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Literature Review on the Consequential Effects of Matching Rules in Clean Electricity Attribution Systems

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Abstract: This article reviews how temporal matching rules in Energy Attribute Certificate (EAC) systems affect their consequential performance in reducing emissions. Partly driven by the 24/7 Carbon-Free Electricity (CFE) procurement initiative, which combines temporal, regional, and additionality matching criteria, a growing body of literature has developed consequential power-system models of different matching regimes. Drawing from this targeted corpus, we construct a unified comparative framework to assess annual, hourly, and 24/7 CFE procurement systems in terms of emissions reductions, transformation of the electricity mix, and induced costs. The literature converges on the limited ability of annual matching to generate structural system impacts and additional emissions reductions. By contrast, literature shows significant environmental benefits from the 24/7 CFE procurement initiative, which more strongly directs investment toward decarbonized technologies available during residual hours of variable renewable generation, thereby reducing reliance on fossil fuels. However, we find that none of the studies isolate the effect of a standalone hourly-matching reform. Moreover, we highlight the limitations of the simulation results, including modeling assumptions, additional induced costs, and alignment with the attribution market architecture. This work illustrates a trade-off between a low-cost annual mechanism, which has a weaker potential grid impact but can generate high EAC demand due to low prices, and a more expensive 24/7 CFE procurement market, which offers greater intrinsic potential impact on the grid but may lead to lower EAC demand due to high prices. This contributes to the ongoing discussion on potential reform of the GHG Protocol.

Keywords: Energy Attribute Certificates; Attribution System; hourly matching; 24/7 Carbon-Free Electricity Procurement; Green Electricity market; GHG Protocol

1 Introduction

The consideration of energy-related challenges in the fight against climate change, combined with the increasing electrification of end-uses, has led to greater consumer attention to the origin and carbon content of their electricity. Companies, households, and public institutions seek to align their consumption with renewable generation through the contractual concept of “green electricity”. This attribution relies on Energy Attribute Certificates (EACs), which provide the sole proof for assigning specific generation to a given withdrawal. As a consequence, EACs are used as a signal of decarbonized electricity consumption for corporate activity, and to differentiate electricity offers between retailers (World Resources Institute, 2015; Jansen et al., 2016). The “market-based” method, which includes certificates to account for electricity-related emissions, relies on annual matching, allowing a consumer to declare fully renewable electricity consumption provided the annual volume of certificates acquired equals their total annual consumption.

However, the transparency principle underlying the attribution system has led several studies to question the temporal aggregation embedded in annual matching, in which certificates generated during periods of abundant renewable production can be used to cover consumption in periods of lower availability of carbon-free electricity (Scholta & Blaschke, 2025; IRENA, 2026). These works conclude that annual matching can obscure the consumers’ residual dependence on fossil generation during seasonal, monthly, or intra-daily periods of renewable scarcity. This raises concerns about the environmental claims inherent in the mechanism, but it also reveals the potential for decarbonization through greater grid transparency under revised EAC systems. Specifically, a new body of literature seeks to simulate the “consequential” effects, thereby quantifying benefits in terms of emission reductions, grid transformation, and the costs of a temporal attribution reform of the EAC system. This literature specifically studies hourly matching, correcting the temporal arbitrage, and the “24/7 Carbon-Free Electricity” (24/7 CFE) practices (Google, 2021), which further incorporate geographical and additionality requirements, aiming to cover an actor’s consumption with carbon-free assets available at the same hour, within the same electrical zone, and promoting development of new capacities.

These works consistently conclude that the annual matching rules, currently in use, may limit the consequential impact of attribution mechanisms and result in low to negligible impact depending on context. By contrast, by replicating the scarcity of decarbonized generation throughout the day, the hourly-based practices, thus hourly matching and the 24/7 CFE initiative, encourage voluntary consumers to favor flexible decarbonized technologies and thereby understand and limit dependence on fossil fuels. However, the simulated results integrate heterogeneous contexts and assumptions impacting a potential general conclusion directly. Nevertheless, this potential reform of the attribution system raises methodological and economic challenges that affect its actual environmental impact, cost, and integration within the existing contractual framework.

This analytical review of the literature aims to clarify the results of the modeling studies by harmonizing them under a common comparison framework. While Langer et al. (2024) review the potential for emissions reductions under stringent attribution systems, this contribution provides a more granular analysis of the decarbonization potential of each matching policy by interpreting the literature results in light of key modeling assumptions including exogenous demand levels, CFE participation levels, eligible technology portfolios, or additionality criteria. Second, we interpret the simulated outcomes in light of the associated costs to assess their applicability to the broader EAC market, highlighting the lack of consideration of demand motivation and price elasticity in the existing literature and the need to account for these factors in future research. The remainder is organized as follows: Section 2 examines both the current EAC system and its integration into carbon accounting. Section 3 discusses the ambitions of transparency mechanisms for both annual and hourly practices, which motivate the modeling literature of interest. Section 4 presents the modeling corpus of interest used to evaluate the consequential impact of EAC systems and specify a methodological basis for comparing results. Section 5 summarizes the different literature outcomes on emission reduction, grid transformation, and overall costs with a reflection on real-world applicability. Section 6 concludes.

2 Current System of Electricity Attribution

2.1 Green Electricity Supplies

The acceleration of climate ambitions and the energy transition has led to a heightened demand for transparency within the electricity grid, and more specifically, regarding the origin of consumed electricity. In this context, various societal actors, such as companies, public institutions, and residential consumers, seek to voluntarily associate their electricity consumption with renewable production sources. This trend has resulted in the emergence of the concept of "green electricity" in power markets identified through several contractual formats that enable consumers to claim "green electricity consumption" (detailed in O'Shaughnessy et al., 2025): Utility green pricing, Utility renewable contracts, competitive supplier, unbundled RECs, Community Choice Aggregation (CCA), Power Purchase Agreement (PPA).

Each scheme relies on a traceability mechanism for renewable electricity production, referred to in the United States as RECs, which, in general, corresponds to Energy Attribute Certificates (EACs) and serves as the contractual foundation of the attribution system. In reality, within an interconnected electricity grid, the electricity injected by various power plants is mixed, making any direct traceability between a producer and a final consumer impossible. As a result, the electricity consumed by an actor originates from the instantaneous mix of the network as a whole. Thus, the notion of "green electricity" does not refer to a physical distinction of renewable electricity from the rest of the grid, but rather to a contractual claim based on the acquisition of EACs, which allocate the share of renewable electricity generation to the certificate holder.

2.2 Energy Attribute Certificates

EAC markets are voluntary markets complementary to the electricity market, guaranteeing only the origin of the production source. Each certificate corresponds to one megawatt-hour of electricity injected into the grid and enables transferring the environmental attributes associated with that generation.

In Europe, certificates are called Guarantees of Origin (GO), introduced by Directive 2001/77/EC on the promotion of electricity produced from renewable sources. The RED II directive defines the guarantee of origin as an instrument whose "sole function is to demonstrate to a final customer that a given share or quantity of energy was produced from renewable sources" (Directive (EU) 2018/2001).

In the United States and Canada, certificates take the form of Renewable Energy Certificates (RECs), which are used both for compliance with Renewable Portfolio Standards (O'Shaughnessy et al., 2025) and in the voluntary green electricity market. Other jurisdictions have developed similar systems (REGO, GEC, etc.), but for the purposes of this study, we will focus solely on voluntary attribution markets, collectively referred to as EAC. However, our analysis will focus on the green electricity market, referring to a broad definition of decarbonized technology certificates. Indeed, our literature of interest examines the decarbonization of the electricity grid across different technology portfolios, ranging from sole reliance on renewable production to the use of carbon-free technologies, thereby expanding the conventional definition of green electricity.

2.3 Market-based approach and emissions accounting

The electricity attribution system directly affects organizational emissions accounting. Under the GHG Protocol, Scope 2 emissions, which represent carbon emissions due to electricity use, can be reported using two complementary methods: market-based and location-based (World Resources Institute, 2015). The market-based method assigns to the organization the emissions associated with contractually selected electricity using EACs (see section 2.1) and, for the uncovered portion, a residual mix. The residual mix is calculated using the mean carbon intensity of uncancelled electricity across all production in the considered mix. At the end, an organization's carbon footprint is calculated by multiplying the uncovered electricity volume by the carbon intensity of the residual mix (since covered electricity is associated with a zero-emission intensity). Alternatively, the location-based method assigns an average emission factor, calculated at the relevant geographical scale of the grid (regional, subnational, or national), to the entire consumption. These two methods are therefore based on distinct allocation principles, reflecting different ways of determining which electricity-related emissions should be attributed to each consumer.

3 Ambition and Motivation

3.1 Willingness to pay for green electricity

3.1.1 Estimation

To understand the participation in the attribution system and the potential impacts of temporal matching reform on the energy transition, it is necessary to consider the literature on willingness to pay (WTP) for renewable generation and green electricity consumption. First, meta-analyses of households' stated-preference studies find a significantly positive WTP for renewable electricity: Sundt and Rehdanz (2015) report a mean WTP of $13.13/month in their sample of studies for an increasing share of renewables in the electricity mix; Soon & Ahmad (2015) estimate a random-effects summary WTP of $7.16/month as a premium to the electricity price to shift to renewable sources use; Cerdá et al. (2024), by selecting only choice experiment studies, estimate a minimum WTP between 113.3 and €124.3/year per household for renewable electricity projects. Wang et al. (2024) report a sample mean of $7.92/month, acknowledging substantial variation across scenarios. However, all these studies highlight significant heterogeneity in estimated values depending on the methodology used, location, and scenarios. Alternatively, Danne et al. (2021) find, using a discrete choice model, that for a 1% increase in the share of renewables in the mix, German households are willing to pay an increase of €0.022/kWh, ceteris paribus.

However, these estimates do not directly correspond to the WTP for green electricity attribution, as it reflects how much consumers are willing to pay to support renewable generation, including both mandatory (for example taxes or Renewable Portfolio Standard) and voluntary financial participation. Green electricity consumers instead pay a voluntary premium to benefit from undifferentiated grid electricity, while standing out through contractual recognition of renewable attribution. Knowing this, it is necessary to distinguish the "responsibility" motive, which reflects the willingness to support grid transformation, from the "transparency" motive, which is only related to knowing where the electricity comes from. Regarding the impact of voluntariness, Menges & Traub (2009) show, using the example of green generation support, that annual WTP for green electricity is substantially higher under a collective public payment mechanism than under an individual, voluntary, market-driven contribution, with contributions of about €59/year and €19/year, respectively. Regarding specifically the attribution system, Bösch & Blaschke (2026) show that consumers' acceptance of a green electricity premium decreases when they are informed that annual matching does not ensure real-time correspondence between renewable generation and consumption: across premiums of €4 and €8 /month/person, acceptance falls from 46.1% in the control group to 39.2% in the unmatched group, corresponding to roughly a 15% relative reduction in acceptance. This provides an initial indication that part of voluntary market demand may rely on an incomplete understanding of the attribution mechanism, and that WTP estimates for renewable generation should not be directly interpreted as WTP for voluntary contractual attribution.

3.1.2 Determinants

Looking at the determinants of the WTP for green electricity globally, the literature also shows that it varies with technological and geographical attributes. On the one hand, several studies highlight a gradient among technologies, with solar and wind generally valued more than biogas or hydropower (Borchers et al., 2007; Danne et al., 2021; Bösch, 2025). On the other hand, proximity of production can also be valued by consumers (Kalkbrenner et al., 2017; Lehmann et al., 2022). The literature also shows that residential consumers are positively influenced by their environmental awareness and green values, creating a resonance between their electricity consumption and their expectations regarding carbon impact (Danne et al., 2021; Lehmann et al., 2022).

From a responsibility perspective, instruments such as corporate PPAs and citizen or renewable energy communities reflect a willingness to create a more direct link between electricity consumption and renewable generation. While PPAs allow companies to contract with renewable producers, energy communities enable citizens to participate collectively in renewable production, sharing, and governance (Caramizaru and Uihlein, 2020). Sumner et al. (2023), in a report on the state of the voluntary green electricity market in the United States, show that large companies have distinct electricity procurement guidelines: Google promotes energy and decarbonization outcomes, whereas Apple adopts broader social objectives. Thus, by creating physical or monetary value linked to transparency and responsibility, carbon-free generation can benefit from an additional and sustainable financial source and is consequently encouraged to develop.

3.2 Use of Green Electricity

Beyond electricity-choice motivations, it is also worth examining how society uses the attribution system to understand the indirect motivations that drive actors to participate. Indeed, green electricity consumers may have indirect incentives for decarbonization through institutions, business coalitions, or mechanisms that reward participation. The market-based logic of the GHG Protocol is a major example of these indirect mechanisms, as it mobilizes participation from companies seeking to achieve the best possible footprint aligned with their mitigation targets (Bjørn et al., 2022). Voluntary organizational initiatives such as RE100 and SBTi encourage participation by structuring strategies for emissions reduction and electricity procurement to tackle climate change (Ruiz Manuel and Blok, 2023; Egli et al., 2023). Moreover, enrolled companies gain from external validation and public visibility of their environmental commitment, thereby generating competitive and reputational benefits (Shimizu & Goto, 2024). This indirect motivation specifically concerns the organizational aspect of demand and must be quantified in future research to inform price reactions and WTP.

3.3 Motivation Behind the Hourly Matching Logic

3.3.1 An Initial Observation

The move toward hourly matching reform marks a turning point in voluntary demand for green electricity. While the traditional green electricity market can be partly explained by residential consumers' WTP for attributes such as technology type or proximity, an hourly-based system is a technically distinct approach with a focus on closer production and decarbonization claims. The demand for hourly matching extends the motivations of transparency and responsibility discussed above but relocates them within the carbon accounting framework, implying that hourly matching is primarily a corporate and institutional initiative to bolster the credibility of claims, rather than an additional residential preference. In that sense, Bösch & Blaschke (2026) show that studied households do not exhibit a significantly higher WTP for hourly certificates than for existing green electricity offers, partly because they tend to assume that real-time matching is already in place.

Against this background, the desire for precision in matching consumption and production follows the principle of transparency and is based on observations of the current attribution market. The literature on hourly matching highlights a common observation regarding the attributional method: the temporal and physical dissociation between green electricity consumption and clean generation. At the beginning of their study, Xu et al. (2024) present a stylized example in which, for a defined electricity consumption pattern, one can achieve 100% renewable correspondence using the annual volume method and 75% correspondence using the hourly method, the former equalizing annual green electricity consumption and annual renewable generation, while the latter accounts for the hours of the year during which consumption and production are matched. More accurately, Scholta & Blaschke (2025) assess this correspondence through an ex-post analysis of the 2016-2021 European attribution market and show that matching scores decrease as the accounting resolution becomes finer (from monthly to hourly), revealing the gap between green electricity demand and actual renewable generation. In hourly logic, they note that the nighttime interval between 7 p.m. and 8 a.m. has the highest rates of unmet green electricity demand. This hourly mismatch between supply and demand demonstrates that renewable generation is not aligned with green electricity demand and that claims of 100% renewable electricity consumption stem from the global purchase of certificates over a year, while a reliance on fossil-based electricity remains a grid reality. Although these studies follow an attributional approach in which the consequential effect on emissions is not calculated, they conclude that the mechanism has potential, whereby a temporal reform could lead to a new approach to decarbonization.

3.3.2 A More Specific Ambition: Availability of Decarbonized Assets

The shift from an annual to an hourly system is primarily motivated by the desire to reduce carbon emissions from the power system, while also accounting for power-system constraints related to the availability of carbon-free assets. The hourly matching literature focuses on the extent to which these temporal availability constraints should be accounted for in the attribution mechanism, particularly in the context of carbon footprint accounting. This question has given rise to an analytical and modeling literature assessing how different attributional methods affect the consequential benefits of the green electricity market.

Any temporal-precision reform will first reinforce the transparency of the attribution system by narrowing the gap between claims and production (see 3.3.1) and improving traceability in the carbon accounting method. Yet beyond the claim debate, hourly certification presents a key opportunity for the electricity market: assigning certificates and claims at an hourly granularity makes the temporal scarcity of renewable electricity observable. Indeed, the energy transition has been driven mainly by the increasing share of grid supply from Variable Renewable Energy sources, primarily solar and wind, which jointly accounted for 96.6% of global net renewable capacity additions in 2024 (IRENA, 2025). These technologies are prevalent and economically advantageous, but they generate power at specific times of day and depending on weather conditions. Solar output follows a diurnal pattern, with abundant generation during daytime hours and a sharp drop in the evening, while wind output is more exposed to weather-driven variability (IRENA, 2026). In high-solar systems, this generation profile contributes to the well-known “duck curve” in net load (Chen et al., 2025).

However, electricity demand does not exhibit the same temporal profile, rising sharply at the start of the night when VRE output declines. This mismatch highlights that continuing to invest solely in VREs does not eliminate the need for flexible supply during off-peak renewable hours and leads to a residual reliance on fossil-fuelled units, as they remain the primary source to meet this demand (IEA, 2019). Consequently, this dependence reveals an environmental problem through emissions-generating production and an economic problem of higher prices due to the carbon price. By reflecting the hourly scarcity of renewable generation, the attribution highlights the need for carbon-free resources able to complement renewable generation. Current matching policy hides this structure because clean generation produced during periods of abundance can be used to substantiate consumption during periods of scarcity. Hourly matching removes this intertemporal substitution and therefore reveals the deeper need for decarbonized resources available throughout the day.

Economically, hourly matching creates tension within the voluntary market of attribution. If companies want to cover their activities with 100% carbon-free electricity on a more precise basis, they must account for this intermittency and compete for more expensive green supply during hours of lower renewable output. Therefore, the mechanism creates a new signal on the scarcity cost of carbon-free electricity and a new revenue signal for decarbonized, available production means, thereby inducing diversification of technologies such as storage, nuclear, or geothermal. By modeling the economic mechanism associated with the 24/7 CFE initiative, Riepin et al. (2025) illustrate that combined hourly, geographic, and additionality restrictions can help to create new financing signals for certain low-carbon technologies that are still under-deployed, for which technological learning could enable a gradual reduction in costs. In conclusion, the difference between the annual and hourly attribution systems is reflected in financial flows: the annual system is directed toward aggregated carbon-free generation over the year, whereas the hourly system is directed toward “available” carbon-free generation during hours of scarcity.

4 Methodology

4.1 Studied Corpus

4.1.1 Selection

To analyze the impact of hourly matching on the green electricity system, our review is based on a primary corpus of studies meeting two criteria. On the one hand, the selected studies must focus on prospective modeling of the evolution of the electricity system, taking into account different matching policies. On the other hand, these works must have been published in a scientific journal to ensure academic validation. Accordingly, we identified four contributions: Xu et al. (2024), Riepin & Brown (2024), Gagnon & Brown (2026), and Bistline et al. (2026). Each contribution presents different samples: Xu et al. (2024) conduct their analysis in the western United States, covering six regions, with a focus on California and the Wyoming–Colorado pairing; Bistline et al. (2026) model the entire U.S. electricity system, divided into 16 regions; Gagnon & Brown (2026) use a continental U.S. framework, corresponding to the 133 balancing areas of the U.S. interconnected system. Finally, Riepin & Brown (2024) assess the effects of the 24/7 CFE initiative at the European scale, across 37 zones, with specific studies on Ireland, Germany, and Denmark. In addition, out-of-corpus studies cited in the results provide additional information supporting the conclusions drawn from the selection, while not being peer-reviewed or directly related to a modeling study (Scholta & Blaschke, 2025; Riepin et al., 2025).

4.1.2 Objective

The corpus's studies share the common objective of analyzing, from a consequential perspective, the impact of different electricity attribution systems on the power grid. By relying on electricity system modeling, they compare various matching policies (annual, hourly, 24/7 CFE initiative) to assess the capacity of these mechanisms to drive investment in low-carbon technologies, modify the structure of power generation, reduce system emissions, and generate additional implementation costs.

4.1.3 Attribution methodology

Primarily, we highlight a large disparity in the definition of the attribution methodology. Although they rely on the "hourly matching" and "annual matching" mentions, the actual modeling literature makes different assumptions due to potential integration of regionality and additionality restrictions (as referenced in Table 1).

First, annual matching must be carefully interpreted, as three of the four studies present the “best case” of annual matching, which includes regionality and additionality restrictions. Only Gagnon & Brown (2026) test the effects of restrictions on annual matching. When the authors mention annual matching, they refer to a 100% correspondence between consumption and generation on an annual basis.

Secondly, from Table 1, we must address the first observation on the corpus: none of the corpus’s studies address the isolated hourly reform on the attribution mechanism. The corpus mainly focused on hourly matching, with additional restrictions on regionality and additionality, and only Bistline et al. (2026) analyzed the reliance effect of these restrictions.

Thirdly, we will define a common definition of the implemented 24/7 CFE initiative in the models. Google’s 24/7 CFE methodology (Google, 2021) requires that the electricity consumed must be available at the same hour and within the same regional grid as the decarbonized generation. Compliance is summarized by a participation percentage score named ‘CFE score’, derived hourly as the share of load covered by decarbonized resources that satisfy the temporal and geographical restrictions. For each hour, the score first counts the CFE-eligible electricity directly contracted by the consumer. If contracted selection does not cover the entire hourly load, the remaining load is attributed to the default carbon-free share of the regional grid's electricity mix. The CFE score is then calculated as the average of these hourly scores over the year. Moreover, Google’s methodology document (2021) mentions three supplementary principles: inclusion of all carbon-free technologies, promotion of capacity development through additionality, and grid decarbonization. Among these principles, additionality is treated in the modeling corpus as an eligibility restriction, while technology inclusion defines the eligible technology scope and grid decarbonization refers to the intended system-level outcome. In the overall corpus, the 24/7 CFE initiative is always evaluated in the context of an additionality restriction, where hourly, geographic, and additionality restrictions are considered jointly and sometimes described as the “Three Pillars” (Bistline et al., 2026). Consequently, this paper considers the modeled 24/7 CFE system as an attribution system in which hourly, geographical, and additionality criteria are combined.

Table 1: Description of models studied per article

	Studied systems	Demand level studied (%)	Participation level studied (CFE score)
Riepin & Brown (2024)	• Annual under G+A ("best case") • 24/7 CFE	10% of C&I demand	Granular approach (from 80 to 100% CFE)
Xu et al. (2024)	• Annual under G+A ("best case") • SRMER • 24/7 CFE	10%; 25% (50% and 100% test) of C&I demand	Granular approach (from 84 to 100% CFE)
Gagnon & Brown (2026)	• Annual • Annual under A • Annual under G • Annual under G+A ("best case") • 24/7 CFE	From 0 to 50% of total electricity demand	100% CFE only
Bistline et al. (2026)	• Annual under G+A ("best case") • Hourly under G • Hourly under A • 24/7 CFE	10%; 50% of C&I demand	100% CFE only

Legend: "Annual" means a 100% correspondence between electricity consumption and certificate use on an annual basis. "Hourly" means a 100% correspondence between electricity consumption and certificate use on each hour during one year. G: geographical restriction, A: additionality restrictions, G+A: geographical and additionality restrictions. 24/7 CFE refers to the "Three Pillars" with the % of hourly correspondence defined by the CFE %. SRMER: Short-Run Marginal Emissions Rate. C&I: Commercial and Industrial (defined in next sub-section)

Finally, the studies differ in how they define additionality and regionality restrictions. Regarding additionality, Bistline et al. (2026), Xu et al. (2024), and Riepin & Brown (2024) follow a greenfield procurement logic in which clean electricity certificates must come from newly built resources induced by the procurement constraint. By contrast, Gagnon & Brown (2026) define additionality through a vintage requirement, by comparing scenarios where EACs from installations more than 15 years old are either excluded or allowed. This procurement difference makes Gagnon & Brown (2026) the only study that allows for existing installations to be part of the procurement strategy. Regarding deliverability, all studies use a "spatial" constraint that requires participating demand and eligible generation to be located in the same relevant electricity region, although the spatial unit differs across models: Bistline et al. (2026) use model regions, Xu et al. (2024) use model zones, and Riepin & Brown (2024) use European bidding zones and Gagnon & Brown (2026) use grid regions.

4.2 Model Structure

As previously mentioned, each study illustrates the effects of different matching systems according to specific designs involving various parameters. We will reference them so as to better interpret the results in the following sections.

4.2.1 Modeling Electricity Attribution Demand

As shown in Table 1, most studies model demand as mandatory participation in a share of Commercial and Industrial (C&I) electricity load by 2035, assuming exogenous levels of 10%, 25%, or 50%. C&I load denotes the non-residential electricity consumption such as firms, commercial facilities, industrial sites, and large institutional buyers. Only Gagnon & Brown (2026) study demand through a linear variation in the share of total electricity demand.

4.2.2 Permitted Technology Portfolio

The permitted technology portfolio is a central methodological assumption because it determines the means of generation available to meet the matching constraints during residual hours. The studies in the corpus present different ranges of technologies, which directly affect the technical feasibility of hourly matching, scenario costs, and the nature of induced investments. Riepin & Brown (2024) thus distinguish three successive "palettes" ranging from a portfolio based on variable renewable electricity sources such as wind, solar, and batteries, to configurations integrating long-duration storage, then to dispatchable low-carbon technologies called "clean firm." Xu et al. (2024) use a similar logic by contrasting established technologies with advanced non-combustion technologies, and then with a comprehensive portfolio that includes carbon capture and storage (CCS) and decarbonized fuels. Bistline et al. (2026) similarly compare a case limited to variable renewable energies (VRE) and batteries, a broader decarbonization portfolio, and a case extended to lower-emission technologies, including carbon capture. Finally, Gagnon & Brown (2026) allow for emerging technologies such as small modular reactors (SMRs) and generators with CCS in their model. To compare these configurations on a consistent basis, we adopt a common classification of technology portfolios, presented in Table 2. This typology is intended to facilitate the interpretation of results in terms of costs, emissions, and abatement costs.

Table 2: Description of a Common Portfolio in the Literature

General category	Description	Associated technologies
Portfolio A	Variable renewable supply (VRE) and short-duration flexibility	Wind, solar, batteries (and geothermal in some studies)
Portfolio B	Long-duration carbon-free flexibility without combustion	**Portfolio A** + long-duration electricity storage (LDES), hydrogen storage, advanced geothermal
Portfolio C	Dispatchable low-carbon generation / “clean firm” resources	**Portfolio B** + advanced nuclear, carbon capture and storage (CCS), Allam cycle, decarbonized fuels

4.2.3 Political Environment and Reference Scenario

The consequential approach of the attribution mechanism aims to show the impacts of its existence on the overall power system. This requires a comparison with a reference scenario in which the system does not exist. However, this counterfactual itself constitutes a structuring parameter, since the results of attribution systems depend on the level of decarbonization that would have been achieved given existing policies. Thus, to define their model, the various studies needed to describe reference scenarios that differ according to how the political environment is treated for decarbonized energy. Bistline et al. (2026) incorporate current U.S. government policies as well as variants with or without support, such as the Inflation Reduction Act (IRA). Xu et al. (2024) conduct their analysis in the context of current U.S. electricity sector policies. Riepin & Brown (2024), over the 37 EU regions, take into account regional resources, national policies, and degrees of interconnection. Finally, Gagnon & Brown (2026) compare an "unsupportive" environment with a “supportive” one to identify how the political context modifies the real impact of different matching methods. The former “unsupportive” scenario describes conservative assumptions about incentives and renewable energy costs, while the latter “supportive” scenario includes the application of Section 111 of the Clean Air Act, compliance with IRA trajectories, and moderate structural assumptions for renewables.

5 Summary of the Literature's Results

5.1 Result 1: Annual matching achieves low or negligible emissions reductions at low cost

The modeling literature converges on the observation that annual matching limits the consequential effect of attribution mechanisms. By allowing volumetric compensation on an aggregated basis, it fulfills an accounting logic of compliance without imposing enough direct transformation on the electricity system. Hence, annual matching often entails no or limited emission reductions in the system.

Projections of network evolution under different attribution rules by Xu et al. (2024) specifically show that annual matching "best case" (see Table 1) yields either null or limited long-term emissions reductions. Only one annual modeling case in California, with 25% C&I participation, displays a non-zero emissions reduction. Technically, system adjustment mainly amounts to an increase in renewable generation capacity to cover green electricity demand, but with intra-renewable displacement that leaves fossil generation largely untouched (across all technology portfolios). Annual procurement allows strategic investment throughout the year, leading to the development of intermittent technologies: since these are the least expensive, the study notes that each region will invest in its most advantageous intermittent technology (solar in California and wind in Wyoming), thereby taking advantage of the possibility for temporal compensation over the year. More broadly, the authors observe that this configuration results in a stacking of renewable production during the same time periods, causing a cannibalization effect likely to undermine the profitability of other renewable installations. Results from Bistline et al. (2026) point in the same direction, with lower emissions reductions for annual matching than for hourly matching. They note that annual matching "best case" reduces CO2 emissions by 1 Mt per year compared to 42 Mt for the "Three Pillars" case, equivalent to 100% 24/7 CFE (portfolio B and 10% C&I level demand). They suggest that most compliance is achieved through renewable capacity that would have existed even without voluntary demand, where political planning in the reference scenario was already driving capacity development.

To contrast these results, Gagnon & Brown (2026) show, at the aggregated U.S. scale, that "all accounting approaches see plausible ranges of non-impactful claims" that depend on the level of total electricity demand procuring EACs. More broadly, their approach allows distinguishing the effects of additionality and geographical restrictions on the consequential results of annual matching: adding additionality to annual matching, through vintage restrictions, engages new clean generation and emissions reductions at a higher level and at an earlier stage of the demand level. Geographical restrictions mandate that decarbonized electricity be provided regionally and correct potential compensation between carbonized and greener regions, thereby enabling earlier global clean generation and emissions reductions than would be achieved by annual global matching, while the overall impact diminishes with increasing demand. Moreover, they show that annual matching effects are highly dependent on the reference scenario (whether the political planning will occur): In the supportive case where IRA is supposed to be completed, the consequential effect is almost null on average, whereas it is more visible in the unsupportive case. Emissions reductions associated with annual matching become particularly significant only at higher participation levels, around 25% of total electricity demand. Studying European countries, Riepin & Brown (2024) show, conversely, that annual matching "best case" does induce emissions reductions (e.g. 11.1 MtCO2/year for Germany at 10% C&I demand), via a volume effect linked to the deployment of additional renewable capacities. Nevertheless, they find similar results to previous studies on the robust development of intermittent technologies, mainly solar and wind. They further find that a relative inefficiency of annual matching increases as the electricity mix becomes cleaner: the mere addition of renewable volumes becomes decreasingly distinguishable from the reference scenario, while the advantage of 24/7 regimes lies more in a profile effect during critical hours.

5.2 Result 2: 24/7 CFE matching increases consequential impact through diversification of decarbonized technologies

In contrast to annual matching, the literature presents simulations showing that 24/7 CFE matching yields higher consequential emissions reductions, precisely because it requires a stricter temporal structure. According to Bistline et al. (2026), 24/7 CFE matching results in a reduction of the dissociation between attribution mechanism and consequential impact, as hourly matching necessitates investments that would not exist with annual matching. Systems with hourly matching induce greater technological diversity, including battery storage and nuclear (portfolio B). Consequently, these systems achieve greater emissions reductions, primarily by replacing fossil-fuel emissions during off-peak hours. However, the authors also note, through sensitivity tests on restrictions, that the effectiveness of hourly matching depends on its coupling with policies for regionality, additionality, and sufficiently high demand. At a 10% C&I demand level, hourly matching without additionality and regionality combined yields little to no emissions reduction. By contrast, at 50% participation, the impact difference between the matching regimes is clear: -20 MtCO2/year for annual matching with both additionality and regionality, -224 MtCO2/year for 100%

hourly matching with regionality, -275 MtCO2/year for 100% hourly matching with additionality, and -466 MtCO2/year for the regime meeting all “Three Pillars”—the equivalent of 100% 24/7 CFE.

Additionally, the results of Riepin & Brown (2024) confirm significant emissions reductions associated with the 24/7 CFE regime at a 10% C&I demand level in several European configurations. Their analysis shows that 24/7 CFE matching (with a minimum engagement of 90% CFE Score) consistently produces greater emissions reductions than annual matching “best case”, due to electricity systems with a different mix and available decarbonized technologies (portfolios B and C). Using Germany as an example, the authors show that a 10% C&I demand commitment under 100% 24/7 CFE reduces emissions by 14 MtCO2/year compared to 11 MtCO2/year for annual matching. Importantly, this superiority does not come from additional capacity investment alone, but rather from a change in the system's temporal structure. Thus, the authors illustrate two distinct effects: a volume effect, through injecting more green electricity, and a profile effect, by reducing reliance on marginal fossil units during critical hours. Finally, both previous articles highlight that the relative advantage of the 24/7 CFE initiative tends to increase as the share of variable renewables increases. As variable renewables become more abundant, the limitations of annual matching become more apparent, particularly due to intra-renewable cannibalization phenomena. In this context, 24/7 CFE matching should not be interpreted as a stricter version of annual matching, but rather as a distinct mechanism that directs investments toward hours with the greatest supply constraint for decarbonized generation. The work of Xu et al. (2024) reaches the same conclusions while introducing nuances regarding accessible technologies. The study clearly shows that as 24/7 CFE commitment increases (measured via the CFE Score), the system and its investments benefit from diversifying the accessible technology portfolio from renewable technologies and batteries (portfolio A) to diverse decarbonized generation (portfolios B & C). Thus, the effects of emissions reductions depend on the available technologies. Nevertheless, the literature unanimously emphasizes that hourly matching can accelerate the early deployment of emerging decarbonized technologies (e.g. Gas CCS, nuclear energy, Allam Cycle) alongside intermittent renewable technologies. In this respect, Riepin et al. (2025) highlight a consumption pattern likely to accelerate the learning, diffusion, and cost reduction of technologies that are currently undervalued by supply under annual matching.

However, the literature identifies several factors that moderate the differences in consequential effects between matching policies. As previously mentioned, the contributions highlight the importance of demand size: the greater the modeled demand volume, the larger the gap between the impacts of annual matching and hourly-based matchings. This relationship is particularly evident in the research by Gagnon & Brown (2026), who examine the impact of gradual increases in demand under different matching regimes. Similarly, the higher the 24/7 CFE commitment, the more the gap can widen (Riepin & Brown, 2024). However, the superior impact of 24/7 CFE matching over annual matching "best case" is primarily due to a minimum CFE commitment level that varies by region. For example, in Germany, the environmental benefit of 24/7 CFE engagement appears from 95% hourly coverage, while in Poland it is around 90% (portfolio C, 10% C&I). Beyond this threshold, the advantage increases with further engagement, owing to a strengthened profile effect.

Thus, it is evident that modeling assumptions, and more specifically the regulatory environment surrounding the attribution system, significantly influence the results. The implementation of regionality and additionality rules is a key factor in both emissions reduction and the widening of the gap between regimes. Moreover, the application of environmental policy planning (see the methodology section) mitigates the impacts, as such planning also provides substantial support for decarbonized technologies (Bistline et al., 2026; Gagnon & Brown, 2026).

5.3 Result 3: Temporal Precision in Matching Increases Attribution Costs

The previous sections show that results from the literature tend to show different investment decisions, depending on the matching approach, annual or hourly: the former expands the total amount of renewable capacity through intermittent technologies, while the latter focuses on technologies available to enable decarbonization during hours under scarcity constraints. This phenomenon reflects a significant difference in system costs. On the one hand, the literature notes that annual matching tends to favor the deployment of variable renewable technologies, which, thanks to their maturity, are associated with low costs. Xu et al. (2024), in the context of California with a 25% C&I demand level, estimate that annual matching incurs attribution costs of around \$4/MWh (across all portfolios). Gagnon & Brown (2026) simulate an average national price from \$0/MWh at a 5% total electricity demand to \$33/MWh at a 50% level (unsupportive case).

On the other hand, hourly and 24/7 CFE matching require different investment strategies to ensure a decarbonized electricity supply at every hour. The literature thus observes a dependence on available technologies, implying additional expenditures intrinsically linked to their costs and coverage potential. As noted, increasing 24/7 CFE engagement drives greater deployment of available technologies. Since these technologies are new, they entail high costs, which increases matching costs as engagement rises. However, the literature identifies a threshold effect, where the rise in 24/7 CFE compliance costs is nonlinear. Riepin & Brown (2024) highlight strong cost nonlinearity as the 100% CFE target is approached, confirming the existence of a last-percent problem. As long as the target remains at 90–95%, the cost premium relative to 100% CFE remains relatively contained. In contrast, moving toward near-total coverage requires financing underutilized but essential capacities to cover residual hours, notably long-duration storage, dispatchable low-carbon resources, and other forms of flexibility (see portfolio C). According to Xu et al. (2024), the additional cost associated with 84% hourly matching is about $8/MWh in California with 10% C&I participation, but it rises rapidly when the constraint becomes stricter, reaching up to $27/MWh (25% C&I, portfolio A without storage). The study also observes a significant dependence on accessible technology in terms of costs. When only intermittent technologies are available, 24/7 CFE engagement leads to overinvestment in unsuitable technologies, resulting in a drastic increase in compliance costs and cannibalization of generation, impacting the profitability of the entire solar and wind fleet. Conversely, when flexible technologies are available, participants in attribution mechanisms can better direct their investments. In addition to engagement level, the demand volume strongly affects costs. Gagnon & Brown (2026) show the growing development of flexible technologies with demand volume and find, at the national average, that the cost of 100% 24/7 CFE engagement results in a national average cost of $7/MWh for 5% of total electricity demand, $15/MWh for 10%, $31/MWh for 20%, up to $69/MWh for 50%. They also emphasize that compliance costs vary greatly by region and that, across their whole analysis, 46% of hours at 100% 24/7 CFE have non-zero cost, while 1.4% exceed $100/MWh, with a maximum observed at $3,679. The results of Bistline et al. (2026) finally confirm that the additional cost of hourly matching is neither uniform nor negligible across U.S. regions, exceeding $100/MWh in less favorable regions (average 2035 hourly price). This heterogeneity shows that the comparison between annual and hourly matching cannot be made solely based on a national average cost; it depends on the local electricity mix, resource availability, degree of interconnection, and admissible technology portfolio.

5.4 Result 4: Limitations under the Current EAC Market

Ultimately, the transferability of regime cost results to EAC technical architecture and prices remains limited. First, the equilibria for each granularity are calculated using an optimization model with exogenous demand and participation levels. Indeed, the models discussed follow investment-model logic, minimizing costs under a greenfield procurement approach (except in one study). The price in $/MWh resulting from these studies, therefore, reflects the shadow price of the matching constraint or a direct procurement price premium. It thus differs from the actual functioning of the EAC system, which is based on a market for attribution characterized by current-generation allocation and equilibrium prices of supply and demand.

On the technical front, the literature presents a technology-optimized path under 24/7 CFE constraints using different technology portfolios, although their integration into the attribution system is still in progress. The role of storage is especially critical, since modeled hourly matching and 24/7 portfolios often rely on batteries (Bistline et al., 2026; Xu et al., 2024; Riepin & Brown, 2024), while existing certificate frameworks have not integrated the accounting treatment of stored electricity and its associated attributes. Carbon-free production, such as advanced nuclear or gas with CCS, is used to achieve the CFE objective but is not fully recognized by attributional systems worldwide. The promotion of these technologies in the name of decarbonization can also face political barriers; for example, the European Union defines the sole legal function of European EACs as providing proof of renewable origin, while also recognizing their potential to contribute to the development of renewable generation under RED II (Directive (EU) 2018/2001), rather than to support decarbonized gas or nuclear sources. Nevertheless, modeling such technologies illustrates their potential role in achieving a decarbonized grid.

On the economic front, Gagnon & Brown (2026) highlight the difference in level between the price for 100% 24/7 CFE compliance and the prices in the unbundled EAC market. Indeed, unbundled EAC prices in the EU have historically remained below €5, except during the 2023 dry event (Diehl et al., 2025), whereas implicit prices for 100% 24/7 CFE matching in the models quickly exceed $10/MWh, depending on demand size (Xu et al., 2024; Bistline et al., 2026). One must keep in mind that this comparison may be criticized, as current annual certificates differ in both object and ambition from hourly-based certificates. However, this raises the question of the price and, more importantly, the demand level of hourly-based certificates under market functioning. The actual prices on the EAC market and the WTP evaluated in Section 3.1 reflect the value of the annual certificate. Therefore, moving to finer temporal granularity brings new objectives of deeper decarbonization of the electricity consumed and ultimately assumes that buyers are willing to pay for a different environmental attribute that will become more scarce, more differentiated, and potentially more expensive. However, no evidence of WTP for hourly-based certificates has been delivered in the literature. In the market context, the literature studied makes a strong contribution to optimizing the supply of hourly certificates, whereas hourly matching and 24/7 initiatives have not been studied in terms of demand.

This raises the question of the consequential effect of matching under the demand level and the sustainability of a 90%, 95%, or 100% commitment to 24/7 CFE constraints, given buyers’ actual WTP in current EAC markets. Gagnon & Brown (2026) show, in the US case, the increasing gap between annual and 24/7 CFE matching in terms of emission reduction across demand levels.

However, at the same time, the authors pass on the difference in cost increases between matchings, as the technological deployment differs. As an example, they model that a 100% 24/7 CFE regime at a 15% total electricity demand is consequently equivalent to an annual matching under a 25% level (unsupportive scenario, portfolio C). But simultaneously, the 100% 24/7 CFE will reflect an EAC price at $20/MWh, while the annual regime will be at $12/MWh (national average). One must integrate this result in the context of cost heterogeneity across regions, implying more costly transformation for carbon-reliant regions. Nevertheless, this example illustrates the trade-off consumers will face in a market context, comparing a low-cost certificate system whose impact depends on high demand to a high-cost system with a more direct impact but likely reduced demand due to price reaction. On the other side, one can question the level of participation in the CFE initiative, given the increasing relation with cost (seen in the 5.3 section). As hourly-based matchings include price formation at each hour, market participants will face strong price variability, which can discourage participation. Gagnon & Brown (2026) observe that 46.0% of a 100% 24/7 CFE matching hourly prices are non-zero, 1.4% exceed $100/MWh, and the maximum price reaches $3,679/MWh. In the event of responsive demand, these extreme price events pose a threat of non-sustainability to the last-percents CFE market. In conclusion, in a market system, the demand for hourly certificates, in both volume and participation, will depend on the average price level and its variance. This potential demand reaction strongly influences the consequential impact difference between the matching regimes and must be evaluated as a research priority.

6 Conclusion and Policy Implications

This review has examined the debate on temporal matching rules within the broader discussion regarding systems for attributing decarbonized electricity. The annual system allows consumption to be contractually associated with renewable generation, but its temporal aggregation can conceal residual dependence on fossil generation. The mechanism is now established in electricity markets and carbon accounting systems; implementing stricter matching on an hourly basis can improve the accuracy of carbon accounting claims but also reflects new ambitions regarding the role of EACs in directing the electric transition by addressing periods of renewable scarcity. In this perspective, a new body of modeling literature estimates how stricter matching rules can contribute to the decarbonization of the electricity grid. This corpus of interest simulates the consequential impacts of annual, hourly, and 24/7 CFE matchings on emission reduction, electricity mix transformation, and induced costs.

This corpus highlights distinct properties of annual and hourly-based regimes. On the one hand, annual matching is characterized by low compliance costs, due to increased capacity enabled by intermittent renewable technologies. However, the significance of its effect on total emissions varies across conditions, such as high demand volumes and regional specificity, as it depends on allocating renewable resources during decarbonized hours or on those already induced by public policies. Regarding hourly-based matchings, we find that hourly matching is not evaluated without supplementary restrictions on additionality and regionality, which primarily lead to its study through 24/7 CFE frameworks. Nevertheless, the literature concludes on more targeted investment signals for residual hours by leveraging available and decarbonized technologies that can effectively meet demand. We highlight significant environmental benefits of the 24/7 CFE initiative as it produces larger emissions reductions than annual matching due to a clearer transposition of the intra-day grid carbon footprint, but this attribution shift translates into higher certificate prices and a need for sufficient participation (CFE score).

This leads to a clear trade-off between diffusion and commitment: annual matching can support a broad, low-cost market, with consequential effects contingent on the scale of demand. Alternatively, the hourly regime, coupled with regionality and additionality restrictions (“Three Pillars”), significantly modifies the electricity mix and its associated emissions, but faces non-linear and hourly-sensitive costs as demand and participation are increased. Moreover, these costs are clearly above those observed in the current voluntary market. By placing the simulations in a voluntary market setting, we signal a potential decrease in demand and participation, implying uncertain equilibrium outcomes. To better understand demand behavior in the face of these new costs, it is necessary to measure the willingness to pay and price elasticity of organizational demand for hourly certificates. Standardizing carbon reporting rules under hourly matching must rely on studies of company engagement to avoid undermining the consequential effects of the overall system they support.

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