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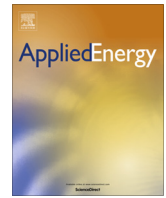
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Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare



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HIGHLIGHTS

- RES-E support policy design space is systematically explored using 'design elements' and agent based modelling
- Bounded rationality is incorporated in investment decisions to reflect true uncertainty.
- Uncertainties significantly impact design elements, and corresponding RES-E schemes.
- Design elements matter, irrespective of the RES-E scheme.

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ABSTRACT

The governance of renewable electricity in Europe beyond 2020 is still uncertain. The only certain aspects are that national level targets will be abolished beyond 2020, and that most renewable electricity support schemes will take the form of competitive bidding. The objective of this paper is to assess the impact of policy choices, the so-called Design Elements, related to renewable electricity support schemes on social welfare. Presently, simulation and optimisation models are commonly applied for assessing the value of policy choice. Typically however, such models do not account for bounded rationality, and true uncertainty in investment decisions, and assume perfect information. However such assumptions can hardly be expected to hold in the real-world, especially in sectors where investment decisions which happen under knowledge of past trends and imperfect foresight, are a major determinant of welfare outcomes. The approach employed in this work is fundamentally different in that firstly, there is a shift from a 'policy' view to a 'design element' based approach of renewable electricity support assessment, and secondly investment decisions are simulated using agent-based modelling. We find that the combination of design elements that provides the highest increase in social welfare is the quantity warranty, with electricity market price accounted for ex-ante, and with technology specificity. Given the current debate on the governance of renewable energy generation in the European Union beyond 2020, the present paper offers guidance to policy makers and analysts who would like a better understanding of the relationship between policy design and social welfare.

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1. Introduction

1.1. Motivation and research objective

In a recent article on the transition towards a green economy David Newbery [2] argues for the merits of a renewable support policy comprising of a Contract for Differences (CfD) with a standard Feed-in-Tariff (FiT) as opposed to a Premium FiT, proposed by the 2015 EU Energy Union Package [3]. It has been more a

decade since the first Renewable Energy Sources (RES) directive, and the debate on how best to design support for renewable electricity is still raging. The European commission only specifies that there will be no national level targets beyond 2020, and that most Renewable Energy Sources for Electricity (RES-E support schemes should take the form of competitive bidding. It still remains to be seen whether these choices will lead to the triad of competition, sustainability, and affordability being achieved in the energy sector.

Since the first RES-E Directive was released in 2001, there have been numerous works that have evaluated renewable support schemes from theoretical and empirical standpoints; refer for

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Nomenclature

Abbreviations

NPV	Net Present Value
WACC	Weighted Average Cost of Capital
$WACC_{rev}$	WACC adjusted for risk aversion

Subscripts

*	asterisk in the exponent denotes equilibrium values.
g	power plant index
rep	repetition index per scenario
s	segment index
t	time step in years

Symbols

$a_{g,s}$	available capacity of power plant g , in segment s [in MW]
$CF_{Op,g}$	expected cash flow for power plant g , during operation [in Eur]
$fc_{g,t+n}$	fixed costs of power plant g , in time $t + n$ [in Eur/MW h]
I_g	investment cost of power plant g in t [in Eur]
K_g	nominal capacity of power plant g [in MW]
n	number of years ahead of current tick, for which value is being computed

n_{rep}	number of repetitions per scenario [1]
n_{tick}	number of ticks per repetition [1]
$p_{s,t+n}$	electricity spot market price for segment s , estimated at time t , for a period n years ahead
$payment_{g,t}$	payment of subsidy to RE producer for plant g at time t [in Eur]
r_D	rate of debt
r_{Eb}	basic rate of equity
r_{Ep}	price risk component of rate of equity
r_E	rate of equity
$r_{g,t+n}$	running hours of power plant g , at time $t + n$ [in hours]
$rGen_t$	total renewable energy generation at time t [in MW h]
t_b	power plant construction time
t_D	power plant depreciation time
$target_t$	total target for renewable energy generation at time t [in MW h]
$vc_{g,t+n}$	variable costs of power plant g , in time $t + n$ [in Eur/MW h]
$Xante_g$	total subsidy per MW h of generation for plant g , discounted to present value [in Eur/MW h]
$Xpost_g$	total cost per MW h of plant g , discounted to present value [in Eur/MW h]

instance [4,5,1,6,7]. Such literature so far on renewable support schemes has mainly focussed on comparing different policies¹ or support schemes² that have been implemented in various member states of the European Union (EU). The key here however is not a choice between policy A or B, but between how either policy instrument should be designed. This allows the policy maker such as the European Commission to decide what design features are essential in an RES-E scheme, rather than propose an entire scheme itself. This idea has been upheld by several authors such as [8–10].

We propose that any RES-E policy can be broken down into a closed set of components that are common to all renewable electricity support schemes. We refer to these components as ‘design elements’; the design elements now form the smallest level of analysis. The objective of this research is to assess the impact of design elements of Renewable Energy Source Electricity (RES-E) support schemes on a single (isolated, uncongested) region modelled approximately similar to the power sector in the Netherlands, using a long-term agent-based model of the electricity market, with endogenous investment. We introduce the design elements in Section 2.1, and demonstrate that it is possible to model elements individually in Section 2.3. The policies are then modelled as combinations of design elements. The design elements analysed are *price warranty versus quantity warranty*, electricity market revenue accounted for *ex-post* or *ex-ante*, and *technology specificity versus technology neutrality*. The performance indicators in this study are effectiveness of policy in terms of cost and target achievement, and social welfare and distributional implications on producer, consumer, and the government.

The following subsection comprises of a review of literature in the field, and outlines how this work contributes to literature. This is followed by Section 2, which includes a detailed description of the methodology used: the design elements considered, the model, the hypotheses and experiment design. The subsequent section

includes the results and their discussion. This is then followed by the conclusion.

1.2. Literature review

The current work relates to two strands of literature, one where RES-E schemes have been analysed, and the other where they have been modelled.

RES-E schemes have been compared analysed at great depth since the first RES-E directive. Recent literature in the field still indicates that policy comparisons dominate the field [2,11–14]. Nevertheless, perceiving RES-E support schemes in terms of design elements has been done qualitatively before by some authors. For instance, [15] and the beyond2020 project by [16] present a list of design elements for RES-E support schemes. Del Rio and Linares (2014) [8] provide an in-depth review of auction schemes for renewable electricity around the world; they identify and assess design elements of such auctions and propose a coherent integration of several design elements to improve auction designs. The design elements described in the above papers however are not common across all policies, thus still making them policy-specific; the disadvantage being that it is not possible to objectively analyse the impacts of specific features of a policy on the system. Also importantly, all the aforementioned works only qualitatively discuss design elements, but provide no quantitative analysis regarding their long-term dynamic effects and welfare distributional implications.

There have been several quantitative modelling efforts to evaluate the effectiveness of RES-E support schemes. Capros et al. [17] provide a detailed description of seven large scale EU energy economy models that have been used to model decarbonisation pathways. Works which use models that have simulated and quantitatively compared different RES-E support policies in some detail include the Green-X model [18], the REBUS (Renewable Energy Burden Sharing) model [19], the PERSEUS-RES-E (Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading) model by [20], and an

¹ Policy is a general term used to describe a formal decision or a plan of action adopted by an actor, such as the government, to achieve a particular goal.

² The word *policy* is used interchangeably with the word *scheme* in this work.

extended version of the TIMES-D (The Integrated MARKAL-EFOM System) model by [11], henceforth referred to as the TIMES-D-Extension Model.

In terms of the research objective and experiment design, the work using TIMES-D-extension model is the most comparable to the current one. Like the others, it compares support schemes themselves - the Feed in Tariff scheme to a Tradable Green Certificate mechanism. However, like this work, it comprises of a long-term evaluation of the support schemes, under design criteria which include technology specificity and technology neutrality. Hence, further comparisons to literature will primarily be limited to the TIMES-D-extension model. The TIMES-D-extension model is a partial equilibrium energy system model, which employs an objective function representing the total discounted system costs across the years 2000–2050,

These models can be classified into one of the three trends in electricity market modelling: optimisation models, equilibrium models, and simulation models [21]. Optimisation models include both deterministic, and stochastic programming. Typically, with respect to investment decisions, the aforementioned models assume perfect foresight, and perfect competition. Some models use stochastic parameters and/or scenario analysis to account for certain uncertainties. However, even these scenarios or probability distributions need to be estimated by the analyst.

Such methods imply that investment decisions are made under the premise of minimisation of system expenditure across time. As [20,22] point out however, such assumptions imply that capacity or production decisions can be taken instantaneously, under conditions of free entry and exit. These assumptions can hardly be expected to hold in the real-world, especially in sectors where investment decisions, which happen under knowledge of past trends, and imperfect foresight, are a major determinant of welfare outcomes.

1.3. From scenario analysis of policies to design elements

In a scenario analysis, the uncertainty about parameters or components of the system is modelled by a small number of versions of sub-problems derived from an underlying optimisation problem. These correspond to different scenarios, suggesting some kind of limited representation of information on the uncertain elements or how such information may evolve.

The critical question then is how to determine which components of the system comprise each scenario, and why a certain set of scenarios are sufficient. So far, in modelling studies related to renewable electricity support schemes such as those aforementioned, different scenarios are formed by established current policies in their entirety. In other papers, variations of designs within one single established policy are analysed. However, it is critical to note that two seemingly different policies can be designed such that they have an equivalent effect on the market. For instance, a Tradable Green Certificate (TGC) scheme with long term contracts resembles a tender. A Feed in Premium (FiP) scheme with long term contracts resembles a Feed in Tariff (FiT) [16]. The underlying idea therefore is that it is not the policy but the design element which is the vital component of analysis. In effect, the decision variables are no longer the policies, but the design elements that they are composed of.

The design element approach allows us to systematically explore the entire RES-E policy design space, even creating new policies that have not been implemented before. More importantly, it allows us assess the impacts of a specific feature of a policy on the system. This feature could be technology specificity, price vs. quantity warranty, or type of price setting. With such information, it is possible to advice the EC on what design features are essential in an RES-E scheme, rather than proposing an entire scheme itself.

1.4. Choice of modelling approach

The methodology and work presented herewith is fundamentally different from the aforementioned works in two main aspects. One is a shift from a policy view to a design element based view of RES-E support assessment. The second fundamental difference lies in the methodological approach employed in this work, Agent-Based Modelling (ABM). ABM is recognised as a methodology that provides a framework to model agents with bounded rationality, their interactions with other agents, and the environment around them, as [23–25] have explained.

The ‘base model’ employed, EMLab, consists of generation companies as agents who individually make investment decisions. The investment decisions of the past affect those of the future, and agents make decisions under imperfect foresight. Agents create their own forecasts using regression techniques of past values of demand and fuel price trends, much like in the real-world, to arrive at endogenous investment patterns. Such real world representations help analyse how different designs of RES-E support affect investment incentives, and consequently affect the energy transition. The base model, on which this work has been built, is described in detail in Section 2.2, and with flowchart in Appendix B, and is represented in Fig. 1. The design elements, and consequently the RES-E policies, that have been modelled as part of the current work, are described in Section 2.3.

This approach is markedly different from the aforementioned modelling methods because of the following reasons. Firstly, since each agent makes individual investment decisions based only under current knowledge of the system, we implement bounded rationality; this often leads to sub-optimal choices when assessed ex-post, much like reality. Secondly, in equilibrium models, typically the policies are modelled close to how they work in theory. It is implicitly assumed that the policy in place would achieve its target, as modelled. However, this method does not help identify reasons that a policy would not work as intended; interpretation is left to the analyst. Including uncertainties and bounded rationalities in the model, helps pin-point which micro decisions lead to which macro outcomes in the model. Thirdly, unlike optimisation models, the focus of our model is not a final minimum cost state, but to analyse dynamics in the path of an energy transition, while including specific uncertainties.

Such modelling takes us a step closer to representing the real world. The base model has so far been applied to study long term dynamics of the electricity market in relation to security of supply and carbon trading, in various publications [27,26,28].

2. Methodology

2.1. Design elements: an introduction

We define design elements as a closed and complete set of attributes of an RES-E policy. The attributes used to characterise an RES-E support policy have been chosen based on the work of the Beyond 2020 Project by [16,15], and adapted for this work. It is proposed that these design elements can be identified in any RES-E policy; conversely, any RES-E policy can be represented in terms of these design elements.

The theoretical basis for the design element approach to policy analysis is based on a combination of institutional analysis as well as an empirical study of a variety of existing RES-E schemes in Western Europe. In this work we model and analyse three specific design elements; they have been presented in Table 1. The full list of design elements are presented in A.3.

The foremost of the design elements analysed is price or quantity warranty of the commodity being regulated. The choice of

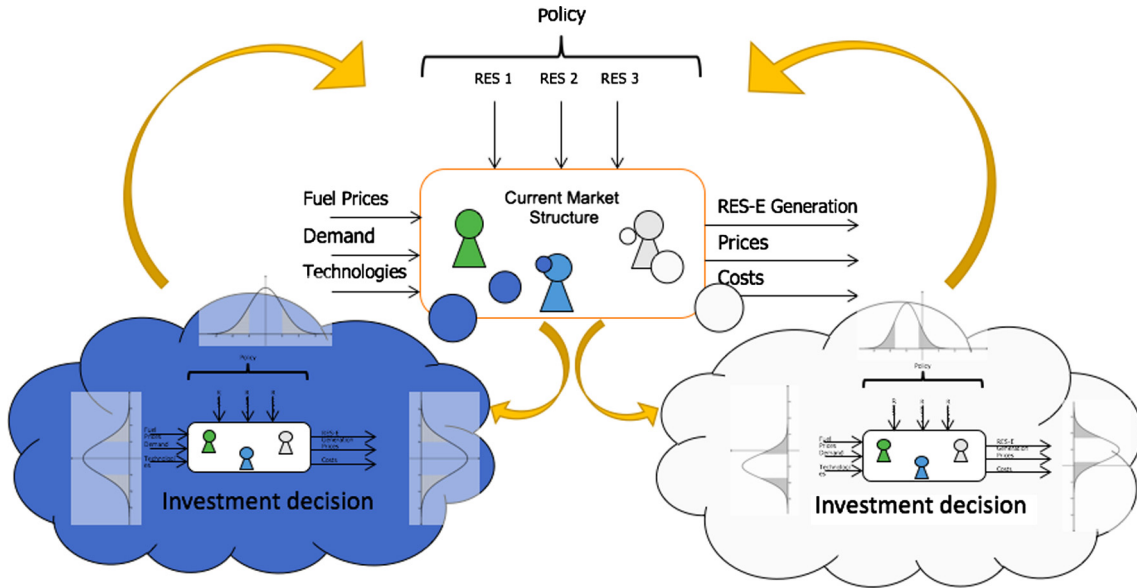


Fig. 1. High level diagram of behaviour of agents and their interaction with environment in EMLab. Adapted from [26].

Table 1
Policy design elements for stimulation of RES-E in Europe.

Design Element	Definition
Quantity Warranty or Price Warranty	A mandated quantity of electricity supply or consumption from RES technologies or a mandated price per unit of electricity generated from RES
Setting of electricity market price	Revenue from the electricity market can be accounted for ex ante, or ex post
Technology Specificity vs. Neutrality	The design element which specifies which technologies are eligible for a certain support scheme

which element to regulate, as [29] showed, largely depends on uncertainties existing in the system, and the shapes, to the extent they can be determined, of the cost and benefit curves. The design element regarding whether market revenue accounted for ex-post versus ex-ante could have significant welfare impacts based on uncertainties regarding future forecasts, and is little studied in literature. Technology-specificity versus technology-neutrality is another feature which could have appreciable implications on social welfare distribution.

2.2. Description of existing model

This section briefly describes the 'base model', on which the design elements are built. The main agents are electricity generation companies; they make short term decisions such as bidding competitively into the electricity spot market, purchasing fuel, and long term decisions such as investing in new power plants. They affect the model environment with such decisions, and consequently their own state (e.g. cash position). The base model includes two main algorithms: one, an electricity spot market clearing algorithm, and two, the investment algorithm. A brief description of the two algorithm are presented below. They are complemented by flowcharts in Appendix B. A much more detailed version of the base model is presented in of the doctoral thesis by [26].

2.2.1. Market clearing algorithm

A uniform electricity market clearing has been implemented algorithmically. The load duration curve for a full year is represented in terms of 20 load-segments, where each load segment is

a demand (in MW) and time (in hours) pair. For each load segment, the bids (price, quantity pairs) from the energy producer are stacked according to their merit order, and a uniform market clearing price is determined at the intersection of demand and supply for that load segment.

2.2.2. Investment behaviour

Each agent makes decisions about investments of plants by forecasting demand and fuel prices based on past data, and thereby estimating their own merit order, and future electricity prices $p_{s,t+n}^*$. Producers differ from each other in terms of the initial mix of their generation portfolios, and the order in which they take investment decisions. Each agent considers demand and fuel price data of the previous 5 years to create geometric regression trends for the future. The future time point, n , for which they make investment decisions is 2 years ahead. They do have perfect knowledge only about investments made thus far by the other agents, and when they will come online. That the agents have a limited knowledge of the future is an important feature of the model, as it leads to sub-optimal decisions being made. This corresponds to reality where expectations often differ from actual outcomes, as explained by [27].

Based on the expected electricity market prices, marginal costs $vc_{g,t+n}$, the fixed operation and maintenance cost $fc_{g,t+n}$, segment-dependent available capacity of power plant $a_{g,s}$, and the expected running hours $r_{s,g,t+n}$, which is also calculated from the expected electricity prices and marginal cost per segment, the cash flow for reference year $t + n$ of operation for the power plant is calculated as follows.

$$\begin{aligned}
 CF_{Op,g} &= CInflow_{Op,g} - COutflow_{Op,g} \\
 &= \sum_s p_{s,t+n}^* \times r_{s,g,t+n} \times a_{g,s} \\
 &\quad - (\sum_s vc_{g,t+n} \times r_{s,g,t+n} \times a_{g,s} + fc_{g,t+n})
 \end{aligned} \quad (1)$$

The economic viability of each power plant of capacity K_g is then assessed with initial capital costs, I_g , over the building period $0 \dots t_b$, and the service period, $t_b + 1 \dots t_b + t_D$. The Weighted Average Cost of Capital (WACC) is used as the discount rate. The Net Present Value (NPV), which discounts all future costs and benefits into present value, is calculated by each energy producer for each technology in order to make an investment decision:

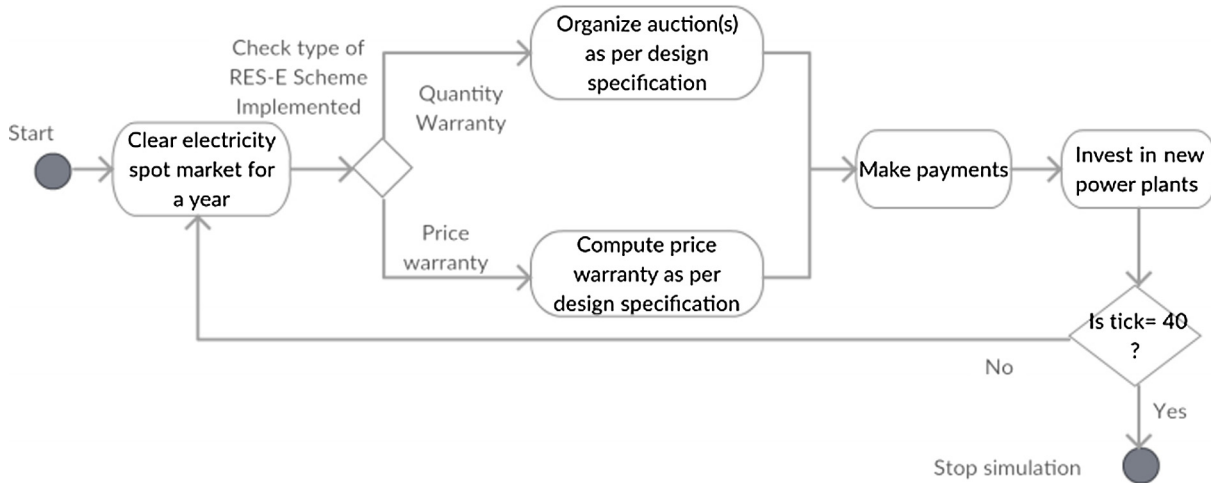


Fig. 2. Relationship between base model and RES-E schemes.

$$NPV_g = \left(\sum_{t=0}^{t_b} \frac{-I_g}{(1+WACC)^t} + \sum_{t=t_b+1}^{t_b+t_D} \left(\frac{CInflow_{Op.g}}{(1+WACC_{rev})^t} - \frac{COutflow_{Op.g}}{(1+WACC)^t} \right) \right) / K_g \quad (2)$$

$$WACC = r_D \times (D/V) + r_{Eb} \times (E/V) \quad (3)$$

$$WACC_{rev} = r_D \times (D/V) + (r_{Eb} + r_{Ep}) \times (E/V) \quad (4)$$

where D is the debt-value, E is the equity-value, V is the total value. The debt equity ratio is set at 70:30. In Eq. (2), risk aversion to price volatility is incorporated in the inflow or revenue component by an adjusted WACC, called the $WACC_{rev}$. The rate of equity component in the $WACC_{rev}$, described in Eq. (4), r_E , is expressed as the sum of a basic equity rate, r_{Eb} set to 11%, and a price risk equity rate, r_{Ep} set to 3%. The cost of debt, r_D is set at 5.5%. This is based on data from the [30].

Each agent thus iteratively computes the NPV for every technology, and invests in the technology with the highest positive NPV. This algorithm is presented in Fig. B.9b. This description so far forms the base model, on which RES-E support design elements have been built. The conceptual model of RES-E policies is explained below. The model is implemented in Java and the source code is openly accessible.³

2.3. Modelling of design elements

In the previous section, the main algorithms of EMLab have been described. In this section we present the core of the contribution of this paper, the modelling of RES-E schemes in the form of their design elements.

The design elements are modelled such that, when presented as an RES-E scheme, they create incentives for agents to invest in specific technologies. The algorithmic relationship between the RES-E schemes and the investment behaviour is indicated with the help of a flowchart in Fig. 2.

As far as modelling is concerned, an RES-E scheme is represented as an entity with a set of properties, and related methods, much like a class in object-oriented programming. The design elements identified in the previous step together make up the properties of the RES-E class. This is represented in Fig. 3. The processes or behaviours related to the different properties are the methods of the class.

2.3.1. Design Element 1: price versus quantity warranty

This design element can be defined as a mandated quantity or price for electricity supply or consumption from RES technologies. It is modelled as two separate algorithms, their descriptions follow.

2.3.1.1. Quantity warranty scheme. The quantity warranty scheme, is algorithmically implemented in the form of yearly auctions, as per the following steps.

1. Quantitative targets for renewable energy generation are exogenously for each year set by extrapolating the targets mentioned in the National Renewable Energy Action Plan [31]. This comprises the demand-side of the auction.
2. The quantity warranty is implemented as a sealed-bid uniform price auction, for contracts that span a pre-decided period of years,⁴ like a tender.⁵
3. Depending on the specification of design element 3, *technology specificity*, annual auctions are organised for each technology separately or for all technologies simultaneously.
4. Producer agents submit bids each year for new projects, by computing the expected cost and benefit of the project either by Eq. (5) or (7), depending on whether the scheme is designed ex-post or ex-ante.
5. The payments are then made annually for the winning bids, for the duration of the contract period (20 years) according to Eq. (6) or (9).

2.3.1.2. Price warranty scheme.

1. The price warranty is computed by matching the exogenously specified inelastic target on the demand side, with the (cost, quantity) pairs on the supply side.⁶
2. The regulator agent depending on specification of design element 3, computes a price warranty for each eligible technology, or a single price for all technologies if the scheme is technology neutral.
3. The price, with ex-ante considerations of electricity market price, is computed as per Eqs. (5) and (6), and with ex-post considerations of electricity market price is computed as per Eqs. (7) and (9).

⁴ The duration of contract is 20 years.

⁵ This step is approximately modelled on the French EOLE auctions [32].

⁶ It is assumed that the regulator has full knowledge of power plant costs and realistic technology potentials.

³ <https://github.com/Kaveri3012/emlab-generation/tree/feature/SocialWelfareAnalysis>.

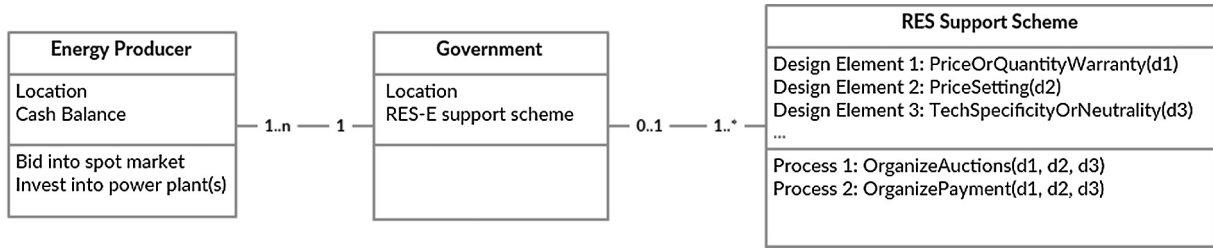


Fig. 3. Specification of Java class structures of Agents and RES-E scheme using design elements.

4. Investment decisions are made by each energy producer taking into published revenue from the applicable subsidy schemes. Payments are made annually till the end of the contract duration (20 years) according to Eq. (6) or (9).

2.3.2. Design Element 2: ex-ante versus ex-post

The contract can be designed in a way that for computing the subsidy i.e., the additional remuneration for RES-E technologies, revenue from the electricity market is accounted for either ex-ante (before the actualisation of electricity prices) or ex-post (when the electricity price is known). This process of organizing the remuneration takes place in two steps. A first step is where supply and demand are matched, to arrive at a quantity X , and a second step where payment is made to the energy producer, based on the amount of generation each year. It is important to note that this quantity X holds different meanings in ex-post and ex-ante versions of remuneration.

2.3.2.1. Ex-ante. In this version, the revenue from the electricity market is taken into account ex-ante, for the calculation of the remuneration. In the first step, a quantity $\sum_{t=0..d} \frac{X_{ante_g}}{(1+WACC)^t}$ equivalent to the total subsidy required by a plant is computed. As can be seen in Eq. (5), this quantity is computed as the discounted value of investment cost plus operating cost minus estimated revenue. The annual payment to eligible power plants is organised by Eq. (6). This way, the risk of volatility of future electricity prices is relegated to the producer.

$$\sum_{t=0..d} \frac{X_{ante_g}}{(1+WACC)^t} = \sum_{t=0}^{t_b} \frac{I_g}{(1+WACC)^t} - \sum_{t=t_b+1}^{t_b+t_D} \left(\frac{CInflow_{Op,g}}{(1+WACC_{rev})^t} + \frac{COutflow_{Op,g}}{(1+WACC)^t} \right) \quad (5)$$

$$payment_{g,t} = \sum_g \sum_s (X_{ante_g} \times a_{g,s}) \quad \text{where } t \in \{t_b \dots t_D\} \quad (6)$$

2.3.2.2. Ex-post. In this version the electricity market prices are accounted for after the prices have been realised in actuality. Since the subsidy is only paid once the electricity price is known, the only quantity that needs to be published ahead is the 'total cost per unit' of the technology, variously known as the 'base cost' or 'strike price' in the different support schemes that implement ex-post remuneration. In the model, this is implemented in two steps; in the first step, a quantity equivalent to the total discounted cost (fixed and variable) of a plant, represented by the term $\sum_{t=0..d} \frac{X_{post_g}}{(1+WACC)^t}$ is calculated in Eq. (7). In the second step, the annual payment to eligible power plants is organised by Eq. (9). This shifts the price related uncertainty and risk from the electricity producer to the government.

$$\sum_{t=0..d} \frac{X_{post_g}}{(1+WACC)^t} = \sum_{t=0}^{t_b} \frac{I_g}{(1+WACC)^t} + \sum_{t=t_b+1}^{t_b+t_D} \frac{COutflow_{Op,g}}{(1+WACC)^t} \quad (7)$$

where

$$COutflow_{g,t+n} = \sum (vc_{g,t+n}) * r_{s,g,t+n} * a_{g,s} - \sum fc_{g,t+n} \quad (8)$$

$$payment_{g,t} = \sum_g \sum_s (X_{post_g} - p_s^*) \times a_{g,s} \quad \text{where } t \in \{t_b \dots t_D\} \quad (9)$$

The risk faced by the energy producer is lower in the ex-post scenario, since there is no price risk in the revenue component of the NPV. This is represented in the following manner. The rate of equity component, which indicates price risk, r_{Ep} in Eq. (4), is set to 0%.

2.3.3. Design Element 3: technology specificity versus neutrality

In the *technology-specific* scenarios, a different quantity X is calculated for each technology. When technology specificity is applied with *quantity warranty* of design element 1, a different auction is cleared for each technology by the regulator agent, resulting in one X for each technology type, where supply and demand meet. Inelastic RES-E production targets (demand-side) are set for each technology type at each tick exogenously. Producer agents compute their offer prices for each available technology-type in the model, either by Eq. (7) or (5), and submit it to the auction. In a price warranty scheme, the regulator agent is assumed to have the same information on costs, and assumptions regarding discount rates, as the producer agent. Again, the regulator agent consequently determines the quantity X for each technology.

In the *technology-neutral* scenarios, a single quantity X is calculated irrespective of the technology type. In a quantity warranty scheme, a single auction is conducted for all technologies. In a price warranty scheme, the regulator agent is assumed to have information regarding technology costs and technology potentials. With this knowledge and given the exogenously set RES-E target, the agent constructs a supply-demand curve, and computes a single quantity X for all technologies.

2.4. Input data: case of the Netherlands

A single (isolated, uncongested) electricity market is considered, with four energy producer companies, whose initial portfolio is based approximately on the existing generation mix in the Netherlands. However, to ensure focus on assessing RES-E design elements, the model is simplified such that all conventional capacity in the Netherlands is represented by the Combined Cycle Gas Turbine (CCGT) technology. Given recent Dutch laws regarding the phasing out of coal, see [33], and equivocal opinions on nuclear technology, refer [34], it is reasonable to assume that a significant part of the conventional generation mix will be dominated by gas technologies. Along with CCGT, three renewable technologies are considered, and assumptions regarding their characteristics are described in Table C.6. The intermittent nature of renewable generation sources is represented by hourly availability factors, which are then aggregated to segment-based⁷ availability factors. The data

⁷ In order to represent variability of load across the year, the load duration curve is divided into segments; each segment being a (load, time) pair value, and each segment is cleared separately.

for hourly availability for the renewable technologies is obtained from [35]. The model runs for 40 ticks, with each tick representing a year starting from 2014.

The targets and realistic potentials for renewable technologies have been set based on data from [37,37], and extrapolated, as described in Appendix C.1. Fuel prices of natural gas and electricity demand, are modelled as stochastic trends, using a triangular distribution to determine the year-on-year growth rate. The assumptions for modal growth rate, and its upper and lower bounds are summarised in Table C.5. The initial load duration function is based on 2014 ENTSO-E data for Netherlands. A value of lost load of 2000 Eur/MW h has been used for this work, based on [39–40].

2.5. Experimental design

2.5.1. The base case set

The fundamental premise of this work is that design elements are the building blocks which allow the policy analyst to create all possible types of RES-E support schemes. Thus all combinations of the three design elements introduced above, where each design element can hold two values, lead to 2^3 RES-E policy scenarios. This is shown in Table 2.

If one were to draw parallels between some of the scenarios and actually implemented schemes, P_Ante would be akin to the German Feed-in-Tariff scheme, P_Post to the German Feed-in-Premium, and Q_PostTS is comparable to the UK's contract-for-differences scheme, where ex-post contracts are allocated on a technology-specific basis, via auctions, and the SDE+ in the Netherlands is similar to Q_Post, where technology neutral auctions are held for ex-post type of contracts. However, not all RES-E policy scenarios exist currently or have been implemented in reality, so names for such policies do not exist. Also, policies with the same names are implemented differently in different countries. For this reason and to keep intact the relationship between each policy scenario, and the design elements that it is composed of, we propose a naming convention as provided in Table 2.

2.5.2. Sensitivity analysis

The impacts of the design element *ex-ante* vs *ex-post* inter alia depends on how well the expectations of producers' electricity price match actual prices. The development of electricity prices in a system dominated by CCGT technology is in turn largely dependent on gas prices. In order to understand this relationship better, a sensitivity analysis is executed for increasing and decreasing gas prices. The gas price for the base scenario is set constant at the current⁸ approximate price of 4 Eur/GJ. The Gas High scenario has an annual growth rate of 2% while the Gas Low scenario has one of –2%.

2.5.3. Experiment setup: randomness and repetitions

Agent-based modelling in general, and this model in particular, require multiple runs to arrive at statistically significant conclusions. This is because two runs of the same scenario are differentiated by randomness in the following parameters such as (a) randomised agent iteration in order to prevent first-mover artefacts, (b) stochastic demand growth trends, randomness in initial age of power plants, as the age is drawn from a uniform distribution between 0 and the technical lifetime of a power plant, and finally (c) randomness in initial power plant ownership. After performing a simple descriptive statistical test for the variance of results, it was deemed that 40 repetitions were sufficient to obtain statistically significant outcomes.

Table 2

Base case experiment set – naming convention.

RES-E Policy Scenario Name	Design Element 1: Warranty type	Design Element 2: Price Setting	Design Element 3: Tech Neutral vs Specific
P_Ante	Price Warranty	Ex_Ante	Neutrality
P_Post	Price Warranty	Ex_Post	Neutrality
P_AnteTS	Price Warranty	Ex_Ante	Specificity
P_PostTS	Price Warranty	Ex_Post	Specificity
Q_Ante	Quantity Warranty	Ex_Ante	Neutrality
Q_Post	Quantity Warranty	Ex_Post	Neutrality
Q_AnteTS	Quantity Warranty	Ex_Ante	Specificity
Q_PostTS	Quantity Warranty	Ex_Post	Specificity

2.6. Critical review of modelling assumptions

One assumption that impacts the analysis is that there are no interconnections or storage in the system. This implies that as the share of renewable production increases, a greater share of the energy generated will not be consumed, due to spillage.⁹ This leads to the cost effectiveness of a subsidy reducing over time, as the share of renewable generation in the system increases, which would not occur as sharply in the presence of storage or interconnections. Another important assumption is that the energy producers construct a market clearing for one time point in the future and extrapolate those revenues for the lifetime of the plant. This implies that actual costs and benefit might be very different from those expected. The next major assumption is that the regulator agent has full knowledge of costs of technologies, and uses the same rates of return as the energy producers. While this assumption may not hold in reality, it helps to isolate and study the impacts of design elements better.

3. Results and discussion

This section comprises of two subsections: the first consists of the results as per the performance indicators mentioned in Section 1.1. The performance indicators are effectiveness of policy, and social welfare and distributional implications. The second consists of a discussion and interpretation in Section 3.2, primarily in terms of impacts of design elements. Condensing large sets of granular results to a few key indicators is a challenging activity, and must be done carefully.

3.1. Results

3.1.1. Effectiveness of policy

Effectiveness of policy is measured using two indicators: *cost effectiveness* and *target offset*. *Cost effectiveness* is defined as total subsidy cost per MW h of renewable electricity generated,¹⁰ summed across all 40 ticks, in Eur/MW h. It is then averaged across all 40 repetitions of the scenario. *Target offset* measures the difference between the actual renewable energy generation and the exogenously specified target. It is expressed as percentage, and then averaged across all ticks and 40 repetitions per scenario.

$$\text{targetOffset} = \frac{\sum_{rep} \sum_t \frac{(rGen_{t,rep} - \text{target}_{t,rep}) \times 100}{\text{target}_{t,rep}}}{n_{rep} \times n_{tick}} \quad (10)$$

Fig. 4 indicates these values for each scenario. The evolution of capacity in each of the scenarios is shown in Fig. 5.

⁹ Greater amounts of renewable energy will be generated when there is insufficient demand for it.

¹⁰ All renewable energy technologies are considered.

⁸ June, 2016.

Design Elements	RES-E Policy Scenario Name	Average Subsidy/Unit (in Eur/MWh)	Target Offset (%)
Ex Ante	P_Ante	79.72	-14.25
Ex Post			
Ex Ante	P_Post	93.39	10.97
Ex Post			
Ex Ante	P_AnteTS	27.88	-77.46
Ex Post			
Ex Ante	P_PostTS	35.95	6.14
Ex Post			
Ex Ante	Q_Ante	74.08	2.2
Ex Post			
Ex Ante	Q_Post	78.67	2.43
Ex Post			
Ex Ante	Q_AnteTS	28.92	-3.77
Ex Post			
Ex Ante	Q_PostTS	36.28	-3.68
Ex Post			

Fig. 4. Policy effectiveness measured in subsidy costs and target achievement.

At the outset, it is to be noted that the target has been grossly under-achieved in scenarios P_Ante and P_AnteTS. This is, concisely put, a consequence of the regulator agent's short-sightedness with respect to expectations of future electricity prices.¹¹ It is for the same reason that this is visible only in the ex-ante scenarios, as there is no need to compute expected electricity price in the ex-post scenarios. The effect is exacerbated in the technology-specific scenario, as a price warranty is calculated for each technology, while in the technology-neutral scenario, a price warranty is only calculated for the marginal technology. It is useful to note here that target achievement has little relation to the *Average Subsidy Cost/Unit*, as the latter is normalised with respect to generation in MWh.

The results indicate the following:

- (a) Quantity-warranty schemes are on average 4.5% more cost-effective and meet their targets more consistently than their price-warranty counterparts. This is because price-warranty schemes induce investment in technologies up to the point at which the realistic potential of a technology is reached, and not the administrative target which is lesser than the potential. Greater the amount of renewables in the portfolio, greater the spillage¹² and lower the generation. Therefore,

unless there is an interconnector to a region with complementary demands during hours of spillage, or the presence of storage, or demand response, the higher the share of renewables, the lower the cost-effectiveness.

- (b) Technology specific schemes are 60.3% more cost-effective than their technology neutral counterparts. This is due to windfall profits to non-marginal technologies in the technology neutral scenarios.
- (c) Ex-post schemes are 15.8% less cost effective than their ex-ante counterparts. In the ex-ante schemes, the expectations of revenues from electricity market are higher than actual, over a twenty year period. The subsidy in ex-ante schemes in the model therefore tend to be lower than necessary. This result is sensitive to the future electricity prices; impacts of high or low gas price scenarios can be observed in Fig. D.10a and b.

3.1.2. Social welfare and distributional implications

The welfare implications are presented in Fig. 6, indicating the change in welfare for the consumer, producer, government, and total social welfare, for each scenario. The change is computed by comparing each scenario with a base case, where no policy is implemented. Change in consumer expenditure,¹³ change in producer costs, and change in government expenditure are used as proxies for calculating the changes in consumer, producer, and government welfares.

Overall, the results indicate that the greatest increase in social surplus occurs in the scenario Q_AnteTS, where a technology-specific, quantity-warranty, ex-ante scheme is implemented. The results will now be detailed per welfare group. In all scenarios, consumer welfare increases; this is primarily caused by a fall in the average electricity prices due to the merit order effect. Government welfare is only affected by the amount of subsidy spent. The main design element affecting government welfare is therefore technology specificity. Welfare is more negative in technology neutral scenarios, compared to their corresponding technology-specific counterparts due to the windfall profits mentioned earlier.

Producer surplus is affected by costs (fixed and variable) and revenues (electricity spot market revenue and RES-E subsidies) for various technologies. Fig. 7 shows the break up of producer surplus per technology and per policy scenario, for all 40 years. In technology-neutral scenarios, as one would expect, producer surplus is high for non-marginal renewable technologies. Furthermore, for a certain capacity of RES-E capacity, the ex-ante scenarios show lower surpluses than their ex-post counterparts. This is again due to the overestimating of revenue from the electricity market by either the producer or the regulator. CCGT however shows a negative producer surplus in all scenarios.¹⁴

The cost-benefit impacts of each policy scenario on a single technology, such as for instance Wind Offshore, is illustrated in Fig. 8.

3.2. Discussion and interpretation

In this subsection, the results from the previous section are positioned in theory, and discussed in terms of their relevance to the real-world.

¹¹ This is because when the regulator agent calculates the required price warranty, her expectation of revenue from the electricity price is calculated by taking into account all the electricity plants that are expected at that moment. However, after this calculation if investments do incur in the same tick, due to which the expected electricity price drops, the regulator does not make a reassessment of revenue expected from the electricity market for the same tick. Therefore, the regulator's assessment of revenue from the electricity market becomes higher than it actually is, and the corresponding price warranty becomes lower than it needs to be, at the time of investment.

¹² Spillage can be defined as renewable capacity generating more than the demand at a certain hour.

¹³ The Consumer agent in the model only spends on electricity costs, the subsidy is assumed to be borne entirely by the government for the sake of the model. In reality the cost burden is either borne by only the consumers of electricity or all tax payers.

¹⁴ This is because fixed O&M and variable costs of CCGT are consistently higher than revenues from the electricity market. This is exacerbated by the fact that decommissioning of power plants is age based (40 years) in the model, and not economic. In addition, reducing average electricity prices due to the merit order effect also reduce their revenue.

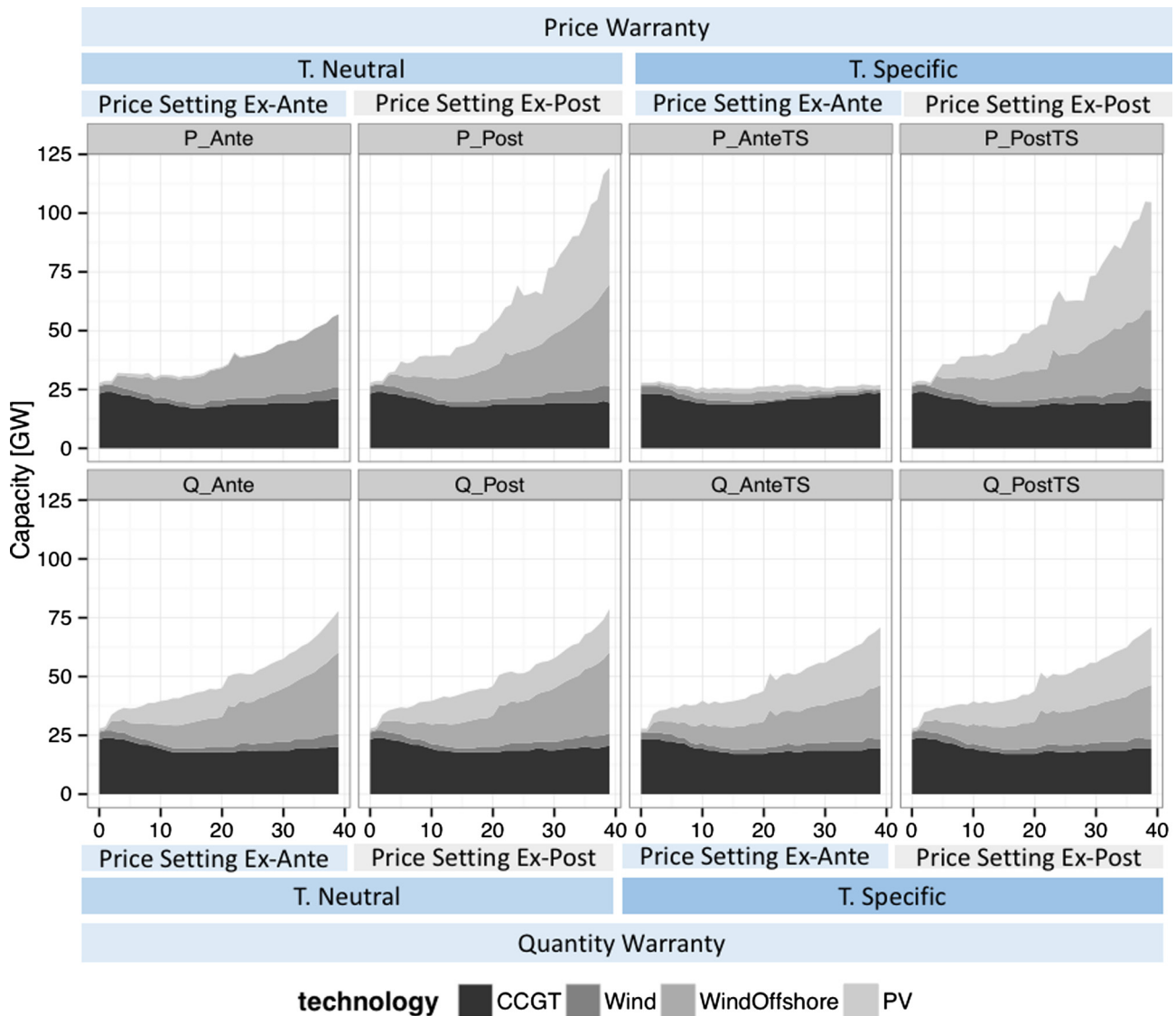


Fig. 5. Capacity growth in GW per policy scenario with time (in years) on x-axis.

3.2.1. Quantity-warranty vs price-warranty

Quantity warranty schemes are more cost-effective than price-warranty schemes, because price-warranty schemes induce investment in technologies up to the point at which the total potential of a technology is reached. As explained, this result in the model is a direct consequence of the lack of storage, demand response, or interconnections. However, this indicates that control over quantity is tenuous at best under price warranty schemes, unless there are additional quantity-based measures in place. Given this, at higher levels of penetration of RES-E, under pure price warranty schemes, storage and/or demand response options hold utmost importance.

3.2.2. Technology-specificity vs technology-neutrality

Theoretically as pointed out by [11], two effects are possible: the first is that expensive technologies are incentivised before their time in technology-specific scenarios, therefore making technology specificity more expensive, and the second is that cheap technologies do not get windfall profits in technology-specific scenarios, therefore making those scenarios more cost-effective. In the case of the Netherlands, it seems as if the second effect is much stronger

than the first, making the technology-neutral option more expensive. This corroborates with the results of [11], where technology neutral options incur almost twice as much the subsidy costs as technology specific options. This effect would however not be evident if the targets were much lower, making the marginal technology the cheapest one.¹⁵ Another factor which could impact this result is if technology cost reductions are different than assumed.

3.2.3. Ex-ante vs ex-post

Two effects could contribute to the impact of this design element: the first is that there is a component of higher risk to the producer in the ex-ante scenarios, therefore increasing their cost of capital, and consequently their subsidy costs. The second effect is that higher (lower) expectations of future electricity price than reality lead to lower (higher) subsidy costs in ex-ante (ex-post) scenarios. The results indicate that the second effect overtakes the first. The isolated impact of the second effect can be seen in Fig. D.11a. In this scenario set, the same risk aversion of 11% is

¹⁵ See Fig. D.11b to observe results for a scenario set where the RES-E generation target remains constant at 10% of total consumption throughout the time-period.

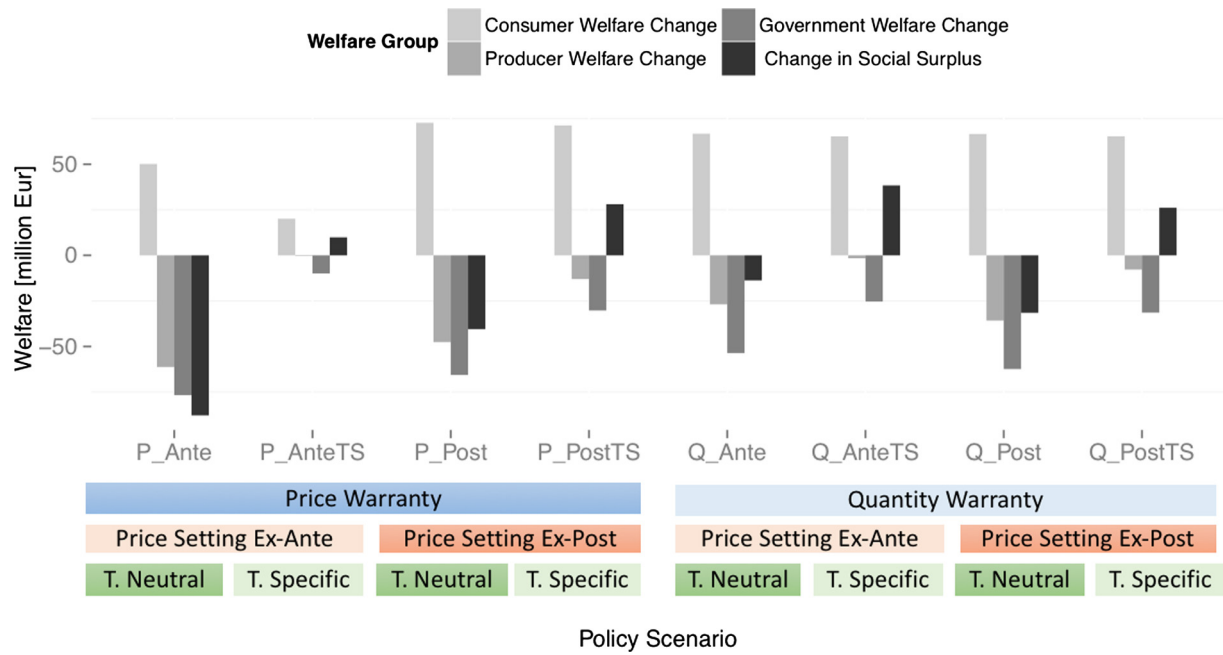


Fig. 6. Change in Welfare for producer, consumer, government, and society (total) in 40 years.

assumed in both ex-ante and ex-post scenarios (r_{Ep} is reduced to zero in ex ante scenarios), under constant gas prices. The ex-ante scenarios show an average of 4% decrease in subsidy costs in same risk set compared to the base case set. This effectively quantifies the impact of extra risk in ex-ante scenarios in the base case set. Ex-post scenarios in the same risk scenario set are however 18% more expensive than ex-ante scenarios to the government due to the merit order effect. A comparison between base case scenario set and the same-risk scenario set is shown in Table D.8.

This design element is highly sensitive to expectations of future electricity prices, which in turn depend greatly upon the merit-

order effect of RES-E, and long term gas price development. Even so, the absolute impact of this design element on policy cost effectiveness or social welfare is at most half as significant as technology-specificity vs neutrality. Therefore, while highly uncertain, it does not impact the socio-technical system as much as technology-neutrality does.

3.3. Applicability of the design element approach

By quantitatively demonstrating that mere design elements, irrespective of the RES-E policy they belong to, have significant

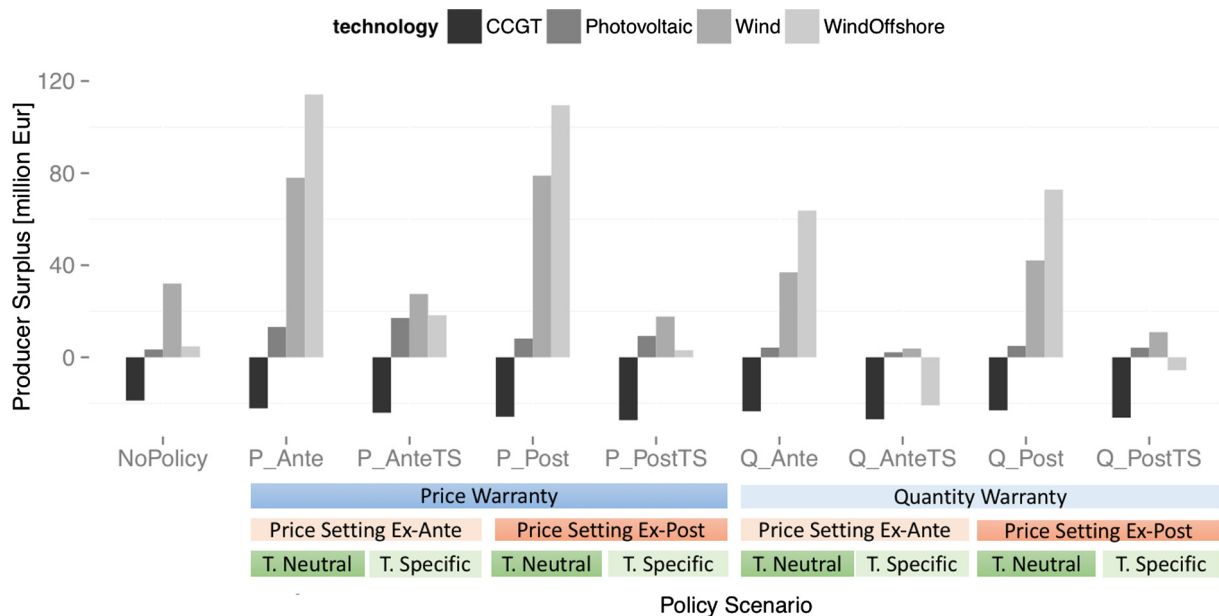


Fig. 7. Producer Suplus per technology and policy scenario.

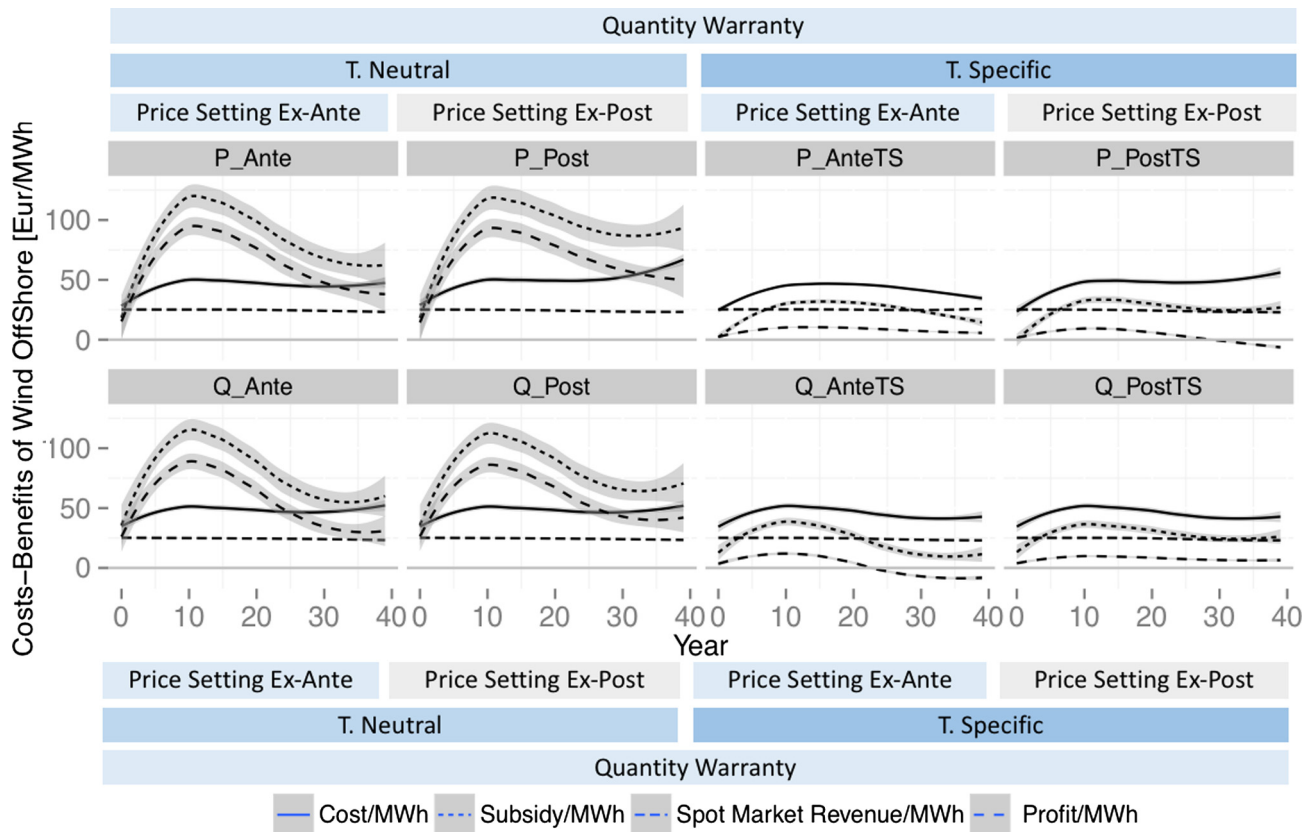


Fig. 8. Cost, revenue, subsidy, and profit for WindOffshore per MWh over 40 years.

impacts on the energy system and on welfare distribution, the design element approach questions the current approach to policy making and policy analysis in the realm of RES-E support in Europe. It takes the debate beyond a choice between say, an auction or a feed-in-tariff, to ask how either should be designed in order to achieve long term objectives of the system. While the concept of whether renewable policies matter at all has been gaining traction off late in academic literature, [13], it remains distant from ongoing policy discussions, as we elucidate below.

The 2014 State Aid Guidelines proposed that competitive bidding, or auctions, should be the main form of support [41] for utility scale renewable plants. This is proposed in the place of the more popular price-based mechanisms in Europe. Competitive bidding is modelled as 'quantity warranty' in this work. This research interestingly demonstrates that more than the feature of competitive bidding or *quantity warranty*, the design element *technology specificity*, would incur far greater implications in terms of welfare distribution in the Netherlands, over a period of 40 years.

Related to this, the fragmentation of the European internal electricity market due to country-specific renewable support schemes, and security of supply policies is causing increasing concern [42]. Among the primary concerns of the European Commission now, is to be able to promote renewable electricity without causing unintended cross border impacts [43]. A part of their strategy to address this seems to be to promote competitive bidding in member states. However, it is possible that even competitive bidding, when designed differently in neighbouring states (for instance in

terms of technology-specificity), could result in unintended cross border effects. The design element method has the potential to provide insight into which aspects of the policies need to be harmonised (or not); and if yes, to what degree. This method allows the analyst to examine, element-by-element, which of them lead to cross-border interactions between two neighbouring countries in the same electricity market.

4. Conclusion

Most ongoing policy discussions relating to RES-E support schemes, both within and outside of academia, compare existing policies. However, two seemingly different policies can be designed in a way that they have an equivalent effect on the market: for instance, a tradable-green-certificate market with a long term contract is similar to a tender. Conversely, two similar policies could have very different impacts on the system, if designed slightly differently; for instance competitive bidding organised specific to a technology would yield very different results from one that is technology neutral. Therefore the core idea is that, it is the design features that form the vital component of analysis, and not the policies in their entirety. We employ core design elements and combine them to systematically arrive at a set of possible RES-E policy scenarios, considered complete with respect to the design elements, thus exploring the complete policy design space. The design elements modelled are *quantity warranty* vs. *price warranty*, *technology specificity* vs. *neutrality*, and *ex-ante* vs.

ex-post price setting. We employ this design element view in combination with agent based modelling to quantitatively assess impacts of individual design elements on the socio-technical system.

The results demonstrate that design elements, irrespective of the RES-E policy they belong to, do have significant impacts on the energy system and on welfare distribution, and therefore that the approach is a useful one. The agent-based modelling framework enables modelling of bounded rationalities in investment decisions, allowing the modeller to incorporate real-world uncertainties in agents' behaviour. An important uncertainty in the real world is that of long-term electricity price development. The model interestingly demonstrates that accounting for future electricity prices *ex-ante* in the subsidy calculation may reduce the overall cost of subsidy by about 15%, since the actors are likely to overestimate the future electricity price. This is a consequence of underestimating the impact of the merit order effect on expected electricity prices over the long-term. Other significant results are that *technology specificity* could reduce the cost of subsidy by up to 60%. Results regarding the design element, *quantity vs price warranty* corroborate established literature: quantity warranty helps achieve targets better. The design element configuration that leads to the highest increase in social welfare is the combination of quantity-warranty, *ex-ante* accounting for electricity prices, and technology-specificity.

With regard to policy implications, the State Aid Guidelines of the European Commission promote competitive bidding to incentivize investment, while largely supporting technology neutrality. At the outset, our results corroborate with the choice of competitive bidding. They however indicate that the feature technology specificity has a significant implication on welfare impacts, subject to the assumption of regulator's knowledge of real costs being the same as the energy producer. Differences in such features of RES-E policy between member states could lead to unintended cross border effects. The design element method has the potential to provide insight into which aspects of the policies need to be coordinated at the European level.

Acknowledgements

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Table A.3

Other policy design elements for stimulation of RES-E in Europe.

Design Element	Definition
Contract Length or Project Duration	The length of time for which the contract is valid
Location Specificity	This element would allow the differentiating of support levels by location
Size specificity	This element would allow the differentiating of support levels by size
Cost burden	The cost of the RES-E support could be borne either by the consumers or by the tax payers (state budget)
Cost containment mechanisms	Adaptation of support levels to technology costs and state budget related political feasibility concerns. Ex: capacity caps, generation caps, cost caps
Penalty for non compliance	Penalties are means to deter non compliance of the regulation
Frequency of Change in Warranty	The number of times the price or quantity signal changes over the lifetime of a power plant. For instance, in a tradable green certificate market the quantity warranty changes every year, however, in a tender system, a contract ensures that the remuneration remains constant as per the quantity warranty set once

Appendix A. Design elements

See [Table A.3](#).

Appendix B. Base model flowcharts

The two flowcharts in this section indicate the main algorithmic processes in EMLab. Market clearing within one tick (year) is performed using an annual load duration curve. The time resolution is indeed yearly. However, the annual load duration curve, comprising 8760 h of different loads, is approximated into twenty segments in view of computational resource constraints. Each segment is represented by a pair of values: a load (in MW), and period (in hours). For instance, segment 1 is (8160.778 MW, 17 h), segment 2 is (8390.36, 77 h) and so on. For each load segment, the electricity spot market is cleared individually according to uniform price clearing, and price volume pairs are determined for each of the 20 load segments.

Appendix C. Data

C.1. Target and potential curves

The targets for renewable energy generation have been set by extrapolating the targets mentioned in the National Renewable Energy Action Plan of the Netherlands; [31]. The trends in csv format are attached in the zipped folder.

Data points for 'realistic potentials' at different years have been used to linearly extrapolate trends for the whole time scope of the model. The data points and their sources are mentioned in the table below (see [Tables C.4 and C.5](#)).

C.2. Assumptions: technology characteristics

See [Tables C.6](#).

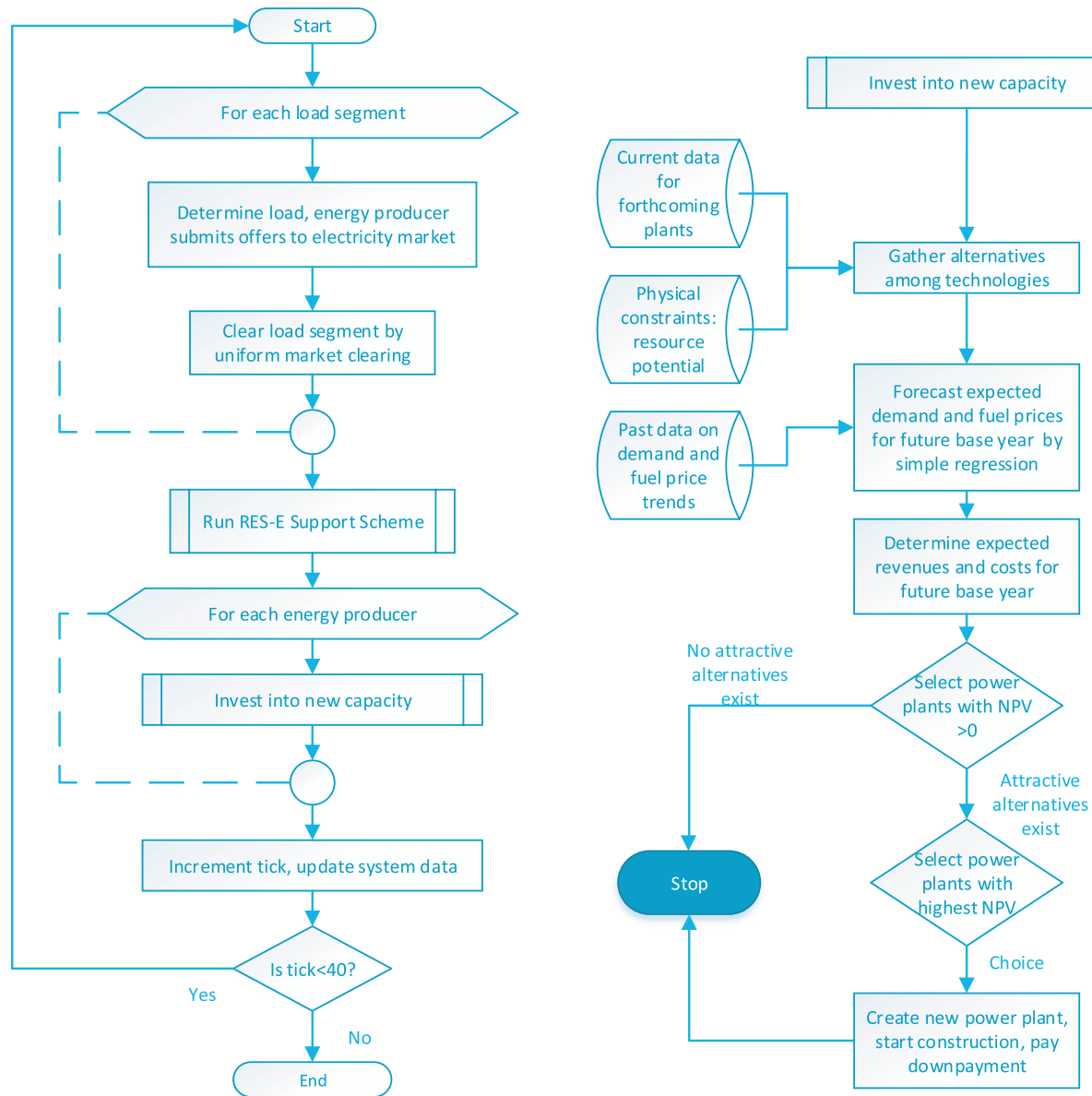
Appendix D. Results

D.1. Figures

See [Figs. D.10 and D.11](#).

D.2. Tables

See [Tables D.7 and D.8](#).



(a) Main EMLab Algorithm

(b) Investment Algorithm

Fig. B.9. Flowcharts showing the overall EMLab algorithm, and the investment algorithm.**Table C.4**
Realistic technology potentials.

Technology	Year	Potential (in GW h)	Source
Wind Onshore	(2010, 2040)	(2151.62,9032)	[36]
Wind Offshore	(2010, 2040)	(837.27,58756)	[36]
Photovoltaic	(2013, 2020)	(1065.19,10839.8)	[37]

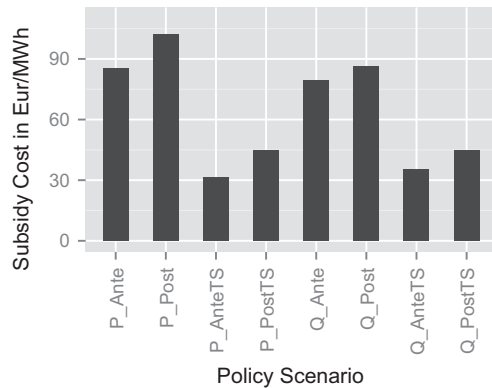
Table C.5
Demand and fuel price trends.

	Start value	Growth Rate		
		Mode	Min	Max
Electricity demand growth rate	1	1.1	0.99	1.03
Gas price – Basecase	4	1	1	1
Gas price – high	4	1.02	1.04	1
Gas price – low	4	0.98	0.96	1

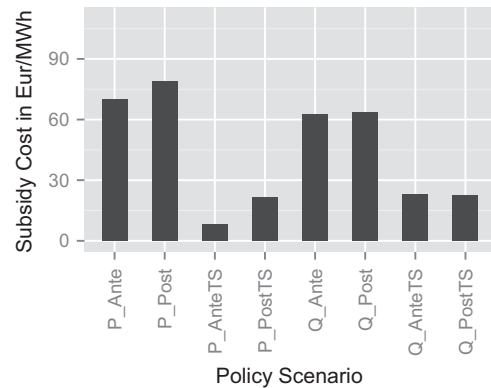
Table C.6

Assumptions regarding technologies.

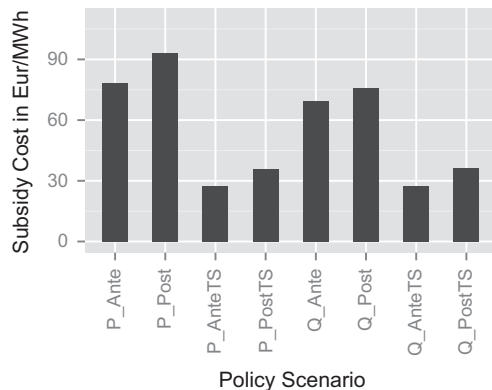
Technology	CCGT	Wind Offshore	PV	Wind Onshore
Capacity [MW]	776	600	500	600
Construction time [Years]	2	1	1	1
Permit time [Years]	1	0	0	0
Technical lifetime [Years]	40	20	20	20
Depreciation time [Years]	15	20	20	20
Minimum Running hours	0	0	0	0
Fuels	Natural Gas	-	-	-



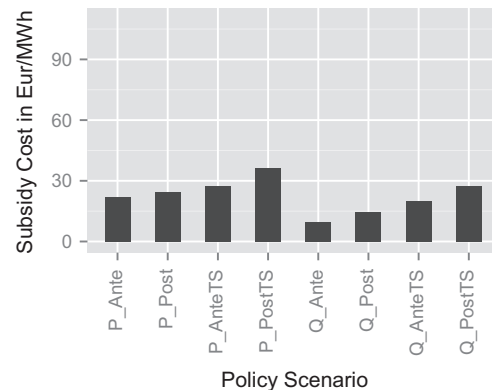
(a) Subsidy costs in Gas Low scenario



(b) Subsidy costs in Gas High scenario

Fig. D.10. Subsidy costs in scenarios with increasing or decreasing gas price trends.

(a) Subsidy costs in scenario set with the same risk aversion



(b) Policy cost effectiveness in scenario set with constant RES-E target

Fig. D.11. Subsidy costs of scenarios addressing each effect on price setting individually.**Table D.7**

Distributional implications in million Eur.

Scenario	Δ Consumer Surpl.	Δ Producer Surpl.	Δ Govt Surpl.	Δ Social Surpl.
P_Ante	46.91	-61.86	-74.66	-89.61
P_AnteTS	18.12	-3.39	-10.73	4.00
P_Post	72.68	-47.84	-65.79	-40.96
P_PostTS	71.06	-13.15	-30.27	27.64
Q_Ante	65.24	-33.09	-58.71	-26.56
Q_AnteTS	65.45	-2.23	-26.49	36.73
Q_Post	65.34	-36.61	-61.91	-33.19
Q_PostTS	65.32	-7.71	-31.73	25.89

Table D.8

Comparison of average subsidy between base case set and same risk scenario set.

Scenario Name	Base Case Scenario	Same Risk Scenario	Difference
	Avg Subsidy/Unit (Eur/MW h)	Avg Subsidy/Unit (Eur/MWh)	
P_Ante	79.72	78.34	1.38
P_Post	93.39	93.11	0.28
P_AnteTS	27.88	27.24	0.64
P_PostTS	35.95	35.96	-0.01
Q_Ante	74.08	69.32	4.76
Q_Post	78.67	76.09	2.58
Q_AnteTS	28.92	27.48	1.44
Q_PostTS	36.28	36.30	-0.02

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