity that has already been procured through corporate purchases. As a corollary of this, the annualised hourly carbon intensity calculated using this methodology generally tends to be “cleaner” than the annual residual mix. This is due to the consequence of hourly matching, where less certificates are cancelled and thus, more clean generation ends up in the hourly residual mix, making it slightly cleaner overall.

There are notable differences to this rule, such as Austria with a residual carbon intensity of 0 gCO2/kWh reported by AIB. Switzerland also shows a much lower annual residual carbon intensity, relative to the annualised hourly residual carbon intensity *and* the location-based grid intensity. This can be explained by the shift in technologies that constitute the power mix. As Figure 30 shows, around 88 % of the Swiss power mix is made up of carbon-free technologies, with the rest coming from unknown origins. However, this is not the case for the Swiss residual mix, of which only 66% are carbon-free technologies. As a result, the annualised carbon intensity of the hourly residual mix is larger than the annualised location-based carbon intensity.

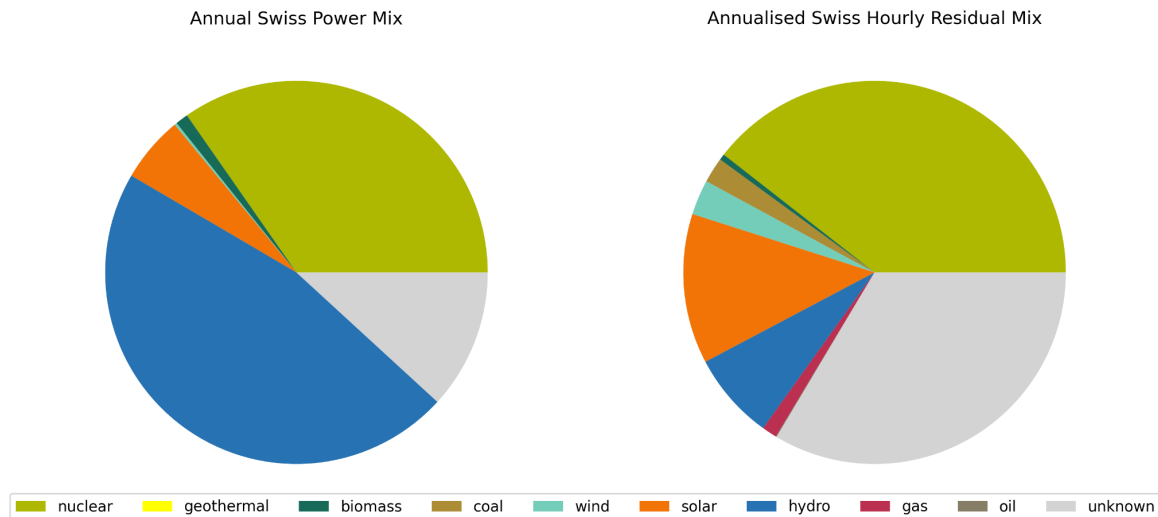


Figure 30. Comparison between the Annual Swiss Power Mix and the Annualised Swiss Hourly Residual Mix

Comparison between different Carbon Intensities

Overall, the difference between the annual residual carbon intensity and the hourly residual carbon intensity using the proposed methodology is showcased in Figure 31 below. With the exception of some countries, the annual carbon intensity is observed to be higher than the hourly residual carbon intensity. This indicates that a significant number of renewables that are tracked on an annual basis are not matchable on an hourly basis. The unmatched portion goes back into the residual mix, as it never should have existed as a viable tracked source of electricity. When conducting similar analysis to compare the carbon intensity of the annualised HRM and annualised hourly averages (Figure 32) it can be observed that HRM carbon intensities generally exceed annual averages. As discussed above, this is a sensible result given the fact that averages include all renewable electricity generation.

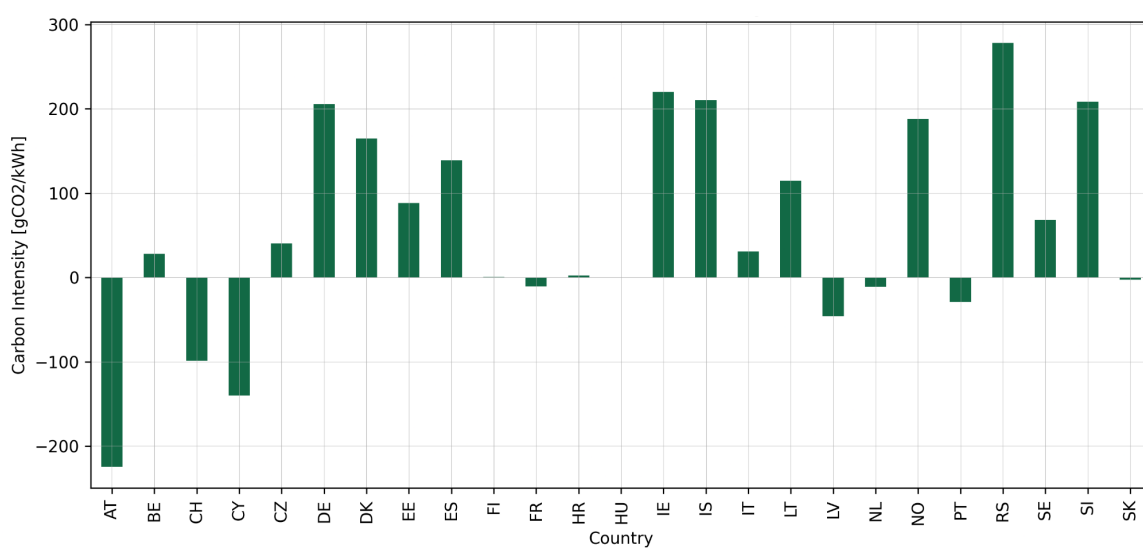


Figure 31. Difference between AIB Residual Mix and Annualised Hourly Residual Mix Emission Factors

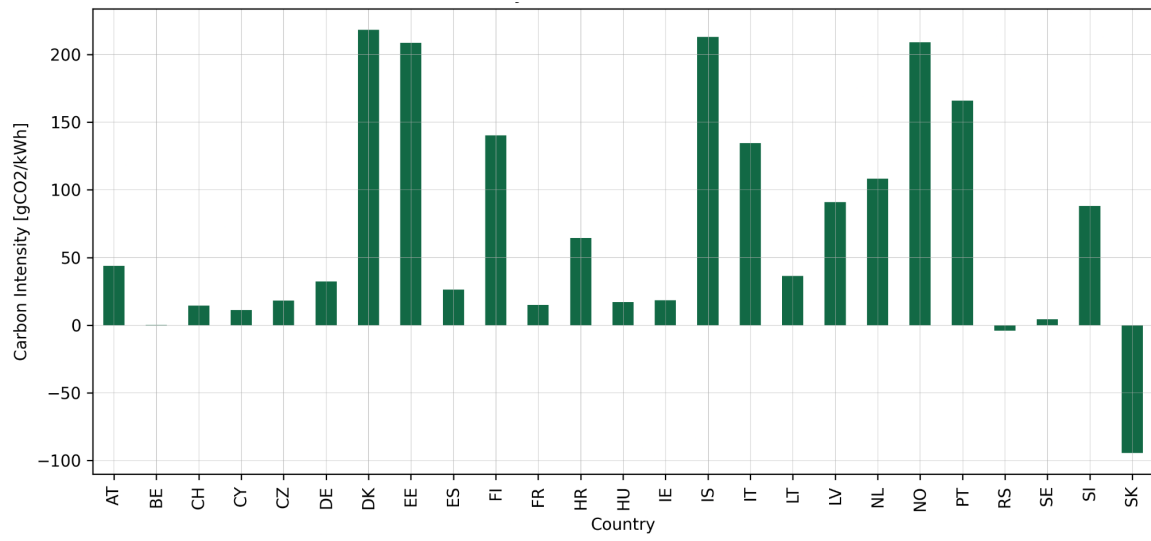


Figure 32. Difference between Annualised Hourly Residual and Annualised Location-based Emission Factors

Use Case

Scope 2 Hourly Carbon Accounting

7. Use Case - Scope 2 Hourly Carbon Accounting

To better provide an overview on how the hourly residual mix can be applied and what consequences this would yield, this section will focus on a case study. Specifically, a Scope 2 carbon accounting analysis is conducted in four different countries, which are Spain, France, Czech Republic and Denmark. The specific Scope 2 accounting cases are:

Table 4. Specific Scope 2 accounting cases considered

Case	Method	Temporal Granularity	Emission Factor
Case 1	Location-based	Hourly	Grid Average
Case 2	Market-based	Annual	AIB Residual Mix
Case 3	Market-based	Hourly	Grid Average
Case 4	Market-based	Hourly	Residual Mix

These 4 accounting cases will be conducted for three different consumers using their individual load profiles, which includes a data center, a manufacturing company, and a consumer goods company. For the market-based cases, the assumption is made that the consumers each have contracted a Power Purchasing Agreement (PPA) to cover 60 % of their annual load with wind (Wind-Case) and solar (Solar-Case) respectively. Note that case 3 is included in this analysis, as it is a common approach to use a grid average for market-based accounting in the absence of a residual mix.

7.1. Data Requirements and Review

The following datasets are required for the analysis:

- **Annual Residual Mixes** published by AIB for each of the countries [gCO₂/kWh]
- **Hourly Residual Mix** [gCO₂/kWh] for each of the countries computed using the HRM methodology presented in the paper.
- **Representative hourly load profiles** for each of the consumers considered [kWh].
- **Representative hourly generation profiles** for both solar and wind [kWh]
- **Hourly grid intensity** [gCO₂/kWh] for each country

Before conducting the analysis, it is useful to compare the different carbon intensity data sets. Table 5 below provides an overview of the different emission factors for the year 2021 at an annualised level (i.e. hourly values have been aggregated to the annual level).

Table 5. Values considered for the use case

Country	Annualised Hourly Grid Intensity (gCO ₂ /kWh)	Annual Residual Mix (AIB) (gCO ₂ /kWh)	Annualised HRM (gCO ₂ /kWh)
Spain	130.91	295.83	157.04

France	44.20	48.57	59.10
Czech Republic	491.38	549.96	509.53
Denmark	146.47	529.32	364.72

It is worth noting that the carbon intensities of the hourly residual mix obtained in this study are generally lower than the carbon intensities of the annual residual mix published by AIB. As indicated above, tracked generation that cannot be cancelled is returned back into the residual mix and thus, particularly the loss of solar affects this. As solar is returned into the residual mix, the share of renewable energy increases, resulting in a lower carbon emissions rate. This is particularly evident in countries such as Spain, which have a higher share of renewables compared to countries like the Czech Republic or France. Related to this, one can observe the difference between the hourly grid intensities and the hourly residual mix intensities, with the latter being higher. This makes sense since grid intensities include all generation, while residual intensities should not include any tracked generation (which is predominantly renewable). The following graphs showcase how the average grid intensities differ from the hourly residual mix on an hourly basis for two of the countries described above.

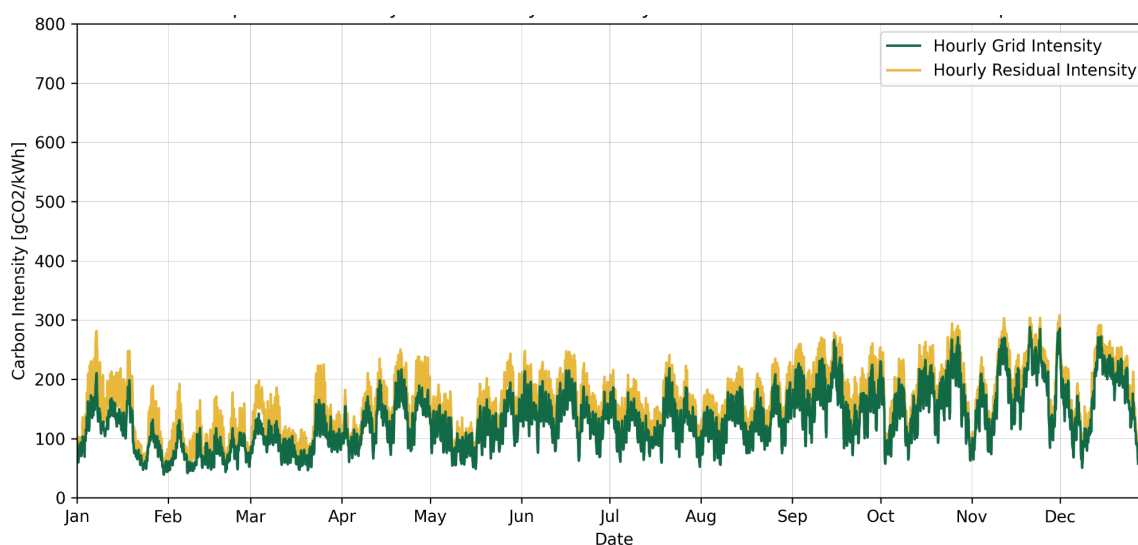


Figure 33. Comparison of Hourly Grid Intensity and Hoursly Residual Mix Carbon Intensities - Spain

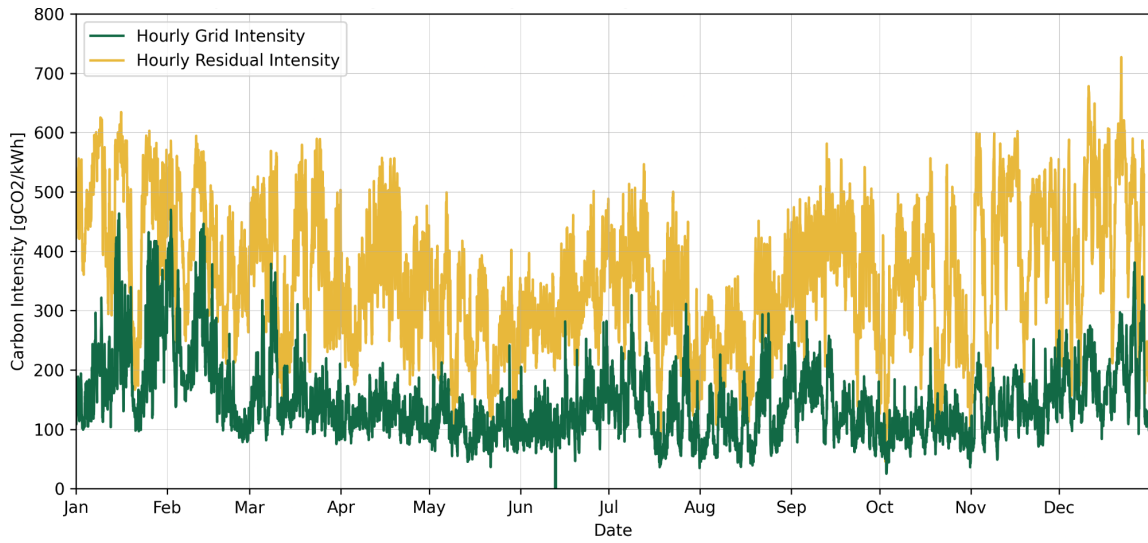


Figure 34. Comparison of Hourly Grid Intensity and Hourly Residual Mix Carbon Intensities - Denmark

7.2. Impact on the Market-Based Emissions Calculation

To compare how the different signals influence carbon accounting calculations, some example calculations below are performed. The focus of these calculations is on hourly granular accounting, both for the location- and market-based method. Already today, some companies conduct their market-based carbon accounting using granular data, though as hourly residual mix data is unavailable, they resort to hourly average grid emission data. Hourly location-based emissions ($HourlyLBE$), hourly market-based emissions using average grid intensity ($HourlyMBE_{CI}$), hourly market-based emissions using the hourly residual mix ($HourlyMBE_{HRM}$) as well as annual market-based emissions are calculated following the equations below:

$$EF_h^{grid}$$

$$HourlyLBE = \sum_{h=1}^{8760} (Consumption_h * EF_h^{grid}) \quad (Eq.10)$$

$$AnnualMBE = \max(0, (Consumption_{year} - REGen_{year}) * EF_{year}^{residual}) \quad (Eq. 11)$$

$$HourlyMBE_{CI} = \sum_{h=1}^{8760} \max(0, (Consumption_h - REGen_h) * EF_h^{grid}) \quad (Eq. 12)$$

$$HourlyMBE_{HRM} = \sum_{h=1}^{8760} \max(0, (Consumption_h - REGen_h) * EF_h^{residual}) \quad (Eq. 13)$$

As mentioned above, the market-based calculation is performed by simulating that the three different customers contract renewable electricity via a PPA that covers 60 % of their load, one case for wind and another for solar. This is modelled using the variable $REGen$ in the above formulas.

The results of the analysis are summarised in the following tables below. Table 6 shows the wind PPA case, the second to the solar PPA case. Additionally, the percentage difference between the resulting emissions of Case 3 and Case 4 (i.e. hourly market-based with grid average and hourly residual mix emission factors) is presented in the last column.

Table 6. Wind PPA Case - Scope 2 Emissions [tCO2]

Consumer	Location	Case 1 Location-based Hourly Grid Average	Case 2 Market-based Annual AIB Residual Mix	Case 3 Market-based Hourly Grid Average	Case 4 Market-based Hourly Residual Mix	Difference between Case 4 and Case 3
Data Center	Spain	6297.09	5701.84	3221.75	3843.78	19.31%
Manufacturing		1003.88	912.10	571.82	683.27	19.49%
Consumer G.		402.81	381.43	238.18	284.50	19.45%
Data Center	France	2131.27	936.14	984.07	1161.65	18.05%
Manufacturing		339.55	149.75	179.25	213.33	19.01%
Consumer G.		134.59	62.62	72.40	86.64	19.68%
Data Center	Czech Republic	23670.21	10599.95	11730.80	12018.65	2.45%
Manufacturing		3765.78	1695.63	2093.23	2154.58	2.93%
Consumer G.		1542.25	709.09	894.47	926.34	3.56%
Data Center	Denmark	7064.37	10202.13	3392.19	8468.39	149.64%
Manufacturing		1121.52	1631.99	604.27	1498.31	147.95%
Consumer G.		472.26	682.48	267.15	634.85	137.64%

Table 7. Solar PPA Case - Scope 2 emissions in [tCO2]

Consumer	Location	Case 1 Location-based Hourly Grid Average	Case 2 Market-based Annual AIB Residual Mix	Case 3 Market-based Hourly Grid Average	Case 4 Market-based Hourly Residual Mix	Difference between Case 4 and Case 3
Data Center	Spain	6297.09	5701.84	3946.78	4708.20	19.29%
Manufacturing		1003.88	912.10	589.85	709.80	20.33%
Consumer G.		402.81	381.43	197.41	238.84	20.98%
Data Center	France	2131.27	936.14	1413.20	1666.96	17.96%
Manufacturing		339.55	149.75	216.00	259.18	19.99%
Consumer G.		134.59	62.62	74.16	90.73	22.35%
Data Center	Czech Republic	23670.21	10599.95	9811.73	9943.88	1.35%
Manufacturing		3765.78	1695.63	1401.47	1421.36	1.42%
Consumer G.		1542.25	709.09	363.02	369.14	1.68%
Data Center	Denmark	7064.37	10202.13	4830.62	12350.13	155.66%
Manufacturing		1121.52	1631.99	738.51	1883.64	155.06%
Consumer G.		472.26	682.48	272.15	676.16	148.46%

Performing analysis on such cases is valuable, as it further highlights some of the issues that were observed during the development of this methodology. Specifically for each accounting case:

- Hourly Location-based using Grid Average Emission Factors:**
 Since the impact of procuring electricity through a PPA has no impact on location-based emissions, it is not surprising that location-based both for the solar and wind case are equivalent.
- Annual Market-based using Annual Residual Mix Emission Factors (AIB):**
 As can be seen in the results using the annual market-based method, procuring electricity through a PPA has an impact on scope 2 emissions. However, it is important to highlight that the outcome both for the solar and wind case is identical. This indicates that there is no difference between sourcing electricity from wind or solar assets on an annual basis, despite the fact that both technologies have very different generation profiles. This further highlights the issue that an annual accounting system does not differentiate between distinct generation profiles of different technologies.
- Hourly Market-based using Average Grid Emission Factors:**
 Similar to the annual market-based method, procuring electricity from either solar or wind has an impact on total emissions. However, reducing the granularity from the annual to the hourly level leads to differences in the resulting emissions. This is due to the different production profiles of solar and wind which vary significantly on an

hourly level. For instance, while a consumer might still consume wind during the night, they would not be able to do so if they closed a solar PPA, as the sun does not shine during this time. Note that since residual mix emission factors are not available, companies fall back on average emission factors to calculate emissions from their untracked consumption.

- **Hourly Market-based using Hourly Residual Mix Emission Factors:**

As indicated in this report, hourly residual mix emission factors are generally higher than average grid emission factors. Therefore, using average grid emission factors to calculate hourly market-based emissions can lead to significantly underestimated emissions. As highlighted in the results above, using hourly residual mix emission factors for hourly market-based emissions would lead to up to 152 % higher emissions for the case of Denmark, and around 20% higher emissions for the case of France and Spain. Interestingly, the difference between Case 3 and Case 4 is very small for the Czech Republic, which indicates that the residual mix must be similar to the power mix. Indeed, when comparing the Czech annual power mix with the annualised hourly residual mix, it can be seen that they are very similar.

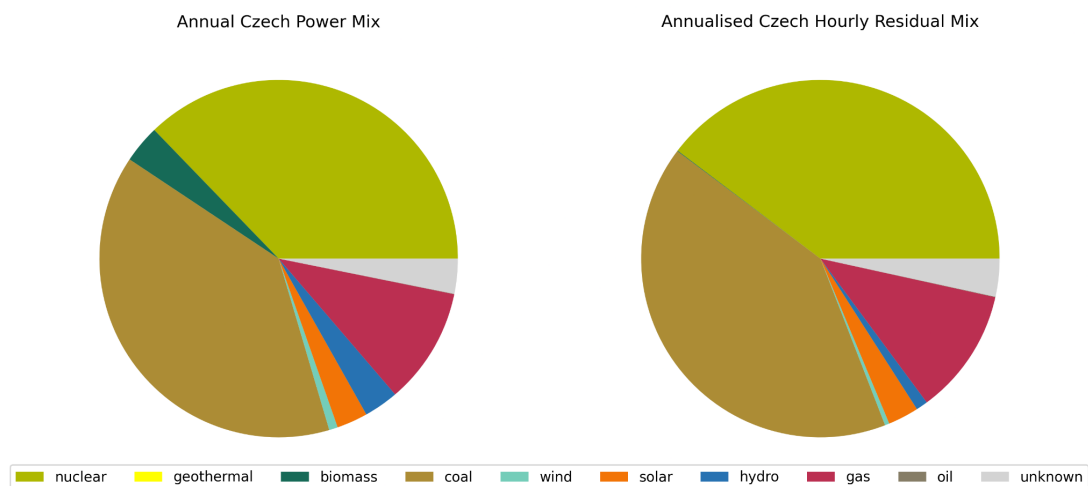


Figure 35. Comparison of Annual Czech Power Mix and the Annualised Czech Hourly Residual Mix

Overall, these findings further highlight the importance of conducting analysis on a more temporal and spatial level, in order to take into account the temporal variation of production technologies, as well as the local grid conditions and purchasing behaviour.

Future Work and Recommendations

8. Future Work and Recommendations

This work has been conducted with the awareness of the current limitations to obtain an hourly residual mix methodology. The purpose of this section is to highlight friction points that were encountered during the development of the HRM methodology and its application using currently available data. For the benefit of the industry and practitioners, the friction points should be discussed by a wider audience.

The first limitation of this methodology (and seemingly for any other hourly methodology) is that hourly residual mix can only be calculated once the production-based certificate dataset is readily available at the required time intervals. The availability of data is defined by the reporting cycles of AIB members, which are usually finalised up to 12 (18) months after the relevant period. Without changes to the reporting cadence, an hourly residual mix can only be calculated on a Y+1 basis, similar to what is happening with the publication of the annual residual mixes published by AIB. There is a need to increase the reporting cadence of AIB and its registries so as to reduce the lag between certificate actions and their reporting. This would result in simpler and more regular hourly residual mix calculations.

As it currently stands, it is impossible to trace certificates from their source to their sink. The production-based AIB statistics provide data on the origin of certificate issuances as well as the location where a certificate cancellation occurred. To the understanding of the authors however, the production-based AIB statistics do not provide information about the domain a cancelled certificate originated from. Because of this, it is currently not possible to trace a certificate from its origin domain to its domain of cancellation and thus develop an hourly residual mix methodology that includes considerations of physical deliverability. Providing such information on all certificates, or making such information more accessible for everyone will be beneficial to more accurately trace the flow of certificates and thus, better represent the physical reality of the grid. This could be done by combining the flow-tracing methodology [14] currently employed by Electricity Maps with certificate flows and verifying the deliverability on an hourly and zonal level.

An important aspect that needs to be highlighted is the presented approach on how hourly cancellation demand is simulated. As mentioned above, this methodology assumes a Business-as-Usual behaviour for the cancellation of certificates, as it better represents today's prevailing behaviour. The consequence of this is that there will be a significant amount of unserved certificate demand and additional expiries that would not occur using the annual approach - especially for the case of solar. While it would be possible to model hourly cancellation demand under the assumption of a strategic behaviour, such an approach would yield more favourable results than today's behaviour would result in. The large discrepancy of actual cancellations between the annual and the hourly approaches highlights that annual aggregation omits important temporal dynamics of power generation, such as the diurnal variation of solar generation. This could lead to inaccurate or misleading claims of renewable electricity consumption, as many such claims are physically impossible. Moving from an annual certificate system to a more granular (e.g. hourly) system has two core benefits:

1. It more accurately represents the temporal dynamics of power generation, especially of variable renewables.
2. It allows organisations to demonstrate strategic energy procurement behaviour, whereby hourly electricity consumption is matched with actual renewable electricity generation at an hourly level.

Finally, it is important to discuss the applicability of this methodology to other regions. The focus of this work was to analyse how hourly residual mix can be realised within the AIB region. The reason why it was possible to look into the AIB region is the uniform regulatory environment and standardised methodology of calculating residual mix across the market. Developing an accurate residual mix for any market region (not only hourly, but also annual) requires both a regulatory and methodological alignment across all regions that interact with the specific market region not only on the residual mix, but also on the underlying certificate system. A market region that allows the coexistence of multiple different certificate standards and residual mix methodologies inevitably will face the issue of ambiguous information not only for certificate market participants, but also for the regulatory body. This is because the residual mix tries to represent the untracked portion of energy and thus, multiple different criteria of what energy can be tracked will lead to multiple different residual mix values. This particular case can be observed in the United States, where it is already difficult to obtain a reliable annual residual mix - let alone a residual mix at an hourly level. For the benefit of the industry, but also for the benefit of comparing a company's energy-based inventory, it would be impactful to support the harmonisation of standards and methodologies across market regions.

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Annex

Annex

Detailed Steps on the Hourly Residual Mix Methodology

As mentioned during the paper, the goal of this work is to present a first iteration for a methodology to obtain an hourly residual mix for AIB regions. This annex is intended to provide a detailed overview of how the methodology functions.

Overall, the methodology is separated into three main processes and 8 steps:

A. Correlating production and load data with certificates data

- Step 1. Calculating hourly issuances per domain
- Step 2. Calculating hourly cancellation demand per domain

B. Balancing certificates across the European market

- Step 3. Calculating available certificate supply and cancellation demand in the European Pool
- Step 4. Computing actual serviceable cancellations for each generation technology at the European Pool level
- Step 5. Distributing cancellations from the European Pool to domain-level
- Step 6. Calculating hourly expirations at domain-level

C. Residual mix calculation

- Step 7. Computing the residual mix
- Step 8. Computing the residual carbon intensity

Below, each of these processes will be broken down into multiple steps.

The following list represents the notations and variables used during the methodology development:

- $G_{i,m}$: Physical generation of zone i, technology m [MWh]
- L_i : Physical load of zone i [MWh]
- $I_{i,m}$: Issuance of zone i, technology m [MWh]
- $\hat{C}_{i,m}$: Cancellation demand in zone i, technology m [MWh]
- $C_{i,m}$: Actual cancellations in zone i, technology m [MWh]
- $E_{i,m}$: Expirations in zone i, technology m [MWh]
- $RG_{i,m}$: Residual generation in zone i, technology m [MWh]
- $RM_{i,m}$: Residual mix in zone i, technology m [%]
- $\alpha_{i,m}$: Issuance coefficient in zone i, technology m [-]
- $\beta_{i,m}$: Cancellation demand coefficient in zone i, technology m [-]

- $I_{Pool,m}$: Issuances at pool level per technology m [MWh]
- $\hat{C}_{Pool,m}$: Cancellation demand at pool level per technology m [MWh]
- $E_{Pool,m}$: Expirations at pool level per technology m [MWh]
- $C_{Pool,m}$: Actual cancellations at pool level per technology m [MWh]
- $k_{Pool,m}$: Fulfillment coefficient, ratio between actual cancellations and cancellation demand per technology m [-]
- $\varepsilon_{pool,m}$: Expiration coefficient per technology m [-]
- $DED_{i,m}$: Domestic expiration demand in zone i, technology m [MWh]
- $DEP_{i,m}$: Domestic expiration potential in zone i, technology m [MWh]
- $DRG_{i,m}$: Domestic residual generation in zone i, technology m [MWh]
- $DRM_{i,m}$: Domestic residual mix in zone i, technology m [%]
- ERG_m : European residual generation per technology m [MWh]
- ERM_m : European residual mix per technology m [%]
- RCI_i : Residual carbon intensity in zone i [kgCO2/MWh]

Table 8. Required inputs

Type	Unit	Per Country	Per Technology
Certificate Issuances	MWh	✓	✓
Cancellation Demand	MWh	✓	✓
Electricity Generation	MWh	✓	✓
Emission Factors	kg CO2 per MWh	✓	✓

Table 9. Obtained Outputs

Type	Unit	Per Country	Per Technology
Residual Generation	MWh	✓	✓
Residual Mix	%	✓	✓
Residual Carbon Intensity	kg CO2 per MWh	✓	✗

A. Correlating production and load data with certificates data

As a starting point, the approach is taken to calculate hourly issuances, cancellations and expirations of certificates by using actual annual certificate data and the power system data (load and generation) available per country. Hourly issuances are approximated by multiplying an issuance coefficient with hourly electricity generation, which ensures that certificates can only be issued according to prevailing local generation. Cancellation demand is approximated by multiplying a cancellation coefficient with hourly consumption curves.

This assumes that the cancellations demand follows the prevailing load curves of each domain, i.e. the cancellations demand is proportional to the local load curve. As a reminder, cancellations demand represent the amount of certificates cancelled on an annual approach, while actual cancellations refer to the cancellations that can be served by available certificate issuance supply on an hourly level.

Step 1. Calculate Hourly Issuances per Domain

The issuance coefficient represents the quantity of certificates that are issued per unit of electricity produced by country i using technology m . A country's yearly issuances per technology can be related to a country's yearly generation for each technology using the issuance coefficient $\alpha_{i,m}$:

$$\alpha_{i,m} = I_{i,m} / G_{i,m} \quad \forall \quad i, m \quad (\text{Eq. 14})$$

To make this definition robust against missing values (considering data availability issues of certificates), we propose the following adjustment:

$$\frac{I_{i,m}}{n_1} = \alpha_{i,m} * \frac{G_{i,m}}{n_2} \quad \forall \quad i, m \quad (\text{Eq. 15})$$

where n_1 and n_2 represent the number of hours of the assessed period. By using such a formulation, it is possible to account for the worst cases of data availability. Here, the ratio of average values, instead of the ratio of yearly values are put in relation. Following the above definition, the issuance coefficient $\alpha_{i,m}$ can be defined as:

$$\alpha_{i,m} = \left(\frac{I_{i,m}}{n_1} \right) / \left(\frac{G_{i,m}}{n_2} \right) \quad \forall \quad i, m \quad (\text{Eq. 16})$$

Given the formulation above, for a full year of data, the condition $n_1 = n_2 = n$ will hold. In this case, the above equation simplifies to:

$$\alpha_{i,m} = \left(\frac{I_{i,m}}{n_1} \right) / \left(\frac{G_{i,m}}{n_2} \right) = \frac{n_2}{n_1} * \frac{I_{i,m}}{G_{i,m}} = \frac{I_{i,m}}{G_{i,m}} \quad \forall \quad i, m \quad (\text{Eq. 17})$$

Once the issuance coefficient is known, it is possible to approximate hourly issuances for different generation technologies m for each country i by multiplying the issuance coefficient with hourly electricity generation data:

$$I_{i,m,t} = \alpha_{i,m} * G_{i,m,t} \quad \forall \quad i, m, t \quad (\text{Eq. 18})$$

Such a formulation ensures that hourly certificates are only issued whenever corresponding electricity was in fact generated. This means that there can never be more certificate issuance (in energy volume terms) than actual electricity generation of the corresponding technology.

Step 2. Calculate Hourly Cancellation Demand per Domain

The cancellation coefficient represents the number of cancellations that are demanded for each unit of electricity consumed by country i and technology m . It allows estimating a country's cancellation demand based on its 'appetite' for cancellations per technology. The inherent difference between issuances and cancellations is the fact that, unlike issuances, it is impossible to relate a cancelled certificate to where it has been originally issued. On top of that, certificate cancellations within a domain are not connected to the electricity physically consumed per technology in this domain, since a domain can cancel certificates issued in another AIB domain. For instance, a country might cancel hydro certificates even though it does not produce any electricity from hydropower.

It is assumed that hourly cancellations per technology are proportional to the yearly cancellations per technology (the same procedure can be followed with monthly data, instead of yearly). Similar to the approach above for issuances, one can relate a country's yearly cancellations per technology with a country's yearly consumption using the cancellation coefficient $\beta_{i,m}$:

$$\beta_{i,m} = C_{i,m} / L_i \quad \forall \quad i, m \quad (\text{Eq. 19})$$

It is important to highlight that this definition includes a country's yearly consumption or load that is not differentiated by technology.

To make this definition robust against missing values (considering data availability issues of certificates), we propose the following adjustment:

$$\frac{C_{i,m}}{n_1} = \beta_{i,m} * \frac{L_i}{n_2} \quad \forall \quad i, m \quad (\text{Eq. 20})$$

where n_1 and n_2 represent the number of hours of the assessed period. As outlined above, by using such a formulation it is possible to account for the worst cases of data availability. Here, the ratio of average values, instead of the ratio of yearly values are put in relation. By reformulating the equation above the cancellation coefficient $\beta_{i,m}$ can be defined as:

$$\beta_{i,m} = \left(\frac{C_{i,m}}{n_1} \right) / \left(\frac{L_i}{n_2} \right) \quad \forall \quad i, m \quad (\text{Eq. 21})$$

Given the formulation above, for a full year of data, the condition $n_1 = n_2 = n$ will hold. In this case, the above equation simplifies to:

$$\beta_{i,m} = \left(\frac{C_{i,m}}{n_1} \right) / \left(\frac{L_i}{n_2} \right) = \frac{n_2}{n_1} * \frac{C_{i,m}}{L_i} = \frac{C_{i,m}}{L_i} \quad \forall \quad i, m \quad (\text{Eq. 22})$$

Once the cancellation coefficient is known, it is possible to approximate the hourly cancellation demand per technology m and country i by multiplying the cancellation coefficient with hourly electricity load data:

$$\hat{C}_{i,m,t} = \beta_{i,m} * L_{i,t} \quad \forall \quad i, m, t \quad (\text{Eq. 23})$$

B. Balancing Certificates Across the European Market

Once hourly issuances and cancellation demand have been obtained per country, the next step relies on checking if the cancellation demand can be fulfilled with the amount of issuances for each specific hour at European market level. As a reminder, certificates can be freely traded amongst AIB regions, therefore the certificate balance must hold at European market level, and not on country level (as issued certificates in one country can be cancelled in another). This section of the methodology contains the required steps to guarantee the balance of certificates on the European market level and to obtain hourly actual cancellations and issuances at country level.

Step 3. Calculating Available Certificate Supply and Cancellation Demand in the European Pool

The origin of issued certificates is easily traceable, however since the AIB dataset does not provide any origin on cancelled certificates, there needs to be another approach to distributing certificates to countries. A concept called the European Certificate Pool is proposed, which collects all issued certificates in the European market in one pool. The purpose of this pool is to capture the total number of certificates issued in all member domains, differentiated by generation technology. This information helps understand how many certificates per technology are available for distribution at any given time interval. The total issuances in the European Certificate Pool (ECP) per technology can be calculated as the sum of all issued certificates over all countries i :

$$I_{Pool,m} = \sum_i I_{i,m} \quad \forall \quad m \quad (\text{Eq. 24})$$

where $I_{i,m}$ represents issuances by country i and technology m and $I_{Pool,m}$ the issuances aggregated over all AIB domains (countries) per technology m .

The same procedure is applied for the aggregation of cancellation demand and European Certificate Pool level. So that:

$$\hat{C}_{Pool,m} = \sum_i \hat{C}_{i,m} \quad \forall m \quad (\text{Eq. 25})$$

where $\hat{C}_{Pool,m}$ represents the aggregated cancellation demand per generation technology m , and $\hat{C}_{i,m}$ the cancellation demand per country i and generation technology m .

The Figure below should serve as a figurative example to facilitate this dynamic.

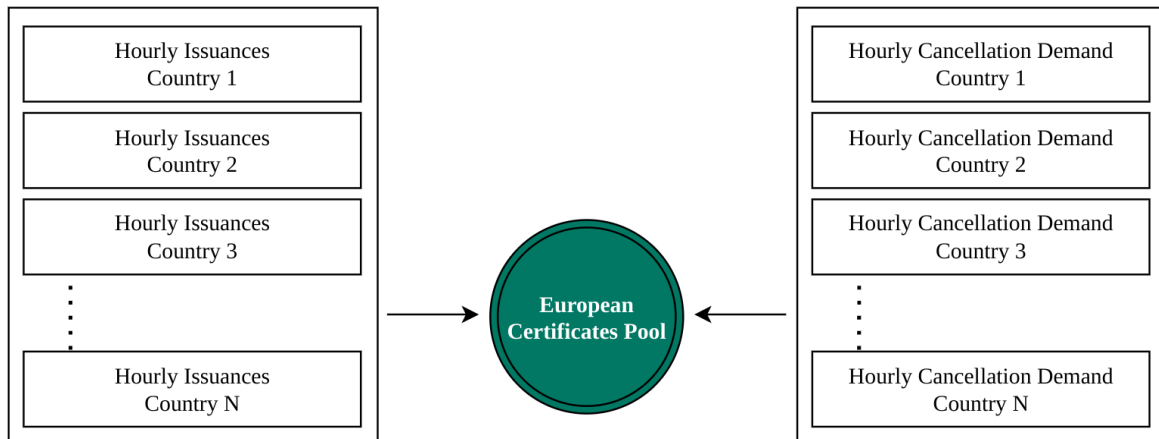


Figure 36. Dynamics of the European Certificates Pool

Step 4. Computing Actual Serviceable Cancellations for Each Generation Technology at the European Pool Level

Before being able to distribute certificates from the ECP to countries, one needs to determine the demand for cancellations per technology and country, and whether the demanded cancellations can be serviced by the available certificate supply (=issuances). In other words, it needs to be verified whether the demanded cancellations of technology m in the European Pool can be supplied by the issuances of technology m that are available in the European Pool and thus fulfil the conservation of certificates introduced previously. Mathematically, this can be described as:

$$I_{Pool,m} - C_{Pool,m} - E_{Pool,m} \equiv 0 \quad \forall \quad m \quad (Eq. 26)$$

The goal of this step is to ensure that each certificate is either cancelled or expired. Note that this conservation of certificates must hold over the aggregated European Pool but will not hold on a country level (as issued certificates in one country can be cancelled in another).

To uphold the conservation of certifications on the European level, one needs to ensure that cancellation demand per generation technology aggregated over all countries is equal or lower than issuance supply per generation technology aggregated over all countries. In this methodology, any certificate demand that cannot be serviced with available certificate supply is curtailed.

Having defined both parameters $\hat{C}_{Pool,m}$ and $I_{Pool,m}$ there are now two cases to be considered in order to determine whether cancellation demand can be serviced or not:

- **Case 1:** aggregated issuance supply per technology is larger than or equal to aggregated cancellation demand and thus all demanded cancellations will be serviced. Actual cancellations $C_{Pool,m}$ are set equal to cancellation demand $\hat{C}_{Pool,m}$, as all demand can be served. The surplus will be marked as expired.

$$\begin{aligned} \circ \quad & I_{Pool,m} \geq \hat{C}_{Pool,m} \\ & \rightarrow C_{Pool,m} = \hat{C}_{Pool,m} \\ & \rightarrow E_{Pool,m} = I_{Pool,m} - C_{Pool,m} \geq 0 \end{aligned} \quad (Eq. 27)$$

- **Case 2:** aggregated issuance supply per technology is smaller than aggregated cancellation demand - in other words, there are not enough issued certificates to service the demand in cancellations. In this case, cancellation demand cannot be served and thus, must be limited to the issuance supply. Actual cancellations $C_{Pool,m}$ are set equal to aggregated issuance supply $I_{Pool,m}$, as this represents the maximum amount of certificates that can be cancelled.

$$\begin{aligned} \circ \quad & I_{Pool,m} < \hat{C}_{Pool,m} \\ & \rightarrow C_{Pool,m} = I_{Pool,m} \\ & \rightarrow E_{Pool,m} = I_{Pool,m} - C_{Pool,m} \equiv 0 \end{aligned} \quad (Eq. 28)$$

A helpful measure to assess to what degree demanded cancellations can be serviced by available certificate supply is the fulfilment coefficient $k_{Pool,m}$, which represents the ratio between actual cancellations per technology and cancellation demand per technology.

$$\text{where } k_{pool,m} = \frac{C_{pool,m}}{\hat{C}_{pool,m}} \quad (\text{Eq. 29})$$

Step 5. Distributing Cancellations from the European Pool to Domain-Level

The fulfilment coefficient $k_{pool,m}$ is an essential metric to allocate cancellations from the European Certificate Pool to countries. For instance, if 50 % of all hydro cancellation demand can be serviced by issued hydro certificates, each country will receive 50 % of hydro cancellations it demanded in the specific time interval. Following this, actual cancellations per technology for each country can be calculated as:

$$C_{i,m} = k_{pool,m} * \hat{C}_{i,m} \quad \forall i, m \quad (\text{Eq. 30})$$

Where, $\hat{C}_{i,m}$ represents cancellation demand of country i per technology m , while $C_{i,m}$ represents actual cancellations of country i per technology m .

Example:

To better understand how cancellations are distributed, refer to the figure and explanation below.

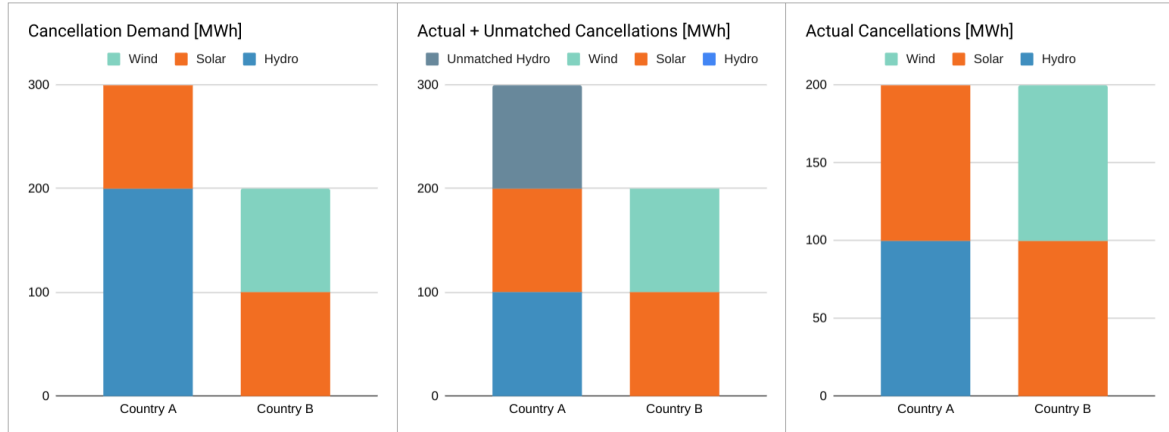


Figure 37. Example from Cancellation Demand to Actual Cancellations Serviced

As can be seen from the graphs, the countries in this example show the following cancellation demands:

$$\hat{C}_{A,m} = (\hat{C}_{A,Hydro}, \hat{C}_{A,Solar}, \hat{C}_{A,Wind}) = (200, 100, 0) \quad (\text{Eq. 31})$$

$$\hat{C}_{B,m} = (\hat{C}_{B,Hydro}, \hat{C}_{B,Solar}, \hat{C}_{B,Wind}) = (0, 100, 100) \quad (Eq. 32)$$

In this example, it is assumed that the cancellation demand of wind and solar can be covered by the available issuances, however only 50 % of hydro cancellation demand can be covered by available hydro issuances. Due to this, the resulting fulfilment coefficient is:

$$k_{Pool,m} = (k_{Pool,Hydro}, k_{Pool,Solar}, k_{Pool,Wind}) = (0.5, 1, 1) \quad (Eq. 33)$$

By multiplying the fulfilment coefficient with the cancellation demand as shown in the equation above, it is possible to calculate actual cancellations for each country.

$$C_{A,m} = k_{Pool,m} * \hat{C}_{A,m} = (0.5, 1, 1) * (200, 100, 0) = (100, 100, 0) \quad (Eq. 34)$$

$$C_{B,m} = k_{Pool,m} * \hat{C}_{B,m} = (0.5, 1, 1) * (0, 100, 100) = (0, 100, 100) \quad (Eq. 35)$$

Step 6. Calculating Hourly Expirations at Domain-Level

Similar to issuances and cancellations, expirations are modelled both at the domain and European Pool level. Since issuances and cancellations are aggregated at a European level and redistributed according to specific criteria, this also holds true for expirations. The expiration algorithm needs to consider transfers of issuances and cancellations across countries, while at the same time take into account that some domains will cancel certificates without the appropriate domestic generation. For instance, this is the case for domains that import hydro cancellations, without any domestic hydro production. In a first step, domestic expiration demand based on local generation, certificate issuance and certificate cancellation are determined.

As mentioned previously, due to the trade of certificates between domains, the certificate balance only holds at a European level. In the current system, domains are allowed to import certificates of any production technology, even if there is no local generation of that specific production technology. As a result of this, a country can have hydro cancellations, without any local hydro generation and thus no hydro issuances. For such cases, it is important to differentiate between net-exporters and net-importers of certificates. Net-exporters are domains that have more local certificate issuances than certificate cancellation demand (and vice-versa). To identify which domains fall into which category, we introduce the so-called Domestic Expiration Demand (DED) for each domain, which is calculated as:

$$DED_{i,m} = I_{i,m} - C_{i,m} \quad \forall \quad i, m \quad (Eq. 36)$$

Note that the $DED_{i,m}$ only serves as a placeholder metric to identify net-certificate exporters and importers. A positive $DED_{i,m}$ indicates a net-exporter of certificates, while a negative $DED_{i,m}$ indicates a net-importer of certificates for each technology m . Aggregating $DED_{i,m}$ across domains into the European Pool results in the correct expirations at the pool level, since net-importers and net-exporters of certificates balance out:

$$DED_{pool,m} = \sum_i DED_{i,m} \quad \forall \quad m \quad (Eq. 37)$$

Since it is impossible to verify the flow of certificates as well as differentiate between cancellations that have been made possible through local issuances, or through issuances that have been traded into the domain, we need to resort to a non-discriminatory allocation approach. For this, it is assumed that certificates can only expire in countries that are considered net-exporters of certificates, since it is impossible to say whether a cancellation originates from a local or purchased issuance. To assess the potential of certificates that can expire in these net-export domains, the Domestic Expiration Potential $DEP_{i,m}$ is introduced, which includes all non-negative values of the Domestic Expiration Demand $DED_{i,m}$.

- Case 1: For net-exporters, domestic expiration demand is greater or equal to 0.

$$\begin{aligned} \circ \quad DED_{i,m} &\geq 0 \\ \rightarrow DEP_{i,m} &= DED_{i,m} \quad \forall \quad i, m \end{aligned} \quad (Eq. 38)$$

- Case 2: For net-importers, domestic expiration demand is less than 0.

$$\begin{aligned} \circ \quad DED_{i,m} &< 0 \\ \rightarrow DEP_{i,m} &= 0 \quad \forall \quad i, m \end{aligned} \quad (Eq. 39)$$

The expiration potential can be aggregated across countries to the expiration potential at the European Pool:

$$DEP_{pool,m} = \sum_i DEP_{i,m} \quad \forall \quad m \quad (Eq. 40)$$

In essence, domestic expiration potential represents the amount of certificates that are available for expiration in each domain. Once domestic expiration demand and domestic expiration potential at the European Pool level are determined, one can calculate the share of

expiration potential $\varepsilon_{pool,m}$ - also called expiration coefficient - for each technology that will in fact expire as a result of the reallocation of certificates:

$$\varepsilon_{pool,m} = \frac{DED_{pool,m}}{DEP_{pool,m}} \quad \forall \quad m \quad (Eq. 41)$$

The share of expiration potential is used to determine the domain-level expirations:

$$E_{i,m} = DEP_{i,m} * \varepsilon_{pool,m} \quad \forall \quad i, m \quad (Eq. 42)$$

Note that the certificate balance does not hold at a country level, but only at the European Level.

C. Residual Mix Calculation

Up until this point, the methodology has been focusing on how to obtain issuances, cancellations and expirations on an hourly level. With that information, then the residual mix and the corresponding carbon intensities can be obtained following a similar approach on what Grexel uses today to obtain the annual residual mix (which has been introduced on the first part of the paper).

Step 7. Computing the Residual Mix

At this step of the methodology, issuances, cancellations and expirations are available per technology and per country. Consider that this example is for a specific period of one hour, these calculation steps are conducted for every hour in the methodology. In order to facilitate understanding of the next steps, a stepwise example using three countries is followed.

As a starting point, the following information is available:

Table 10. Generation Volumes, Issuances, Cancellations and Expirations for the example

	Generation Volumes [MWh]				Issuances [MWh]				Cancellations [MWh]				Expirations [MWh]			
Country A	0	50	50	100	0	45	0	0	0	30	0	0	0	1	0	0
Country B	50	100	50	0	0	100	0	0	10	100	0	0	0	3	0	0
Country C	100	30	0	100	40	30	0	0	20	40	0	0	10	1	0	0
Pool	150	180	100	200	40	175	0	0	30	170	0	0	10	5	0	0

■ wind ■ solar ■ coal ■ gas

From the table above, it can be confirmed that the balance of certificates holds at pool-level, but not on a country level. For example, if we take the example of Country C for solar, there are more cancellations than issuances.

With these values, the domestic residual generation $DRG_{i,m}$ for each domain i and technology m can be obtained using the following equation:

$$DRG_{i,m} = G_{i,m} - I_{i,m} + E_{i,m} \quad \forall \quad i, m \quad (\text{Eq. 43})$$

The aggregated domestic residual generation DRG_i for domain i can be calculated as

$$DRG_i = \sum_{m=1}^n DRG_{i,m} \quad (\text{Eq. 44})$$

with the Domestic Residual Mix being defined as:

$$DRM_{i,m} = \frac{DRG_{i,m}}{\sum_{m=1}^n DRG_{i,m}} \quad (\text{Eq. 45})$$

For the example given above, the following $DRM_{i,m}$ are obtained for the respective countries:

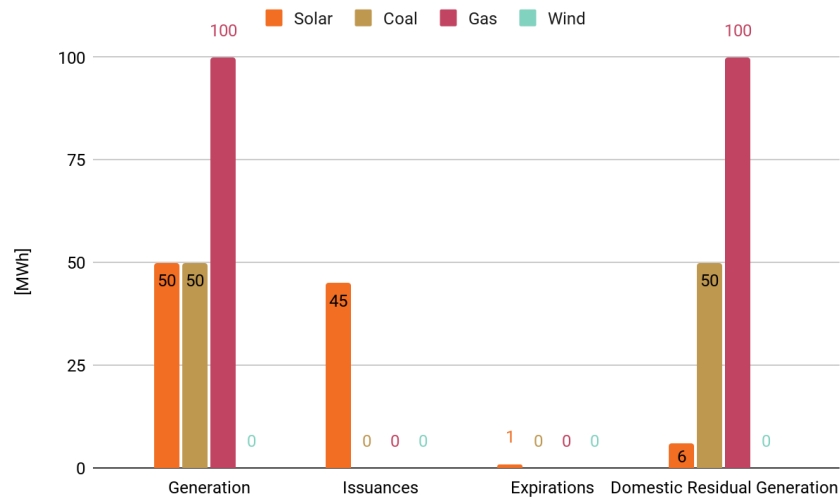


Figure 38. Country A - Domestic Residual Generation

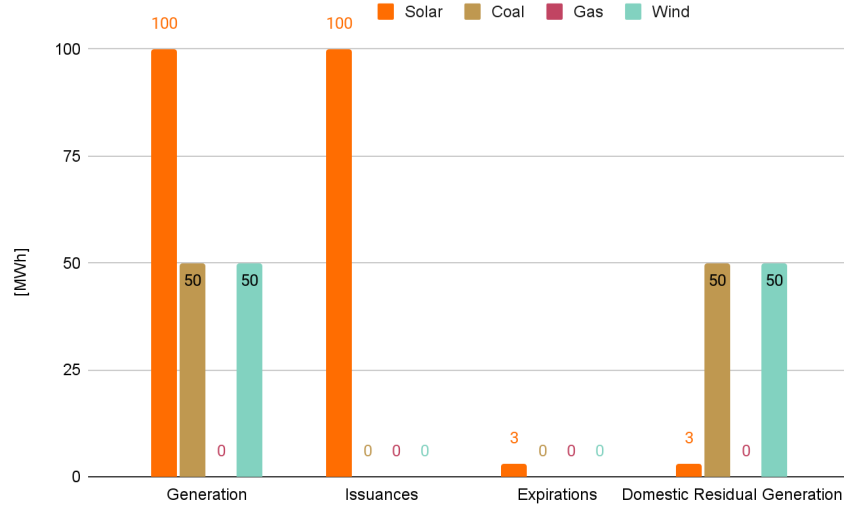


Figure 39. Country B - Domestic Residual Generation

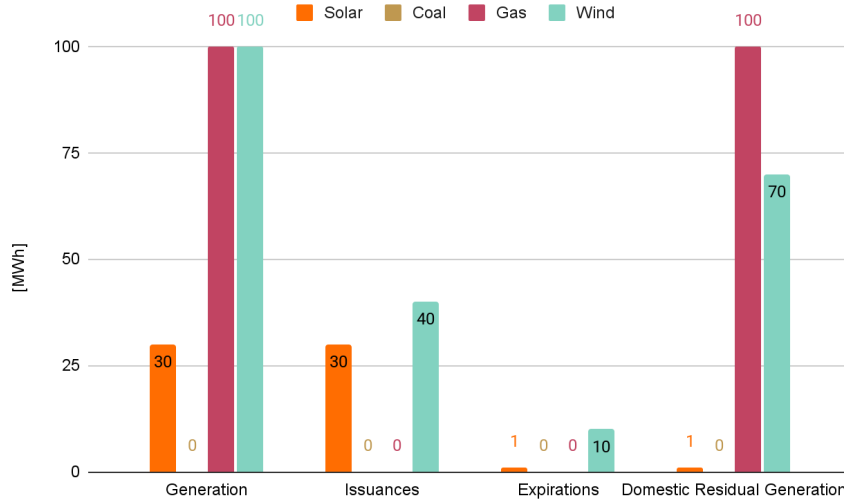


Figure 40. Country C - Domestic Residual Generation

Surplus and Deficit Hours in each Domain:

Depending on the electricity generation and certificate cancellations within a domain and hour, each domain can fall into two categories: Surplus Domains or Deficit Domains. Note that this can and will change depending on the hourly generation and certificate dynamics.

1. Surplus Domains

$$\text{If } \sum_{m=1}^M [DRG_{i,m} + \sum_{m=1}^M C_{i,m}] > L_i \quad \forall \quad i \quad (\text{Eq. 46})$$

In surplus domains, the total volume of domestic residual generation and cancellations is larger than the domain's load. In this case the excess volume of energy will be made available to the so-called European Residual Generation Pool (EGRP) according to the local residual generation mix (=equal to the technology shares of the domestic residual mix).

For surplus domains, the total volume that can be transferred to the European Residual Generation Pool can be calculated as:

$$\Delta T_i = \sum_{m=1}^M [DRG_{i,m} + \sum_{m=1}^M C_{i,m}] - L_i \geq 0 \quad \forall \quad i \quad (\text{Eq. 47})$$

Using the domestic residual mix $DRM_{i,m}$, it is possible to calculate the surplus volumes for each surplus domain per technology:

$$Surplus_{i,m} = DRM_{i,m} * \Delta T_i \quad \forall \quad i, m \quad (\text{Eq. 48})$$

This means that surplus domains transfer their surplus energy to the European Pool differentiated by technology - they do not receive any energy volume in this particular time step. The below figure represents the dynamic for surplus countries aggregated in the pool as an illustrative example.

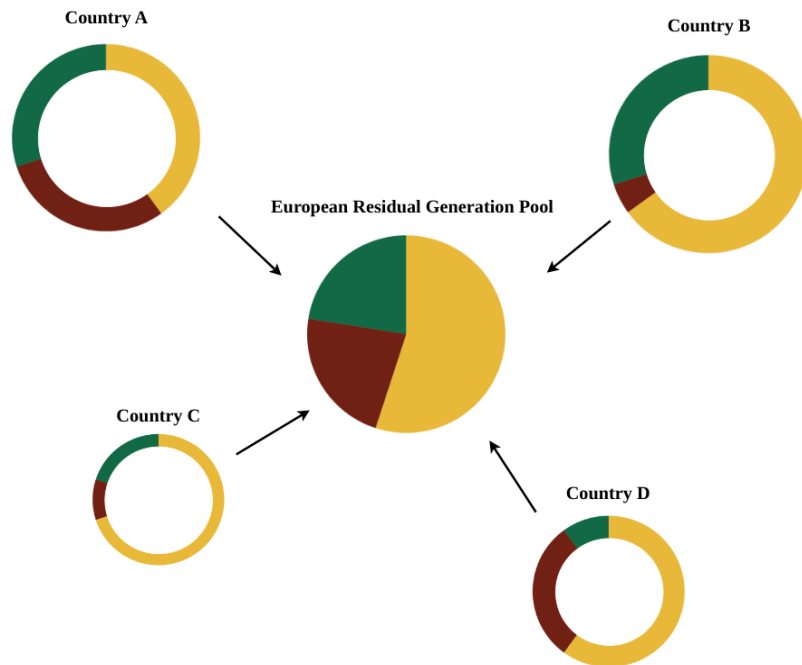


Figure 41. Addition of surpluses in the European Residual Generation Pool

The overall surplus per technology in the ERGP is the aggregate surplus over all domains, the so-called European Residual Generation ERG_m :

$$ERG_m = \sum_i Surplus_{i,m} \quad \forall \quad m \quad (Eq. 49)$$

With the corresponding European Residual Mix ERM_m

$$ERM_m = \frac{ERG_m}{\sum_m ERG_m} \quad \forall \quad m \quad (Eq. 50)$$

A surplus country's final residual generation $RG_{i,m}$ can be calculated as:

$$RG_{i,m} = DRG_{i,m} - Surplus_{i,m} \quad (Eq. 51)$$

With the corresponding residual mix

$$RM_{i,m} = \frac{RG_{i,m}}{\sum_m RG_{i,m}} \quad \forall \quad i, m \quad (Eq. 52)$$

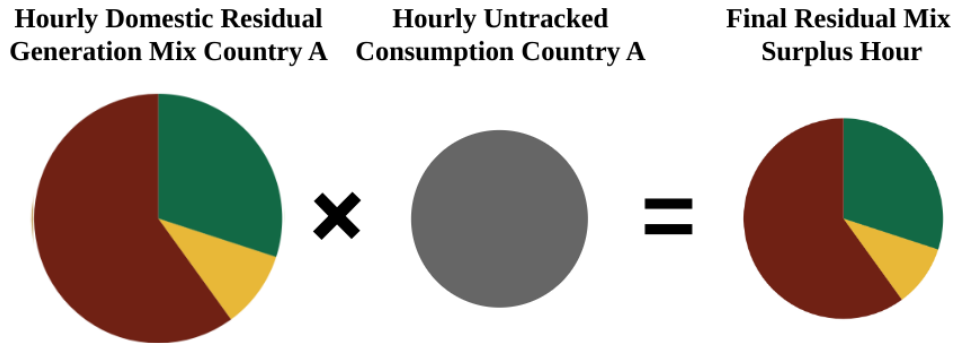


Figure 42. Obtention of the Residual Mix for Surplus Hours.

2. Deficit Domains

$$\text{If } \sum_{m=1}^M [DRG_{i,m} + \sum_{m=1}^M C_{i,m}] < L_i \quad \forall \quad i \quad (Eq. 53)$$

In deficit domains, the aggregated domestic residual mix and the cancellations cannot meet the load of the domain. The lacking energy volume of deficit countries will be served by the European Residual Generation Pool according to the pool's residual generation mix (=the technology mix of the ERGP defines the power mix that is transferred to deficit domains).

For deficit countries, the total volume that needs to be transferred from the European Residual Generation Pool to each domain i can be calculated as:

$$\Delta T_i = L_i - \sum_{m=1}^M [DRG_{i,m} + \sum_{m=1}^M C_{i,m}] \geq 0 \quad \forall \quad i \quad (\text{Eq. 54})$$

Using the European Residual Mix ERM_m , it is possible to calculate the allocated volumes for each deficit country per technology:

$$Deficit_{i,m} = ERM_m * \Delta T_i \quad \forall \quad i, m \quad (\text{Eq. 55})$$

The below figure represents the dynamic for deficit countries.

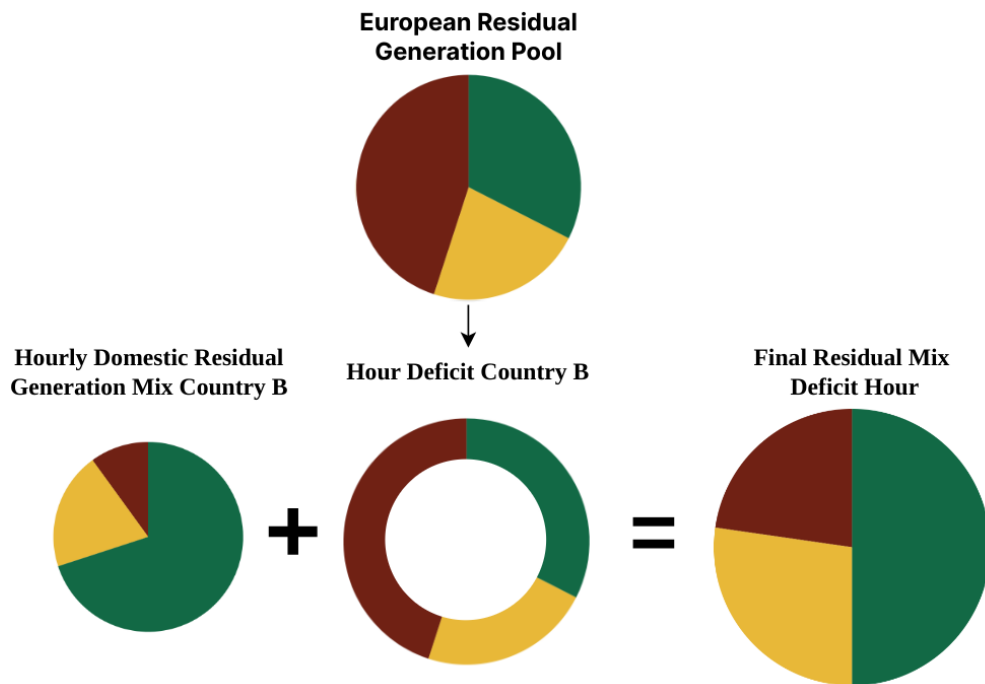


Figure 43. Determining the Residual Mix for Deficit Hours.

A deficit country's final residual generation can be calculated as:

$$RG_{i,m} = DRG_{i,m} + Deficit_{i,m} \quad (\text{Eq. 56})$$

With the corresponding residual mix

$$RM_{i,m} = \frac{RG_{i,m}}{\sum_m RG_{i,m}} \quad \forall \quad i, m \quad (\text{Eq. 57})$$

It is important to highlight that deficit hour countries do not supply any energy volume to the European Residual Generation Pool, and instead receive an allocation according to their transfer volume and the prevailing ERGP mix.

For the example provided, there are two deficit countries (A,C) as the sum of their domestic residual generation and the cancellations do not meet the demand. On the contrary, as country B's domestic residual generation together with its cancellations exceed the demand, it is considered a surplus country. The following figures represent this step for the different countries analysed in this example:

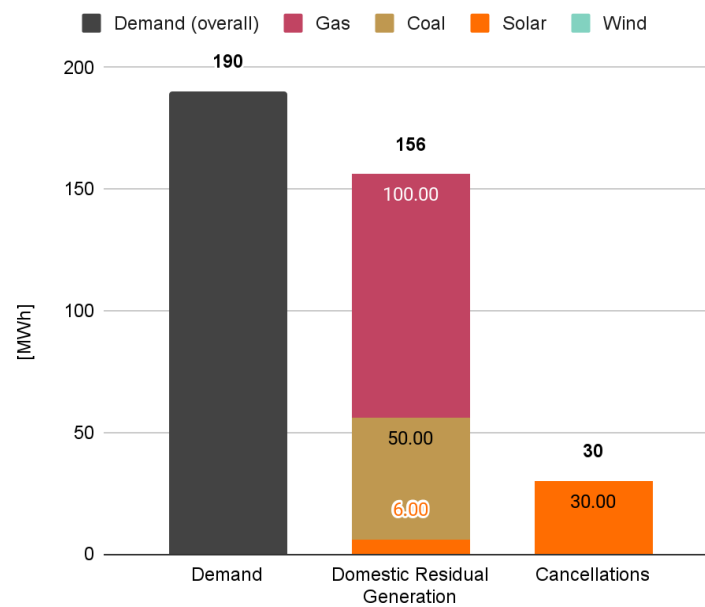


Figure 46. Country A - Deficit Hour

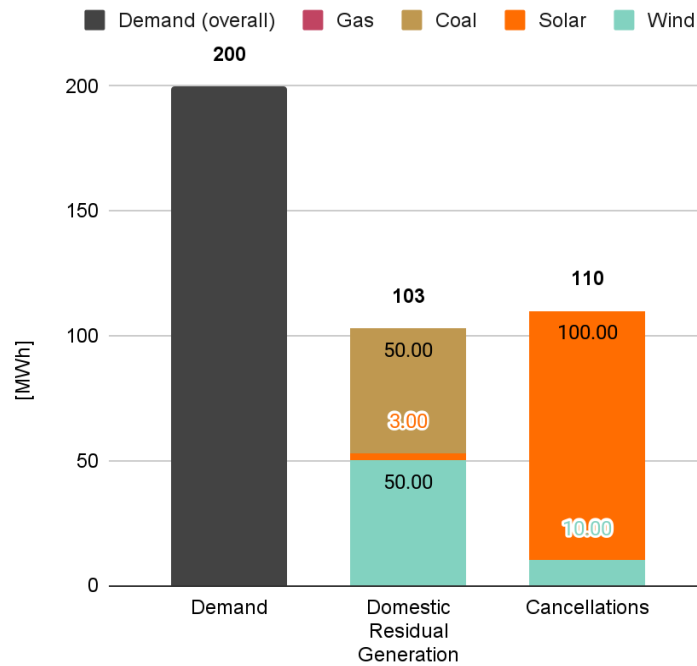


Figure 46. Country B - Surplus Hour

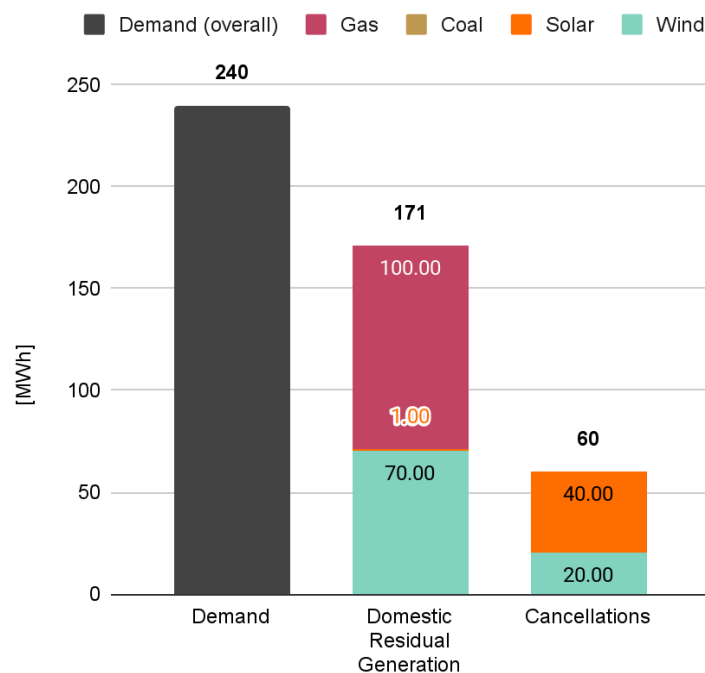


Figure 46. Country C - Deficit Hour

As the only surplus country, country B will allocate its surplus to the European Residual Generation Pool. The surplus mix that will be allocated to the pool is equal to the domestic residual mix. Visually, this is represented as follows:

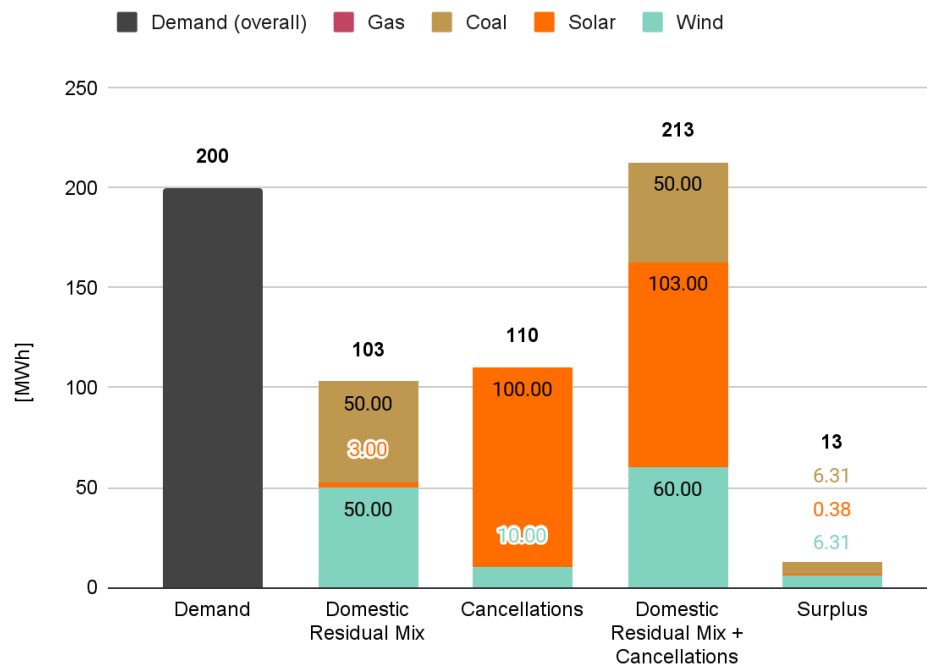


Figure 47. Calculating the surplus for Country B - Surplus Hour

In this example, the European Residual Generation Pool will only be composed of surplus energy originating from Country B. As a result of this, the energy allocated from the pool to deficit countries will have a technology mix that matches the surplus mix provided by country B. This can be represented for Countries A and C as following:

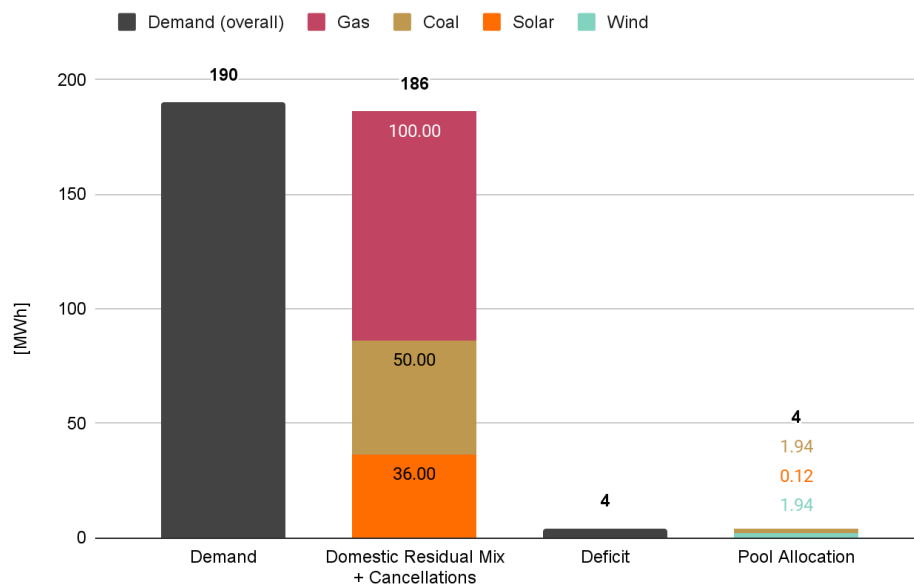


Figure 48. Determining the deficit and pool allocation for Country A

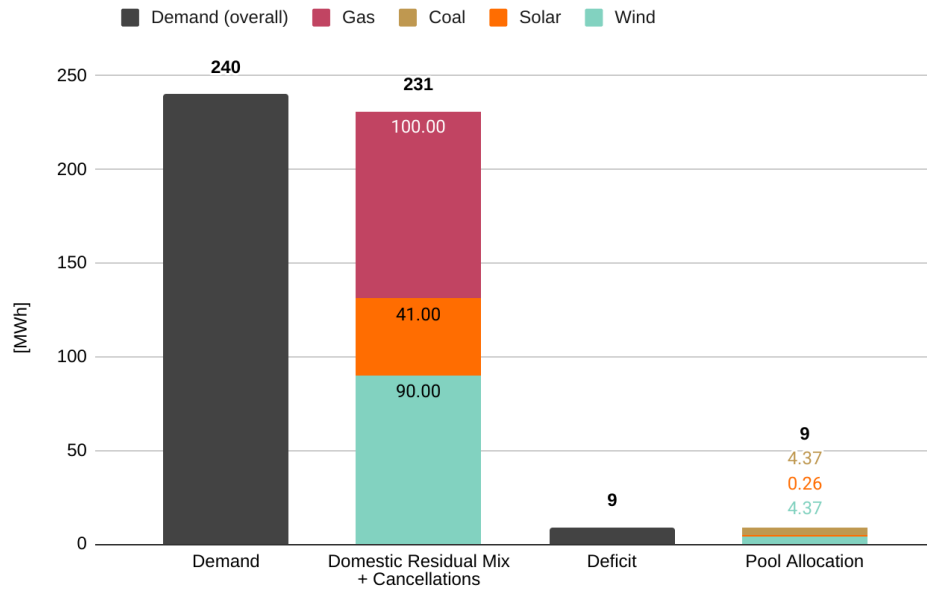


Figure 49. Determining the deficit and pool allocation for Country C

Once the allocation from the pool to deficit countries has been determined, the final residual generation and thus the final residual mix can be determined for each of the countries in the example according to equations 52 and 57. For surplus countries, the final residual generation is obtained by subtracting the surplus from the domestic residual generation, while for deficit countries, the final residual generation is equal to the sum of the domestic residual generation and the pool allocation.

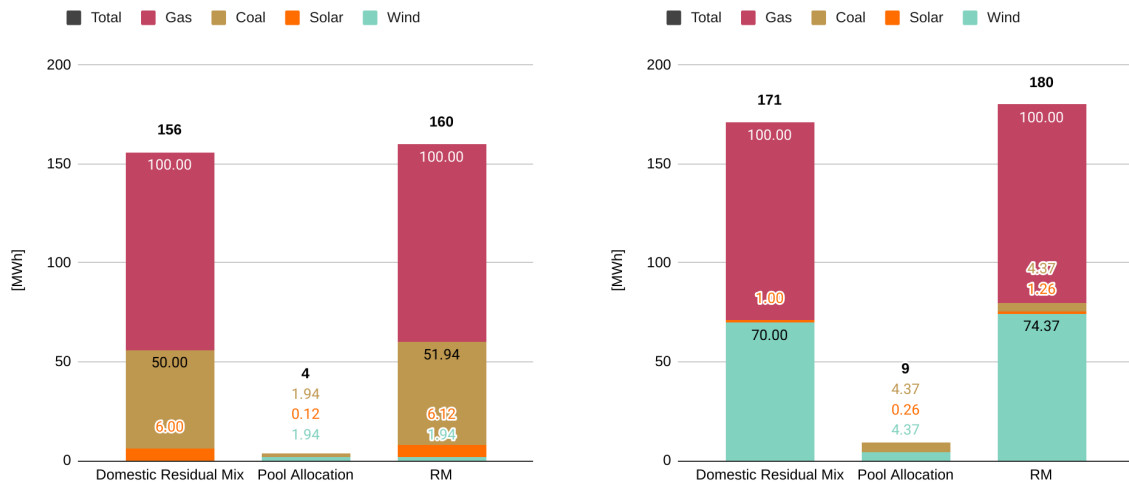


Figure 50. Final Residual Mix for Deficit countries. Country A (left) and Country C (right)

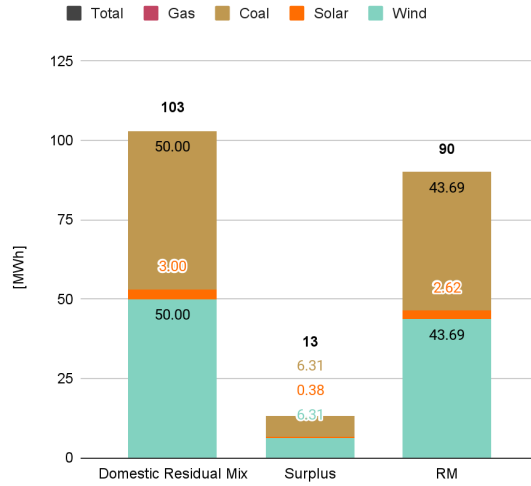


Figure 51. Final Residual Mix for Surplus Country B

Step 8. Computing the Residual Carbon Intensity

Once residual generation has been determined, it is possible to calculate the residual carbon intensity (RCI) on the domain level. The RCI represents the average emission factor of a domain's residual generation:

$$RCI_i = \frac{\text{Residual Emissions of Country } i}{\text{Residual Generation Volume of Country } i} = \frac{\sum_m EF_{i,m} * RG_{i,m}}{\sum_m RG_{i,m}} \quad \forall \quad i \quad (\text{Eq. 57})$$

Electricity Maps provides data on regional emission factors and thus, domain-specific emission factors can be used for calculating the RCI. Note that in this section, no temporal indices have been added to the equations, as the outlined calculation procedure is applicable to any volume of certificate traded during a given time interval.

Thank you for reading

If you have any questions or feedback,
don't hesitate to reach out.

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