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Synergies and Welfare Effects of Combining Carbon Pricing and Renewable-Energy Policies: A Meta-Analysis

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Abstract
Many countries combine carbon pricing with renewable-energy policies. Microeconomic theory predicts this combination yields no additional emissions reductions under cap-and-trade and only potentially under carbon taxation, but at a social welfare loss. We undertook a systematic literature review of emissions-reduction synergy, identifying many ex-ante but only one ex-post study – explained by the lack of policy counterfactuals. In 72% of ex-ante 127 estimates from 80 studies, combining instruments reduces emissions more than either instrument alone. Additional reductions are more common under carbon taxation, as theory predicts, but also occur under cap-and-trade. Across 85 exact synergy estimates, the policy combination yields about 22% greater emissions reductions on average. Regarding welfare effects, 74 of 119 ex-ante estimates from 79 papers indicate some benefit from adding a second instrument. Deviations from theory reflect model assumptions, such as incomplete emissions coverage, implementation constraints, social welfare metrics limited to consumer utility, and market or government failures including fossil fuel subsidies. While ex-post estimates are less likely to detect non-zero synergy, the single ex-post study broadly supports our findings.

Keywords Instrument interaction · Carbon tax · Carbon market · Cap-and-trade · Renewable-energy target

1 Introduction

Among potential instruments of climate policy, carbon pricing can count on most support from economists[1]. Nonetheless, renewable-energy support is the most frequent policy in practice. As of December 2022, 47 national and 36 subnational jurisdictions have intro-

[1] As an example, the European Association of Environmental and Resource Economists "Statement of 2019 (https://www.eaere.org/statement/), "proposed for endorsement to the whole community of economists in Europe and worldwide" reads: 'Economists encourage the emergence of a global carbon price", as'carbon price is the most cost-effective lever to reduce carbon emissions'.

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duced carbon pricing[2]. In comparison, 156 countries have renewable subsidies – feed-in-tariffs/premiums or net metering - or renewable mandates – implemented through targets or tenders -in place.

Worldwide, whenever carbon pricing is in place, it often co-exists with renewable-energy targets or subsidies. This holds true, for example, for many countries in Europe, several states in the USA, Japan and China. However, such overlap defies microeconomic arguments on the expected direction of synergy of instrument combinations, as summarised by, for example, Fankhauser et al. (2010). Theory predicts that combining carbon pricing with renewable-energy policies will bring no additional emissions reduction in the case of cap-and-trade, and only potentially, and at a social cost, in the case of a carbon tax. Under a renewable-energy target, a certain volume of emissions is abated in the energy sector. Yet, this means in the case of emissions trading there is scope for higher emissions elsewhere while staying within the emissions cap, the so-called "waterbed effect". Therefore, overall emissions will not go down. Moreover, costs of meeting the cap will be higher whenever the cheapest abatement opportunities are not in the energy sector. In the case of a carbon tax, a renewable-energy target or subsidy might contribute to additional emissions reduction, if the marginal abatement cost of renewable energy is higher than the tax. But in that case, provided the carbon tax is optimal, the marginal cost will be higher than the marginal benefit of abatement, meaning that the extra abatement comes at a net social welfare loss.

A review by van den Bergh et al. (2021) provides a framework to assess and classify synergy in emissions reduction. Such synergy is judged by comparing the effects on emissions of each instrument separately with those of the policy mix. We build on this review in three ways. First, we collect quantitative evidence on instrument synergy and compare it to theoretical expectations. Second, we assess welfare outcomes and their association with synergy. Third, through meta-regressions and case-by-case analysis of model assumptions, we identify factors influencing synergy and welfare outcomes.

The meta-regressions in the central analysis consider only ex-ante studies because we identified just one ex-post study of emissions-reduction synergy, Tello (2025). As a robustness check, we re-estimate the regressions including the 21 ex-post estimates reported in that study.

We also examine the study in greater detail in a dedicated section (Sect. 6.3). This allows us to identify potentially important characteristics that the joint regression analysis might obscure, given that the sample is heavily skewed toward ex-ante studies with substantial methodological differences. The paper acknowledges that creating counterfactuals to conduct ex-post analysis is challenging in the case of instrument synergy, because countries tend to accumulate rather than alternate policies. Multi-regional longitudinal econometric studies, such as Tello, can provide estimates using classic two-way fixed effects specifications. However, these approaches isolate synergistic effects only under the stringent assumption of no heterogeneity across regions or time periods. We discuss these caveats in a separate section, alongside other ex-post studies that estimate the impact of instrument combination, but on carbon intensity and welfare outcomes, instead of on carbon emissions directly.

We find that in 72% of ex-ante studies − 91 of 127 estimates from 80 papers on emissions-reduction synergy -, the two instruments are more effective in reducing emissions than either one alone. Additional reduction is more common when a carbon tax is in place,

[2] REN21 Renewables Global State Report, available at https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf

as predicted by the theoretical literature. However, additional abatement is also found for cap-and-trade. On average, based on the 85 estimates for which an exact value for synergy is provided, combining the two instruments leads to 22% more emissions reduction. In 74 of 119 estimates from 79 ex-ante papers assessing welfare impacts there is some welfare benefit from adding a second instrument to a pre-existing one. The single ex-post study found supports these findings: when considering ex-post estimates only, once again, additional emissions reduction is more common under carbon taxation but also occurs under cap-and-trade. Depending on how we classify ex-post estimates, the policy mix leads to either 9.7% or 39.6% additional emissions reduction.

The remainder of the paper is organized as follows. Section 2 describes the search procedure undertaken to identify papers suitable for meta-regressions and discusses why ex-post studies are virtually absent. Section 3 explains how we obtain synergy estimates from the selected papers and classify them into categories. Section 4 provides descriptive information about the estimates, such as policy instruments used, model type, category and magnitude of estimates, welfare effects, time horizon and geographical scope. Section 5 undertakes regression analysis to assess the factors correlated with higher synergy and associated welfare outcomes. Section 6 discusses, on a case-by-case basis, the patterns and modelling assumptions that lead to deviations from theoretical predictions as well as the few ex-post studies found. Section 7 concludes.

2 Search and Selection of Studies

For the literature review, we first undertake a snowball search, starting with the studies collected in the recent review by van den Bergh et al. (2021). We complement this with a systematic search in Web of Science (WoS) and Scopus. Scopus identified 90 studies, which covered all those identified by WoS (49). The snowball approach added five papers to the set identified through WoS and Scopus.[3]

The first step, the snowball strategy, ensures we identify a set of papers directly relevant to the theme, which informs the search terms for the systematic search. The second step, the systematic search, is required to ensure completeness, since new papers might have been published in the meantime, and because the original review did not have the exact same scope as the current one. While the previous review by van den Bergh et al. (2021) was geared towards papers addressing instrument interactions in general, here we intend to capture all studies that assess or simulate a combination of the two specific instruments (carbon pricing and renewable-energy policies), even if that is not always their main objective. Another reason for a systemic search is that there are numerous ways to denote carbon pricing and renewable-energy instruments. By expanding the terminology in the search process, we can find a wider set of potentially suitable studies.

As a starting point for the snowball search, we took the papers that reported on the combination of carbon pricing and renewable-energy policy in van den Bergh et al. (2021). We skimmed the reference lists of all these papers. Lehmann and Gawel (2013) stood out as it

[3] From the 5 not detected, 3 are unpublished papers (Abrell and Weigt 2008, Morris 2009, and Böhringer and Rosendahl 2011). One paper, van den Bergh et al. (2013), by what appears to be a technical error, does not have a searchable full text. The fifth paper, Boeters and Koornneef (2011), uses the unusual expression 'carbon policy' to refer to carbon pricing instruments and thus was not captured by our search.

provided 11 references with quantitative estimates of emissions-reduction synergy, divided by the type of model employed. We then proceeded with the snowball approach by searching for any papers citing Lehmann and Gawel (2013) or any of the 11 references it provided. Through this strategy we found a total of 23 suitable papers.

Next, we undertook the systematic search. We structured the search terms to return any article in which carbon pricing instruments and renewable-energy instruments are mentioned in the article title or abstract, while terms hinting at empirical or quantitative results and policy combinations or mixes were referred to anywhere in the text. This strategy is similar to Capstick et al. (2015) whose search term considers certain words as a prerequisite in the title while others can be present anywhere in the text. The search term was informed by the findings of the snowball approach[4]. This specific structure of the search terms allows us to identify studies relevant to our aim, while limiting the total number of papers.

To understand our approach, note that we combined four groups of terms, E (identifying carbon pricing instruments), R (identifying renewable-energy instruments), N (identifying quantitative results) and C (identifying combination of instruments). Table A1 in Appendix A lists all the elements of each group E, R, N and C. The search terms comprise all possible combinations of the elements from these groups, named **e, r, n** and **c**. In formal terms, the search procedure can be described as:

In abstract [(**e**) AND (**r**)] AND [Anywhere in the text [(**n**) AND (**c**)]]

As an example, the following two combinations are included in our search terms:

In abstract[(”ETS”) AND (”green certificate”)] AND [Anywhere in the text [(”numeric”) AND (”interaction”)]]

In abstract[(”carbon tax”) AND (”renewable target”)] AND [Anywhere in the text [(”general equilibrium”) AND (”combination”)]]

This search strategy can be implemented in WoS directly. In Scopus, however, the search engine does not give access to full-texts. Thus, we started with a larger set of papers: those whose abstracts have keywords identifying carbon pricing and keywords identifying renewable-energy instruments (In abstract[(**e**) AND (**r**)]). This yielded a total of 6,354 papers with valid DOIs. We then downloaded the full-texts, and searched within for the remaining groups of keywords, i.e., those relating to instrument combination and to quantitative results ([Anywhere in the text [(**n**) AND (**c**)]). In doing so, we narrowed the set to 2,204 papers[5]. The full procedure is illustrated in Fig. 1.

As it is extremely demanding to screen 2,204 studies manually ensuring consistency, we resorted to ChatGPT-5, which allowed us to conservatively narrow down this set to 508 for manual inspection. We created a prompt asking whether papers - whose full, plain text, we

[4] For example, papers identified often reported quantitative estimates and looked at a combination of instruments but without explicit mention of these in the abstract.

[5] About two thirds of full texts were downloaded manually. For time efficiency, we excluded at this stage any papers we could verify from a quick glance were not suitable - e.g., they were not in english, they were about a different topic, they had no quantitative results or they were book chapters as opposed to academic articles.

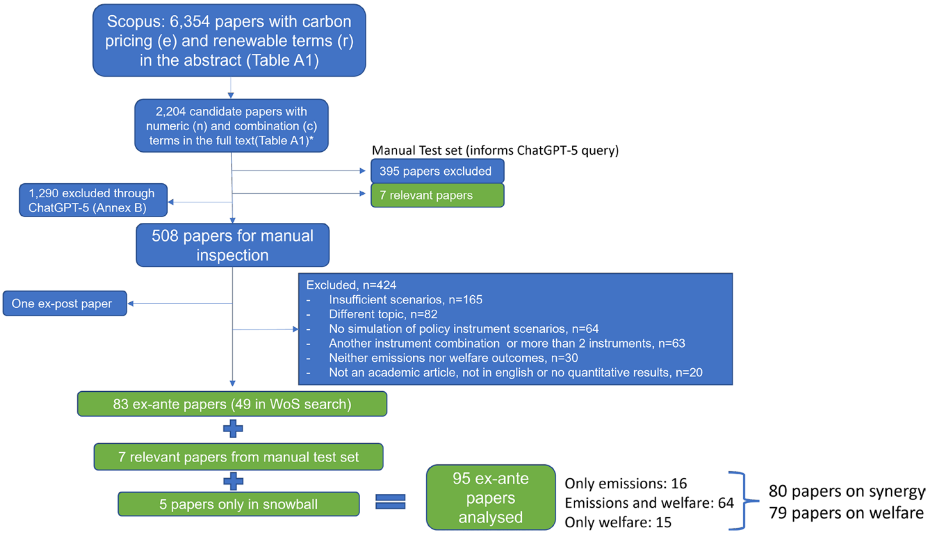

Fig. 1 Sample construction. Note: boxes in green highlight the papers which incorporate the final meta-analysis

provide to ChatGPT-5 - estimate the impact of carbon pricing or renewable energy subsidies, and requesting six exact citations illustrating they do. We evaluated the ChatGPT-5 output based on 402 papers we manually inspected, of which 7 were relevant to our search. There were no false negatives. There were 71 false positives. This is because our prompt was purposely broad: we did not ask whether there were estimates of synergy, but of any impact of policy instruments. If, according to ChatGPT-5, those were present, we then manually inspected the papers to identify if they were actual emissions-reduction synergy estimates[6]. Appendix A.1 provides the exact prompt and an example of the ChatGPT-5 output.

From the 508 papers which we manually inspected, we eliminated 424, on the basis of the following exclusion criteria:

1. ‘Different topic’ refers to papers which are not about policy instruments. Examples include papers where the ETS acronym stands for something other than Emissions Trading Scheme.
2. ‘No simulation of policy instrument scenarios’ refers to papers which speak of policy instruments and their interaction, but do not simulate specific scenarios with numeric results. These papers are discursive or use theoretical microeconomic models. While they cannot be included in the meta-analysis, we do consider them in the discussion of Sect. 6.
3. ‘Another instrument combination’ and ‘more than 2 instruments’ refer to, respectively, papers which are focused on interactions between policy instruments other than carbon pricing and renewable-energy instruments, and papers on combinations of more than two instruments.

[6] Determining instrument overlap is a task which requires manual inspection of tables and charts, which we did not provide to ChatGPT-5, and thus is best accomplished by human scrutiny.

4. ‘Insufficient scenarios’ means a paper did not cover sufficient policy scenarios with quantitative results to allow for a conclusion on the synergy between carbon pricing and the renewable-energy instrument.
5. ‘Neither emissions nor welfare outcomes’ means a paper did not have emissions outcomes nor welfare outcomes. While our primary focus is on emissions, we also keep papers which look at welfare under different instrument combinations even if emissions are exogenously fixed. These are not used for our synergy analysis, but allow to say something about the trade-off between effectiveness and welfare.
6. ‘Not in english’ means a paper was written in another language, ‘not an academic article’ means the source is not an academic article but for example a book chapter instead, and ‘no quantitative results’ means there were no numeric results concerning synergy within the paper.

We found only a single paper offering ex-post estimates of emissions-reduction synergy, Tello (2025). The remaining 83 papers (of which 49 had been found through the initial WoS search), plus the 7 manually found when designing the ChatGPT-5 prompt, plus the 5 papers found only through the snowball approach, form our final sample of 95 (ex-ante) papers (see Table A2). Of these, 80 measure emissions-reduction synergy; the remaining 15 are only used in our welfare analysis, since they keep emissions fixed. Note that the same paper might provide more than one estimate of the interaction between instruments. This explains why 80 emissions-reduction synergy papers generate 127 synergy estimates[7].

The literature we found on emissions-reduction synergy differs substantially from that on single instruments. Döbbeling-Hildebrandt et al. (2024) find 77 ‘single-case’ ex-post studies, for a total of 80 econometric estimates of the impact of carbon pricing on emissions. They thus conduct a meta-analysis of empirical estimates for a single instrument. As we explain in the next section, estimating synergy requires three counterfactuals next to the instrument combination (A and B): absence of any policy, only instrument A and only instrument B. Most single-country or ‘single-case’ ex-post studies are unable to estimate instrument synergy. To do so, a region would have to alternate carbon pricing and renewable-energy policy, before finally combining the two, which rarely occurs. In fact, we did not find any such study. Nonetheless, studies using cross-regional panels, such as Tello (2025), can provide ex-post estimates of instrument synergy, albeit with noteworthy caveats.

To ensure we had not missed any ex-post analyses, we scrutinized all candidate papers again with a different approach. Using the 6,354 papers found through Scopus as a starting

[7] For example, Böhringer et al. (2009) generate three synergy estimates, using three different computable general equilibrium models. Choi and Thomas (2012) provide two estimates of synergy, one where the emission cap is implemented with emission allowances and one without. Fagiani et al. (2014) also provide two estimates of synergy, one where the renewable-energy incentive is a green certificate market and one where it is an feed-in tariff. Liu et al. (2018), De Jonghe et al. (2009) and van den Bergh et al. (2013) provide two estimates of synergy, one with a carbon tax and another with a carbon quota. Liu and Wei (2016) provide two estimates of synergy, one where the emissions trading schemes implemented by two regions are independent and one where they are integrated. Arnette (2017) and Arnette and Zobel (2011) undertake multi-objective linear optimization and generate multiple synergy estimates (3 and 5, respectively) using distinct sets of weights for objectives. We extract two estimates from Boeters and Koornneef (2011), one with inefficient pre-existing fossil fuel subsidies and one without. Dai et al. (2018) generate three synergy estimates as well, one with a uniform carbon pricing, one without any carbon trading, and one with only partial sectoral coverage.

point, we checked carefully every paper with econometric estimates[8]. Within this set, we found the same ex-post paper identified through our systematic search (Tello 2025). Given that we identified only a single ex-post study on abatement, which differs substantially in approach from the ex-ante studies, we chose to first analyze it separately. That is, the central regression analysis focuses exclusively on ex-ante studies. However, we also present a joint regression including the ex-post estimate as a robustness check. In addition, we provide a detailed discussion of the studys characteristics that may drive its results in Sect. 6.3.

We identified another multi-region panel study, Zha et al. (2023), which provides ex-post estimates. However, it analyses the synergy in carbon intensity reduction instead of in emissions reduction. We identified several papers whose datasets might permit an estimate of emissions-reduction synergy but for which none was reported, along with three papers that focused on welfare effects rather than synergy. Their findings are also discussed in detail in Sect. 6.3.

3 Synergy Estimates

The review by van den Bergh et al. (2021) proposed four categories of synergy: 'positive synergy', 'no synergy', 'negative synergy' and 'backfire'. Positive synergy occurs when one instrument reinforces another - e.g., public information campaigns that raise awareness about subsidy schemes; no synergy means the instruments operate independently, so the overall impact equals the sum of their separate effects, e.g. a renewable energy subsidy and a recycling program targeting different behaviors without interaction; negative synergy arises when one policy weakens another, such as the expected theoretical waterbed effect of carbon markets and renewable energy targets; backfire means one instrument offsets or reverses the effect of the other.

Since later we refer a lot to the boundary between 'negative synergy' and 'backfire' we call it 'border of backfire'. This boundary determines whether there is any advantage in terms of emissions in piling instruments, i.e., any additional abatement. Moreover, 'negative synergy' denotes that the combination of instruments achieves more emissions reduction than either instrument alone but excludes the case of backfire. In addition, we divide backfire into 'single backfire' and 'double backfire': the first denotes that the combination of instruments reduces emissions less than the most, but more than the least, effective instrument; the second indicates that the combination of instruments reduces emissions even less than the least effective instrument. Figure 2 illustrates these categories, alongside the 'border of backfire' case, which sits exactly on the border between negative synergy and backfire.

To assess the exact synergy between two instruments, four (counterfactual) scenarios are needed: no instrument, one instrument only (instrument 1 with abatement A), the other instrument only (instrument 2 with abatement B), and the two together (combination of instruments 1 and 2 with abatement effect A&B).

In the case of three scenarios, it is not possible to measure synergy precisely, yet, it is still possible to provide a range. From the 127 synergy estimates, 85 estimates are exact, based on simulations covering all four scenarios. The extra 42 additional estimates come from

[8] These papers were identified through a keyword search (any paper which had at least one of the following expressions: "specification*", "regress*", "panel data", "cross*sectional", "time*series", "econometrics", "fixed effect*", "random effect*") and through skimming.

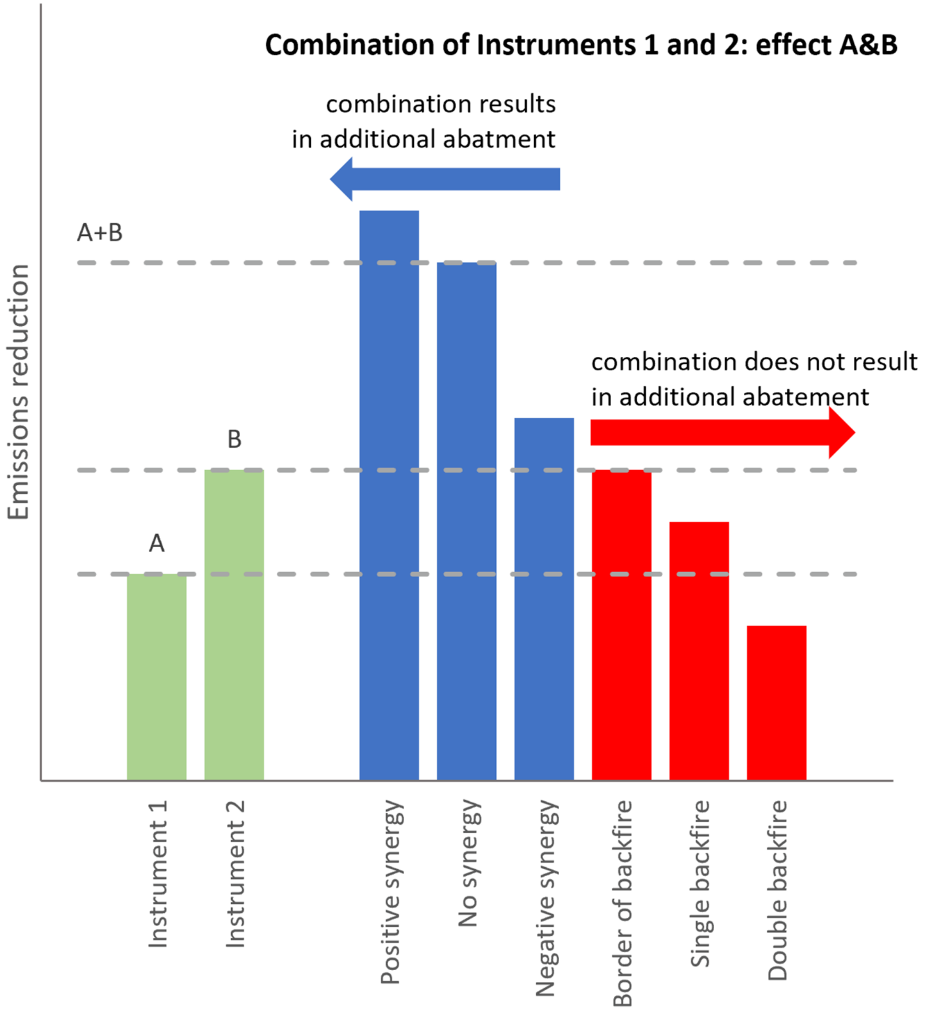

Fig. 2 Synergy categories

simulations with only three scenarios - no instrument, one instrument, and their combination. Of these, 36 involve simulation of a carbon pricing instrument alone, but not of the renewable-energy instrument alone (Table 1).

Papers where one scenario is missing can be classified into three types, to allow for further insights into synergy:

- Type I - 'at best, border of backfire': The combination of instruments 1 and 2 has the same effect as instrument 1 (A&B equals A);'
- Type II - 'at best, positive synergy': The combination of instruments 1 and 2 has a larger effect than instrument 1 (A&B is larger than A);

Table 1 Number of estimates by the number of scenarios simulated

Scenarios	No. of estimates
all four scenarios	85
missing 'renewable-energy instrument alone'	36
missing 'carbon pricing instrument alone'	6
Total	127

- Type III (not found in our sample): The combination of instruments 1 and 2 has a smaller effect than instrument 1 (A&B is smaller than A).

We now demonstrate, using Fig. 3, why exactly papers of Type I and of Type II correspond respectively to 'at best, border of backfire' and 'at best, positive synergy'. We do so by varying the (unknown) effect B. We start in Fig. 3a, where B > A&B for papers of Type II, and reduce B step by step, until we reach Fig. 3f. We highlight the changes in the synergy categories in bold.

The figure illustrates that the range of possible synergy effects for Type I results is limited, from backfire (cases 3a, 3b and 3c) to border of backfire (cases 3d, 3e and 3f). The range of possible synergy for Type II results, instead, is broader, namely from single backfire (cases 3a) until positive synergy (case 3f). In all cases, studies of Type II have better synergy outcomes. We will also make use of the distinction between Type I 'at best, border of backfire' and Type II 'at best, positive synergy' in the descriptive results and statistical analysis in subsequent sections.

4 Descriptive Results

4.1 Policy Instruments

The estimates we collect cover four instruments - carbon caps, carbon taxes, renewable-energy targets (RET) and renewable-energy subsidies (RES). We distinguish RET from RES based on whether they are implemented as quantity instruments or price instruments, respectively. The term 'carbon cap' encompasses mandated ceilings on emissions without tradable certificates and carbon markets. The RET are likewise either mandated and modelled as constraints in a model, or represented by a Green Tradable Certificates market. Most estimates (80/127) come from models with carbon caps instead of carbon taxes. RET are more common than RES (75 vs. 50). Table 2 provides more details on the instrument combination. A case-by-case classification is available in the Table we provide as Supplementary Information.

4.2 Model Type

The ex-ante synergy estimates come from model simulations and not from observational or experimental data. However, models use empirical data (to different extents) to calibrate model parameters.

Most estimates are derived from general equilibrium models (43), followed by models optimizing the power sector (38) and partial equilibrium models (26). The second group

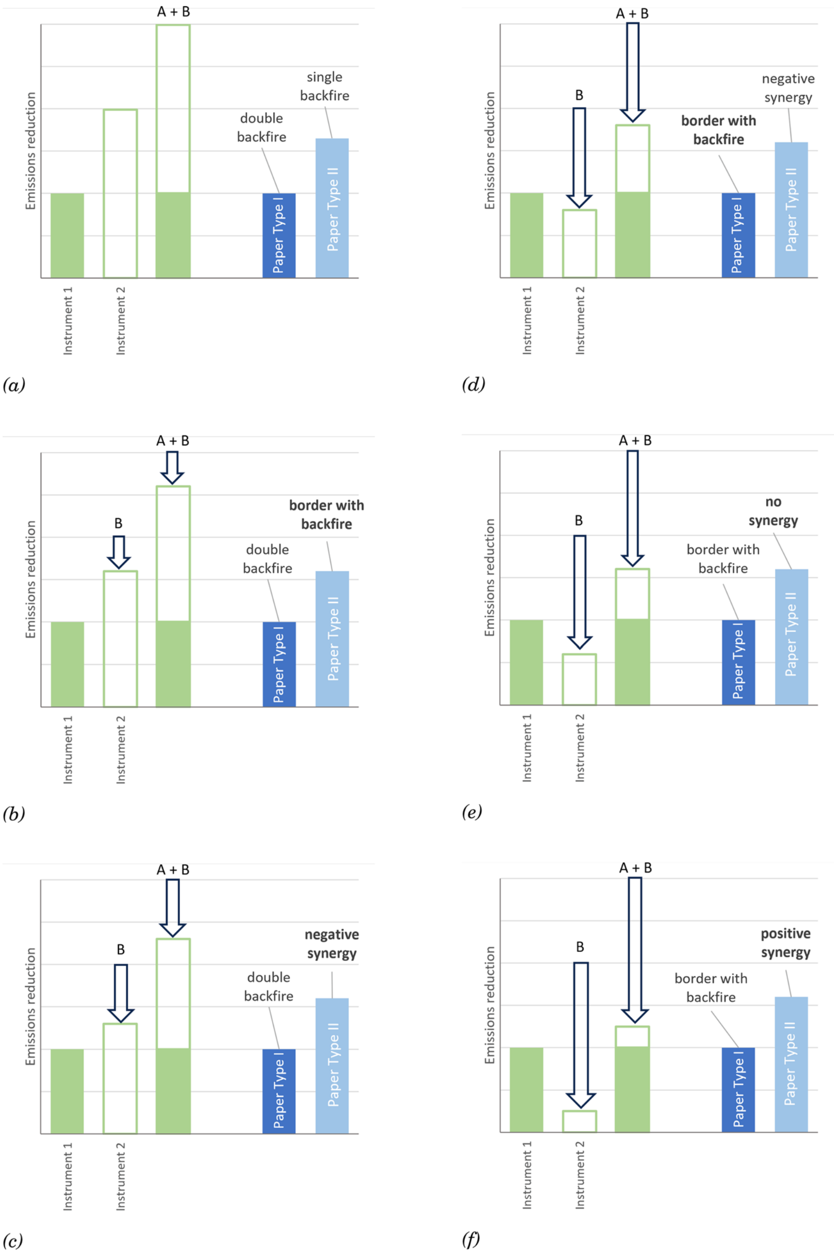

Fig. 3 Possible synergy categories when instrument 2 is missing (in bold when there is an improvement in the synergy category)

fixes demand and minimizes the cost of energy provision, while the third group considers endogenous demand when maximizing profits for the energy sector (see Fig. 4).

General equilibrium models include Computable General Equilibrium (CGE), Dynamich-Stochastic General Equilibrium (DSGE) and general equilibrium microeconomic models.

Table 2 Type of instrument interaction

Type of Interaction	No. of estimates	
Carbon cap	80	
of which, with RES		25
of which, with RET		55
Carbon tax	45	
of which, with RES		25
of which, with RET		20
generic carbon price*	2	
Total	127	

*Estimates come from models with an exogenously set carbon price

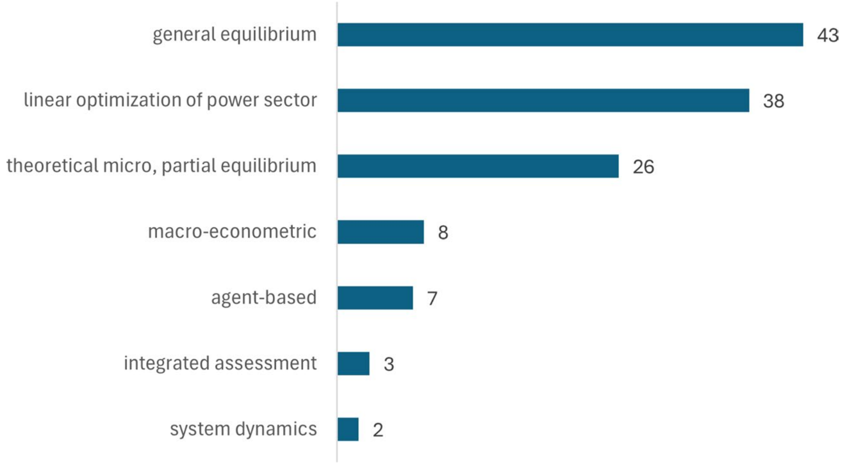

Fig. 4 Types of model used

Partial equilibrium models can be classified by the level of detail of the energy engineering system compared to that of the economic system. Several of the models are ‘energy system models’, based on the MARKAL and TIMES frameworks. The remaining models have a stylized energy dispatch system, but higher economic complexity. Some consider energy providers to have market power (instead of assuming perfecting competition), others include innovation, investment, environmental externalities other than CO2-related or a social planner.

Two papers use the 3EME modelling framework (Mercure et al. 2014 and Knobloch et al. 2019), a self-designated macro-econometric approach. These use structural equations with econometrically estimated parameters, and do not impose equilibrium nor optimality conditions. A third paper, Radpour et al. (2021), follows the same strategy, and provides six estimates. Four papers (seven estimates) use agent-based modelling (ABM) - Liu et al. (2011), Fagiani et al. (2014), Richstein et al. (2015), and Nieddu et al. (2024). Three papers use integrated assessment models (IAM) - Rezai and van der Ploeg (2017), Zhang et al. (2025) and Shukla and Chaturvedi (2012). Finally, Shuyue and Yue (2025) uses a system dynamics approach and provides two synergy estimates.

4.3 Optimization and Time Horizon

Eighteen estimates come from models where no optimization takes place. We classify models which do perform optimization into three categories: intertemporal, recursive-dynamic or single-period optimization[9]. In meta-regressions of CGE models, the type of optimization often plays a significant role (see, for example, Anderson 2020).

The majority indicate a time horizon over which optimization is performed, with 2020, 2030 and 2050 being the most frequently used final years. This makes sense, as these correspond to policy targets for a low-carbon transition as set by the UN and national states. In comparing studies, we use cumulative measures (until the end of the period) whenever they are available. If results are only presented for specific years, we use the final year reported. Figure 5 illustrates the distribution of the years for the collected estimates. We will later assess whether the final year of analysis affects study findings. Detailed information on the period considered for each estimate is available in the Table we provide as Supplementary Information.

4.4 Geography and Policy Coverage

Except for three synergy estimates coming from highly stylized models (Clancy and Moschini 2018, Wang et al. 2024, Liu et al. 2011), all estimates come from models which study a specific region. They do so most often by simultaneously providing region-specific model outcomes and calibrating parameters to the historical data of the region. As Table 3 shows, the majority of papers focus on China, following by the the EU or subsets of countries within the EU, followed by the US, and by the world as a whole.

The geographical focus of a case study does not necessarily determine how policies are implemented within the model. A model representing a specific country might not simulate carbon pricing and renewable-energy incentives as they are applied in reality. For example, Linares et al. (2008b) discuss Spain within the context of the EU-ETS, but simulate

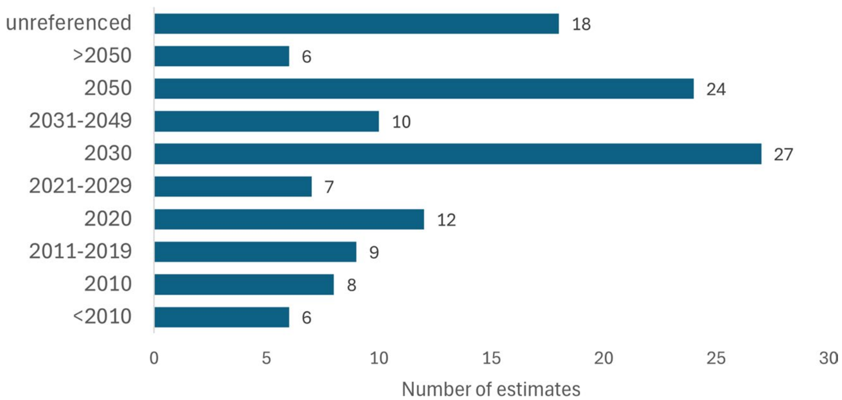

Fig. 5 Final year of analysis

[9] In the case of CGE models, static optimization was classified as single-period optimization.

Table 3 Regional breakdown

Region (outcome)	No. of estimates
China	46
China region	8
EU	8
EU country	17
EU group of countries	9
EU + China	2
US	5
US region	11
World	7
other	11
stylized	3
Total	127

the emissions cap at the national (Spanish) level rather than the broader EU level. Therefore, understanding policy implementation requires a thorough examination of each model's structure. This structure ultimately determines whether the 'waterbed effect' is present – if so, the model aligns with the textbook case. Through a detailed, case-by-case analysis, we assess whether the 'waterbed effect' is expected and classify synergy estimates accordingly as aligning with textbook coverage or not. Given the diversity of models, deviations from textbook coverage can occur in various, often subtle, ways. Below, we provide a non-exhaustive list of examples.

One case is where a model describes emissions in one country where carbon pricing is uniformly applied. If the model excludes other countries, as for instance, Morris (2009) does, it mimics textbook coverage. However, if other countries are included and trade is considered, the scenario changes: the waterbed effect may no longer apply due to potential carbon leakage, and thus, we classify the model as deviating from textbook coverage. This is the case for, for example, Traber and Kemfert (2009). A similar approach applies to the renewable-energy incentive. If a renewable quota is implemented solely within a national electricity market and there is no electricity trade, the model aligns with coverage as in the textbook case – this is true for Linares et al. (2008b). But if the model includes endogenous electricity imports and exports, as in Pothen and Hübler (2018), these interact with the quota, resulting in a deviation from the textbook scenario.

In models with a single region, determining whether estimates align with textbook coverage depends primarily on whether carbon pricing is uniform. For instance, Dai et al. (2018) conduct three analyses. In two cases, deviations from textbook coverage occur: in one, only a subset of sectors is subject to carbon pricing; in the other, emissions trading between sectors is absent. Both cases show welfare (GDP) gains from combining the policies. In the third analysis, carbon pricing is uniform, aligning with coverage as in the textbook case, and – consistent with theoretical predictions - welfare does not increase. Overall, we find some deviations from coverage in the textbook case in 26 of the 127 synergy estimates (20.5%). The full details are available in the Table we provide as Supplementary Information.

4.5 Estimates of Emissions-Reduction Synergy

As explained in Sect. 3, we know with certainty the emissions-reduction synergy from 85 estimates. Of these, 63 estimates indicate that the combination of instruments results in

Table 4 Synergy category when four scenarios are present

Synergy category	No. of estimates
backfire	2
border of backfire	20
negative, no border of backfire	53
positive	10
Total	**85**

Table 5 Synergy range when three scenarios are present

Synergy range	No. of estimates
at best border of backfire (Type I)	14
at best positive synergy (Type II)	28
Total	**42**

additional abatement. In ten of these, the synergy is positive, but, in all the 53 remaining cases, it is negative (see Table 4).

For the 42 estimates for which the emissions-reduction synergy is not known with certainty we provide a range, following the approach of Sect. 3. We find 14 estimates of Type I – where the combination of instruments achieves no additional abatement, with the possible synergy ranging from double backfire to border of backfire. The remaining 28 are of Type II and the combination of instruments might deliver additional abatement, with possible outcomes ranging from single backfire to positive synergy (see Table 5).

These results do not indicate striking differences between papers with four and three scenarios (compare Tables 4 and 5). In the latter group, we know 14/42 do not result in additional abatement (papers of Type I). If we assume that for most papers of Type II the combination of instruments contributes some additional emissions reduction - arguably a realistic assumption[10] -, we would end up with similar shares of papers with an emissions reduction in terms of piling instruments.

We express additional abatement as the increase (or decrease) in emissions reduction when implementing both instruments versus implementing only the most effective one. This means in the 'border of backfire' case − 20 out of 85 estimates - additional abatement is 0. In the two single backfire cases, emissions reduction is −3.2% and −24.1%. Of the 63 with negative synergy (53) or with positive synergy (10), the additional emissions reduction is on average 30%, with a maximum increase of 149% (and a median increase of 14%). If we take the average of all estimates, the additional reduction in emissions is 21.7%.

4.6 Welfare Benefits from Instrument Combination

We now look at whether there are any positive effects of implementing two instruments as opposed to only one, apart from the emission impact. Studies in which emissions are exogenously fixed were omitted from the analysis on emission synergy, but are included here if they present welfare outcomes.

[10] As shown in Fig. 3, in 4 out of 6 cases, papers of Type II are better than 'border of backfire'. Moreover, the two cases where they are not − 3a and 3b - require the missing instrument to provide substantially more abatement than the instrument analysed. The instrument most often missing is the renewable-energy one (in 9 out of the 12 Type II estimates), which, according to the literature, is highly unlikely to provide substantially more abatement than carbon pricing on its own.

Table 6 Welfare effects of two instruments versus only one

Welfare effects	No. of estimates
Negative	40
Zero	5
Positive	74
Total	119

The definition of 'welfare' varies widely across papers. Some papers, for example, exclusively look at generation costs of the energy system or at producer surplus, while others consider GDP, or focus only on consumers. A total of 72 estimates provide information on consumer-focused metrics, namely, Hicksian equivalent variation, consumer surplus, discounted consumption and lower retail electricity prices. For 74 out of the 119 estimates we find some advantage in terms of welfare when implementing both instruments instead of only one (see Table 6).

5 Regression Analysis

Next we undertake a meta-regression of theoretical models, similar to Patuelli et al. (2005). We construct binary variables, as done in the meta-regression by Anderson (2020). We run several logistic and Tobit regressions to identify factors explaining positive results of a policy interaction, in terms of abatement or welfare. We use one fundamental binary independent variable, carbon tax, which takes a value of 1 if the carbon pricing instrument is a tax and 0 if it is a market. This allows testing the theoretical prediction of possible additional abatement for taxes versus markets with renewable energy policy.

Following the approach of meta-regressions by Patuelli et al. (2005) we include an indicator of whether the estimates come from a general equilibrium model. This distinction is relevant because the textbook case is based on a general equilibrium framework, unlike partial equilibrium analyses used by some of the models, namely energy system models. All general equilibrium models involve optimization, with computable general equilibrium models more commonly resorting to recursive-dynamic optimization. Therefore, we include the optimization strategy – categorized as intertemporal, no optimization, single-period or recursive-dynamic – since it correlates with model type and could influence results, as it is does in the meta-regressions of Anderson (2020).

We also take into account the final year of the analysis. Models looking further ahead might find additional abatement for the policy combination, especially if parameters change, since these deviate substantially from the static, single-period, textbook case. Finally, we include proxies for different parameter values, specifically, the region of calibration (China, EU, US, World, or other).

When we consider only estimates from papers with four scenarios, we find through a logistic regression that carbon taxes are associated with higher probability of additional abatement than caps. Yet, if we control for the type of optimization and for whether the model focuses on the power sector only, this association is no longer statistically significant. Instead, we do find that intertemporal optimization is more likely to find additional abatement, as are power sector only models. We do not find any significant effect regarding general equilibrium models (see Table C1 in Appendix B).

To increase statistical power, we combine the synergy estimates from models with four and three scenarios. We also include a variable capturing if estimates come from models with four scenarios or not. Using the terminology of Sect. 3, for papers with three scenarios, we know that those of Type I have a zero probability of additional abatement. Papers of Type II, instead have a probability of additional abatement of 66.7% (28/42, as shown in Table 4). We thus can treat our variable on the probability of additional abatement as a continuous variable, bounded between 0 and 1, and resort to Tobit regressions. As a robustness check, in the Appendix we estimate ordered logistic models, to represent the dependent variable by three categories, ordered by the probability of additional abatement.

As Table 7 shows, the combination of instruments is more likely to bring additional abatement with a carbon tax rather than with a cap. This result holds even when considering the type of optimization, a dummy for the use of four scenarios, whether the model only looks into the power sector, and the final year of the period. In the ordered logistic models in Appendix, described in Tables C2 and C3, the variable is also significant.

While it would at first seem GE models are less likely to find additional abatement from the instrument combination, this association is no longer statistically significant once we

Table 7 Tobit estimation of the probability of additional abatement from an instrument combination

	Probability of additional abatement				
	(1)	(2)	(3)	(4)	(5)
Carbon tax	0.305***	0.233**	0.181*	0.236**	0.287**
	(0.102)	(0.101)	(0.096)	(0.111)	(0.121)
GE model	−0.252**	−0.205**	0.035	−0.046	−0.078
	(0.105)	(0.102)	(0.203)	(0.215)	(0.253)
Four scenarios		0.281***	0.128	0.129	−0.059
		(0.105)	(0.103)	(0.107)	(0.131)
Intertemporal optim. (base category)			-	-	-
No optimization			−0.058	−0.078	−0.125
			(0.149)	(0.161)	(0.172)
Recursive–dynamic			−0.631***	−0.572***	−0.776***
			(0.150)	(0.155)	(0.170)
Single–period			−0.270**	−0.272**	−0.612***
			(0.112)	(0.116)	(0.157)
Power sector only			0.120	0.163	0.066
			(0.189)	(0.201)	(0.233)
China (base category)			-	-	-
Europe				−0.229*	−0.203
				(0.122)	(0.143)
Other regions				−0.138	−0.069
				(0.191)	(0.213)
United States				−0.267	−0.073
				(0.164)	(0.181)
World				0.021	0.144
				(0.204)	(0.214)
Final year					−0.003
					(0.002)
Constant	0.531***	0.359***	0.538***	0.609***	6.525
	(0.072)	(0.096)	(0.206)	(0.232)	(4.177)
Observations	125	125	125	122	106

*p<0.1; **p<0.05; ***p<0.01

Table 8 Average marginal effects of logistic regression of positive welfare outcomes

	Positive welfare outcomes	
Positive probability of additional abatement		0.1658
		(0.1249)
Consumer metric	0.2121**	0.2343**
	(0.1054)	(0.1104)
Carbon tax	0.0612	0.0282
	(0.1083)	(0.1134)
GE model	−0.1246	0.0144
	(0.1123)	(0.1311)
Four scenarios	−0.1105	−0.0552
	(0.1060)	(0.1231)
Innovation	0.0888	−0.0534
	(0.1353)	(0.1519)
Observations	104	104

*p<0.1; **p<0.05; ***p<0.01

account for the optimization strategy. Models which conduct intertemporal optimization are more likely to find additional abatement, followed by single-period analysis, models without optimization and finally recursive-dynamic models.

There is some evidence that studies focusing on Europe are less likely to find additional abatement. The final year the studies consider is not statistically significant.

Regarding welfare impacts, we first note that all papers which have environmental damages explicitly in the welfare function (9) have positive welfare outcomes. The same is true for all papers which include fossil fuel subsidies (3). In our sample, they are sufficient conditions for positive welfare outcomes, meaning that these variables are crucial for the results. For the ensuing analysis, we keep only estimates where neither of these elements are present[11].

Table 8 shows the marginal effects from the logistic regression. We do not find any evidence of a trade-off between emissions-reduction synergy and welfare effects - the association between positive welfare outcomes and additional abatement is not significant (and positive). We also find that whenever welfare is measured through consumer metrics, the probability to find a positive outcome of the combination is 21 to 23 p.p. larger. The presence of an innovation mechanism is not statistically significant, neither is whether the estimates come from a general equilibrium model.

As a robustness test, we expand the sample to include the synergy estimates from the single ex-post study found on emissions-reduction synergy, and re-run the regression analysis. All ex-post estimates, drawn from this single study, pertain exclusively to the power sector. Detailed results are presented in Appendix D. This results in adding 21 synergy estimates, which pertain to different regions and types of instruments (auctions or feed-in-tariffs; carbon taxes or carbon markets). Of these, 5 are significantly different from zero: 4 show positive synergy and 1 backfire. None of the other 16 synergy estimates is statistically different from zero. To incorporate these estimates in our regressions, we classified them in two ways. Under significance-based coding, statistically non-significant coefficients for the interaction of instruments are treated as implying zero additional abatement from the policy

[11] Including these variables in a logistic regression is problematic, since the dependent variable perfectly predicts them, meaning a maximum likelihood estimate does not exist.

mix. This strategy results in the average additional abatement from the policy combination to be 39.6%. Under sign-based coding, non-significant coefficients are classified according to the sign of their coefficient ratios. Under such classification, the policy mix yields 9.7% additional abatement. Additional abatement again appears more frequently under carbon taxation, but it also arises in some cap-and-trade cases: 5 of 9 estimates indicate additional abatement under carbon taxation, compared with 2 of 12 under cap-and-trade.

By adding ex-post estimates to the regressions, the central result is unchanged: carbon taxes, as opposed to carbon caps, are more likely to result in additional abatement of the instrument combination (see Tables D1 through D4). Models which consider only the power sector are more likely to find gains under some specifications, and there is some evidence (at the 10% level) that models studying Europe are less likely to find gains, as was also found for the ex-ante analysis (see Tables D1 and D4). The type of equilibrium model - partial versus general - does not play a role.

We chose to consider 'ex-post' as one possible 'optimization' strategy, more accurately renamed estimation strategy. The possible estimation strategies are 'ex-post', 'intertemporal optimization', 'recursive-dynamic optimization', 'single-period optimization', and 'no optimization (ex-ante)'. Intertemporal optimization remains the type of estimation for which models are most likely to find gains from instrument combination, followed by no-optimization, single-period optimization, and recursive-dynamic optimization.

We find that analysis of ex-post synergy estimates is less likely to identify gains than that of ex-ante synergy estimates (as shown in Tables D2, D3 and D4). This gap is amplified under significance-based coding, since coefficient estimates must then not only be positive but also statistically significantly greater than zero to account for sampling variability.

6 Discussion

6.1 Emissions-Reduction Synergy

We find that papers with a carbon tax, as opposed to a carbon cap, are more likely to find additional abatement from the instrument combination. This association is found across all specifications. However, some papers go against what the theory predicts and find additional emissions reduction even with cap-and-trade. In our sample, this is a result of either: i) partial coverage of policies or ii) intermittent, lagged, or otherwise constrained climate policy. We expand on these two cases below.

In the case of partial coverage, one of the policy instruments does not cover all regions or sectors. Regarding carbon caps, additional abatement is identified in Fais et al. (2015) and Weigt et al. (2013), where the FIT only covers Germany, while the cap is the EU-ETS. Weigt et al. (2013) not only find additional emissions reduction, but actually positive synergy. Liu and Wei (2016) find that when a Chinese ETS and a EU-ETS are set up independently – each only covers one of the regions-, renewable-energy policy results in additional emissions reduction.

In terms of constrained carbon pricing, Lecuyer and Quirion (2013, 2019) find that intermittent or non-dynamic carbon pricing implies combining it with a renewable-energy subsidy results in additional abatement. Intermittent carbon pricing means that in certain periods carbon pricing might be suspended. Non-dynamic carbon pricing, instead, reflects that the carbon price might not be easily adjusted upwards. Political constraints can lead to both situations. Shahnazari et al. (2017) similarly argue that RET leads to a reduction of political uncertainty compared to a carbon tax. Under the RET, a signal is sent to the market which makes investment into renewable-energy less risky. Through a real options model, the authors conclude abatement will be less costly for private investors under the instrument combination than with either instrument alone. The study refers to Australia as a case study, where a carbon tax was implemented, and a posteriori removed.

Yi et al. (2019) present a case for China where carbon pricing only has meaningful effects after several years. This is because carbon pricing triggers the construction of nuclear energy infrastructure, which takes considerably more time than creating renewable energy installations. They estimate that due to learning by doing and lock-in effects, the combination of the policies leads to higher abatement in the short-run. Estimates from models undertaking intertemporal optimization are more likely to find additional abatement from the policy combination. This coincides with the idea that when certain transitory conditions are in place, the combination can be advantageous. Intertemporal optimization, by using a cumulative measure, should show higher abatement under a combination of instruments, unlike single-period optimization as then transitory advantages are simply not accounted for. The final year of the analysis and the aggregate region of analysis do not have a statistically significant impact on the probability of additional abatement, while longer periods are statistically associated with lower probability of additional abatement.

6.2 Welfare Effects

Whenever the welfare function explicitly includes environmental damages - in nine estimates - we find a positive welfare effect from the instrument combination (see the Table provided as Supplementary Information). Silva et al. (2021), with a carbon tax, find additional abatement from the combination, and higher welfare. Clancy and Moschini (2018) find, again under a carbon tax, additional abatement from the combination and simultaneously higher welfare. They include environmental damages, but also innovation externalities. Xiao et al. (2024) and Wu et al. (2024) include damages from other air pollutants and find the combination is advantageous.

Boeters and Koornneef (2011) find higher welfare for certain parameter values, specifically, when the costs of the first units of renewable expansion are low and there are inefficient pre-existing energy subsidies. One of the three computable general equilibrium estimates provided in Böhringer et al. (2009) reports slightly higher welfare as measured by Hicksian equivalent variation (with a carbon cap) due to 'prior distortions in the energy market', specifically, fossil fuel subsidies.

Rausch and Reilly (2015) find GDP gains from the instrument combination, alongside emissions reduction. This is explained by avoiding adjustment costs of energy capacity expansion. Feng et al. (2022) combine the policies with reduction of other distortionary taxes and incentives to energy efficiency and find a higher GDP under the policy combination. Bauer et al. (2012), focusing on consumption, find higher welfare of the combination of instruments when carbon pricing policy lags.

Measures which focus on consumers are 21 to 23 p.p. more likely to find gains in our sample. Out of 21 papers which consider as the only outcome retail electricity prices, 14 find lower prices under the combination than with carbon pricing alone. Often, using the renewable-energy instrument alone reduces consumer costs (Jensen and Skytte 2003 expand on the issue). However, in several instances, the existence of emissions trading makes the introduction of renewable energy more beneficial to consumers as well (see Linares et al. 2008b for a stylized example based on the Spanish electricity market).

Other papers find lower financial costs for consumers, namely, Fagiani et al. (2014), who report it alongside additional abatement, and Huang et al. (2013). Kalkuhl et al. (2013) also find benefits in terms of retail electricity prices from the policy combination. Mu et al. (2018) finds the predicted decrease in GDP and social welfare but also an increase in employment, a policy-relevant variable. Fischer et al. (2017) and Hirth and Ueckerdt (2013) find that the combination leads to higher consumer surplus, but much lower producer surplus, than carbon pricing alone. Whether the policy mix is advisable, given carbon pricing is first-best in terms of total surplus, depends on whether redistribution – in the previous cases, from producers to consumers - is feasible. A flagrant example of possibly limited redistribution is Liu and Wei (2016), who find that the combination brings higher consumer welfare for both the EU and China under the instrument combination but only higher total welfare in China. Implementing carbon pricing is first-best in terms of allocative efficiency, yet, it would require transfers across borders. Several papers such as Kalkuhl et al. (2013) and Kalkuhl et al. (2015) analyse the policy mix from this second-best perspective, admitting that a global carbon tax is infeasible due to limits to social transfers between countries.

6.3 Ex-post Studies

There are very few ex-post studies for reasons already explained in Sect. 2. We also indicated there that we identified only one ex-post study that assesses synergy based on emissions-reduction, Tello (2025). It explores a multi-country panel and generates quasi-experimental, Difference-In-differences estimates for the impact of single instruments on CO2 emissions of electricity per capita. But it claims it cannot do the same for interactions “due to the sample size constraint”. Instead, it provides estimates of impact of policy combinations using two-way fixed effects, using interaction terms. In the overall sample, no interactions are statistically different from zero: not the interactions of carbon tax with FIT or with auctions, neither of carbon cap with FIT, nor with auctions. For Middle East and North Africa instead, the latter two interactions are statistically significant and show positive synergy, resulting in, respectively, 256% (−57% points (p.p.)/-16p.p.) and 325% (−68p.p./-16p.p.) additional abatement. The results suggest that for high-income countries, adding auctions to a carbon cap results in a double backfire scenario (and 337.5% lower abatement), with 19 p.p. lower abatement on average (instead of 8 p.p. higher abatement with auctions alone or 1 p.p. higher abatement with the cap alone). For the same high-income countries, adding auctions to a carbon tax would result in a positive synergy and 425% additional abatement, by delivering 42 p.p. higher abatement on average. Adding auctions to a carbon tax also leads to positive synergy when considering Europe and Central Asia (162.5% additional abatement).

Under significance-based coding, 16 estimates are classified as “border of backfire” (where the coefficient of the policy mix equals that of the single most effective instrument, due to the non statistically significant interaction terms). Under sign-based coding, 12 are classified as backfire, one as border of backfire, and three as positive synergy. On average, the policy combination yields 39.6% additional emission reduction under significance-based coding and 9.68% under sign-based coding. Through the integration of these estimates in the meta-regressions, we find that ex-post studies are less likely than ex-ante studies to detect non-zero synergy in both coding approaches, yet the gap is larger under significance-based coding.

The ex-post study focuses on the electricity sector, as do several of the ex-antes studies. The overall conclusion is that for certain countries, there has been additional abatement from the instrument combination. Some caution is needed, though, in interpreting interaction terms as synergy estimates. The limited sample size remains a concern, since there are very few observations for certain policy combinations. Furthermore, we rarely have the same country enacting only one policy, only the other, and then both, thus, different countries serve as counterfactual for countries with a policy combination. The underlying assumption – that policy combinations have the same effect across countries and time periods - is strong.

We also want to mention a few additional ex-post studies which do not investigate impacts on emissions but on carbon intensity and welfare. We found one other ex-post study, by Zha et al. (2023), for a panel of Chinese regions. The paper derives an empirical estimate of synergy of carbon-intensity-reduction, as opposed to synergy of emissions-reduction. It considers the combination of cap-and-trade and two types of renewable-energy policy (subsidies for solar/wind power or tradable green certificates). They find additional reductions in carbon intensity for the combination of carbon pricing with subsidies. Under an assumption of exogenous electricity demand, the findings are interpretable as additional abatement and classifiable as a negative emissions-reduction synergy. This study is also specific to the power sector.

Several other papers have similar cross-regional panel datasets and would have been able to estimate emissions-reduction synergy through interaction terms (e.g, Wang et al. 2025 and Fernández et al. 2018). However, they limited themselves to assessing the impacts of each instrument separately.

We found three additional empirical studies which address questions related to the welfare benefits of combining the instruments, but without taking into account emissions. Kim et al. (2017) considers the propagation of innovation and finds evidence that when both carbon pricing and renewable-energy incentives are in place, the cost-per-unit installed of renewable power is lower. This means a positive welfare outcome, which is consistent with findings of several of the ex-ante synergy studies. This study, moreover, finds that cost reduction operates through learning-by-doing, i.e., as installed capacity grows. The same mechanism, when incorporated into ex-ante synergy studies in the sample, leads to positive welfare effects.

Finally, two studies focus on the price transmission process between carbon prices, tradable green certificate prices and electricity prices. The first, Wu et al. (2024), shows that electricity prices tend to decrease when the price of green certificate increases whereas they increase when the carbon price increases. This confirms the findings from our analysis of ex-ante studies: there might be benefits in terms of a lower electricity price to consumers if a renewable-energy incentive exists alongside carbon pricing compared to having carbon pricing alone. The second, Schusser and Jaraitė (2018), also looks at the relationship between electricity prices, carbon prices, and prices of tradable green certificates. In reviewing the theoretical literature, they cover many studies discussed in our review. They find that higher carbon prices raise certificate prices, a result that runs counter to much of the theoretical literature.

Overall, the ex-post literature supports the ex-ante finding that there might be additional abatement from the instrument combination, and more frequently under carbon taxation than under cap-and-trade. Moreover, it confirms that learning-by-doing can lead to positive welfare effects. Finally, it illustrates how price interactions between renewable-energy incentives and carbon pricing defy theoretical predictions and can translate into gains for the consumer from the instrument combination, as found in our meta-regressions.

7 Conclusions

We have collected quantitative estimates from the literature on the emissions-reduction synergies of combining carbon pricing with renewable-energy policies. Our meta-analysis identifies 95 ex-ante studies. The results are as follows: In 72% of cases, the two instruments together reduce emissions more than either instrument alone. The scope for additional, meaningful abatement is substantial. On average, combining a carbon-pricing instrument with a renewable-energy instrument yields 22% more emissions reduction than using only the most effective single instrument. Among cases showing additional abatement, the mean (median) increase is 30% (14%).

A notable finding from this review is the lack of complete information in many studies. Model simulations often omit a scenario with only a renewable-energy instrument. To address this gap, we compiled 42 additional estimates from studies missing one scenario. While synergy cannot be classified with complete certainty in these cases, we are able to provide a range. We find very similar results, with 67% of estimates likely reflecting additional abatement.

Theoretical arguments suggest that additional abatement is less likely with a carbon cap, as opposed to a carbon tax. This result holds across our meta-regressions. Nevertheless, some studies find additional abatement under a cap, typically due to partial policy coverage, or intermittent, lagged, or otherwise constrained carbon pricing.

Partial coverage of carbon pricing will persist as long as global policy coordination remains incomplete. Under such conditions, adding renewable-energy policy provides a stable price signal and stimulates long-term investments. This intertemporal mechanism might explain our finding that combined instruments tend to perform better under intertemporal optimization. In contrast, single-period optimization does not. Whether long-standing political-economy constraints on carbon pricing can be eliminated or whether combining the two instruments remains the most workable option is largely a matter of political economy.

Ex-post studies of instrument synergy on emissions are almost nonexistent, largely because counterfactuals are absent and regional heterogeneity complicates analysis. We identified only one such study, Tello (2025), which we discussed in detail separately, and integrated in the regression analysis as a robustness test. This study assessed emissions reduction by the electricity sector, using a multi-country panel, finding positive synergy between a carbon cap and either a renewable-energy subsidy or quota for the Middle East and North Africa, and between a carbon tax and a renewable-energy quota in high income countries and in Europe and Central Asia. By contrast, for high income countries, the combination of a cap and a renewable-energy target is found to backfire. Under significance-based coding, the remaining 16 estimates are at the "border of backfire", bringing no additional abatement. When classifying synergy on the basis of the sign of coefficient ratios, we find additional abatement for carbon taxation in 5 out of 9 cases, and for cap-and-trade in 2 out of 12 cases, consistent with theoretical predictions. On average, the policy combination yields 39.6% higher abatement under significance-based coding and 9.7% under sign-based coding.

Another study, Zhang et al. (2023), finds that carbon intensity of electricity declines more when cap-and-trade is combined with renewable-energy subsidies than when either instrument is implemented alone. Under the assumption of exogenous electricity demand, this can be interpreted as evidence of additional emissions abatement from the policy combination. Taken together, these ex-post findings are consistent with the broader conclusion that combining instruments can, in some cases, enhance emissions reduction, and that such gains appear more frequently under carbon taxation than under cap-and-trade.

Regarding welfare, we find gains in 63% of ex-ante cases. We detect no evidence of a trade-off between additional abatement and welfare improvements. Whenever environmental damages are explicitly included, the combination of instruments increases welfare. The same result holds when inefficient pre-existing energy subsidies or distortionary taxes are present; in all such cases, the combination yields synergy.

Consumer-focused measures – such as Hicksian equivalent – variation, household consumption, and especially retail electricity prices – are more likely to reveal welfare gains from combining instruments. An ex-post study, although not analyzing emissions-reduction synergy, likewise finds lower electricity prices under the combined policy. Several ex-ante studies also report GDP gains alongside additional abatement, driven by learning-by-doing in renewable-energy technologies and by lower adjustment costs in the energy system. One ex-post study confirms that learning-by-doing lowers costs when instruments are combined. In these cases, as with co-benefits, renewable-energy policy addresses an underlying market failure.

Our review shows that certain modeling assumptions – notably, the type of optimization – affect emissions-reduction synergy estimates. Moreover, whenever a model incorporates at least one of three elements – environmental damages, learning-by-doing, or market failures – the combination of instruments produces welfare gains. Therefore, to extrapolate ex-ante results to real-world policy settings, it is essential to assess whether these factors are relevant in each context, and to what degree. These assumptions play a major role in shaping outcomes, whereas other case-study characteristics – such as calibration years or geographical scope – are less influential.

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Declarations

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