ZEROgrid

Review of Research on the Impact of Voluntary Energy Procurement

Nat Steinsultz, WattTime

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The ZEROgrid Impact Advisory Initiative convenes a group of leading researchers to advance consensus and use of consequential impact assessment methods. This paper was introduced to the Impact Advisory Initiative process for consideration and received unanimous support from the assembled experts. The following advisors elect to add their names in support of this paper:

Gavin McCormick, WattTime
Lee Taylor, REsurety
Fabrizio Finozzi, Open Energy Transition
Wilson Ricks, Princeton University

Introduction

In response to growing climate concerns, many corporations have committed to procuring renewable energy as a means of reducing greenhouse gas emissions. Traditionally, corporate energy procurement strategies have focused on annual matching, in which companies purchase a volume of renewable energy equivalent to their total electricity consumption over the course of a year. While this approach supports renewable energy deployment, it does not take into account the way clean energy needs vary by time and location.

As a result, new procurement strategies have emerged to enhance the impact of voluntary energy purchases:

- **24/7 Carbon-Free Energy (CFE) Matching:** A strategy that seeks to match electricity consumption with carbon-free energy on an hourly basis.

- **Emissionality-Based Procurement:** A strategy that prioritizes purchasing renewable energy from regions where it has the highest impact on emissions reductions, rather than being constrained to the company's physical location or the timing of its consumption.

Numerous studies have examined the effectiveness of these approaches, particularly comparing 24/7 hourly matching with traditional annual matching. Some research has explored emissions-based procurement but often within limited geographic constraints. To date, no study has explicitly analyzed emissionality strategies that allow procurement from any grid region. However, in studies where multiple regions are modeled, annual matching in the region with the highest emissions can be analyzed as a reasonable proxy for emissionality.

Critically, these studies rely on consequential emissions analysis, which measures changes in total system-wide emissions rather than attributional emissions analysis, which measures emissions within a defined boundary. Due to the complex system behavior of electric grids, it is important to look at the impact on the total system, and not limit it to accounting for narrow attributional changes in emissions.

An important element of all procurement strategies is additionality — a measure of whether a project would have been built without corporate action. Additionality is critical because non-additional projects will have no impact on total system emissions. While some studies simplify the additionality requirement by structuring their models so that the modeled corporate procurement is assumed to be additional, other studies take a different approach and find that whether or not a strategy is additional depends on the economics of renewables in the grid region and policies like clean energy standards (CES).

In addition to studies considering voluntary corporate procurement, there have also been works analyzing the impact of annual versus hourly matching requirements for Hydrogen electrolyzers. While these two applications have different constraints that may lead to different optimal strategies, there is a lot of useful information from these studies that can inform the question of voluntary procurement and help interpret results from simulation studies more broadly. A report from Spees et al. summarizes the body of research around hydrogen production. Langer et al. provides a review of studies of both voluntary procurement and hydrogen production; however it does not seek to compare results across regions within the same study.

This paper synthesizes existing research on voluntary renewable procurement strategies and their impact on emissions reductions. Specifically, we:

1. **Compare the impact of different procurement strategies** (annual matching, 24/7 matching, and emissionality-based approaches) in reducing system-wide emissions.

2. **Analyze how regional differences in grid emissions intensity affect procurement impact,** drawing from studies that model multiple locations.

3. **Assess key modeling assumptions,** particularly around additionality, clean energy standards, and grid constraints, to understand how they influence research conclusions. Understanding the specific conditions that are modeled in each study is important before drawing conclusions broadly to scenarios that were not specifically modeled.

By integrating insights across multiple studies, we aim to provide a clearer understanding of which procurement strategies maximize emissions reductions, how modeling choices shape findings, and where future research is needed to refine best practices for corporate clean energy purchasing.

Summarizing existing research

On the means, costs, and system-level impacts of 24/7 carbon-free energy procurement

(Riepin and Brown, 2024)

Riepin and Brown model many procurement scenarios in the European ENTSOE-E grid using the PyPSA tool. They model the grid as 37 bidding zones with interconnections, and estimate the change in total emissions from all sources on the grid in response to interventions in one of four selected zones: Ireland, Denmark (zone DK1), Germany, or Poland. They model grid solutions for both 2025 and 2030. They model procurement using a local annual volume match and for local temporal matches with varying levels of match from 80% to 100%. Their model assumes that all corporate procurement is additional by solving the capacity expansion model first for the grid without the participating load, and then solving with the additional load and procurement. In this way, the procurement does not compete with the rest of the grid's expansion, so every project is additional by definition of the model.

Their results show that both annual matching and 24/7 matching reduce total emissions in all scenarios, with high levels of temporal matching having somewhat higher avoided emissions rates. However, the difference between avoided emissions rates in different locations is much higher than the difference between matching strategies within a given location. For example, annual volumetric matching in Poland has an avoided emissions rate of 1,008 gCO_2/kWh in 2025, which is greater than 90% 24/7 matching in any other location in the study, and is 2.8 times larger than the avoided emissions rate of 100% temporal matching in Ireland (365 gCO_2/kWh). Thus for any load located in locations other than Poland, emissionality can avoid more emissions than the majority of temporal matching profiles, using portfolios that are more cheaply and quickly deployed.

Notably, the avoided emissions rates drop substantially from 2025 to 2030, driven by low-cost renewable energy and national clean energy policies. While it is still true that annual matching in Poland has a higher avoided emissions rate than most 24/7 matching levels in other countries, the gap is much smaller; annual matching in Poland avoids 460 gCO_2/kWh, which is only 64% higher than the 280 gCO_2/kwh avoided in 100% 24/7 matching in Ireland.

System-level impacts of 24/7 carbon-free electricity procurement

(Xu et al., 2021)

Xu et al. model two grid regions in the United States — California and PJM — using the open-source electricity system optimization model, GenX. They use a 6-zone and 15-zone model for California and PJM, respectively, and they include emissions from the importing regions in their calculations. They model the impact of multiple strategies in each region, along with the generation and dispatch decisions of their neighboring grids. In this study, they assume that procured renewable energy is 100% additional to state CES requirements. This is an important assumption to note, as CES requirements play a significant role in determining the additionality of new projects (see Importance of defining additionality and CES policies below).

Their results showed that at sufficiently high levels, 24/7 matching can achieve higher rates of avoided emissions in California. However, in PJM, temporal matching only exceeds the impact of annual matching in the advanced technologies, no combustion portfolio. Furthermore, annual matching in PJM exceeds 24/7 matching in CAISO at levels below 100%. Annual matching in PJM has an avoided emissions rate of 218 gCO_2/kWh, 2.4 times higher than that of 80% 24/7 matching in California (89 gCO_2/kWh).

System-level impacts of voluntary carbon-free electricity procurement strategies

(Xu et al., 2024)

In a follow up study, Xu et al. examined volumetric, temporal, and local emissions matching strategies in 2030 in two regions: California and Wyoming/Colorado. Unlike the previous study, they did not assume that any procured energy is 100% additional to state CES standards.

In this model, both regions are part of the same grid interconnection. In this work, they found that volumetric and emissions matching showed little to no impact on consequential emissions:

> *"..participating consumers meet matching goals most cost-effectively by procuring the cheapest available renewable energy resources in bulk. Although both matching strategies implicitly assume that this procurement offsets CO_2-emitting fossil-fired generation, we find that it instead almost exclusively displaces capacity additions and generation from other renewable resources. In other words, all or nearly all of the carbon-free energy procured by voluntary market participants pursuing volumetric or emission-matching strategies would have been generated anyway."*

However, they find that 24/7 matching can reduce total emissions, and that 24/7 matching above 98% can exceed the emissions induced by the load. While this is a significant result that indicates that temporal matching is more impactful than any volumetric procurement strategy, there are two important elements that should be considered. First, this study considers two interconnected regions, where the model projects 74% CFE generation in the reference case, higher than the current CES policies. As a sensitivity analysis, they modeled emissions rates under a binding 80% CES standard, and found that volumetric matching was additional under that constraint. Second, even though these results show that local temporal matching has a greater impact than local volumetric matching, it does not conclude that local temporal matching is the most impactful strategy available:

> *"Finally, we recognize that none of the matching strategies investigated in this paper may represent the theoretically optimal means of reducing grid CO_2 emissions via voluntary CFE procurement. Although temporal matching is the most consistently effective of the three modeled strategies, its focus on aligning procurement with the participant's demand profile does not necessarily target times when the consequential carbon impact of bringing online new clean generation is greatest."*

For example, they find that 100% temporal matching in Colorado and Wyoming has an avoided emissions rate twice as high as 100% temporal matching in California. Optimizing for technologies that avoid the most emissions may lead to even higher benefits, even in scenarios with high levels of CFE.

Cambium 2023 mid-case scenario

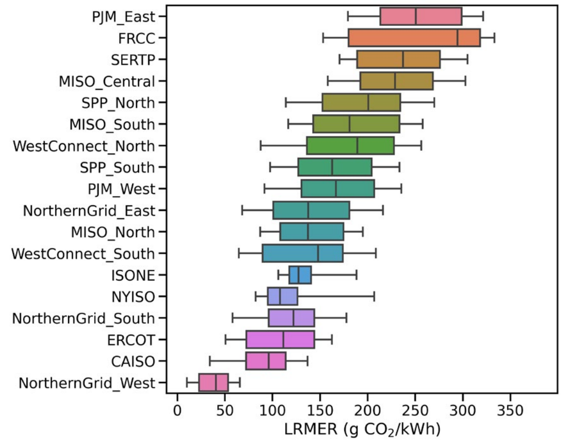
(NREL, 2024)

Researchers at the US National Renewable Energy Laboratory (NREL) have developed the Cambium modeling tool, which models future grid development in the United States under a variety of scenarios. Cambium simulates both capacity expansion and dispatch at multiple time steps, which allows for the calculation of the long run marginal emissions rate (LRMER), which captures effects from changes to both capacity and generation.

The Cambium model has not been used to study the topic of voluntary procurement, and thus has not compared 24/7 and emissionality or addressed the question of additionality of corporate renewable projects. However, Cambium has modeled a large number of grid regions and finds a substantial spread in LRMERs, with an over six-fold difference between the regions with the highest and lowest rates.

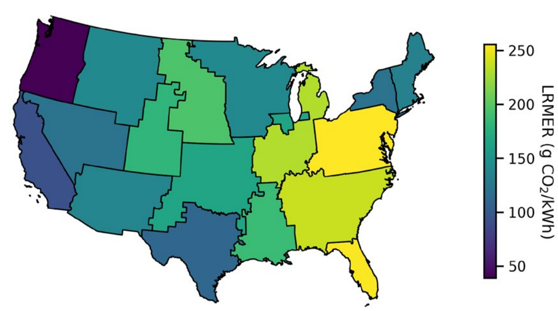
To the extent that new renewable energy projects are additional, reducing load in regions in the Southeast United States is much more impactful than reducing load in the Northwest. This wide variation in long run emissions rates supports the conclusion that variation between geographic regions is much larger than the temporal variation within a region.

LRMER from the Cambium 2023 mid-case scenario



Time levelized long-run marginal emissions rate (LRMER) from the Cambium 2023 mid-case scenario: the box marks the 25–75 percentile range, the whiskers the 10–90 percentile range, and the line marks the median.

Average LRMER in 2030 for each region viewed geographically



The influence of additionality and time-matching requirements on the emissions from grid-connected hydrogen production

(Giovanniello et al., 2024)

Giovanniello et al. modeled the impact of annual and hourly matching requirements for hydrogen production in the United States, under a wide range of economic and policy scenarios, including two different modeling definitions of additionality. In the "non-compete" definition of additionality (which corresponds to the methodology in Riepin and Brown), resources for hydrogen production are optimized after the baseline scenario is optimized; thus all resources are additional. In the "compete" definition (which corresponds to Xu et al., 2024), resources are optimized for the base load and the additional load simultaneously, such that resources procured for hydrogen production could displace resources that would have been otherwise procured for the base load.

While this study does not look at the impact of voluntary renewable procurement for commercial and industrial (C&I) load, it does provide important insight into the difference between these two modeling approaches. Consistent with other studies, they find that in the “non-compete” scenario, annual matching and hourly matching both drive sufficient reduction in consequential emissions. However, in the “compete” scenario, annual matching has substantially higher emissions, while hourly matching has sufficiently low emissions.

They also modeled both definitions of additionality under different policy and economic scenarios. Consistent with Xu et al., 2024, and E3, they found that under high CES policies, the consequential emissions of annual matching decreases substantially. They also modeled scenarios where renewables have a cap on deployment rate to mirror the current delays in deploying renewables from the interconnection queue. In that scenario, they found that the hourly matching strategy had a substantial increase in emissions compared to the unconstrained case. They find that *“the standard runs under the ‘compete’ additionality framework in many contexts may in practice overestimate emissions for annual matching and underestimate emissions for hourly matching.”* They also conclude *“Our results provide robust evidence for our original thesis: one cannot generalize emissions impacts of a specific time-matching requirement in isolation from how other qualification requirements are defined and other existing policies.”*

Consequential impacts of voluntary clean energy procurement

(E3, 2024)

The environmental economic consultancy E3 produced a report studying the consequential impacts of annual and hourly matching in voluntary renewable procurement using their economic optimization model, RESOLVE. They only modeled results in CAISO but analyzed a variety of conditions across multiple time steps. Their main result focuses on the role of clean energy demand and state CES policies on the impact of voluntary procurement. Similar to Xu et al., 2024, they find that under a high CES requirement, demand for clean energy attributes surpasses supply, resulting in additional renewable generation and reduced emissions from voluntary renewable procurement. In this scenario, they find that both annual and hourly matching strategies reduce emissions.

Under low CES requirements with low demand for clean energy attributes, they find that annual matching strategies do not reduce emissions, with C&I procurement simply displacing renewable projects that would have been procured anyways due to economics. They find that hourly matching strategies can reduce emissions in this scenario, but that the impact disappears in future time steps if the participating load is not large. In this case, the procured energy is accounted for in reduced renewable energy build in the future.

Summary of studies reviewed in this report

Study	Regions studied	Model used	Procurement strategies compared	Assumptions on additionality
Riepin and Brown (2024)	European ENTSO-E grid (Ireland, Denmark, Germany, Poland)	PyPSA	• Annual matching • 24/7 hourly matching	Non-compete
Xu et al. (2021)	US (California, PJM)	GenX	• Annual matching • 24/7 hourly matching	Non-compete
Xu et al. (2024)	US (California, Wyoming and Colorado)	GenX	• Annual matching • 24/7 hourly matching • Emissions matching	Compete
E3 (Energy & Environmental Economics, Inc.)	US (California)	RESOLVE	• Annual matching • Hourly matching	Compete
Giovanniello et al. (Hydrogen Study)	US (multiple regions)	DOLPHYN (built using GenX)	• Annual matching • Hourly matching (for hydrogen electrolysis)	Non-compete and compete
Cambium (NREL 2023 Mid Scenario)	US (multiple grid regions)	Cambium	None, but provides Long-Run Marginal Emissions Rate (LRMER)	None

Summary of studies reviewed in this work. Non-compete refers to models where all new projects are assumed to be additional, compete refers to models where procured projects may displace others that would have been built in the reference scenario.

Summary of quantitative results from three studies

Paper	Compete	Location	Annual	CFE 80%	CFE 90%	CFE 100%	Emission-ality
Riepin and Brown	Non-compete	Poland	460	433	433	440	460
Riepin and Brown	Non-compete	Germany	402	386	386	419	460
Riepin and Brown	Non-compete	Denmark	384	355	355	407	460
Riepin and Brown	Non-compete	Ireland	232	222	241	280	460
Xu (2021)	Non-compete	PJM	218	209	214	214	218
Xu (2021)	Non-compete	CAISO	126	89	170	228	218
Xu (2024)	Compete	CAISO	0	-	157	314	0
Xu (2024)	Compete	WY & CO	0	-	156	648	0

Summary of quantitative results from the three studies where a comparison of annual volumetric, 24/7 matching, and emissionality strategies is possible. All results in this table are for 10% CI load participation in 2030.

Conclusions

The effectiveness of voluntary renewable energy procurement strategies varies significantly based on location, timing, and policy context. While high levels (>90%) of 24/7 hourly matching consistently achieve greater emissions reductions than local annual matching within the same region, studies show that procurement in high-emissions grid regions often has an even greater impact than local hourly matching. The additionality of renewable purchases also depends heavily on existing clean energy standards and market conditions, meaning that strategies that are effective in one region may not be equally impactful elsewhere. Moving forward, optimizing procurement to target both high-emissions locations and high-impact time periods — rather than focusing solely on annual or hourly matching — could yield greater system-wide emissions reductions. However, ensuring that voluntary procurement leads to genuine additionality remains a critical challenge that requires further research.

Emissions impact varies substantially across grid locations

In all of the studies that consider more than one grid location, there is substantial variation in the avoided emissions rate between locations for the exact same matching strategy. These variations are usually at least double between the highest and lowest avoided emissions rates, with one dataset (Cambium) even demonstrating a six-fold difference. This result is not surprising as each grid has differing existing capacity and renewable resource potential. This suggests that the emissionality approach can have a higher impact on avoided emissions when used in some grid regions. It also suggests that the local deliverability requirement of 24/7 matching limits corporations that would otherwise voluntarily pursue options with an even larger impact on emissions reductions.

While every study showed that very high levels of 24/7 matching had a higher impact than local annual matching, some studies found that annual matching in one grid region could have a higher impact than 24/7 matching in a different region. Even in cases where annual matching is not shown to be additional, hourly matching in a different region can have a higher avoided emissions impact than local hourly matching. These studies also did not consider other methods for optimizing the reduction of long-term emissions. It is likely that there are more optimal strategies considering system-wide grid needs that avoid more emissions but do not optimize for hourly load matching.

Under certain conditions, hourly matching can have a greater impact than annual matching within the same region

At sufficiently high levels of matching (>90%), with fully deliverable generation, 24/7 matching has a greater impact on emissions reductions than local annual volumetric matching within the same grid region. The cause of the larger impact from 24/7 matching can be broken into two different components: the volume effect and profile effect. The volume effect is simply the amount of renewable energy procured in megawatt-hours. Because temporal matching counts CFE already on the grid toward its matching goal, the total volume of procured energy under temporal matching varies substantially between grid regions and between different levels of CFE matching. This effect is separate from the profile effect, which considers the impact of the specific temporal profile of the generation portfolio. Because renewable energy is highly intermittent and self-correlated, new renewable energy projects can displace each other. But 24/7 matching incentivizes development of generation at times when CFE is not available, leading to generation that displaces fossil fuels instead of other clean energy sources.

The volume effect is important to understand because it leads to 24/7 having drastically different impacts depending on the level of matching targeted. At lower levels of 24/7 matching (<90%), the total emissions are often higher than under 100% volumetric annual matching. This is because in grids that already have higher levels of CFE, lower levels of temporal matching can be achieved with a smaller volume of procured energy. Therefore, when considering temporal matching standards, it is important to specify the target level for matching, or add an additional volumetric constraint, since it can lead to lower impact.

At high levels of hourly 24/7 matching, studies estimate that the purchaser needs to procure a higher volume of energy than they consume in order to meet demand at hours when CFE has low availability — sometimes in excess of 200% of their load. This leads to larger reduction in emissions, but is not always as large when normalized per megawatt-hour or dollar spent. It is also worth exploring assumptions about the price premium that purchasers are willing to pay to determine if very high 24/7 matching targets are a reasonable comparison point.

The profile effect is also important to understand, because temporal dynamics are critical to modeling the grid, particularly under high levels of renewable generation. While current studies have only considered volumetric or temporal load-matching generation, an emissions-optimized approach could focus on the portfolio that has the largest reduction in total emissions, regardless of the consumer's load profile. The optimal time profile would not necessarily be the same as an hourly matched portfolio, though this was not examined in these studies.

Importance of defining additionality and CES policies

One important conclusion from these studies is that lower-cost bulk renewable projects may not be truly additional depending on the economic and policy conditions in the region. In these situations, annual matching does not drive additional demand for renewable attributes, and leads to no change in total emissions (i.e., no additionality). Hourly matching can lead to additional demand in these circumstances, however, because the temporal requirements are different from the most economically viable renewable projects. In many places, renewables are the cheapest source of new energy and are being built at increasing rates.

Without a sufficient CES policy, the amount of renewable energy that would be built regardless exceeds the demand for the environmental attributes of that energy. In this case, companies procuring renewable energy may just be displacing projects that would have been built anyway for economic reasons and projects that generate at other times can drive more impact in the region. While this condition is true in some grid regions, it seems likely that it is not true in every grid region. Areas where renewables are not being deployed today are presumably regions where new renewable projects are likely to be more additional. For example, wind and solar only accounted for 5.5% of generation in PJM and 3.7% in SOCO in 2024, compared with 34.4% in ERCOT and 34.2% in CAISO.

The relationship between supply and demand of renewable energy attributes is sensitive to predictions of both future economic conditions and regulatory policies. There also exists a possible feedback loop where low-cost renewables lead to increased CES requirements because higher standards are more achievable. Further research is needed to better understand which grids are likely to be in high and low clean energy demand scenarios and the relative risk and sensitivity of those classifications. For example, the Clean Energy Buyer's Institute (CEBI) outlines a qualitative approach to estimating risk to consequential impact. Future research could provide greater information and support for making those assessments.

Limitations of capacity-expansion models

All of the studies under consideration use similar capacity-expansion models that have to make some assumptions that differ from the real world in order to make the problem tractable. First, they do not consider transmission constraints within a grid region and assume that any project in the region is deliverable to any load in the region. However, intra-regional transmission constraints can drive substantial differences in marginal emission rates. Procuring projects that address transmission constraints to deliver more renewable energy may be impactful in ways that have not been studied in these models.

Capacity expansion models also rely on input data such as technology costs and regulatory policies that have to be predicted over long timescales and are very uncertain. While these models can provide insight into system dynamics and behaviors, they are not necessarily predictive of future grid states, and depend on the input assumptions and data. Additionally, capacity-expansion models project the future state of the grid by solving for the most economically efficient results given the set of modeled costs and constraints.

Real-world development is not always economically efficient. I n places where there is political opposition or grid operator misalignment like self-scheduled non-economic dispatch, renewable deployment may lag behind model projections. These models also do not include the impacts of financial risk and the ways in which corporate offtakers can help secure financing for projects. In this way, new projects may have higher additionality in practice than is represented in the models.

Directions for future research

The existing research highlights that marginal emissions vary substantially between locations, often much more than variations in time within a single location, suggesting that emissionality may be a high-impact strategy for renewable procurement. However, recent studies find there are circumstances where non-hourly matched procurement may not be additional at all. More research is needed to better understand the technical and policy circumstances where volumetric energy purchasing is or is not additional. Performing studies in a wider range of geographies, particularly in the Global South, will help to understand where renewables have the highest likelihood of being additional. Furthermore, comparing different models and approaches in the same region will help to elucidate the impact of certain modeling assumptions on the estimated impact.

While emissionality highlights the impact of regional differences, 24/7 matching highlights the impact of timing differences. It is possible there are other strategies that could reduce emissions at a higher rate by combining the strengths of these two approaches. For these strategies to be operationalized, there needs to be an observable and quantifiable metric so that voluntary actors can set goals and measure progress against them. One strength of 24/7 matching is that it provides a clear and observable metric. Emissions-based signals may provide a more impactful metric, but for them to be useful, they need to be produced in a way that is clear, observable, and widely accessible. This may be possible with an emissions signal produced with an open model and clear, verified assumptions. Further research comparing the impact of existing signals and metrics would help identify the most impactful strategies.

However, maximizing impact is only one dimension to evaluate standards. Observability and certainty are other qualities that must be considered when choosing an appropriate standard. The current research suggests that while emissionality may be a more impactful strategy under many circumstances, there are conditions under which only 24/7 matching has a net impact on emissions. There is a tradeoff between maximizing impact and maximizing certainty of impact that must be considered by policy and standards makers.

Finally, where capacity expansion models are useful for modeling the complex behavior of grids in multiple different future scenarios, they also have limitations to the extent to which they can represent reality. There are also methods for predicting grid capacity expansion using historical data and empirical methods, such as the marginal build emissions rate defined in the GHGP guidelines. Research into empirical methods for forecasting grid behavior can provide a different perspective on the problem. Empirical models do not need to make the same simplifying assumptions and can incorporate the effects of many complex phenomena. However, since they are based entirely on historical data, it is unclear the extent to which they can be predictive of future outcomes. A backcast analysis of both empirical and capacity expansion models could be helpful in understanding the strengths and limitations of each model.