National Renewable Policies in an International Electricity Market
A Socio-Technical Study

Iychettira, Kaveri

DOI
10.4233/uuid:d247e271-3321-4661-b29a-08070ae9090f

Publication date
2018

Document Version
Final published version

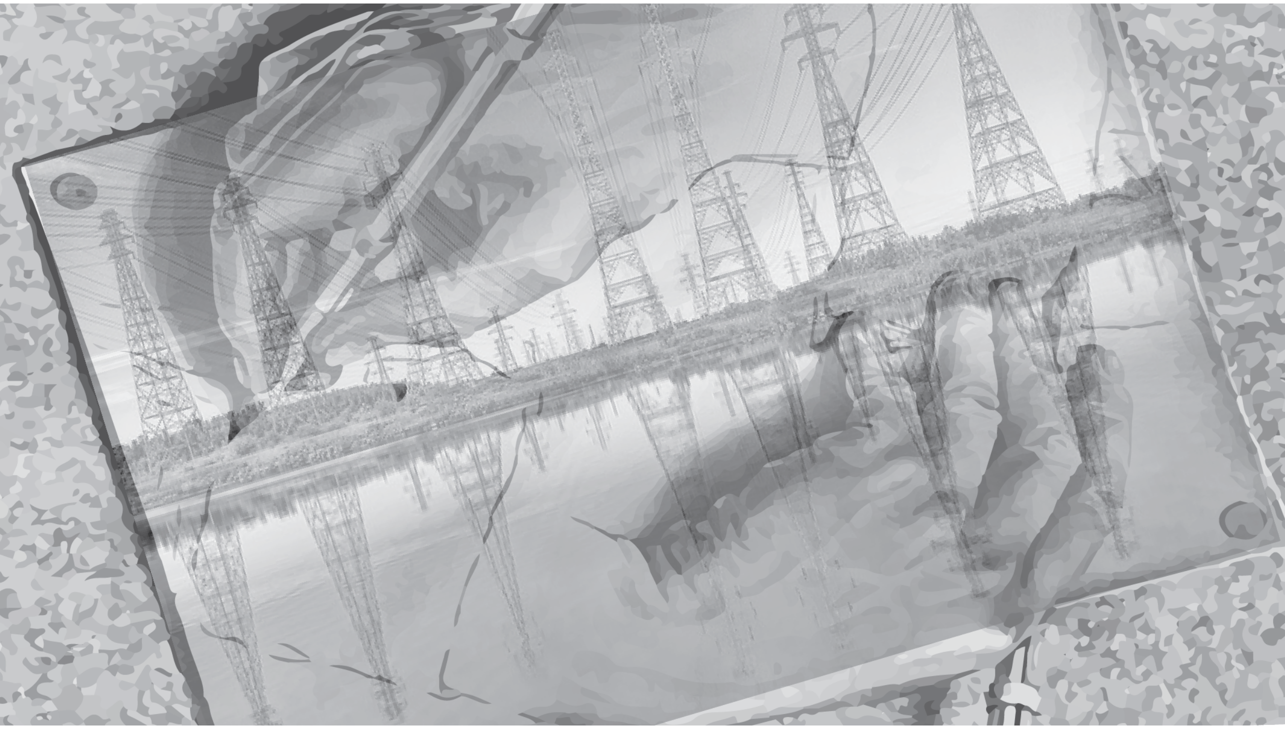
Citation (APA)
Iychettira, K. (2018). *National Renewable Policies in an International Electricity Market: A Socio-Technical Study*. [Dissertation (TU Delft), Delft University of Technology, KTH Royal Institute of Technology, Comillas Pontifical University]. https://doi.org/10.4233/uuid:d247e271-3321-4661-b29a-08070ae9090f

Doctoral Thesis
Delft, The Netherlands 2018

National Renewable Policies in an International Electricity Market:

A Socio-Technical Study

Kaveri K. Iychettira



NATIONAL RENEWABLE POLICIES IN AN INTERNATIONAL ELECTRICITY MARKET

A SOCIO-TECHNICAL STUDY

Kaveri Kariappa IYCHETTIRA

NATIONAL RENEWABLE POLICIES IN AN INTERNATIONAL ELECTRICITY MARKET

A SOCIO-TECHNICAL STUDY

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology,
by the authority of the Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
Chair of the Board for Doctorates,
to be defended publicly on,
Friday 6 April 2018 at 10:00 o'clock

by

Kaveri Kariappa IYCHETTIRA

Master of Science in
Engineering and Policy Analysis
Delft University of Technology, the Netherlands
born in Bangalore, India.

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairman
Prof. dr. ir. M.P.C. Weijnen	Delft University of Technology
Dr. ir. R.A. Hakvoort	Delft University of Technology
Independent members:	
Prof. dr. ir. R.W. Künneke	Delft University of Technology
Prof. dr. ir. M.L. Rivier Abbad	Comillas Pontifical University
Prof. dr. K. Blok	Delft University of Technology
Dr. ir. M.R. Hesamzadeh	KTH Royal Institute of Technology
Prof. dr. J. Watson	University of Sussex

ISBN 978-94-6233-904-0

The doctoral research has been carried out in the context of an agreement on joint doctoral supervision between Comillas Pontifical University, Madrid, Spain, KTH Royal Institute of Technology, Stockholm, Sweden and Delft University of Technology, the Netherlands.

Keywords: RES-E, policy design, support schemes, renewable electricity, agent-based modelling, investment, electricity, cross-border effects, IAD framework

Printed in the Netherlands

Thesis Supervisors:

promotor: Prof. dr. ir. M.P.C. Weijnen
copromotor: Dr. ir. R.A. Hakvoort

Members of the Examination Committee:

Prof. dr. ir. R.W. Künneke	Delft University of Technology
Prof. dr. ir. M.L. Rivier Abbad	Comillas Pontifical University
Prof. dr. K. Blok	Delft University of Technology
Dr. ir. M.R. Hesamzadeh	KTH Royal Institute of Technology
Prof. dr. J. Watson	University of Sussex

TRITA-EECS-AVL-2018:12
ISBN 978-94-6233-904-0

Printed by: Publisher

Keywords: RES-E, policy design, support schemes, renewable electricity, agent-based modelling, investment, electricity, cross-border effects, IAD framework

Front cover: The cover picture is a depiction of independent entities trying to create a common electricity grid together. Kaveri has superimposed an image of the electricity grid by James W. Smith obtained on Flickr, on a painting by M.C. Escher.

SETS Joint Doctorate

The Erasmus Mundus Joint Doctorate in ***Sustainable Energy Technologies and Strategies***, SETS Joint Doctorate, is an international programme run by six institutions in cooperation:

- Comillas Pontifical University, Madrid, Spain
- Delft University of Technology, Delft, the Netherlands
- Florence School of Regulation, Florence, Italy
- Johns Hopkins University, Baltimore, USA
- KTH Royal Institute of Technology, Stockholm, Sweden
- University Paris-Sud 11, Paris, France

The Doctoral Degrees issued upon completion of the programme are issued by Comillas Pontifical University, Delft University of Technology, and KTH Royal Institute of Technology.

The Degree Certificates are giving reference to the joint programme. The doctoral candidates are jointly supervised, and must pass a joint examination procedure set up by the three institutions issuing the degrees.

This thesis is a part of the examination for the doctoral degree. The invested degrees are official in Spain, the Netherlands and Sweden respectively.

SETS Joint Doctorate was awarded the Erasmus Mundus **excellence label** by the European Commission in year 2010, and the European Commission's **Education, Audiovisual and Culture Executive Agency**, EACEA, has supported the funding of this programme.

The EACEA is not to be held responsible for contents of the Thesis.

ACKNOWLEDGEMENTS

"It always seems impossible until it's done," said Nelson Mandela. The same feeling pervades even as I write this. During the last four years however, there were a lot of people in my life who thought it was possible. Some of whom, through their own challenges showed me it was possible gracefully, and with perseverance. Others showed me the way, and others still helped by making sure I knew that there was much more to life than a PhD. I take this opportunity to acknowledge their contribution and care; they are the village that it took to create this thesis.

I thank my pragmatic, witty, and insightful co-promotor, dr. ir. Rudi Hakvoort, for giving me the opportunity to undertake this journey. Rudi was a mentor, advisor, and friend, therefore so much more than the title 'supervisor' implies. Through it all, he allowed me the freedom to explore my mad ideas, helped keep my perfectionist tendencies in check after first letting them run wild; his light-hearted approach, creative ideas, and supportiveness ensured that I stayed positive, and kept trying when results didn't come through. I thank Prof. dr. ir., Margot Weijnen, my promotor, for her guidance, especially during the later half of my PhD. I thank her for ensuring that I completed the dissertation on time, by keeping my ambitiousness in check at the final stages. During the many meetings with her, she was insightful and friendly, and I never left a meeting without feeling encouraged. I especially thank both Rudi and Margot for their warmth and understanding when my wrists gave in due to repetitive stress injury, as well as for their interest and effort in helping me get to the next step in my career. I also thank Prof. Pedro Linares at Comillas for the academic year I spent in Madrid, Spain. Weekly meetings with him were instrumental in shaping my ideas during the early stages of my dissertation.

I thank the several colleagues I collaborated and co-authored papers with, particularly the EMLab community: Dr. ir. Laurens de Vries, dr. ir. Emile Chappin, Joern, Rob de Jeu, Salman, and Prad. Laurens was also a mentor to me. I am grateful for the opportunities to collaborate with him on several projects, and for all the master students he sent my way. I thank him for the memorable dinners he hosted, for the fun and lively conversations, and for his advice on the process of PhD-ing. I thank Joern for teaching me the ropes of EMLab, and for inspiring me to be a good supervisor and friend to my master students.

I thank Wiebke, whose friendship was the most valuable outcome of the PhD Start-Up course! I am incredibly grateful for her friendship, inspiration and counsel. I thank Yesh for being the big brother he has been: when I had lost hope of ever getting sensible results from EMLab, he managed to convince me that there was light at the end of the tunnel. I thank Siddhartha Mukherjee for his friendship, the fantastic biryanis with Udai, the fun conversations, and for introducing me to Vikram Seth!

I thank the wonderfully 'gezellige' group at the E&I section. The atmosphere was one of camaraderie, and a feeling that we all had each others' backs. The Power Rangers meetings were especially useful, usually indirectly, for my own research. I'm also grateful for conversations with Amineh and Igor, which have influenced ideas in this dissertation. I thank Elta for convincing me to take up the PhD programme, and for being the supportive figure she was through the PhD! I thank Binod, Jorge, and Jose who made my first year a very happy one. I thank Joao, Ben, Esther, Amineh, Arthur, Amit, Shantanu, Ozge, Kasper, Tristan, Frank, Reinier, Cherrelle, Juliana, Chris, Dierdre, and my officemates Victoria, Anna, and Graciela. Arthur, Joao, and Shantanu kept spirits in the department high, and made sure we didn't stay in the office too long after work hours! I also thank Rishab and Ad for all the fun times in my final year. I'm glad I got to know you before I left!

When I went to Madrid for the SETS mobility in Aug 2014, I was immediately made to feel like a part of the Ricci-Spanish family. I thank Adela, Alessandro, Pablo, Checa, Luis, Paco, Elena, Eva, and Zarrar. I also thank the SETS Spanish cohort in that year, Katia, Peyman, Quentin. I thank Sara for her diligence and dedication in helping us get through the various administrative SETS requirements during the 4 years. In KTH, Stockholm too, I was very lucky to have met wonderful people like Francisco, Gudrun, Tin, Viktor, Ravi, Fabian, and Aravind. Their friendship made even Swedish winters seem warm and fun.

I also met a very nice bunch of people from all over the world, in the SETS programme, who made the journey easier together: Christian, Marcin, Nenad, German, Paolo, Anna.

Towards the final stages, a lot of people helped proof-read my dissertation. Some of them were acquaintances, and others family! I can't thank them enough for offering to help under tight time constraints, and doing diligent jobs too. My mum, Raunak Kalra, Layla Abdulkarim, Vivek anna, Ranjani, Yeshambel, and Vikram Srinivas. I thank Wiebke and Ozge for standing by my side as paranymphs. I also thank Prof. James W. Smith from the university of Mc. Master, for letting me use his beautiful photograph for my thesis cover.

I thank my friends from Bangalore - Ranjani Iyer, Chitwan Mahipal, Kaushik Rangarajan, Vidya Shree, Nisha Suresh, Roshan Rao, Santosh Harish, and Anil Kumar who have all been by my side despite the distance. I thank Daddy for being an inspiration in his pragmatic approach to life. He made sure that I didn't let the PhD consume me, and reminded me that there were more important things in life! I thank Mum for her constant care, love, and support. She never let me feel like I lived too far away from family. And finally I thank Vikram, my fiance, whose presence makes every moment more joyful. He is a source of calm strength, and unconditional affection. I look forward to all that life has in store for us!

Kaveri Iychettira
February, 2018

CONTENTS

NOMENCLATURE

NPV	Net Present Value
$WACC$	Weighted Average Cost of Capital
$WACC_{rev}$	WACC adjusted for risk aversion
$*$	Asterisk in the exponent denotes equilibrium values.
g	Power plant index
rep	Repetition index per scenario
s	Segment index
t	Time step in years
$a_{g,s}$	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/MWh]
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 [40]
n_{tick}	Number of ticks per repetition [40]
$p_{s,t+n}$	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, in segment s, at time t+n [in hours]

$rGen_t$	Total renewable energy generation at time t [in MWh]
t_b	Power plant construction time
t_D	Power plant depreciation time
$target_t$	Total target for renewable energy generation at time t [in MWh]
$vc_{g,t+n}$	Variable costs of power plant g, in time t+n [in Eur/MWh]
$Xante_g$	Total subsidy per MWh of generation for plant g, discounted to present value [in Eur/MWh]
$Xpost_g$	Total cost per MWh of plant g, discounted to present value [in Eur/MWh]

EXECUTIVE SUMMARY

The current regulatory framework under which the support schemes for Renewable energy sources specifically for electricity (RES-E) operate, is provided for by the Directive 2009/28/EC. It sets a 20% target for energy consumption, while relying on legally binding, national targets until 2020. The goal to promote RES-E, in the European context, coexists with goals of ensuring a single internal market for electricity, and security of supply in the European Union, and these simultaneous goals are not always congruent with each other.

Today, significant amounts of intermittent RES-E in the energy mix have led to unintended effects. An important consequence is the so called 'merit-order effect', where the spot market electricity price reduces to the extent by which the renewable electricity generation displaces demand along the merit order. There is concern that part of the merit order effect spreads across national borders. Vitally, implications of the merit order effect on the effectiveness of RES-E support schemes are unclear. Another important effect of the price reduction is that, the lower the average electricity market price, the greater the costs of subsidies, making the phasing out of subsidies for renewable, intermittent sources more difficult.

With respect to electricity from renewable sources, this achievement of the three objectives took the shape of "making renewable support schemes more *market-based*", "ensuring renewables are driven by market signals". However, it is not often clear what is meant by such statements in policy documents by the EC. What features of the support scheme are being referred to? What would it mean for renewables solely to be driven by market signals? How would features of support schemes impact for instance, the merit order effect, and vice-versa? These issues are encapsulated in the first problem addressed in the thesis: *to unravel the interactions between renewable support scheme design and a single isolated electricity spot market, with a long term perspective.*

Since countries are now increasingly interconnected, the second major issue tackled in this thesis concerns *cross border effects due to different renewable support schemes between neighbouring countries in a common electricity market.* This issue addresses concerns about the merit-order effect spreading across national borders, and the ensuing distributional implications.

The final issue addressed in this dissertation relates to *the long term economic viability of electricity from renewable sources given the current institutional and physical setting they operate in.* Costs of renewable technologies have dropped dramatically and yet effects such as their reducing market value lead to questions about whether it is possible for them to attain economic viability in a decarbonised power sector. Accordingly, the main research question in this dissertation is:

How do national renewable electricity support schemes interact with the electricity

market over the long term (20-30 years) as the European Union transitions to a decarbonized energy system?

Method and Key Findings

Identifying Design Elements of RES-E Schemes:

The first step towards understanding the design of RES-E support schemes in this work has been to identify the design elements that they comprise of. Design elements are defined as a closed set of components that are common to all renewable electricity support schemes; they form the smallest level of analysis. The underlying idea is not that there exists a choice between policy A or B, but how either policy instrument should be designed. Such a perspective allows the policy maker such as the European Commission to decide which design features are essential in an RES-E scheme, rather than propose an entire scheme itself. To this end, in Chapter 2 a formal approach to RES-E policy design based on Design Theory, the Institutional Analysis and Development (IAD) Framework, and Agent Based Modelling and Simulation is presented. Using this approach, and assisted by a literature review, ten design elements are identified. They are corroborated with empirical data by studying six RES-E support schemes in Europe.

RES-E support schemes were implemented in terms of their design feautures, on an existing, agent-based model of the electricity market, called the **E**nergy **M**arket **Lab**oratory, or "EMLab". EMLab is an initiative of the Energy and Industry section of the faculty of Technology, Policy and Management in TU Delft, built to study various aspects of the energy transition in Europe. At its core, EMLab comprises an electricity market clearing algorithm and an endogenous investment algorithm, where agents who take investment decisions are boundedly rational in their knowledge about the future, much like reality.

Modelling Design Elements of RES-E Schemes:

In order to understand precisely how each design element impacts the overall goals of sustainability, affordability, and security of supply, three design elements are implemented in a model of an electricity market, with RES-E policies. The three design elements are quantity vs. price based policy, technology neutrality vs specificity, and price setting ex-post vs. ex-ante. The objective of Chapter 3 is to assess the impact of design elements of 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. An important uncertainty in the real world is that of long-term electricity price development. The model demonstrates that accounting for future electricity prices ex-ante in the subsidy calculation may reduce the overall cost of subsidy by about 15%, since actors are likely to overestimate future electricity price. The combination of design elements that provides the highest increase in social welfare is the quantity based policy, with electricity market price accounted for ex-ante, and with technology specificity.

Cross border impacts of design elements:

Using EMLab Generation, regions based on Germany and the Netherlands were simulated, to test the effects of different support scheme designs in each country, and the common electricity market, on distributional implications under different scenarios of interconnector capacities. As economic theory would predict, it is found that subsidy costs increase in the smaller country due to spreading of the merit order effect from the larger neighbouring country. However, the increase in subsidy costs remains lower than the reduction in costs of electricity, corroborating earlier, single country analyses on the topic. Therefore, total costs in both countries reduce as interconnection increases, and the invisible hand works its magic. As the share of RES-E increases, interconnection has limited impact on reducing spillage of RES-E while storage becomes increasingly important. The results show that setting targets for RES-E, should not only take into to account the targets of the interconnected neighbouring countries, but also capacity of storage that exists in the system. They raise interesting questions about how subsidy costs should be allocated between countries over the long term when electricity markets they operate in are so intricately connected.

RES-E design in perspective of the energy transition:

Results from previous chapters are, in this penultimate chapter, regarded from the standpoint of the EU energy transition. A literature review examines three major aspects of the energy transition in Europe: the cost and revenue drivers of RES-E technologies, the EU ETS, and finally, the role of flexibility. We find that at relatively high average electricity prices, their impact on subsidy costs is direct and clear; as prices increase, subsidy costs decrease. However, as electricity prices on the spot market reduce on average, the change in subsidy cost trends depend far more on cost curves of each RES-E technology. With respect to the EU-ETS, it is clear that, even if EUA prices play a significant role on the electricity prices today, their influence on electricity prices and RES-E subsidy costs will reduce as the share of RES-E generation increases with time. From results in Chapter 5, it is evident that at high shares of RES-E, interconnection will play a limited role in providing flexibility while storage (long-term, seasonal) will play a pivotal role. Consequently, costs of subsidy for RES-E at high shares substantially depend on the presence of storage in the system.

Conclusion The central question addressed in this thesis is *How do national renewable electricity support schemes interact with the electricity market over the long term (20-30 years) as the European Union transitions to a decarbonized energy system?*

Using an approach based on theoretical foundations of institutional analysis, design theory, RES-E support schemes are broken down into their design elements from a welfare economics perspective. A modelling framework is then introduced, using the modeling paradigm of agent-based modelling, by which RES-E schemes are modelled in EMLab Generation. EMLab Generation mainly comprises an electricity market clearing and an endogenous investment module, enabling the researcher to study long term dynamics of policy designs in the electricity sector. The model shows that the way electricity prices are taken into account while designing subsidies makes a substantial difference to welfare distributions. When multiple countries are considered, spreading of the merit order effect from a larger country to a smaller one would cause the smaller country's subsidy costs to increase. This indicates that even if RES-E support can be designed to be "market-based" at an operational level, designing them to be "market based" at an investment level is far more complicated. It indicates that RES-E targets of countries should take into account the targets of neighbouring countries, as well as the amount of flexibility in terms of interconnection and storage in the system.

In terms of its scientific contribution, the thesis takes a step towards integrating institutional analysis and design theory in order to complement the neo-classical school of thought which arguably dominates energy policy design and analysis in Europe. The framework introduced in Chapter 2 brings together two separate strands of literature: the institutional analysis framework and design theory. The combination is shown to also be coherent with and complementary to the modelling paradigm of agent based modelling and simulation. While the framework does not provide causal relationships which provide insight on why a certain actor behaves in a certain manner under certain conditions, it does make for a strong fundamental basis to simulate a test-bench on which the real world can be represented, and theories or "speculations" tested. Although this framework was applied and demonstrated using renewable support schemes in Europe, its fundamental nature makes it employable to other domains.

A major advantage of the model is that it is open source. Most models that are used to inform the European Commission's policy documents are black box simulations. The assumptions, data, systems used to set policy are not publicly available. Making models open source allows for replicability, transparency, and debating their validity, which are all basic tenets of the scientific method. The results from this dissertation also pave the way towards new questions that need to be resolved as the shares of RES-E increase in the elecricity system. In terms of methodology for long-term energy studies, it is paramount that models employ high temporal resolution at high shares of intermittent RES-E generation, while also being able to model endogenous investment. For instance, they raise pressing questions about the need to further develop a methodology for sharing the subsidy costs between countries. These questions need to be explored in greater detail, and possible mechanisms to cope with the complexities should be evaluated.

SAMENVATTING

De Europese Richtlijn 2009/28/EC biedt het reguleringskader voor de groei van het aandeel duurzaam opgewekte energie, specifiek voor elektriciteit. De doelstelling is dat 20 % van het energiegebruik in 2020 uit duurzame bronnen wordt opgewekt, een en ander te realiseren door middel van bindende nationale doelstellingen. Het bevorderen van duurzame energie in de Europese context staat naast de andere doelstellingen van het realiseren van een interne markt voor energie en het waarborgen van de leveringszekerheid in de Europese Unie. Deze doelstellingen zijn niet altijd met elkaar in lijn.

De grote hoeveelheden energie uit intermitterende bronnen in de energiemix hebben geleid tot onbedoelde neveneffecten. Een van de belangrijkste is het zogenaamde 'merit order effect': de elektriciteitsprijs op de spotmarkt daalt naarmate energie uit duurzame bronnen conventionele elektriciteitsproductie verdringt. Dit merit order effect kan zich over landsgrenzen heen verspreiden. De gevolgen hiervan op de effectiviteit van beleid om duurzame energie te bevorderen zijn onduidelijk (en worden in dit proefschrift onderzocht). Een gevolg van de prijsdaling is verder dat hoe lager de gemiddelde elektriciteitsmarktprijs, hoe hoger de kosten van de toegezegde subsidiëring worden. Dit maakt het uitfaseren van subsidies voor duurzame energiebronnen moeilijker.

In de praktijk is geprobeerd om de drie hierboven genoemde doelstellingen met elkaar in lijn te brengen door "het meer markt-gebaseerd maken van de ondersteuning van duurzame energie" en "het verzekeren dat duurzame energiebronnen worden aangedreven door marktsignalen". Het is meestal niet duidelijk wat met dergelijke uitspraken bedoeld wordt. Aan welke eigenschappen van het ondersteuningsmechanisme wordt er gerefereerd? Wat betekent het dat duurzame energiebronnen alleen door marktsignalen gestuurd worden? Welke eigenschappen van ondersteuningsregelingen hebben impact op bijvoorbeeld het merit order effect, en omgekeerd? Deze kwesties worden in het eerste vraagstuk geadresseerd dat in dit proefschrift aan bod komt: het ontrafelen van de interacties tussen ondersteuningsregelingen voor duurzame energie in een enkele (geïsoleerde) elektriciteitsmarkt, bekeken vanuit een langetermijnperspectief.

Aangezien de elektriciteitssystemen in de Europese landen onderling verbonden zijn, gaat de tweede kwestie die in dit proefschrift wordt behandeld, over de grensoverschrijdende beïnvloeding van verschillende ondersteuningsregelingen voor duurzame energie tussen buurlanden in een gemeenschappelijke elektriciteitsmarkt. Deze kwestie adresseert het verspreiden van het merit order effect over nationale grenzen heen, en de daaruit volgende verdelingseffecten. Het laatste vraagstuk dat in dit proefschrift wordt behandeld, heeft te maken met de economische levensvatbaarheid op lange termijn van elektriciteitsproductie vanuit duurzame bronnen gegeven de huidige institutionele en fysieke omgeving. Hoewel de kosten van duurzame elektriciteitsproductie zijn afgenomen, leidt hun snel dalende marktwaarde tot vragen in hoeverre deze technologieën economisch levensvatbaar blijven in een koolstofarme stroomsector. Bijgevolg is de hoofdonderzoeksvraag in dit proefschrift:

Hoe interacteren nationale ondersteuningsregelingen met de elektriciteitsmarkt op de lange termijn (20-30 jaar) nu de Europese Unie overgaat naar een koolstofarm energiesysteem?

Methode en belangrijkste bevindingen

Identificeren van de ontwerpelementen van ondersteuningsregelingen voor duurzame energie: De eerste stap om ondersteuningsregelingen voor duurzame energie te kunnen ontwerpen is het identificeren van de onderliggende ontwerpelementen. Ontwerpelementen worden gedefinieerd als een gesloten set van componenten die gemeenschappelijk zijn aan alle ondersteuningsregelingen voor duurzame elektriciteit. Zij vormen daarmee het laagste analyseniveau. Het idee hierbij is niet dat er de keus moet worden gemaakt tussen beleid A en beleid B, maar dat allereerst de componenten die in elke beleidsoptie aanwezig zouden moeten zijn, inzichtelijk worden. Een dergelijk perspectief maakt het mogelijk dat een beleidsmaker (zoals de Europese Commissie) eerst beslist welke componenten essentieel zijn om nader uit te werken in plaats van direct een hele regeling te ontwikkelen. Hiertoe presenteert hoofdstuk 2 een formele aanpak voor dit soort ondersteuningsregelingen gebaseerd op design theory, het Institutional Analysis and Development (IAD) Framework, agent-based modellering and simulatie. Gebruik makende van deze aanpak, en ondersteund door literatuuronderzoek, zijn tien ontwerpelementen geïdentificeerd. Deze zijn bevestigd met empirische data door het bestuderen van zes ondersteuningsregelingen voor duurzame energie in Europa. Verschillende soorten ondersteuningsregelingen (ontwikkeld op basis van hun ontwerpelementen) zijn vervolgens geïmplementeerd in EMLab, een agent-based model van de elektriciteitsmarkt. EMLab is ontwikkeld aan de faculteit Technologie, Beleid en Management van de TU Delft en gebouwd om verschillende aspecten van de energietransitie in Europa te bestuderen (EMLab is een afkorting voor 'Energie Markt Laboratorium'). In de kern bevat het een market clearing algoritme voor de elektriciteitsmarkt in combinatie met een endogeen investeringsalgoritme, waarin agenten investeringsbeslissingen maken die rationeel gebonden zijn aan hun kennis over de toekomst.

Modelleren van ontwerpelementen van ondersteuningsregelingen voor duurzame energie: Om de invloed van elk ontwerpelement te begrijpen op de algemene doelen van duurzaamheid, betaalbaarheid en voorzieningszekerheid zijn drie ontwerpelementen geïmplementeerd in EMLab: de keus tussen een gegarandeerde omvang versus een gegarandeerde prijs voor duurzaam opgewekte elektriciteit, technologische neutraliteit versus technologische specificiteit, en een ex-post versus een ex-ante prijsbepaling (dus ook subsidievaststelling). In hoofdstuk 3 worden de gevolgen van de ontwerpelementen op de ondersteuningsregelingen onderzocht, waarbij de analyse zich richt op een enkele (geïsoleerde, niet-verzadigde) regio met kenmerken die soortgelijk zijn aan aan de elektriciteitssector in Nederland. Een belangrijk onzekerheid in de echte wereld is de ontwikkeling van de elektriciteitsprijs op lange termijn. Het model laat zien dat rekening houden met toekomstige elektriciteitsprijzen ex-ante in de subsidieberekening de totale subsidiekosten met ongeveer 15% kan laten reduceren, aangezien de betrokken partijen de toekomstige elektriciteitsprijs waarschijnlijk zullen overschatten. De combinatie van ontwerpelementen die de grootste verhoging van de welvaart realiseert, is een volumegarantie waarbij de verkoopprijs ex-ante wordt vastgesteld, en met technologiespecificiteit.

Grensoverschrijdende invloeden van ontwerpelementen: Gebruik makende van EMLab zijn twee regio's gesimuleerd (gebaseerd op de elektriciteitssystemen in Duitsland en Nederland) om de effecten van verschillende ondersteuningsregelingen in buurlanden te analyseren en de gemeenschappelijke elektriciteitsmarkt te testen op de verdelingseffecten onder verschillende scenario's voor interconnectiecapaciteit. Zoals de economische theorie voorspelt, blijkt dat de subsidiekosten in het kleinere land toenemen als gevolg van van het merit order effect in het grotere buurland. Echter, de verhoging van de subsidiekosten blijft kleiner dan de verlaging van de elektriciteitskosten als gevolg van de interconnectie. De totale kosten in beide landen worden daarmee lager naarmate de interconnectiecapaciteit toeneemt (en de onzichtbare hand zijn magische werk doet). De resultaten tonen verder aan dat de doelstellingen voor duurzame energie in het ene land niet alleen rekening moeten houden met de doelstellingen van (elektrisch verbonden) buurlanden, maar ook met de beschikbare opslagcapaciteit in het systeem. Dit roept interessante vragen op over hoe de subsidiekosten op lange termijn gealloceerd zouden moeten worden tussen landen die onlosmakelijk met elkaar verbonden zijn.

Ontwerp voor ondersteuningsregelingen in het perspectief van de energietransitie: De resultaten van de vorige hoofdstukken worden in het laatste hoofdstuk bekeken vanuit het standpunt van de energietransitie. Op basis van een literatuurstudie zijn drie belangrijke componenten geïdentificeerd: de drivers voor de kosten en opbrengsten van duurzame energietechnologieën, het Europese systeem voor emissierechten (EU-ETS) en de rol van flexibiliteit. Relatief hoge gemiddelde elektriciteitsprijzen hebben een directe en duidelijke impact op de subsidiekosten: als de prijzen stijgen, dalen de subsidiekosten. Echter, als de elektriciteitsprijzen op de spotmarkt gemiddeld dalen, dan zijn de wijzigingen van de subsidiekosten vooral afhankelijk van de kostencurves van elke afzonderlijke technologie. Met betrekking tot het Europese systeem voor emissierechten wordt het duidelijk dat hun invloed op de elektriciteitsprijzen en de subsidiekosten lager wordt naar gelang het aandeel elektriciteitsproductie op basis van duurzame energie in de tijd toeneemt. Uit de resultaten in hoofdstuk 5 blijkt dat bij een hoog aandeel duurzame energie de interconnectiecapaciteit een meer beperkte rol speelt in het realiseren van flexibiliteit terwijl (langetermijns, seizoensgebonden) opslag een sleutelrol zal gaan spelen. Als gevolg hiervan zullen de subsidiekosten bij een hoog aandeel duurzame energie substantieel afhankelijk zijn van de aanwezigheid van opslag in het systeem.

Conclusie De centrale vraag die in dit proefschrift is geadresseerd is: Hoe interacteren nationale ondersteuningsregelingen met de elektriciteitsmarkt op de lange termijn (20-30 jaar) nu de Europese Unie overgaat naar een koolstofarm energiesysteem? Wanneer we gebruik maken van een aanpak die gebaseerd is op theoretische grondslagen van de institutionele analyse en design theory, worden de ondersteuningsregelingen voor duurzame elektriciteitsproductie teruggebracht tot hun ontwerpelementen vanuit een economisch welvaartsperspectief. Modelberekeningen in EMLab tonen vervolgens aan dat de manier waarop elektriciteitsprijzen in het ondersteuningsmechanisme worden ingepast, een substantieel verschil maakt voor de welvaartsverdeling. Wanneer verschillende ondersteuningssystemen in buurlanden worden geïmplementeerd, zorgt het merit order effect in het grote land dat de subsidiekosten in het kleinere land kunnen stijgen. Dit leidt tot de conclusie dat zelfs indien een ‘marktgebaseerde’ ondersteuningsregeling kan worden ontworpen op het operationele niveau, dit geen garanties biedt dat ook het ‘marktgebaseerde’ ontwerp op een investeringsniveau is geborgd. Geconcludeerd wordt dat bij het vaststellen van duurzame energiedoelstellingen in het ene land, de doelstellingen in buurlanden in ogenschouw moeten worden genomen, net als de beschikbare hoeveelheid flexibiliteit in termen van interconnectie en opslag in het systeem. Wat betreft de wetenschappelijke bijdrage zet dit proefschrift een stap naar het integreren van institutionele analyse en design theory om de neoklassieke denkrichting (die het energiebeleid in Europa aantoonbaar domineert) te complementeren. Het raamwerk uit hoofdstuk 2 brengt twee lijnen in de literatuur tezamen: het institutionele analyse raamwerk en design theory. Er is aangetoond dat de combinatie coherent is met en complementair is aan het modelleringsparadigma van agent-based modelleren en simulatie. Hoewel het raamwerk geen causale relaties biedt die inzichten geven in de redenen waarom een speler zich op een bepaalde manier gedraagt onder bepaalde omstandigheden, biedt het wel een fundament voor het ontwikkelen van modelsimulaties die theorieën en ‘speculaties’ kunnen analyseren. Hoewel dit raamwerk is ontwikkeld en toegepast op het gebied van ondersteuningsregelingen voor duurzame energie in Europa, maakt de fundamentele aard ervan het ook inzetbaar in andere domeinen. Een voordeel van het gehanteerde EMLab model is dat het open source is. De meeste modellen die gebruikt worden om de Europese beleidsmaatregelen te analyseren zijn black box simulaties. De veronderstellingen, data en mechanismen om het beleid te parametriseren zijn niet publiekelijk beschikbaar. Open source modellen zorgen voor een betere reproduceerbaarheid, meer transparantie en voor meer inzicht in hun geldigheid van de uitkomsten, alle fundamentele uitgangspunten van de wetenschappelijke methode. Deze dissertatie leidt ook tot nieuwe vragen die geadresseerd moeten worden naarmate het aandeel van duurzame energie in het elektriciteitssysteem toeneemt. Wat betreft de methodologie voor langetermijns energiestudies is het van het belang dat de gehanteerde modellen een voldoende (tijds)resolutie aanbieden om de effecten van intermitterende duurzame elektriciteitsproducten voldoende nauwkeurig te kunnen weergeven. Daarnaast moeten ook endogene investeringen kunnen worden gemodelleerd. Dit leidt vervolgens tot prangende vragen over de noodzaak om (een methodologie te ontwikkelen om) subsidiekosten te verdelen tussen buurlanden. Deze vragen blijven in dit proefschrift liggen om later door anderen te worden opgepakt.

SAMMANFATTNING

Målen med förnybar el, säkerställande av en inre elmarknad och elförsörjningstrygghet i EU är inte alltid förenliga med varandra. Nuförtiden har stora mängder av förnybar el i energimixen lett till oavsiktliga konsekvenser på elmarknaden. Detta är ett problem eftersom mål och stödsystem är utformade på nationell nivå, medan elmarknaden i allt högre grad innebär en sammankoppling över nationsgränserna. Den centrala frågan som tas upp i denna avhandling är hur interna nationella stödsystem för förnybar el kommer att växelverka med elmarknaden på lång sikt (20-30 år) då EU övergår till ett fossilfritt energisystem.

Baserat på teoretiska grunder för institutionell analys, designteori och agentbaserad modellering, är förnybar elproduktions stödsystem uppdelade, ur ett välfärdsekonomiskt perspektiv, i sina designelementöch implementeras i en modell av en energimarknad. Energimarknadsmodellen heter Energy Market Laboratory, eller EMLab Generation vilken huvudsakligen består av en elmarknadsklarering och en endogen investeringsmodul, som gör det möjligt för forskare att studera policydesignens långsiktiga dynamik i elsektorn.

Modellen visar att sättet att ta hänsyn till elpriserna vid utformningen av subventioner skiljer sig betydligt från välfärdsfördelningen. När flera länder betraktas, skulle spridningen av prioriteringsordningen från ett större land till ett mindre, leda till att det mindre landets subventionskostnader ökar. Detta indikerar att även om stödet för förnybar el kan utformas för att vara marknadsbaseratpå operativ nivå, är utformningen av marknadsbaseradestödsystem på investeringsnivå mycket komplicerad. Det indikerar att ländernas mål för förnybar el bör ta hänsyn till målen i grannländerna, liksom flexibiliteten i elsystemet. Med tanke på det vetenskapliga bidraget tar avhandlingen ett steg mot att integrera institutionell analys och designteori för att komplettera den nyklassiska tankeskolan som förmodligen dominerar energipolitisk design och analys i Europa.

1

INTRODUCTION

1.1. BACKGROUND

Energy systems of the world are undergoing a major transformation. Over the last few years, the sheer magnitude of declining costs of renewable energy technologies has taken even the most optimistic of forecasters and analysts by surprise (Carrington, 2017). This decline in costs could be attributed to leaps in technological advancements: increase in capacity factors, decrease in manufacturing costs, and economies of scale. However, such a view would miss the bigger picture, since political will and far-sighted policy-making have been key driving forces. The European Union (EU) and many countries within Europe have been amongst the first to adopt strong support mechanisms to promote CO2 abatement technologies. The demand created by Germany for instance, set up a global production line for manufacturing of PV panels and consequently led to a decline in costs the world over. Whilst a determined policy-driven effort towards decarbonisation was taking place, parallel efforts were being made to liberalize the electricity sector across Europe. This liberalization meant ensuring competition and affordability through a single market for electricity across the EU.

This dissertation comprises an analysis of RES-E policies and their design in the context of a liberalized, multi-national electricity market in Europe. The following sections in this chapter present a brief historical account of renewable electricity governance in Europe, issues that unfolded as shares of RES-E began to become significant, and the most recent questions on the topic.

1.1.1. A BRIEF HISTORY

Energy policy in Europe has traditionally been a matter of national concern. The first indication of a common European energy policy appeared as a consequence of the oil crisis in the 1970s. However, the outcome was only a loose form of intergovernmental cooperation around a set of symbolic objectives related to energy security (De Jong, 2008). In the 1986 Single European Act, energy was acknowledged as a critical economic issue within the process of integration of Europe. It is in this Act that renewable energy

Period	External processes	Institutional milestones	Main energy policy objective(s)	Policy emphasis	Type of EU-level coordination
1974–1985	Oil crises (1973,1979)	Energy policy objectives (1974, 1980)	Energy security	R&D on 'new energy sources'	Intergovernmental
1986–1990	Single Market (1985) Internal Energy Market (1988)	1986 Energy policy objectives	Energy security (and internal market)	R&D on 'non-nuclear energy' (Joule, Thermie)	Policy Coordination Method
1991–1997	Energy market liberalisation Feed-in laws (1988–1994)	1995 Energy White Paper 1996 Electricity Market Directive 1997 RES White Paper	Triad of energy policy objectives: ● Energy security ● Climate change ● Competitiveness	Support to RES demonstration (e.g., Altener)	Policy Coordination Method
1998–2006	Kyoto Protocol (1997) Rising oil prices	2001 RES-E Directive 2003 Biofuels Directive		RES market promotion; 12% by 2010	Regulatory Method
2006–2009	… and gas crises Post-2012 negotiations	2007 European Council 20% targets 2008 Climate-energy package 2009 RES Directive		RES market promotion; 20% by 2020	Regulatory Method

Figure 1.1: Development in EU Renewable Energy policy from 1974-2009. Source: (Hildingsson *et al.*, 2012)

was addressed as a policy priority for the first time. The progression of EU energy policy and the development of renewable energy policy through the decades is presented succinctly in Figure 1.1.

The early 1990s saw the first steps towards the creation of a single internal energy market. In 1995, the European Parliament called for an action plan to further the European Union's engagement in increasing the EU-wide RES share. Around this time, renewable energy also came to be viewed as a solution to environmental and climate change issues, as well as a means to help increase security of supply, and economic competition. Taking a broad political economy perspective, Hildingsson argues that although concern for the environment motivated the promotion of renewable energy, "advancing a policy framework has to be seen against the backdrop of the EU's longer-term ambition to promote liberalised and integrated energy markets" (Hildingsson *et al.*, 2012). The policy entrepreneurship of the Energy Commissioner and the EC during the early 1990s is credited with developing a comprehensive and ambitious proposal for a single internal market in gas and electricity (Nylander, 2001). In the process, from the mid 1990s onwards, the European Commission asserted that the triad of policy objectives of energy security, efficiency, and climate change could be addressed through diversification of energy supply, the liberalisation of energy markets, and deployment of renewable energy (Hildingsson *et al.*, 2012).

The 1997 white paper titled "Energy for the Future: Renewable Sources of Energy" (COM(97)599) (Commission, 1997) outlined a goal of increasing the renewable energy share twofold by 2010. This could be considered the beginning of EU RES policy. As the policy strategy began to transform into a regulatory framework, it met with substantial Member State opposition, especially to the binding nature of the targets. The 2001 RES-E directive therefore only established indicative targets (21% RES-E by 2010) instead of binding ones. In the course of preparing the 2001 RES directive, although propositions were made to harmonise national support schemes, they were strongly contested by some member states (ex: Germany and Spain).

Finally, in January 2007, the European Commission proposed the establishment of the current framework of regulations, which aimed at increasing the share of renewable electricity to 20% by 2020. The current regulatory framework under which support schemes for RES-E operate, is provided by the 2009 RES-E Directive (2009/28/EC). The Directive sets a 20% target for energy consumption, while relying on legally binding, national targets until 2020. The goal to promote RES-E coexists with other goals: ensuring a single internal market for electricity, affordability of supply, and security of supply in the European Union. These simultaneous goals are not always congruent with each other.

During this process of proposing the current framework of regulations, the principle of nationally differentiated and binding renewable electricity targets was broadly undisputed (Hildingsson *et al.*, 2012). However, harmonization of policies, as with the introduction of a "Guarantees of Origin" trading scheme, remained contentious throughout the process of its making. This was resolved after much debate by introducing interstate statistical transfers, joint support schemes, and other mechanisms for cooperation.

The above paragraphs presented a brief history of the governance of renewable energy sources in the European Union up to the late 2000s, in the context of liberalisation of electricity markets. In the following section, a more recent history is presented using both academic literature, and official consultations and reports, to highlight the issues that emerged as renewable electricity began to form a significant share of the electricity mix.

1.1.2. WHEN RENEWABLES ARRIVED

By the late 2000s, renewable electricity technologies had begun to contribute significant percentages to electricity consumption in certain countries, largely due to generous subsidies. In this section some of the major issues that have appeared since renewables arrived in the late 2000s are highlighted. The issues described here primarily relate to concerns raised both by academics and policy makers regarding interactions between the electricity market and renewable electricity or their support schemes. What are the impacts of renewables on wholesale prices? How can renewables be increasingly driven by market signals? Are current institutions suitable for a decarbonised power system?

With increasing shares of renewable electricity production, more and more studies were published on the impact of zero marginal price bids on the electricity prices of the spot market. Sensfuss *et al.* (2008) were amongst the first authors who used empirical data to demonstrate the reduction in wholesale electricity prices due to the presence of renewables. They demonstrated that in 2004, renewable electricity decreased wholesale prices by 2.5 Eur/MWh, and in 2005 by 4.5 Eur/MWh. Several other studies then followed with similar objectives but with different scopes of locations, time periods, and technologies (Cludius *et al.*, 2014; Ederer, 2015; Gelabert *et al.*, 2011; O'Mahoney and Denny, 2013; Traber and Kemfert, 2009, 2011; Weigt, 2009; Würzburg *et al.*, 2013). The phenomenon is now well-established and popularly referred to as the merit-order effect.

Another landmark study evaluated the impact of variable renewable electricity on its own market value (Hirth, 2013). If the market value of renewable electricity were computed as the ratio of its relative price compared to the base price[1], then the authors found that the value of wind power fell from 110% of the average power price to 50-80% as wind penetration increased from 0-30% of total electricity consumption. This finding has im-

---

[1] Relative value is measured as the ratio of the hourly wind-weighted average wholesale electricity price and its time-weighted average (base price)

portant implications on the economic viability of such variable renewable technologies as their market share increases.

Soon after, at the European Commission, questions began to be raised about the cost effectiveness of the support scheme designs at an EU-wide level. The 2015 document "Launching the public consultation process on a new energy market design" (COM(2015) 340) includes a discussion on adapting support scheme to markets (Commission, 2015). It suggests that the national scope of support schemes hinders cost efficiency and that a more coordinated approach could deliver substantially higher gains by promoting investment into renewable electricity in the most optimal geographical locations. This argument came as no surprise: Germany had invested the most in solar energy by 2015, while it would have arguably been more cost-efficient to have had that investment in countries with greater sunshine. Consequently, amongst the questions posed in the consultation document were those such as, *"Should there be a more coordinated approach across member states for renewable support schemes?"* and *"What needs to be done to allow investment in renewables to be increasingly driven by market signals?"*

In a companion report by the European Commission titled "Investment perspectives in electricity markets", the role of the current market framework to ensure investment in a decarbonised power system was questioned (European Commission and Directorate-General for Economic and Financial Affairs, 2015). The report argued that the cost structure of a technology mix in a decarbonised power system exhibits decreasing average costs and positive fixed costs. As long as this cost structure remained, and assuming perfect competition, the report argued that it was uncertain that marginal pricing would produce sufficient revenue to cover the fixed costs of the technologies.

In the preceding paragraphs, some fundamental issues that have emerged in relation to the governance of electricity and the promotion of renewable energy were highlighted. In the following sections, problems tackled in this dissertation are delineated, following which the research objective and research questions are presented.

1.2. PROBLEM DEFINITION AND RESEARCH OVERVIEW

A defining characteristic of energy policy is its long-term nature. Lifetimes of investments in the sector are lumpy and commonly extend over several decades. Policies or regulatory decisions also often have very long-term ramifications. Therefore in this thesis, a long-term view spanning several decades into the future is taken.

Under the current framework, renewable electricity support policies are designed and implemented nationally. They are implemented alongside a common, international electricity market. Under EU state aid guidelines, support should be ‘market-based’. Therefore, the cost of RES-E subsidies are intricately related to the electricity markets they are situated in. As outlined in the above sections, the design of policies to support renewable electricity in Europe therefore has to contend with multiple objectives of competition, sustainability, and energy security. This reconciliation of multiple objectives has been a recurring theme throughout the history of EU energy policy.

Such a reconciliation of multiple objectives took the shape of "making renewable support schemes more *market-based*", "ensuring renewables are driven by market signals". However, it is not often clear what is meant by such statements in EU policy documents. What features of the support scheme are being referred to? What would it mean for renewables solely to be driven by market signals? How would features of support schemes impact for instance, the merit order effect and vice-versa? These issues are encapsulated in the first problem: *to unravel the interactions between renewable support scheme design and a single isolated electricity spot market, with a long- term perspective.*

Since countries are now increasingly interconnected, the second major issue tackled in this thesis concerns *cross- border effects due to different renewable support schemes between neighbouring countries in a common electricity market.* This addresses concerns about the merit-order effect spreading across national boundaries, and its ensuing distributional implications.

The final issue addressed in this dissertation relates to *the long term economic viabiliy of electricity from renewable sources given the current institutional and physical settings they operate in.* While costs of renewable technologies have dropped dramatically, effects such as their reducing market value question whether it is possible for them to attain economic viability in a decarbonised power sector. Accordingly, this research tackles the research questions presented below.

1.2.1. RESEARCH QUESTIONS

The main research question addressed in this thesis is

How do national renewable electricity support schemes interact with the electricity market over the long term (20-30 years) as the European Union transitions to a decarbonized energy system?

The following sub-questions together help address the aforementioned main research question.

- How can policy design options for RES-E support in Europe be systematically and comprehensively explored and modelled?
- How can the impact of various RES-E support design elements on the electricity market be modelled and analysed?
- How do RES-E support policy design elements interact with a single isolated electricity market and what social welfare implications do they actualise?
- How do RES-E support policy design elements interact with an interconnected, congested electricity market?
- How could major developments in the energy transition such as RES-E technology cost trends, the EU ETS, and flexibility influence RES-E support?

1.2.2. SCIENTIFIC CONTRIBUTION

Since the early 2000s, when the first renewable electricity directive appeared, there has been a vibrant debate in literature as to the most effective ways of supporting renewable electricity generation (Huber *et al.*, 2004; Voogt *et al.*, 2001; Most and Fichtner, 2010; Fais *et al.*, 2014). The methods used to perform such analysis were largely based on assumptions of perfect competition and long-term equilibrium (Capros *et al.*, 2014). Furthermore, most literature used an approach where comparisons were made between existing policies (Fais *et al.*, 2014; Newbery, 2016; Dressler, 2016; Winkler *et al.*, 2016; Reuter *et al.*, 2012). More recently, as authors began addressing interactions between electricity markets and support schemes, they proposed the idea that the key to understanding these interactions were design features of policies, rather than policies as a whole (Held *et al.*, 2014; Batlle *et al.*, 2012; del Rio and Linares, 2014). However, they have been empirical observations and classifications, rather than a formal approach to policy design. The scientific contributions emerging from this thesis can be characterised as being of two kinds: one method-oriented, and the other, application-oriented.

From a methodological perspective, this dissertation contributes to the science of policy design, by introducing a new modelling framework based on institutional analysis, design theory, and agent-based modelling. The modelling framework helps structure, simulate, and analyze socio-technical systems, and consequently design policies for such systems. Based on this framework, RES-E support schemes were implemented in terms of their design features, on an existing, agent-based model of the electricity market, called "EMLab", short for Energy Market Laboratory. EMLab is an initiative of the Energy and Industry section of the faculty of Technology, Policy and Management in TU Delft. By creating the RES-E policy analysis module in EMLab, the existing literature on methods used to analyse RES-E policies using the agent-based modelling paradigm was also expanded.

The application-oriented scientific contributions emerged when the aforementioned method was employed to address the research questions mentioned above. The new modelling approach enabled arriving at insights on the impact of design features of renewable electricity schemes on the various actors in the electricity market: consumers, producers, and the government, thus adding to the exisiting literature in the field. Specifically, cross-border impacts of disparate national renewable support schemes operating in interconnected electricity markets have received little attention in literature. Chapters 4 and 5 describe the experiments conducted and the insights that emerged, in detail.

1.2.3. RESEARCH FRAMEWORK AND THESIS STRUCTURE

In order to answer the aforementioned research questions, the following structure has been adopted. In chapter 2, the theoretical foundations for the modelling and analysis of renewable electricity support schemes and electricity markets are established. Using a combination of institutional analysis, the agent-based modelling paradigm, and existing literature, a modelling framework is presented. The theoretical foundations established are applied to empirical knowledge of current renewable electricity support schemes, to identify a set of design elements which provide a sufficient and complete description of a renewable support scheme from a welfare economics perspective.

In Chapter 3, the model itself is presented. This includes a conceptual representation of the physical systems in terms of modelling entities, relationships between the entities, features, agents, their behaviours, and algorithms that represent behaviours and policies.

Chapter 4 presents an evaluation of the impact of design elements of renewable elec-

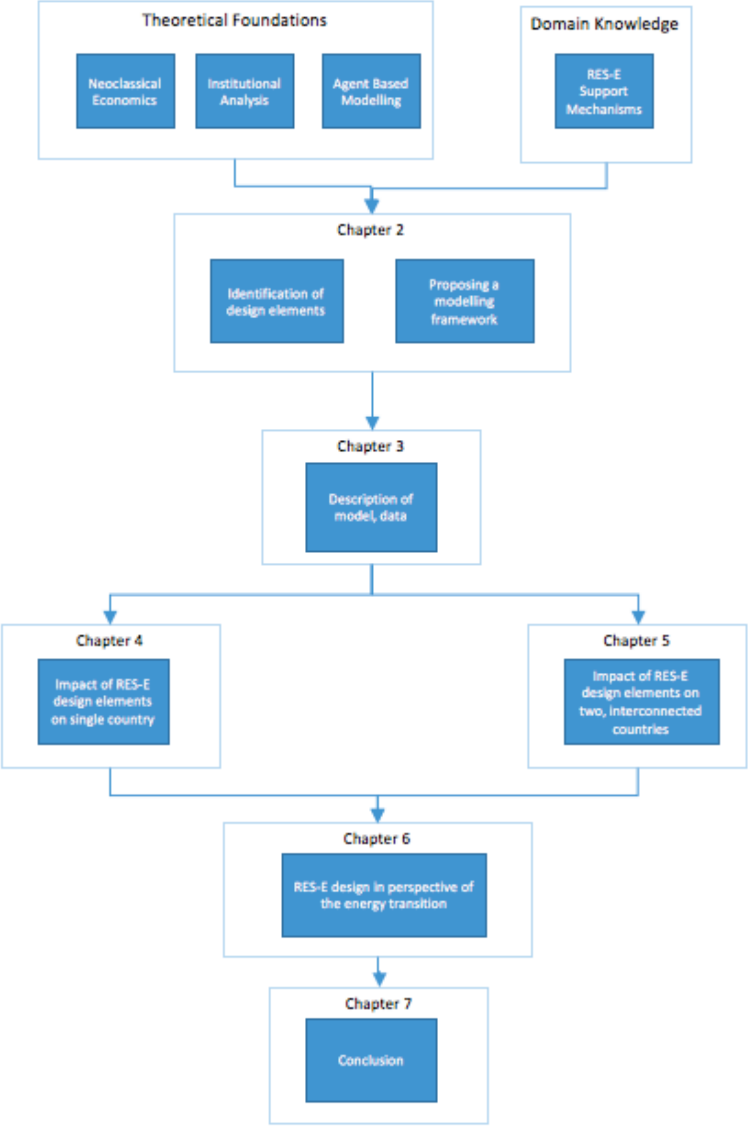


Figure 1.2: Reading guide to the thesis

tricity support schemes on a single (isolated, uncongested) region modelled similar to the power sector in the Netherlands, using the long-term agent-based model of the electricity market, and RES-E support developed earlier. Effectiveness of policy is evaluated in terms of target achievement, social welfare, and distributional implications to producer, consumer, and the government.

In Chapter 5, the model developed earlier is applied to a two-country region, based on Germany and The Netherlands, in order to evaluate long-term cross-border welfare impacts of different renewable support schemes in the two countries as they operate in an interconnected electricity market.

The aim of Chapter 6 is to evaluate factors that impact the phasing out of renewable electricity subsidies in the long term. This is done by specifically studying three aspects of the energy transition - drivers of RES-E subsidy, the EU ETS, and options for flexible capacity. In doing so, this chapter puts the results of previous chapters in a larger perspective of the energy transition.

Finally, in Chapter 7, main conclusions of the dissertation are presented. The results, model, and approach employed are reflected upon, and avenues for future research are discussed.

REFERENCES

D. Carrington, *'Spectacular' drop in renewable energy costs leads to record global boost,* The Guardian (2017).

J. De Jong, *THE 2007 ENERGY PACKAGE: THE START OF A NEW ERA?* in *European energy law report V,* Energy & law series No. 7, edited by U. Hammer and M. Roggenkamp (Intersentia ; Distribution for the USA and Canada [by] International Specialized Book Services, Antwerp ; Portland, OR : Portland, OR, 2008) pp. 96–97.

R. Hildingsson, J. Stripple, and A. Jordan, *Governing Renewable Energy in the EU: Confronting a Governance Dilemma,* European Political Science **11**, 18 (2012).

J. Nylander, *THE CONSTRUCTION OF A MARKET - A frame analysis of the liberalization of the electricity market in the European Union,* European Societies **3**, 289 (2001).

E. Commission, *Energy for the future: Renewable sources of energy,* Tech. Rep. COM(97)599 (European Commission, 1997).

F. Sensfuss, M. Ragwitz, and M. Genoese, *The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany,* Energy Policy **36**, 3086 (2008).

J. Cludius, H. Hermann, F. C. Matthes, and V. Graichen, *The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications,* Energy Economics **44**, 302 (2014).

N. Ederer, *The market value and impact of offshore wind on the electricity spot market: Evidence from Germany,* Applied Energy **154**, 805 (2015).

L. Gelabert, X. Labandeira, and P. Linares, *An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices,* Energy Economics **33**, S59 (2011).

A. O'Mahoney and E. Denny, *Electricity prices and generator behaviour in gross pool electricity markets,* Energy Policy **63**, 628 (2013).

T. Traber and C. Kemfert, *Impacts of the German Support for Renewable Energy on Electricity Prices, Emissions, and Firms,* The Energy Journal **30**, 155 (2009).

T. Traber and C. Kemfert, *Gone with the wind? — Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply,* Energy Economics **33**, 249 (2011).

H. Weigt, *Germany's wind energy: The potential for fossil capacity replacement and cost saving,* Applied Energy **86**, 1857 (2009).

K. Würzburg, X. Labandeira, and P. Linares, *Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria,* Energy Economics Supplement Issue: Fifth Atlantic Workshop in Energy and Environmental Economics, **40, Supplement 1**, S159 (2013).

L. Hirth, *The market value of variable renewables: The effect of solar wind power variability on their relative price,* Energy Economics **38**, 218 (2013).

E. Commission, *Launching the public consultation process on a new energy market design*, Tech. Rep. COM(2015) 340 final (Brussels, 2015).

European Commission and Directorate-General for Economic and Financial Affairs, *Energy economic developments: investment perspectives in electricity markets.* (Publications Office, Luxembourg, 2015) oCLC: 948760359.

C. Huber, T. Faber, R. Haas, G. Resch, J. Green, S. Olz, and S. White, *Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market*, Tech. Rep. (2004).

M. H. Voogt, M. A. Uyterlinde, K. Skytte, M. Leonardi, and M. H. Whiteley, *Renewable energy burden sharing. REBUS. Requirements and expectations of utilities and consumer organisations in the European energy sector*, Tech. Rep. (Energy research Centre of the Netherlands ECN, Petten (Netherlands), 2001).

D. Most and W. Fichtner, *Renewable energy sources in European energy supply and interactions with emission trading,* The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers **38**, 2898 (2010).

B. Fais, M. Blesl, U. Fahl, and A. Voß, *Comparing different support schemes for renewable electricity in the scope of an energy systems analysis,* Applied Energy **131**, 479 (2014).

P. Capros, L. Paroussos, P. Fragkos, S. Tsani, B. Boitier, F. Wagner, S. Busch, G. Resch, M. Blesl, and J. Bollen, *Description of models and scenarios used to assess European decarbonisation pathways,* Sustainable Energy System Changes **2**, 220 (2014).

D. M. Newbery, *Towards a green energy economy? The EU Energy Union's transition to a low-carbon zero subsidy electricity system – Lessons from the UK's Electricity Market Reform,* Applied Energy **179**, 1321 (2016).

L. Dressler, *Support Schemes for Renewable Electricity in the European Union: Producer Strategies and Competition,* Energy Economics , (2016).

J. Winkler, A. Gaio, B. Pfluger, and M. Ragwitz, *Impact of renewables on electricity markets – Do support schemes matter?* Energy Policy **93**, 157 (2016).

W. H. Reuter, J. Szolgayová, S. Fuss, and M. Obersteiner, *Renewable energy investment: Policy and market impacts,* Applied Energy **97**, 249 (2012), energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy.

A. Held, M. Ragwitz, M. Gephart, F. ISI, M. Gephart, E. de Visser, C. Klessmann, and Ecofys, *Design features of support schemes for renewable electricity*, Tech. Rep. (2014).

C. Batlle, P. Linares, M. Klobasa, J. Winkler, F. Isi, A. Ortner, and T. U. W. Eeg, *Interactions between RES-E support instruments and electricity markets*, Tech. Rep. October (Beyond 2020, 2012).

P. del Rio and P. Linares, *Back to the future? Rethinking auctions for renewable electricity support,* Renewable and Sustainable Energy Reviews **35**, 42 (2014).

2

THEORETICAL FOUNDATIONS: IDENTIFYING THE DESIGN SPACE

Parts of this chapter have been published in Energy Policy **187**, 228 (2017) Iychettira *et al.* (2017)

2.1. INTRODUCTION

The outcomes of a certain policy depend on far more than variables such as price and quantity. They depend on explicit or implicit institutions which may be part of the policy or part of the environment surrounding the policy, that shape the socio-technical system. As Polski and Ostrom (1999) point out, "Institutions delimit the capacity for social change. They are important because they are intentional constructions that structure information and create incentives ...thereby imposing constraints on the range of possible behaviour and feasible reforms." This makes institutional analysis paramount in the study of policy design. In addition, such analyses lend to the policy maker, a structured set of policy design characteristics which to operate on the socio-technical system. The challenge then lies in identifying the most essential design characteristics of a policy or set of policies, which are sufficiently informed by their institutional setting, and evaluating their impacts on the socio-technical system.

Some studies have tried to incorporate a more comprehensive approach to RES-E policy design, see for instance work by Bergmann *et al.* (2008), and Batlle *et al.* (2012a). Most literature uses a "policy analysis approach" where comparisons and categorizations are made between and across different *existing policies*; for examples refer to Batlle *et al.* (2012b), Kitzing *et al.* (2012),Kitzing (2014), and Fagiani *et al.* (2013). It is proposed here however, that the basic unit of analysis is not the policy itself, but a set of "design elements". Design elements refer to the detailed components that make up a certain policy; for instance, technology specificity, location specificity, duration of support etc. Two seemingly different RES-E support policies can be designed such that they have an equivalent effect on the market. This idea has been upheld by several authors such as Batlle *et al.* (2012a), del Rio and Linares (2014), del Rio and Mir-Artigues (2014), and Haas *et al.* (2011). However, they have been empirical observations, rather than a formal approach to policy design.

The primary objective of this chapter is to introduce a formal, structured approach to the design of policies for stimulation of RES-E in Europe. To achieve this, we decompose the objective into the following sub-objectives: (1) to identify a set of necessary and sufficient policy design elements to incentivise RES-E in Europe, and (2) to introduce a modelling framework to analyze the impact of policy design elements on the socio-technical system.

In order to accomplish the above sub-objectives we introduce a formal method based on design theory and institutional analysis to identify a policy design space, i.e., a set of necessary and sufficient design variables that we term ’design elements’. These design elements are identified for a certain level of analysis[1], and for a selected set of participants in the socio-technical system. Following this, a modelling framework to facilitate the analysis of the design elements, and identify the impact of each individual design variable on the socio-technical system is presented. The modelling framework is implemented using agent-based modelling and simulation. Such a formal approach would not only help analyse existing policies and their impact on the socio-technical system, but also help explore the full policy design space in a structured fashion, by incorporat-

---

[1] In Chapter 2 of Ostrom (2005) ’levels of analysis’ are described thus: “All rules are nested in another set of rules that define how the first set of rules can be changed... It is useful to distinguish levels of rules that cumulatively affect actions taken and outcomes obtained in any setting.”

ing the institutional context into the analysis.

2.2. THEORETICAL FOUNDATIONS AND METHODOLOGY

The objective of this section is to introduce the methodology to achieve the objectives outlined in Section 2.1. The section consists of an introduction to, and a description of different schools of thought on which the methodology rests. It comprises three main components: the application of design theory to policy design, the application of the Institutional Analysis and Development (IAD) framework for identification of design elements, and finally, the theoretical foundation to create a modelling framework to analyse policies in terms of their design elements.

2.2.1. THEORETICAL FOUNDATIONS

DESIGN THEORY APPLIED TO POLICY

"Ubiquitous, necessary, and difficult" is how Bobrow (2006) qualifies the act of policy design. Governments, irrespective of issue type, are interested in effective realization of their goals, by applying knowledge and empirical data to assess appropriateness of alternatives to achieve those goals, and thus engage in 'design,' (Howlett, 2011). The application of (generic) design theory to policy design and policy analysis is not new. Linder and Peters (1984) are among the earliest, while Howlett and del Rio (2013), Considine (2012), and Taeihagh *et al.* (2009) are among the more recent authors who have contributed to this topic. Read Howlett (2011) for a comprehensive review of policy design literature.

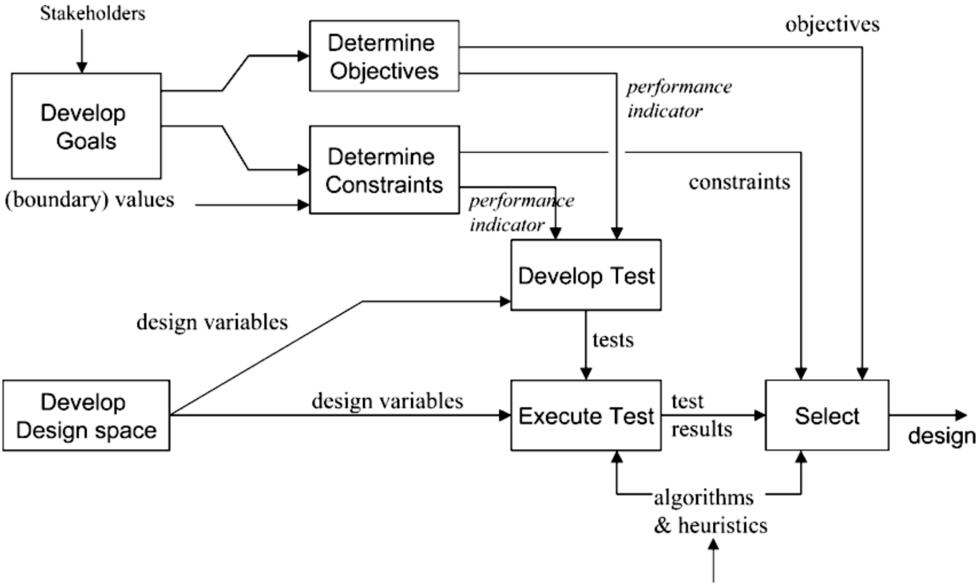


Figure 2.1: Generic Conceptual Design Framework from Herder and Stikkelman (2004)

In Taeihagh *et al.* (2009), an analogy has been drawn between process design and policy design, to inform transport policy. Their work is based on the theoretical frameworks of Process System Engineering. The framework used in this work, the Generic Conceptual Design Framework (GCDF), also has its roots in Process System Engineering.

The Generic Conceptual Design Framework has been developed collaboratively at the Carnegie Mellon University and Delft University of Technology. It is illustrated in Figure 2.1. This work is based on the design framework (specifically the problem definition and conceptual design aspects) initially developed by Westerberg *et al.* (1997), which draws heavily from process system engineering, and is described in detail and applied in Herder and Stikkelman (2004) and Subrahmanian *et al.* (2003). The framework comprises of the following main concepts, which together, structure the content of any level in a design process: 1. design goals; 2. design objectives (selection of goals to be optimized); 3. design constraints (goals that need not be optimised); 4. tests for the goals; and 5. design space.

One may contend, as Rittel and Webber (1973) did, that for most social planning problems or ‘wicked problems’, the concept of design is a technocratic activity and is not applicable to policy making, as policy-making is a value-laden activity, and therefore its appraisal is highly dependent on each participant’s personal value-set. In response, Howlett (2011) writes that there must be a distinction drawn between ‘design’ as a verb, and that as a noun - instead of treating design as an outcome, he urges the reader to view it as a process of "channelling the energies of disparate actors towards agreement in working towards similar goals in specific contexts." And that is the viewpoint that we wish to subscribe to.

INSTITUTIONAL ANALYSIS TO IDENTIFY GOALS AND POLICY DESIGN SPACE

Institutional analysis is a commonly used approach to study socio-technical systems, and especially so in the field of institutional economics; see for instance North (1991), Williamson (1998), and Ostrom (2005). There are several frameworks for institutional studies to describe socio-technical systems. For a concise, yet informative overview of the different frameworks, refer to Chapter 2 of Ghorbani (2013).

As argued in Section 2.1, institutional analysis is paramount in the study of policy design. For the purpose of this research, we choose to employ the Institutional Analysis and Development (IAD) framework developed and applied for several years by Ostrom (2005). Conceptually, this framework dissects the socio-technical system into composite *holons,* defined as ‘a stable sub-whole in an organismic or social hierarchy which displays Gestalt constancy’ Ostrom (2005). This conceptual foundation, of sub-wholes and hierarchies, also corroborates with that of process design theory. Ostrom describes the application of the IAD framework to policy design and analysis, and presents a stepwise process for it in Polski and Ostrom (1999). It also lends itself easily to analysis by computational social sciences such as ABMS, which help construct testable models of socio-technical systems, as Ghorbani *et al.* (2010) illustrate; this is explained in greater detail in Section 2.2.1.

Ghorbani (2013) describes the IAD thus: "This framework is an institutionally driven tool for (1) understanding the underlying structures of a social system, (2) capturing the operational environment, and (3) observing the patterns of interaction and outcomes, given a set of evaluation criteria. The result of this social system analysis is used to give feedback to the system, and as such support institutional change." The framework is depicted in Figure 2.2.

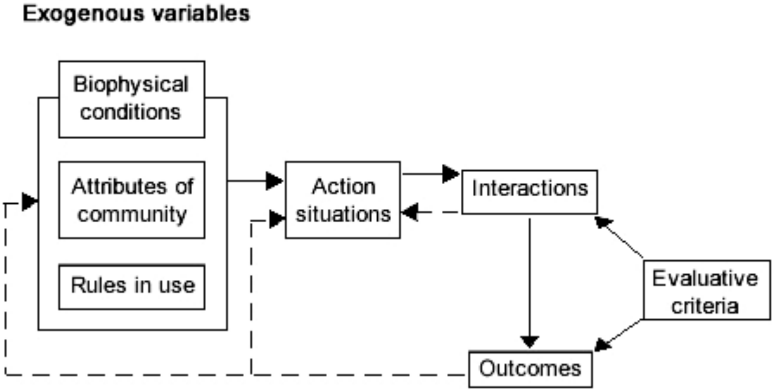


Figure 2.2: IAD Framework from Ostrom (2005)

A note on institutional economic theories: In this work the authors put forth a *framework* while remaining agnostic with regard to the theory that should be used; whether it should be transaction cost economics, neoclassical economics or a combination. We emphasize that we present and apply a *framework*, and not a *theory*, for policy design [2] In order to demonstrate the framework's application to a model, in this particular instance we adopt thories based on neoclassical economics, and also incorporate strong assumptions of imperfect information and bounded rationality. Imperfect information and bounded rationality are assumptions common in the institutionalist perspectives.

AGENT-BASED MODELLING AND SIMULATION

Agent-based Modelling and Simulation (ABMS) has established itself as being naturally well-suited to represent socio-technical systems (Conte *et al.*, 1998; Arthur, 2006). ABMS is a form of computational social science that enables one to model individual entities and their interactions with the environment (Gilbert, 2004). It is then possible to generate emergent patterns at the macro level, simply by specifying properties and interactions at the micro level. They have been successfully used to implement various socio-technical systems, including energy and industrial networks, as shown in Dam *et al.* (2012). Ghorbani (2013) have shown how agent-based modelling can be used to incorporate institutions into social simulations.

---

[2] We adopt the definitions of a theory and a framework presented by (Ostrom, 2005, chap .2); they are reproduced below.
The development and use of a general ***framework*** *helps to identify the elements (and the relationships among these elements) that one needs to consider for institutional analysis. Frameworks organize diagnostic and prescriptive inquiry. They provide the most general set of variables that should be used to analyze all types of settings relevant for the framework.*
The development and use of ***theories*** *enable the analyst to specify which components of a framework are relevant for certain kinds of questions and to make broad working assumptions about these elements. Thus, theories focus on parts of a framework and make specific assumptions that are necessary for an analyst to diagnose a phenomenon, explain its processes, and predict outcomes.*

2.2.2. A POLICY DESIGN FRAMEWORK

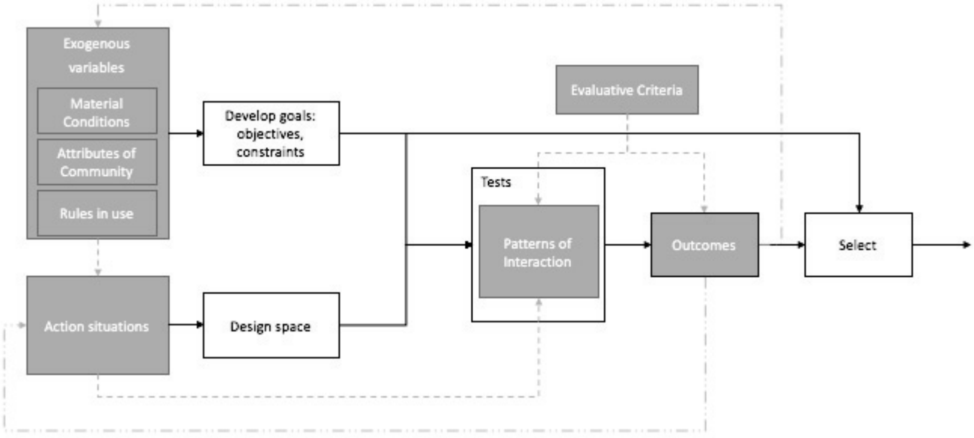


Figure 2.3: A Generic Policy Design Framework

Drawing from the aforementioned frameworks, a new framework for policy design is introduced in this section. This policy design framework maintains the basic structure of the generic conceptual design framework, while allowing different components of the IAD framework to inform it.

On the one hand, the design framework facilitates specification of goals and constraints of the policy maker, the specification of a design space, and provides a framework to evaluate alternatives based on the goals. The IAD framework on the other hand helps, decompose the socio-technical system, and specifications of interactions between participants, and interactions between participants and the physical environment. The latter therefore plays a paramount role in delineating the design space, understanding and specifying possible behaviours of actors, understanding action-outcome linkages, which can then be tested, while the former provides a structure to the process of formulating the goals, and evaluating potential alternatives.

The policy design framework, called 'A Generic Policy Design Framework' is depicted in Figure 2.3. The original design framework itself is depicted within dark, bold lines in the figure, while the grey boxes and dashed lines indicate how the IAD framework contributes to the design process. The Generic POlicy Design framework is explained below.

1. Design goals: The intended goals of the policy to be designed are usually set by the community itself. The concept of 'multiple levels of analysis' described in Chapter 2 of Ostrom (2005), helps identify which participants at what level, frame these goals, and/or constraints. According to Ostrom's definition, the rules-in-use[3] at

---

[3] Rules which affect day-to-day behaviour of participants, in the context of the issue being analyzed.

an operational level are set one level deeper, at a 'collective' level. This is shown in Figure 2.4. In reality, the policy maker exists at least in two levels: the member-state level, and at the European level. However, for the sake of illustration in Figure 2.4, it is assumed that values and objectives of the two entities are aligned. The policy objectives therefore, are derived from the broad objectives of the European Commission as mentioned in European Commission (2014). These objectives are mentioned below. To improve the ease of associating between policy attributes and overall objectives, we operationalize the objectives into specific ones.

- Affordability - low cost per unit production or investment
- Sustainability - effective investment in low carbon technologies and RES-E production
- Security of Supply - also known as 'energy adequacy' refers to whether sufficient operational capacity exists to meet demand, at any given point in time.
- Competition - preventing distortions, when multiple countries are considered, in cross border trade and investments.

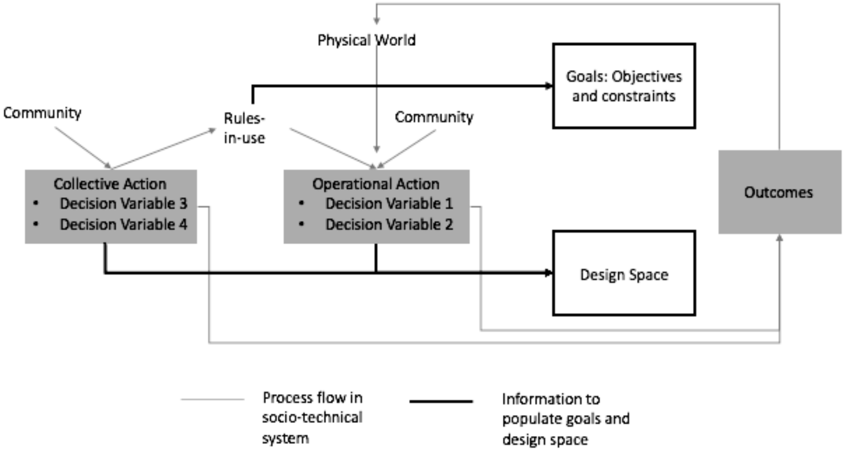


Figure 2.4: Example Specification of Policy Design Framework

2. Design space: Discerning the design space requires the policy analyst to make decisions regarding which design variables are relevant. The action situation in the IAD framework is defined thus, "whenever two or more individuals are faced with a set of potential actions that jointly produces outcomes, these individuals can be said to be "in" an action situation" according to Ostrom (2005). Therefore, the action situation outlines potential actions that participants can take, and outcomes an action could lead to, based on their perceived notions of which actions lead to which outcomes, called 'action-outcome linkages'. For instance, the energy producer must make decisions regarding which technology to invest in, where to place the power plant, and its size. The policy maker would, at the very least, have

to make decisions regarding the manner in which the remuneration is provided - whether a price or quantity warranty [4], whether the cost burden is distributed among the tax payers or only the consumers, whether there is a penalty to non-compliance. Combined across different levels of analysis (i.e., the producer at the operational level and the policy maker at the collective level), this would present a complete set of potential actions that a policy may be designed with, i.e., the design space of the policy. This is depicted in Figure 2.4.

3. Tests: The next step in the design framework calls for developing and executing a test. This test would simulate patterns of interactions, based on design objectives, constraints and design variables discerned in the previous steps. In order to simulate patterns of interactions that lead to outcomes, tests must include specifications of action-outcome linkages. This would mean that simulations must specify behaviour that is theoretically or empirically supported, and that participants are expected to show given certain setting of exogenous variables. The test should help understand and explain which outcomes are created under what different conditions of the design space,. Agent-based modelling is a suitable approach for creating such simulations, as described in Section 2.2.1. A detailed description of the modelling framework created in order to simulate the impact of RES-E design elements is presented in section 3.4.

4. Outcomes and Selection: The outcomes from the simulation help identify which configurations of design variables (design elements) lead to desired outcomes. With the help of the goals identified in step one, it is possible to select a configuration of design elements that meet the objectives and constraints of the policy issue to be resolved.

So far, a rather general overview of the Policy Design Framework has been provided. Central to the objectives of this paper is the identification of a closed set of design elements. Therefore, it is befitting that this aspect of the policy design framework is paid further attention.

DESIGN SPACE: ON IDENTIFICATION OF DESIGN ELEMENTS

Under step 2 above, the Design Space, i.e., the set of ‘design elements’ were established as a combination of decision variables across the relevant levels-of-analysis (collective and operational). In order to elucidate the process of arriving at the decision variables, and consequently the design elements, it is necessary to apply the IAD framework to the policy issue; specifically, this would include description of the action arenas relevant to the energy producer and to the policy maker. In Section 2.3.1, the framework has been applied to RES-E policy making in Europe: the physical and community attributes are outlined, followed by the action arenas themselves.

The *design space* is a set of design elements defined at the community-level, ie., at the level of the policy maker, as a combination of

---

[4] The word warranty here is used to define a promise or committment or guarantee, that a policy-maker makes to an energy producer. For instance, a mandated quantity of electricity supply or consumption from RES technologies would mean a *quantity warranty*, while a mandated price per unit of electricity generated from RES would mean a *price warranty*.

1. decision variables of the policy-maker at the community level (Decision Variables 3 and 4, in Figure 2.4), such as type of warranty, cost-burden, scheme duration etc., and
2. variables which indicate whether the purview of one or more of the above decision variables further apply to each decision variable at the operational level (Decision Variables 1 and 2, in Figure 2.4); for instance whether the warranty could be technology neutral or specific, location neutral or specific, and size neutral or specific.

Depending on the objectives of, and assumptions underlying the analysis, not all design elements may be considered for evaluation. The choice of design elements for evaluation may be strongly influenced by the *frame of analysis*. In an exhaustive work, Bobrow and Dryzek (1987) highlight the different frames of analysis within policy analysis; two such frames are outlined here. A welfare economics perspective would assume a benevolent policy-maker whose only interest is to increase social welfare. A public choice perspective posits that politicians and bureaucrats are more interested in serving their own interests, rather than that of the public. For instance, in the particular case of designing RES-E support, the decision regarding whether the subsidy costs are borne by the state budget versus electricity consumers, would be much more relevant in the public choice perspective, rather than one of welfare economics. This idea is revisited and clarified in Section 2.3.1 and critically examined in Section 2.5.

2.3. APPLYING THE POLICY DESIGN FRAMEWORK TO RES-E SUPPORT DESIGN

In this section, the Policy Design Framework introduced above is applied to the specific case of RES-E support scheme design. In doing this, three steps are followed: the IAD framework is first applied to the case. This forces the analyst to delineate the problem and participants, thus creating boundary conditions, which forms the first and crucial step towards identifying design elements. This also leads to specification of the policy design framework introduced in Figure 2.4, to RES-E support. Subsequently, the design-elements of RES-E support schemes are identified from literature in Section 2.3.2. Finally, a conceptualization of the agent based model for the testing and evaluation of the different designs is presented in Section 3.4.

2.3.1. IDENTIFICATION OF PARTICIPANTS, ACTION SITUATIONS, AND EXOGENOUS VARIABLES

The IAD framework shown in 2.2 requires the identification of physical attributes, community attributes, and "action situations" related to investment in RES-E. Electricity, from renewable energy or otherwise, is an excludable and subtractable commodity. RES-E in particular is produced by installing renewable energy generating capacity, such as for instance, solar PV panels or offshore wind farms.

While there are no specific European level targets beyond 2030 for consumption of electricity from renewable sources, it is recognized in the 2050 roadmap that ‘power generation system would have to undergo structural change and achieve a significant level of decarbonisation already in 2030 (57-65% in 2030 and 96-99% in 2050)’(Commission, 2011). In order to realize this level of decarbonisation, policy makers design schemes to incentivize investment in RES-E sources.

The policy maker implementing a support scheme therefore forms one action-situation. The second action situation involves producers of renewable electricity; they are assumed to be boundedly rational actors attempting to maximize their profits via actions such as investments in electricity producing technologies. Their strategy for investment in RES-E generation capacity is to make a cost benefit analysis, i.e., a net present value calculation for each investment decision, under uncertainty. This is a stylized representation of actors, to make the analysis tractable. It must be noted however that representation is only one instantiation of the modelling framework presented.

The disadvantage of this abstraction is that it does not consider actors who might have other motives (to be autarkic, to self-consume, to create an energy community, to produce green energy for its own sake). On the other hand, the largest share of current energy production comes from utility companies whose primary motive is profitability, irrespective of differences in ownership or corporate structure. Also, even if other ownership structures were in place, it is hard to imagine a scenario where an actor would not be concerned with the profitability of the project. Therefore, in the current modelling framework, we assume that the Energy Producer agent makes an investment only when the cost-benefit analyses indicate profitability.

Ostrom (2005) defines an action situation in terms of the following elements: participants, positions, actions, outcomes, action-outcome linkages, information about the action situation, and payoffs or the costs and benefits. These elements have been defined, and their corresponding values have been identified for the two action situations presented above.

However, information about future prices, and therefore revenue, and therefore whether the decision is a viable one, is notoriously difficult to predict. Uncertainty comes in the form of other actors' decisions on investment, regulatory uncertainty, fuel price uncertainty which impact the electricity market price and therefore the revenue, and uncertainty regarding future electricity prices. It is assumed that producers' strategy is profit maximising, while the government's goal is to reach the renewable target (constraint) in an affordable (cost-effective) manner. It is also assumed that regulators have as much information as the energy producers. And that each energy producer is aware of others' past decisions on investment.

Table 2.1: Specification of Action Arenas

Elements of an Action Situation, defined	**Operational Action Arena**	**Collective Action Arena**
Participants: Decision-making entities.	Energy Producers	Government(s)

Positions: Anonymous slots into and out of which participants move.	Energy producers are sellers of electricity and investors in power plants. They are assumed to be boundedly rational, and profit maximizing.	A policy-maker is a participant with the authority to decide on which type of electricity production is preferred, and how the remuneration is organized. She is assumed to be benevolent and is primarily interested in increasing social welfare.
Action: A selection of a setting or a value on a control variable which a participant hopes will affect the outcome variable.	Act of deciding whether to make an investment in a power plant. This would entail decisions on technology, location, and size	Governments make decisions on how to incentivize RES-E. Based on literature on RES-E support in Europe, and on empirical evidence, the decision variables include price warranty, quantity warranty, contract type (risk allocation), distribution of cost burden, budget limits. These are described in greater detail in section 2.3.2.
Action-outcome linkage: A setting on a control variable is considered "linked" to a state variable when it is possible to use that setting to cause the state variable (1) to come into being, (2) to disappear, or (3) to change in degree.	A decision to invest is taken if the net present value of the investment is positive. An investment occurs, causing a structural change in the physical system, and therefore changing the (expected electricity price) for the next investment.	Each setting of the policy-maker's decision modifies the NPV calculation of the producer in a certain way; different combinations of settings lead to different repeated patterns of interaction, which further lead to different outcomes.
Information: Access to information regarding other participants, their positions, their action sets, and payoffs	Information about how many plants have been invested into is available to each participant at any point in time. However, information about future electricity prices, future fuel prices and future demands, much like in reality, are not available. The producers use forecasting techniques for the same.	It is assumed that the government have the same information as the energy producers.
Costs and benefits	Given by the financial returns of the energy producer equation.	Share in RES-E electricity, at low costs

The IAD framework, thus set-up for impacts of RES-E policies on energy investment, is illustrated in Figure 2.5. The figure also illustrates how information from the IAD framework feeds into the policy design framework, and populates the design space. In the next section explanations of the design elements are provided.

2.3.2. DESIGN SPACE: DESIGN ELEMENTS OF RES-E SUPPORT SCHEMES

The two action arenas and potential actions at each arena were outlined in the previous section. The design space is a collection of decision variables or potential actions that

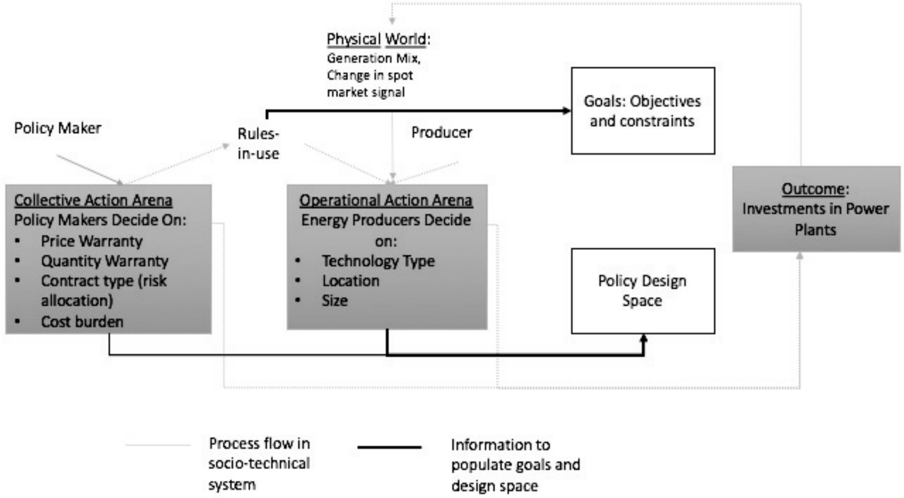


Figure 2.5: Specification of policy design framework for RES-E support

participants at two levels can make: the operational (energy producer), and the collective (policy-maker) levels. As mentioned earlier, the assumption is that the actions are of a benevolent policy maker concerned with welfare economics. This is shown in Figure 2.5. The design elements are based on insights from literature on renewable support schemes. Looking at the problem from the lens of a welfare economics perspective narrows down literature to that extent. The formulation of design elements is also an iterative process, where comparisons are made with a set of existing policies implemented. The comparisons with empirical experiences is presented in Section 2.4.

One could then wonder how the design elements below are different from those determined based on neo-classical economics. While the design elements quantity or price warranty do indeed originate directly from neoclassical economics, many others do not. In a neoclassical firm, the only function of management is to select profit-maximizing quantities of outputs and inputs, which means, determining the quantity and the consequent price that is established; see North (1991). Other core assumptions of neoclassical economics include rationality (utility maximization), and a focus on the existence of an equilibrium; read Himmelweit *et al.* (2011).

Other design elements mentioned in the current paper however, are not typically considered in neoclassical economics. In order to make analyses tractable, equilibrium models frequently make abstractions regarding perfect knowledge of costs, revenues, and competitive positions. Therefore, design elements such as contract duration and frequency of change in warranty do not typically feature in partial or general equilibrium models. Another important abstraction in neoclassical economics is that firms exist to produce an already fully defined product. The idea of diversification or specification of products as interchangeable depending on changing institutions (such as policies on asset specificity) is difficult to incorporate into the analysis as the product has already been defined. Therefore, design elements such as asset (technology, size, location) specificity also do not typically feature in partial or general equilibrium models. Some argue that the institutionalist perspective itself is characterised in terms of how it differs from the neoclassical perspective Himmelweit *et al.* (2011). We provide a method to incorporate these differences and operationalize their analysis.

Another aspect of the way the design elements are chosen, is that they are mutually exclusive from another; if two actions are substitutable, then they become alternative states for one design element. For instance, either a price warranty or a quantity warranty must be chosen by the welfare maximizing policy-maker, he does not set both simultaneously. However, he can choose technology specificity in addition to say, quantity warranty.

Table 2.2 below lists the complete set of design elements, and their possible impacts on the socio-technical system, as hypothesized in literature. Their impacts on the socio-technical system is referred to with the term "action-outcome linkages" as per the IAD framework.

Table 2.2: Design Elements

Design Element	Definition	Action-Outcome Linkages	References
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.	Under a quantity warranty with no long-term contract, investors face a substantial price risk. With a price warranty, quantity of investment highly sensitive to the set price.	Batlle *et al.* (2012b)
Contract w.r.t. electricity market price	Revenue from the electricity market can be accounted for ex ante, or ex post.	When revenue is calculated ex-ante, the uncertainty in future electricity price and consequently the revenue risk lies with agent (either regulator or energy producer) which calculates the subsidy. When calculated ex-post, the electricity market revenue risk lies with the subsidising agent (government).	
Contract Length or Project Duration	The length of time for which the support scheme is valid	Support schemes that last longer are subject to lower regulatory uncertainty, which could mean lower risk for an investor.	Batlle *et al.* (2012a)
Technology Specificity	The design element which specifies which technologies are eligible for a certain support scheme.	It encourages immature technologies. It may lead to more expensive technologies being incentivized early on, but the overall cost of RES generation could be lower than a technology neutral scenario, due to the lack of windfall profits for the energy producers.	Fais *et al.* (2014); Huber *et al.* (2004)
Location Specificity	This element would allow the differentiating of support levels by location.	If higher support is given to locations with less resource endowment, RE power plants would be more evenly distributed in the region, which might lead to a reduced need for grid infrastructure. However, the incentive to use the best locations might be lost.	Batlle *et al.* (2012a)

Size specificity	This element would allow the differentiating of support levels by size.	Larger installations allow for economies of scale, while incentivizing smaller sized applications lead to more decentralized generation, and could reduce market power. With greater smaller sized technologies, distribution grid would need to be reinforced, and the impact on the transmission grid is unclear.	Batlle *et al.* (2012a)
Cost burden	The cost of the RES-E support could be borne either by the consumers or by the tax payers (state budget).	When financed by consumers, the scheme is perceived as less risky as compared to when financed by the state budget. This is because taxpayers finance is usually negotiated annually, while laws involving consumers typically last longer. Financing by tax-payers sets up an implicit cross-subsidy between the tax-payers and electricity consumers. However, since RES-E support is justified by the public good of driving down costs so as to benefit all future users of RES-E, an argument is that the funds should come from general taxation .	Batlle *et al.* (2012b)
Cost containment mechanisms	Adaptation of support levels to technology costs and state budget related political feasibility concerns. Ex: capacity caps generation caps, cost caps.	They are necessary because controlling the costs of RE support is argued to be absolutely vital for its political feasibility and social acceptability.	del Rio and Mir-Artigues (2014)
Penalty for non compliance	Penalties are a means to deter non – compliance of the regulation.	Support schemes are ineffective if developers have the possibility to back-off without consequences. However, penalties may just increase the cost as bidders could include the cost of the penalty into the bid, if the risk of not complying is high enough. Furthermore, penalties may deter participation of small actors.	del Rio and Linares (2014)
Frequency of Change in Warranty	The number of times the price or quantity signal changes over the duration of the support scheme.	If the frequency of change is high, like with the Scandinavian tradable green certificate system, where the signal changes each year, the risk to investment increases. Long term contracts lead to lower prices and they can be used to compensate low support levels.	

2.4. EMPIRICAL REPRESENTATIVENESS OF DESIGN ELEMENTS

RES-E support schemes take various forms across Western Europe - tenders, feed-in-tariffs, tradable green certificates, and their variations and combinations. Here, six RES-E support schemes across five countries in Western Europe have been studied and represented in terms of the design elements that were formulated in Section 2.3.2. Table 2.3 demonstrates that the design elements can indeed be used to represent, and differentiate between, a variety of policies. The table below also shows that this approach lends itself to a broader and better empirically-founded representation of policies than pure neo-classical economics allows for.

Table 2.3: Existing RES-E Support Schemes in terms of Design Elements. Source: Commission (2012)

Design element	**DE EEG FiT**	**DE Premium Tariff**	**FR Tender EOLE**	**NL SDE+**	**UK Contract for Differences**	**Sweden Quota System**
Quantity Warranty / Price Warranty	Price warranty	Price warranty	Quantity warranty (Auction)	Quantity Warranty (Base cost determined based on auction)	Quantity Warranty (Strike price determined based on auction)	Quantity warranty (TGC)
Contract w.r.t Electricity Market Price	Ex-post	Ex-ante	Ex-ante	Ex-post, yearly	Ex-post	Remuneration solely depends on certificate market price
Contract Length (project duration in years)	20	20	15	8,12,15 years, based on technology	<15	15
Technology Specificity	technology specific	technology specific	technology neutral	technology neutral	technology specific [5]	technology neutral
Location Specificity	location neutral	location neutral	location neutral	location neutral	location neutral	location neutral
Size Specificity	<= 10 kW	<= 10 kW	>12MW	differs per technology	none	
Cost Burden	Consumers	Consumers	Consumers	State Budget	Consumers	Consumers
Cost Containment Mechanisms	Quantity cap of 52GW	Max Capacity 400MW	Quantity cap of 52GW	Capped by budget (€ 4 billion in sring 2016)	Capped by quantity	Capped by quantity
Penalty for Non-compliance	None	None	None	None	None	Exists
Frequency of Change in Warranty per Project	Warranty remains same during project duration	Warranty remains same during project duration	Warranty remains same during project duration	Warranty remains same during project duration	Warranty remains same during project duration	TGC market cleared once a year for all plants; warranty varies annually

---

[5] Source: BEIS (2016)

2.5. MERITS AND LIMITATIONS OF THE APPROACH

MERITS

The approach presented enables us identify what actions can be taken by whom under the current framework of rules and regulations, and therefore identifies the 'levers and knobs' so to say, of energy policy design. Systematically identifying these levers that we call 'design elements', at the level of the producers and then at the level of the national regulations, provides the policy analysts and policy makers at the level of the European Commission a much, much wider range of variables to use in their policy recommendations.

Understanding these 'levers and knobs' is especially important because over the past several decades, the European Commission has been implementing directives towards one common internal electricity market. At the same time, national policies and regulations in related topics (such as renewable support or security of supply policies) sometimes seem to work exactly in the opposite direction; see Glachant and Ruester (2013). The approach presented identifies more levers or variables than just quantity and price, with the help of an institutional analysis approach and empirical evidence and thereby assists us in resolving this dichotomy.

For instance, having technology neutral policies in one country would lead producers of non-marginal technologies to establish themselves in the same country, even when purely in terms of wind-resources, a different country would be a better choice. In a similar fashion, policies which shield producers from the risk of electricity price volatility in a certain country might make that country far more attractive than another country with no such policy, but with far better natural resources. Therefore, a design element such as technology specificity or a method of risk allocation (ex-ante vs ex-post electricity price setting) could severely undermine the idea of efficient resource allocation, which the single internal electricity market promotes. The modelling framework, as demonstrated, thus provides a method to identify which of these design elements impact efficient resource allocation among different member states, and to what extent. The model itself indicates that technology specificity vs neutrality would have a much larger impact (60%) on subsidy costs, than the impact of price setting being ex-ante or ex-post (15%).

LIMITATIONS

Important assumptions have been made regarding characteristics of the participants and the action situations that they might find themselves in. For instance, a producer makes decisions mainly regarding economic and physical aspects of the technology. In reality however, there are other action situations through which policy makers could be eventually influenced. For instance, if a severe penalty or taxes were to be introduced, workers could organize a protest. Or if a technology were to be completely banned, as nuclear energy has been in Germany, producers could file a lawsuit against the government like Vattenfall did. Therefore, the analysis is limited in that the design space does not include say, the 'political man' or the 'emotional man', but mainly focuses on the 'rational man', although boundedly so. In that sense, the analysis so far could be characterised as being technocratic. Indeed, if the energy producer agent were to assume multiple identities, such as being politically active and strongly pushing for local autarky, the design elements would be different. Another limitation of the approach as presented, is its computationally intensive nature; further attention could be paid to the process of reducing the number of design elements to suit computationally constrained situations.

Despite the limitations, within the action situation and roles outlined in this analysis, and from a welfare economics paradigm, the approach presented provides a methodology for creating, simulating, and testing a complete policy design space.

2.6. CONCLUSIONS AND POLICY IMPLICATIONS

Energy policy design in Europe is a complex issue: not least because of the co-existence of a common European policy, along with very disparate policies at the member state levels. The policy maker is faced with the daunting challenge of analysing multiple actors, multiple decision criteria, at multiple levels of operation and/or governance. Using a combination of design theory, institutional analysis, and agent-based modelling (ABM), we provide a method to systematically explore policy design options for RES-E support in Europe. This is done firstly by identification of decision variables, which then lead to the design elements of a policy, and secondly by evaluating the impact of each design element on the socio-technical system using an agent-based model.

Given a certain frame of analysis, we propose that it is theoretically possible to identify the complete policy design space. Crucially, this aspect potentially opens up to the policy analyst new avenues for intervention, and allows her to explore, given a range of uncertainties, which element(s) of intervention is(are) the most vital to achieve goals of the community. The applicability of the approach is demonstrated by representing and differentiating between six renewable electricity support schemes from Western Europe in terms of the design elements. The applicability of the modelling framework using ABM, and consequently the Design Element Approach, is demonstrated by evaluating the long-term, dynamic impact of three design elements: *price warranty versus quantity warranty, technology neutrality versus specificity,* and accounting for the electricity market price *ex-ante versus ex-post* on the Dutch electricity sector. A vital result, demonstrated in Chapter 4 and described in section 4.3.1, is that *technology specificity* leads to making the scheme 60% more cost effective than technology neutrality.

It is important to note here that claims of completeness of the design space come with limitations. For instance, if the energy producer agent were to assume multiple identities, such as being politically active and strongly pushing for local autarky, the design elements would be different. The design framework published here therefore pertains mainly to an analysis which lies within the scope of welfare economics, although founded firmly within an institutional framework and empirical experience. Other limitations of the approach include its computationally intensive nature, and the need to prudently select the most important design elements necessary for the analysis.

Avenues for future work are many. The foremost of these involve demonstrating with modelling, the application of this framework to understand impacts of different renewable electricity policy designs in neighbouring countries sharing one common electricity market, on cross-border welfare effects. Such work would pave the way towards quantitatively understanding whether and how renewable support scheme designs in neighbouring member states should be harmonised, in view of the common electricity market. This analysis is being performed for a forthcoming paper. Other possibilities for future work include designing an endogenous policy-maker agent, who dynamically changes values of design variables based on indicators in the model. The most challenging avenue for further exploration would be to identify a design space involving agents with more than just economical considerations and identities, but are more complex involving perhaps political and cultural considerations as well.

The implications of this work are, from the perspective of the authors, most useful for policy makers of RES-E support schemes, at both the member-state and at European levels. Given that governance of renewable energy support beyond 2020 at the European level is still undefined, while a European target for renewables has been set, this work paves the way for a more comprehensive, formal, empirically founded analysis of RES-E policy design than what currently prevails.

REFERENCES

K. K. Iychettira, R. A. Hakvoort, P. Linares, and R. d. Jeu, *Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare,* Applied Energy **187**, 228 (2017).

M. M. Polski and E. Ostrom, *An Institutional Framework for Policy Analysis and Design,* (Indiana University, Bloomington, IN, 1999).

J. Bergmann, C. Bitsch, V. Behlau, and S. Jensen, *A European harmonised policy to promote RES-electricity - sharing costs and benefits*, Tech. Rep. D17 (Vienna University of Technology, 2008).

C. Batlle, P. Linares, M. Klobasa, J. Winkler, F. Isi, A. Ortner, and T. U. W. Eeg, *Interactions between RES-E support instruments and electricity markets*, Tech. Rep. October (Beyond 2020, 2012).

C. Batlle, I. J. Pérez-Arriaga, and P. Zambrano-Barragán, *Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing,* Energy Policy Modeling Transport (Energy) Demand and Policies, **41**, 212 (2012b).

L. Kitzing, C. Mitchell, and P. E. Morthorst, *Renewable energy policies in Europe: Converging or diverging?* Energy Policy **51**, 192 (2012).

L. Kitzing, *Risk implications of renewable support instruments: Comparative analysis of feed-in tariffs and premiums using a mean–variance approach,* Energy **64**, 495 (2014).

R. Fagiani, J. Barquín, and R. Hakvoort, *Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs,* Energy Policy Special section: Long Run Transitions to Sustainable Economic Structures in the European Union and Beyond, **55**, 648 (2013).

P. del Rio and P. Linares, *Back to the future? Rethinking auctions for renewable electricity support,* Renewable and Sustainable Energy Reviews **35**, 42 (2014).

P. del Rio and P. Mir-Artigues, *Combinations of support instruments for renewable electricity in Europe: A review,* Renewable and Sustainable Energy Reviews **40**, 287 (2014).

R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, and A. Held, *A historical review of promotion strategies for electricity from renewable energy sources in EU countries,* Renewable and Sustainable Energy Reviews **15**, 1003 (2011).

E. Ostrom, *Understanding Institutional Diversity* (Princeton University Press, Princeton, New Jersey, 2005).

D. B. Bobrow, *Chapter 5: Policy Design: Ubiquitous, Necessary and Difficult,* in *Handbook of Public Policy* (SAGE Publications, 2006).

M. Howlett, *Revisiting Policy Design: The Rise and Fall (and Rebirth?) of Policy Design Studies,* (Reykjavik, Iceland, 2011).

S. H. Linder and B. G. Peters, *From Social Theory to Policy Design,* Journal of Public Policy **4**, 237 (1984).

M. Howlett and P. del Rio, *Policy Portfolios and their Design: A Meta Analysis,* (Grenoble, France, 2013).

M. Considine, *Thinking Outside the Box? Applying Design Theory to Public Policy,* Politics and Policy **40**, 704 (2012).

A. Taeihagh, R. Banaras-Alcantara, and M. Claire, *Development of a novel framework for the design of transport policies to achieve environmental targets,* Computers & Chemical Engineering **33** (2009).

P. Herder and R. M. Stikkelman, *Methanol-Based Industrial Cluster Design: A Study of Design Options and the Design Process,* Industrial & Engineering Chemistry Research **43**, 3879 (2004).

A. W. Westerberg, E. Subrahmainan, Y. Reich, and S. Konda, *Designing the process design process,* Computers & Chemical Engineering **21, Supplement**, S1 (1997), supplement to Computers and Chemical Engineering6th International Symposium on Process Systems Engineering and 30th European Symposium on Computer Aided Process Engineering.

E. Subrahmanian, A. W. Westerberg, S. Talukdar, J. Garett, A. Jacobson, C. Paredis, A. Christina, P. Herder, and T. Adam, *Integrating Social Aspects and Group Work Aspects in Engineering Design Education,* International Journal of Engineering Education **19** (2003).

H. W. J. Rittel and M. M. Webber, *Dilemmas in a general theory of planning,* Policy Sciences **4**, 155 (1973).

D. C. North, *Institutions, Institutional Change and Economic Performance* (1991).

O. E. Williamson, *Transaction Cost Economics: How It Works; Where It is Headed,* De Economist **146**, 23 (1998).

A. Ghorbani, *Structuring Socio- technical Complexity*, Ph.D. thesis, Delft University of Technology (2013).

A. Ghorbani, A. Ligtvoet, I. Nikolic, and G. Dijkema, *Using institutional frameworks to conceptualize agent-based models of socio-technical systems,* Proceeding of the 2010 workshop on complex system modeling and simulation **3**, 33 (2010).

R. Conte, N. Gilbert, and J. S. Sichman, *Multi-Agent Systems and Agent-Based Simulation: First International Workshop, MABS '98, Paris, France, July 4-6, 1998. Proceedings,* (Springer Berlin Heidelberg, Berlin, Heidelberg, 1998) pp. 1–9.

W. B. Arthur, *Chapter 32 Out-of-Equilibrium Economics and Agent-Based Modeling,* (Elsevier, 2006) pp. 1551 – 1564.

N. Gilbert, *Agent-based social simulation: dealing with complexity,* The Complex Systems Network of Excellence **9**, 1 (2004).

K. H. V. Dam, I. Nikolic, and Z. Lukszo, *Agent-based modelling of socio-technical systems,* May (Springer, 2012).

European Commission, *A policy framework for climate and energy in the period from 2020 to 2030,* (2014).

D. B. Bobrow and J. S. Dryzek, *Policy Analysis by Design* (Pittsburgh University Press, 1987).

E. Commission, *Energy Roadmap 2050*, Tech. Rep. COM/2011/0885 (Brussels, 2011).

S. Himmelweit, R. Simonetti, and A. Trigg, *Microeconomics: Neoclassical and Institutionalist Perspectives on Economic Behaviour*, 1st ed. (Cengage Learning, 2011).

B. Fais, M. Blesl, U. Fahl, and A. Voß, *Comparing different support schemes for renewable electricity in the scope of an energy systems analysis,* Applied Energy **131**, 479 (2014).

C. Huber, T. Faber, R. Haas, G. Resch, J. Green, S. Olz, and S. White, *Deriving optimal promotion strategied for increasing hte share of RES-E in a dynamic European electricity market*, Tech. Rep. (2004).

E. Commission, *RES Legal Europe Database for Regulation on Renewable Energy Generation,* (2012), rES LEGAL Europe is the website on regulations on renewable energy generation. In the database you will find information on the important legislation on the support schemes, grid issues and policies for energy from renewable sources covering all three energy sectors: electricity, heating & cooling and transport. The scope of this database covers all the EU 27 Member States, the EFTA Countries and some EU Accession Countries. The website offers links to all relevant original legislation, is free of charge and is updated on a regular basis.

BEIS, *Contracts for Difference: An explanation of the methodology used to set administrative CFD strike prices for the next CFD allocation round*, Tech. Rep. (Department for Business, Energy and Industrial Strategy, 2016).

J.-M. Glachant and S. Ruester, *The EU internal electricity market : done forever?*, Working Paper (2013).

3

MODELLING: EMLAB GENERATION AND RENEWABLE SUPPORT

Parts of this chapter have been published in Applied Energy **106**, 169 (2017) Iychettira *et al.* (2017)

3.1. INTRODUCTION

In the previous chapters the problem was described, and theoretical, conceptual foundations to perceiving the problem and evaluating alternatives were established. The objective of this chapter is to describe the "testing enviroment", or the model that is used to evaluate various policy options over the course of this dissertation.

The **E**nergy **M**odelling **Lab**oratory, known as EMLab, is an open source energy modelling project initiated at the Energy and Industry section of the Technology Policy Management faculty at the Delft University of Technology. Multiple doctoral and master's students have learnt from and contributed to this project over the past several years. This dissertation builds on the shoulders of those proverbial giants who have contributed to EMLab before me, and have helped me render my own contributions to it.

The initial conceptualisation and implementation of EMLab-Generation was carried out by de Vries *et al.* (2012). The AgentSpring agent-based modelling framework created by Chmieliauskas *et al.* (2012) provided the software architecture platform for the model. Work on power market transition models by Chappin (2011) also contributed to the conceptualisation and implementation of the core modules of EMLab. Richstein (2015) finished its implementation and verified and validated the model. Several conceptual and practical improvements were made: the investment algorithm was improved, banking was incorporated into the CO2 market. This chapter seeks to describe in detail the parts of existing EMLab that have been used for this work, and the additional parts that were especially built to address the research questions of this dissertation.

To help the reader peruse relevant sections, a short reading guide is presented here. Firstly, based on the analysis from the previous chapter, the system to be modelled is delineated, and the main agents whose behaviours are modelled are presented in Section 3.2. Secondly, the parts of EMLab that existed prior to the start of this work, and that are relevant to this work are descibed in Section 3.3. Finally, the parts of EMLab, that were created by the author specially for the purposes of her doctoral programme, i.e., the models of the different RES-E support schemes are described in 3.4.

3.2. SYSTEM DECOMPOSITION OF BASE MODEL IN EMLAB

This section follows directly from Section 2.3.1 in the previous chapter, where participants and action situations were identified. In this section, a testing environment designed to evaluate the impact of design elements that were identified in the previous chapter, is described. The testing environment simulates an electricity market, producer agents taking investment decisions, and a 'government' agent implementing RES-E support policies in terms of their design elements. A brief description of the conceptualization of the model is presented here, to demontrate one instantiation[2] of the framework presented in the previous chapter. The schematic representation of the testing environment for the policy design framework is presented in Figure 3.1. The model consists of a 'base model' where energy producers' decisions are simulated, and an 'RES-E support scheme model'.

---

[2] The word instantiation is used to mean: *'(of a universal or abstract concept) have an instance; be represented by an actual example.'*

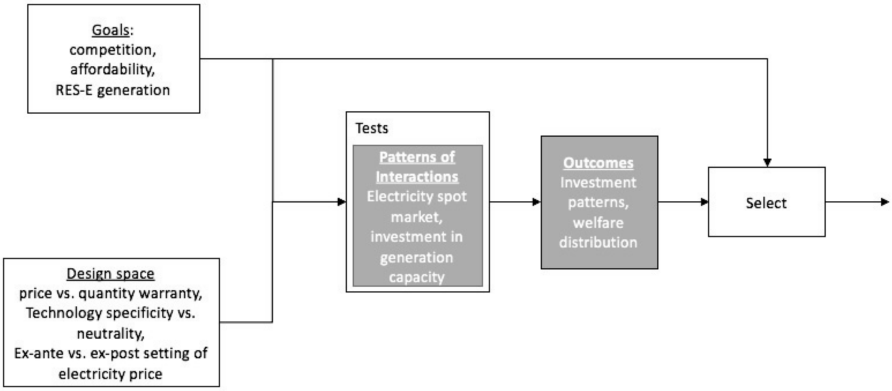


Figure 3.1: Design space is evaluated by simulating patterns of interactions[1].

3.2.1. MODEL CONCEPTUALISATION

Agents are the basic units of an agent-based model. They are characterised by their states, behaviours, and ability to interact. Entities that are not capable of decision-making are objects. Agents can interact with objects.

For instance, the main agents are electricity generation companies; they make short term decisions such as bidding competitively into the electricity spot market (an object), 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 other agents are regulators. They make decisions regarding the design of renewable support scheme. For instance, in a price warranty scheme, the regulator agent decides the amount of subsidy based on his knowledge of the costs of the technology. For a quantity warranty scheme, the agent decides the quantity, and organises an annual market clearing process, in which energy generation companies participate.

The environment is composed of objects such as the electricity market, the annual load duration curve, the renewable support schemes, power plants of various technologies, locations which correspond to electricity market clearing zones. Each of these objects is characterized by its own set of properties. For instance, the electricity market object has the properties *clearing price* and *clearing volume*, instantiated for every year (tick), and for every segment of the load duration curve. The main agents and objects in EMLab are schematically represented in Figure 3.2.

3.2.2. MODEL IMPLEMENTATION

The model has been implemented in Java, which is an object oriented programming language. The EMLab-Generation model identifies different types of Java classes and other files, described below. Classes are grouped into packages in the following manner.

- **Domain** classes are the definitions of things and their properties. Classes such as Energy Producer and EnergyConsumer under package Agent, and classes such as Bid and ClearingPoint under package Market are examples.

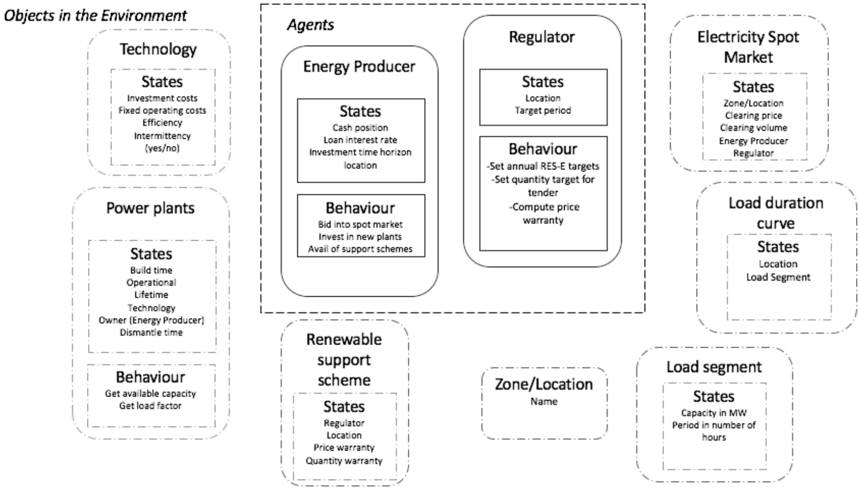


Figure 3.2: System represented as agents and objects

- **Role** classes capture behaviour, executed by specific classes from the domain packages. For instance, the agent EnergyProducer acts the SubmitOffersToElectricityMarketRole.

- **Repository** classes contain functions that deal with interaction of model code and the database. They also assist in updating current information and storing new information.

- **Scenario** xml files consist of all the data required to define and initialize a simulation run. It contains data as well as relations between objects.

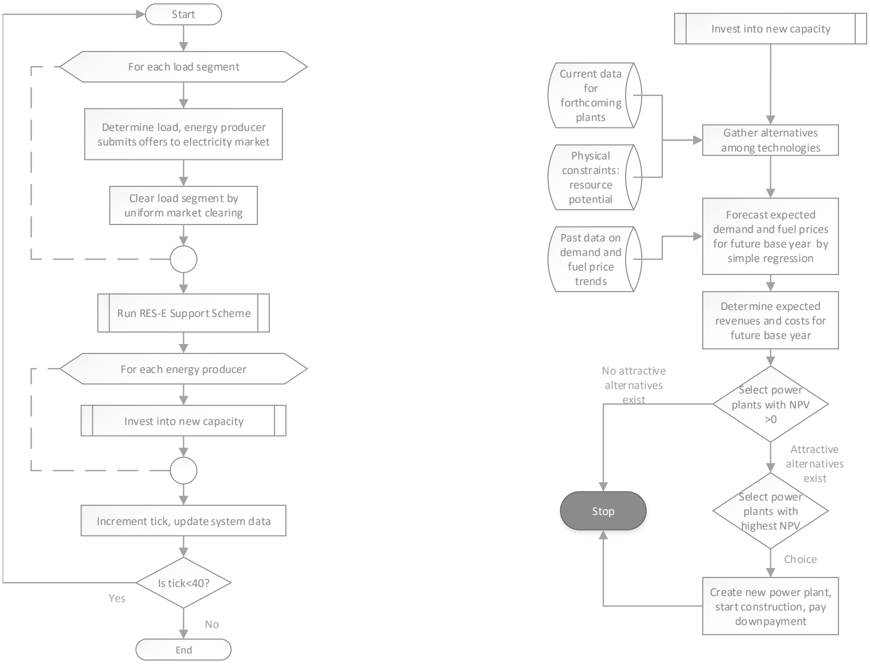
While this section described the what and the who, i.e., things, objects and agents, the following sections are a description of the model narrative. The model narrative is a story that relates the behaviours of the agents with time, i.e., it explains which agent does what with whom and when.

3.3. ELECTRICITY SPOT MARKET AND INVESTMENT

This section briefly describes the 'base model', on which the design elements are built. The base model includes two main algorithms: 1) an electricity spot market clearing algorithm, and 2) the investment algorithm. A brief description of the two algorithms is presented below. They are complemented by flowcharts.

3.3.1. MARKET CLEARING

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. 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 hours 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, 17h), segment 2 is (8390.36, 77h) 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.



(a) Main EMLab Algorithm

(b) Investment Algorithm

Figure 3.3: Flowcharts showing the overall EMLab algorithm, and the investment algorithm.

3.3.2. DYNAMIC DETERMINATION OF LOAD DURATION CURVE

The intermittent nature of the system is represented for renewable electricity generation using actual hourly capacity factors, and for demand with hourly load data. The hourly load data is then aggregated into twenty segments, and called the load duration curve. The generation from renewable electricity is reduced from the load duration curve, leaving the ‘residual load duration curve’ to be cleared against the remaining supply. Further investment in generation capacity of intermittent RES-E leads to changes in the residual load duration curve, which needs to be reflected correspondingly.

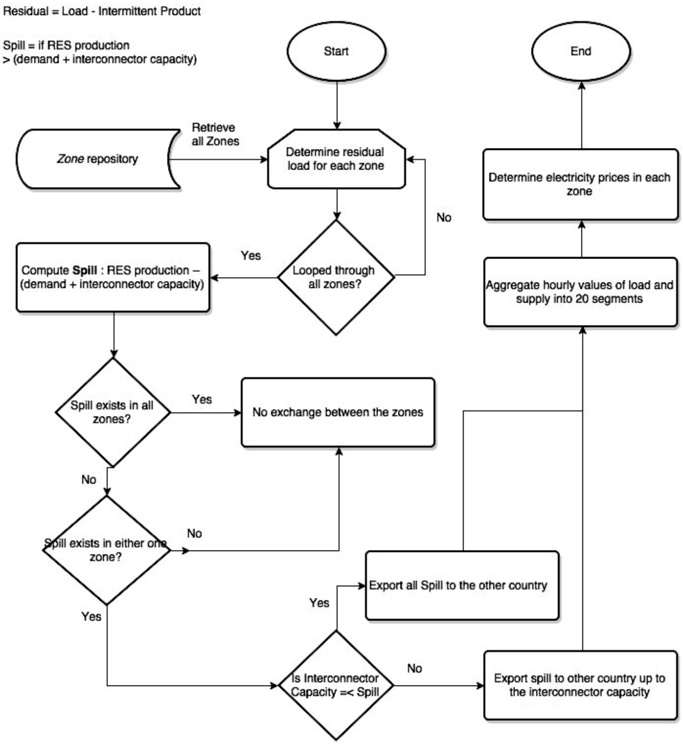


Figure 3.4: Dynamic determination of load duration curve

This dynamic determination of the load duration curve is demonstrated in the flowchart presented in Figure 3.4. The figure shows that the residual load duration curve is determined for each price zone separately. If spillage[3] exists in all zones, there is no exchange between the zones. If spillage exists in either zone, it is exported to the other country upto the extent that the interconnector capacity allows it. Hourly values of load and supply are then aggregated into twenty load segments and the electricity prices are determined in each zone.

3.3.3. INVESTMENT IN GENERATION CAPACITY

Every agent makes decisions about investments of plants by forecasting demand and fuel prices based on past data, 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

---

[3] Spillage is the RES-E production that is greater than the sum of the demand and interconnection capacity.

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 Richstein *et al.* (2014).

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.

$$\begin{aligned} CF_{Op,g} &= CInflow_{Op,g} - COutflow_{Op,g} \\ &= \Sigma_s p^*_{s,t+n} \times r_{s,g,t+n} \times a_{g,s} \\ &\quad - \left(\Sigma_s vc_{g,t+n} \times r_{s,g,t+n} \times a_{g,s} + fc_{g,t+n}\right) \end{aligned} \tag{3.1}$$

The economic viability of each power plant of capacity K_g, is then assessed with initial capital costs,I_g , over the building period $0..t_b$, and the service period, $t_b+1...t_b+t_D$. 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:

$$\begin{aligned} NPV_g = \Big(&\Sigma_{t=0}^{t_b} \frac{-I_g}{(1+WACC)^t} \\ &+ \Sigma_{t=t_b+1}^{t_b+t_D} \frac{CInflow_{Op,g}}{(1+WACC_{rev})^t} - \frac{COutflow_{Op,g}}{(1+WACC)^t}\Big)/K_g \end{aligned} \tag{3.2}$$

$$WACC = r_D \times (D/V) + r_{Eb} \times (E/V) \tag{3.3}$$

$$WACC_{rev} = r_D \times (D/V) + (r_{Eb} + r_{Ep}) \times (E/V) \tag{3.4}$$

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 Equation (3.2), 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 Equation (3.4), 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 DiaCore (2016).

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 Figure 3.3b. 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[4]. It is important to note at this stage, that economic decommissioning of the power plants has not been modelled; the plants are operational through the whole of their technical lifetimes, even if their marginal profits are negative.

---

[4] https://github.com/Kaveri3012/emlab-generation/tree/feature/SocialWelfareAnalysis

3.4. MODELLING RENEWABLE ELECTRICITY SUPPORT

In the previous section, the main algorithms of EMLab have been described. In this section I present the methodology for modelling of RES-E schemes in the form of their design elements. The design elements follow from those identified in 2.2 of this thesis. By specification and configuration of design elements, the policy maker attempts to achieve outcomes of affordability, and sufficient share of RES-E in the energy mix. The modelling framework is represented structurally using a UML class diagram, presented in Figure 3.5. The structure of the model indicates that RES-E Support Scheme is a class, whose attributes are the design elements identified in the previous step. The algorithmic relationship between the RES-E schemes and the investment behaviour is indicated with the help of a flowchart in Figure 3.6.

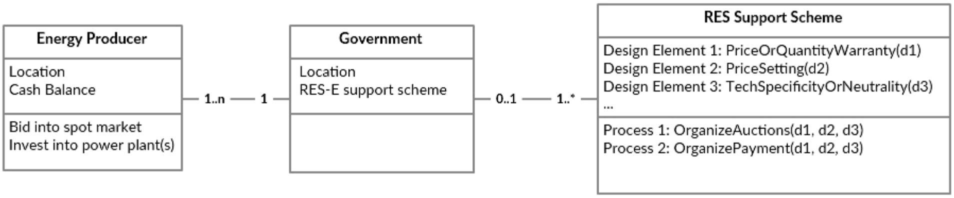


Figure 3.5: Specification of Java class structures of Agents and RES-E scheme using design elements.

At the outset, it must be noted that three design elements have been modelled, while keeping the others constant. A simplification to three design elements allows for clarity in interpretation, is sufficient for demonstration of the framework, and is a strong first step towards incorporating more design elements. Due to these reasons, and in order to keep within time and other resource constraints, we settled with modelling only three design elements.

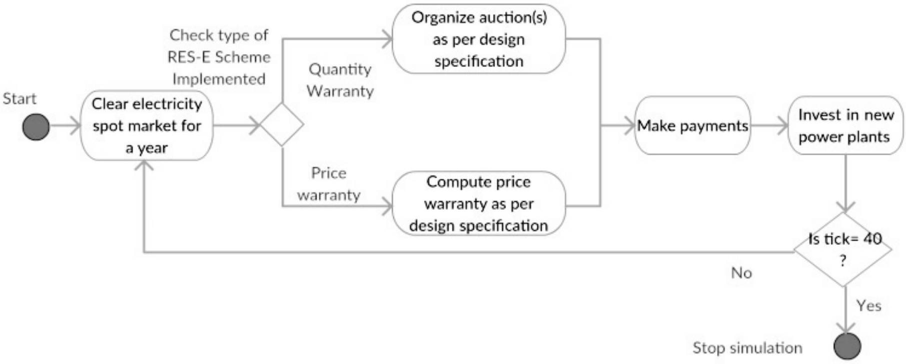


Figure 3.6: Relationship between base model and RES-E schemes

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 3.5. The processes or behaviours related to the different properties are the ’methods’ of the class. The source code is openly accessible [5].

Figure 3.7 shows four of the eight possible inherited RES-E Schemes for three design elements. The quantity based schemes include a function or a method to organize auctions based on the other design elements of the scheme, such as technology specificity, location specificity, contract (ex-post or ex-ante). The price based schemes includes a function to compute the remuneration, depending on specified design elements. A high-level flow chart of the process flow in the model is presented in Figure 3.6.

Different representations of the RES-E Support Schemes are be inherited[6], and contain processes that are functions of design elements. Other classes in the model represent the agents Energy Producer and Government, and their decision-making processes.

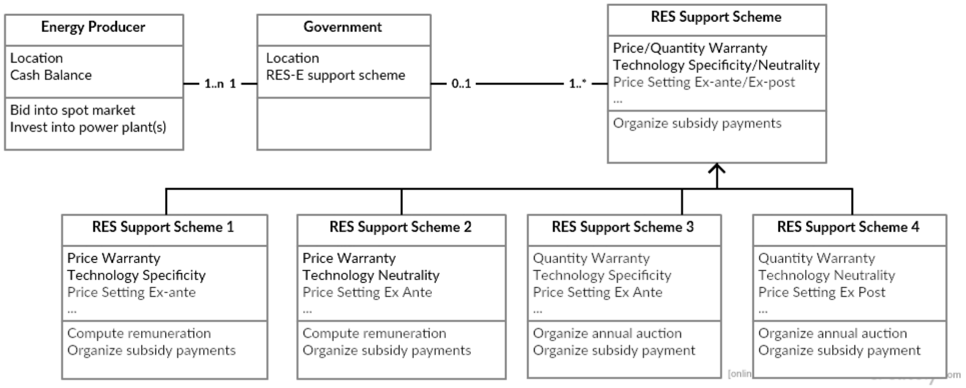


Figure 3.7: Specification of Class Structure

3.4.1. MODELLING OF DESIGN ELEMENTS

The objects characterising the RES-E support schemes were introduced in the previous section. This section consists of the processes, or the sequences of action that implement the eight RES-E support schemes, in EMLab-Generation.

PRICE VS 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 are as follows.

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

---

[5] https://github.com/Kaveri3012/emlab-generation/tree/feature/SocialWelfareAnalysis

[6] Inheritance is the defining of new classes as extensions of existing classes: the existing class is the parent class and the new class is the child class.

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 of Economic Affairs Agriculture and Innovation (2010). 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[7], like a tender [8]
3. Depending on the specification of design element 3, *technology specificity*, annual auctions are organized 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 Equation (3.5) or (3.7), 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 Equation (3.6) or (3.9).

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[9].
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 Equation (3.5) and (3.6), and with ex-post considerations of electricity market price is computed as per Equation (3.7) and (3.9).
4. Investment decisions are made by each energy producer taking into account published revenue from the applicable subsidy schemes. Payments are made annually till the end of the contract duration (20 years) according to Equation (3.6) or (3.9).

TECHNOLOGY NEUTRALITY VS. SPECIFICITY

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 year exogenously. Producer agents compute their offer prices for each available technology type in the model, either by Equation 3.7 or 3.5, 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

---

[7] The duration of contract is 20 years.

[8] This step is approximately modelled on the French EOLE auctions (Laali and Benard, 1999).

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

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.

EX-ANTE VS. EX-POST PRICE SETTING

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 actualization 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.

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 $\Sigma_{t=0..d}\frac{Xante_g}{(1+WACC)^t}$ equivalent to the total subsidy required by a plant is computed. As can be seen in Equation 3.5, this quantity is computed in the following way: *the estimated revenue* is subtracted from the sum of *the discounted value of investment cost* and *operating cost.* The annual payment to eligible power plants is organized by Equation 3.6. This way, the risk of volatility of future electricity prices is relegated to the producer.

$$\begin{aligned}\Sigma_{t=0..d}\frac{Xante_g}{(1+WACC)^t} &= \Sigma_{t=0}^{t_b}\frac{I_g}{(1+WACC)^t}\\ &\quad - \Sigma_{t=t_b+1}^{t_b+t_D}\Big(\frac{CInflow_{Op,g}}{(1+WACC_{rev})^t}\\ &\quad + \frac{COutflow_{Op,g}}{(1+WACC)^t}\Big)\end{aligned} \tag{3.5}$$

$$payment_{g,t} = \Sigma_g\Sigma_s(Xante_g \times a_{g,s}) \qquad where, t \in \{t_b ... t_D\} \tag{3.6}$$

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 $\Sigma_{t=0..d}\frac{Xpost_g}{(1+WACC)^t}$ is calculated in equation 3.7. In the second step, the annual payment to eligible power plants is organized by equation 3.9. This shifts the price related uncertainty and risk from the electricity producer to the government.

$$\Sigma_{t=0..d}\frac{Xpost_g}{(1+WACC)^t} = \Sigma_{t=0}^{t_b}\frac{I_g}{(1+WACC)^t} + \Sigma_{t=t_b+1}^{t_b+t_D}\frac{COutflow_{Op,g}}{(1+WACC)^t} \tag{3.7}$$

where,

$$COutflow_{g,t+n} = \Sigma(vc_{g,t+n}) * r_{s,g,t+n} * a_{g,s}) - \Sigma fc_{g,t+n} \tag{3.8}$$

$$payment_{g,t} = \Sigma_g \Sigma_s (Xpost_g - p_s^*) \times a_{g,s} \qquad where, t \in \{t_b ... t_D\} \tag{3.9}$$

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 Equation (3.4), is set to 0%.

3.5. DATA

This section consists of a description of the data used to model the electricity system. It consists of assumptions regarding load duration curves and demand growth trend assumptions. Characteristics of the technologies, their costs, availability of intermittent technologies are also described.

3.5.1. LOAD DURATION CURVES

As mentioned earlier, hourly load is aggregated into 20 segments of individual load, period pairs, to form a load duration curve. The intial load duration curve is based on 2014 ENTSO-E hourly data for consumption in the Netherlands and Germany (ENTSO-E, 2015). The aggregated curves are shown in Figures 3.8 and 3.9. The load curves for each consecutive year after the first are computed based on a 'demand growth factor ', as explained below.

3.5.2. DEMAND GROWTH TRENDS

The demand growth trends are stochastic trends and determined in the following way.

$$D_{t+1} = \alpha_t \times D_t \tag{3.10}$$

where, D is the demand at year t and α is the "growth rate" calculated from a triangular distribution. A triangular distribution is a is a continuous probability distribution with lower limit (min) a, upper limit (max) b and mode c, where a < b and a ≤ c ≤ b. The values for a, b, and c are presented in Table A.1, in the appendix. The values are based on the EU reference scenario of 2014 (European Commission and Direction générale de la mobilité et des transports, 2014), which predicts a 1% growth rate. The trends are depicted pictorially in Figure A.1.

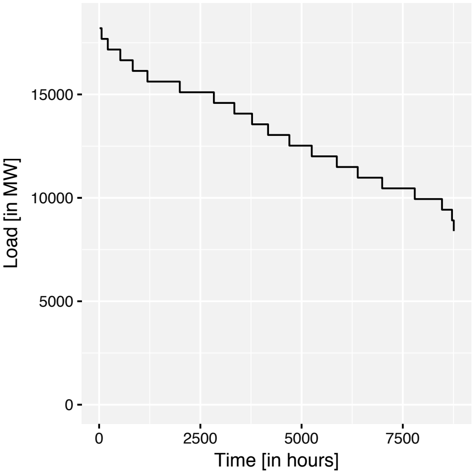


Figure 3.8: The initial load duration curve for the Netherlands split into 20 segments

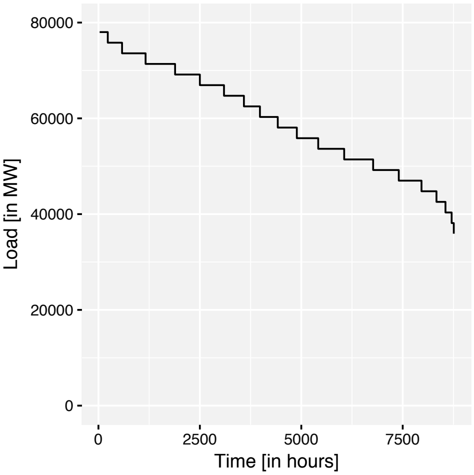


Figure 3.9: The initial load duration curve for Germany split into 20 segments

3.5.3. TECHNOLOGY CHARACTERISTICS

The problem being tackled in this thesis relates to the long-term impact on investment in generation capacity and its interaction with the electricity market under different policies. Therefore the generation technologies have been described or modelled, in terms of such properties as are relevant to the longer-term: their nominal capacity, construction time, technical lifetime, depreciation time, fuels used, their availability if intermittent, and efficiency. Characteristics such as ramp rates which are relevant to the short term operation of the power plant are not considered. The technologies implemented and their characteristics are mentioned in Table 3.1.

Table 3.1: Assumptions about technical characteristics of power generating technologies, where [a] is number of years

Technology	Capacity [MW]	Construction time [a]	Permit time [a]	Technicallifetime [a]	Depreciation time [a]	Fuels
Wind Offshore	600	1	0	20	20	-
PV	500	1	0	20	20	-
Wind Onshore	600	1	0	20	20	-
Coal Pulverised SC	758	4	1	50	20	Coal
Lignite	1000	5	1	50	20	Lignite
Nuclear	1000	5	2	40	25	Uranium
CCGT	776	2	1	40	15	Natural Gas

Fixed costs of technologies Costs of investment, costs of fixed operation and maintenance, and efficiencies are specified for each technology for the duration of the simulation. The learning curves for solar PV were created based on data from ISI (2015). The learning curves for wind, and wind offshore were created based on data from IRENA reports on costs of renewable technologies (IRENA, 2015). The yearly values for the learning curves, and the R code that was used to create them have been uploaded on a publicly accessible data platform, cited in Iychettira (2015). The assumptions made regarding fixed costs of conventional technologies are presented in Table A.3 in the appendix.

Availability of intermittent technologies Data for the hourly availability of intermittent technologies for onshore wind, solar PV, and wind offshore plants were taken from the supplementary data used in the paper by Lion Hirth on the assessment of market value of renewable electricity Hirth (2013). The files containing the data are publicly accessible in CSV format at an online data-hub, here Lion (2013).

3.6. MODEL EVALUATION

The step, "model evaluation", also commonly referred to "verification and validation", is an integral part of building a computer simulation; they are meant to evaluate whether the simulation model is an adequate representation of the target system, relative to the goals of the modelling study. Wendy Parker, a scholar of Epistemology of Computer

Simulation, characterises the process of model evaluation in the following way (Parker, 2008).

"...the question of whether the computer simulation model is an adequate representation of the target system, relative to the goals of the modelling study, is of utmost importance. The activity of model evaluation (also sometimes known as 'validation') aims to collect evidence regarding precisely this question. Depending on the goals of the modelling study, the process of model evaluation might treat the simulation model as a black box and focus only its output, or it might involve opening the black box to investigate the accuracy of particular modelling assumptions and/or the adequacy of the process by which solutions to the continuous model equations are estimated."

In her writing, she is also at pains to emphasize that model evaluation should be perceived as *"an investigation of the model's adequacy for purpose, not an investigation of its truth or falsity, whatever that might mean. A model that is constructed with the use of a variety of false assumptions about a target system might nevertheless be an adequate representation of that target system, relative to the goals of the modelling study. "*

Drawing from the above, this section is split into two parts: Verification, where the mathematical task of confirming whether the simulation code is implemented correctly with respect to the conceptual model is discussed, and Validation, where the fitness of purpose is discussed.

3.6.1. VERIFICATION

In order to assess whether the simulation code of the agent-based model represents the conceptual model, the following steps can be employed, based on the recommendations in Dam *et al.* (2012).

1. **Recording and tracking agent-behaviour**: This procedure involves recording the relevant input, the states, and the outputs of the individual agents and each of their internal processes. This is usually performed by using loggers throughout the code, or by using a debugger, available in the integrated development environment.

2. **Unit testing**: In this procedure, small parts of the code are tested by predefining inputs and providing expected outputs, after which they can be automated to evaluate individual units through various inputs. Two important parts of unit testing are: 1) theoretical prediction and sanity checks 2) extreme value testing. The disadvantage of this method is that for a large code composed of a multitude of modules, they only provide insight on individual parts of the code, and not whether the code works correctly together as a whole.

3. **Interaction testing in a minimal model**: In this step, an evaluation is performed to test whether multiple agents interact with each other in a manner that is expected, using a minimal model. This step is also used to test whether multiple modules work as expected.

4. **Multi-agent testing**: In this step, the full model, with the complete number of agents is tested for coherent behavioural patterns. In addition to sanity checks described above, variability testing and timeline sanity check is also performed.

The above tests were applied the implemented model, as described below. In tables 3.2 and 3.3, each test, the module or role or agent behaviour to which they were employed, and outcomes are mentioned.

Table 3.2: List of checks performed to verify the correct implementation of quantity warranty schemes

Unit	Function	Test	Outcome
Calculate Renewable Tender Target	An exogenous target, specified as a percentage of generation to come from renewable sources, is converted into its corresponding value in MW, for every year, depending on whether the policy is technology specific or technology neutral.	• Check whether the target for renewables is computed as expected for each technology in technology specific policy designs. • Check whether target is computed as expected for all renewable technologies together, in technology neutral scenarios.	Verified
Submit Tender Bid Role	• Each energy producer bids for as many plants as the target allows, using only his costs for the technology if the support scheme employs ex-post pricing, and his expected revenue if the support scheme uses ex-ante pricing.	• Check whether the bids correspond to the costs specified exogenously. • Check whether expected revenue in the bid calculation corresponds to agent's forecasted demand, fuel prices, and merit order 2 years into the future. • Check whether, under technology neutrality, the bids correspond to the cheapest technology first. • Check whether the number of bids are limted also by the technology potential, in case targets are higher than potential.	Verified
Clear Renewable Tender Role	Given bids from all producers, the regulator matches supply and demand, and determines the clearing price. This is organized with technology specificity or neutrality, as determined by the support scheme design.	• Check whether the accepted quantity matches the target, as determined in step 1. • Check whether the clearing price corresponds to last accepted bid.	Verified
Create Power Plants of Accepted Bids Role	To declare and initialize new power plant objects, their corresponding financial entities, including loans, downpayments.	• Check whether a new plant has been created, corresponding to the accepted bid.	Verified
Organize Renewable Tender Payments Role.	To process cash flows for each tender contract with a power plant in each year.	• For ex-post policies, check whether annual subsidy = cost - revenue from electricity market. • For ex-ante policies, check whether subsidy = tender clearing price * power generated.	Verified.
Full tender algorithm		Are the investments upto the target set? Are the cash flows as expected?	Verified

Table 3.3: List of checks performed to verify the correct implementation of price warranty schemes

Unit	Function	Test	Outcome
Compute premium role	The regulator agent computes the premium for each technology, based on the costs and expected revenues to the power plant owner, assuming he has the same information as the power plant owner.	• Check whether the regulator agent computes the same costs in this role as the power plant owner does during an investment decision.	Verified.
Feed in premium role.	For a new elegible plant, a contract is made. For each eligible power plant, the support price is calculated and payment made	• For ex-post policies, check whether annual subsidy = cost - revenue from electricity market. • For ex-ante policies, check whether subsidy = tender clearing price * power generated.	Verified.
Full price warranty algorithm		• The investments should be upto the potential of the technology.	Verified.

3.6.2. VALIDATION

Wendy Parker provides the following strategies to determine the internal and external validity of a code[10] (Parker, 2008). Although it is too early in the dissertation to discuss the validity of the results, a framework for testing validity is presented, based on the insights drawn from strategies in physical experiment validation to code evaluation. The strategies and their application to the code presented is discussed below.

- *Simulation output fits closely with observational data:* In the context of the model presented, this strategy would be similar to historical validation. When input data such as demand, initial supply, and fuel prices match historical values, the outputs such as electricity prices should also match their corresponding historical values. While the analysis presented in Chapter 4 is indicative, historical data has been used for the analysis presented in Chapter 5, and consequently a discussion is presented on the similarities of the results with observational data in that Chapter.

- *Simulation results change as expected after intervention on model parameters:* This strategy is largely evident in the observations and interpretations of the results. For instance, when revenue from electricity prices increase, the subsidy costs are expected to decrease. When the price warranty is sufficient, there is investment up to the realistic technical potential of the technology.

- *Simulation model is constructed using well confirmed theoretical assumptions:* For the simulation of a socio-technical system, assumptions need to be made regarding the behaviour of agents who represent actors in the system. Predictions from neo-classical economics are well-confirmed under certain conditions, but not all. For instance, in a spot market, actors largely behave as theory predicts: submitting bids at the marginal costs. However, for investment decisions, behaviour is

---

[10] Internal validity concerns what is true of a particular experimental system and the validity of its associated result statements, while external validity concerns generalizability

far more complicated than what neo-classical economics allows for. While decisions are taken based on cost-benefit analyses, the outcome is rarely a long-term equilibrium due to factors such as imperfect information. For such analyses, assumptions that are face validated are used; assumptions that are validated by experts in the field - through peer review, presenting works at conferences, talking to practitioners etc.

- *Simulation results are reproduced in other simulations or in traditional experiments:* For a socio-technical system simulating 3 decades into the future, a "traditional experiment" is impractical to conduct. However, comparisons with other simulations are made in the discussion sections of Chapters 4 and 5, to the extent that the scope of other studies are comparable to the ones presented here.

3.7. CONCLUSION

Having laid down theoretical foundations in the previous chapter, this chapter conceptualized and formalized the algorithms employed, and the primary narrative embodied in the simulation. The instrument used to perform the core of the analysis was described in detail in this chapter. The process of gathering data was also briefly described: the sources and means of obtaining the information on generation technologies, demands, costs, plausible assumptions for trends related to expectations of future growth.

No simulation is complete without checking whether it is verified and validated. The final section of this chapter therefore described what verification entails for an agent-based model of investment in the power sector. The various checks performed to ensure the code was built as intended were described. This was followed by a discussion on the framework to assess its suitability for its intended purpose, and how that has been implemented in the thesis. The following chapters present the experiments that were conducted with the simulation described, the major analysis, and insights that follow.

REFERENCES

K. K. Iychettira, R. A. Hakvoort, and P. Linares, *Towards a comprehensive policy for electricity from renewable energy: An approach for policy design,* Energy Policy **106**, 169 (2017).

L. de Vries, E. J. Chappin, and J. C. Richstein, *Decarbonisation of the Power Sector,* Tech. Rep. (Delft University of Technology, Delft, 2012).

A. Chmieliauskas, E. J. L. Chappin, C. B., I. Nikolic, and G. P. J. Dijkem, *New Methods for Analysis of Systems-of-Systems and Policy: The Power of Systems Theory,Crowd Sourcing and Data Management,* in *System of Systems*, edited by A. V. Gheorghe (InTech, 2012) dOI: 10.5772/28796.

E. J. L. Chappin, *Simulating Energy Transitions.* (Next Generation Infrastructures Foundation, Delft, 2011) oCLC: 840444784.

J. Richstein, *Interactions between carbon and power markets in transition* (Delft University of Technology, Netherlands, 2015).

J. C. Richstein, E. J. L. Chappin, and L. J. de Vries, *Cross-border electricity market effects due to price caps in an emission trading system: An agent-based approach,* Energy Policy **71**, 139 (2014).

DiaCore, *The impact of risks in renewable energy investments and the role of smart policies*, Work Package 3 Leader Organisation: ECOFYS IEE/12/833/SI2.645735 (Ecofys, 2016).

M. of Economic Affairs Agriculture and Innovation, *National Renewable Energy Action Plan of the Netherlands: Directive 2009/28/EC*, Submitted to European Commission (2010).

A.-R. Laali and M. Benard, *French wind power generation programme EOLE 2005 Results of the first call for tenders,* Renewable Energy **16**, 805 (1999).

ENTSO-E, *Country Data Packages,* (2015).

European Commission and Direction générale de la mobilité et des transports, *EU energy, transport and GHG emmissions trends to 2030: reference scenario 2013* (Office for official publications of the european communities, Luxembourg, 2014) oCLC: 889309007.

F. ISI, *Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems.*, Study on behalf of Agora Energiewende. 059/01-S-2015/EN (Freiburg, 2015).

IRENA, *Renewable Power Generation Costs in 2014.*, Tech. Rep. (2015).

K. Iychettira, *Fixed costs of renewable technologies. - the Datahub,* (2015).

L. Hirth, *The market value of variable renewables: The effect of solar wind power variability on their relative price,* Energy Economics **38**, 218 (2013).

H. Lion, *Hourly capacity factors for intermittent generation - Datasets - the Datahub,* (2013).

W. S. Parker, *Franklin, Holmes, and the Epistemology of Computer Simulation,* International Studies in the Philosophy of Science **22**, 165 (2008).

K. H. V. Dam, I. Nikolic, and Z. Lukszo, *Agent-based modelling of socio-technical systems*, May (Springer, 2012).

4

RENEWABLE SUPPORT INTERACTS WITH THE ELECTRICITY MARKET

Parts of this chapter have been published in Applied Energy **187**, 228 (2017) Iychettira *et al.* (2017)

4.1. INTRODUCTION

4.1.1. MOTIVATION AND RESEARCH OBJECTIVE

In a recent article on the transition towards a green economy, Newbery (2016) 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 (European Commission and Directorate-General for Economic and Financial Affairs, 2015). 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 instance Batlle *et al.* (2012a); Couture and Gagnon (2010); Schmalensee (2012); Neuhoff *et al.* (2013); (IEA) (2008). Such literature so far on renewable support schemes has mainly focussed on comparing different policies[1] or support schemes [2] 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 del Rio and Linares (2014); del Rio and Mir-Artigues (2014); Haas *et al.* (2011).

It was proposed in earlier chapters that any RES-E policy can be broken down into a closed set of components that are common to all renewable electricity support schemes. These components are referred to as ‘design elements’; the design elements now form the smallest level of analysis. The objective of this chapter 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 2.2.2, and demonstrate that it is possible to model elements individually in Chapter 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 4.2, which includes a detailed description of the methodology used: the design elements considered, the

---

[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.

model, the hypotheses and experiment design. The subsequent section includes the results and their discussion, followed by the conclusion.

4.1.2. 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 (Newbery, 2016; Fais *et al.*, 2014; Dressler, 2016; Winkler *et al.*, 2016; Reuter *et al.*, 2012). Nevertheless, perceiving RES-E support schemes in terms of design elements has been done qualitatively before by some authors. For instance, Held *et al.* (2014) and the beyond2020 project by Batlle *et al.* (2012b) present a list of design elements for RES-E support schemes. del Rio and Linares (2014) 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.* (2014) 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 (Huber *et al.*, 2004), the REBUS (Renewable Energy Burden Sharing) model (Voogt *et al.*, 2001), the PERSEUS-RES-E (Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading) model by Most and Fichtner (2010), and an extended version of the TIMES-D (The Integrated MARKAL-EFOM System) model by Fais *et al.* (2014), 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: optimization models, equilibrium models, and simulation models Ventosa *et al.* (2005). Optimization 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 types of 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 Most and Fichtner (2010) and Olsina *et al.* (2006) 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 with knowledge of past trends, and imperfect foresight, are a major determinant of welfare outcomes.

4.1.3. 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 optimization 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) (Batlle *et al.*, 2012b). 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 create new policies that have not been implemented before. More importantly, it allows us assess the impact 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.

4.1.4. 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 recognized as a methodology that provides a framework to model agents with bounded rationality, their interactions with other agents, and the environment around them, as Epstein (2007), Manson (2006), and North *et al.* (2013) 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

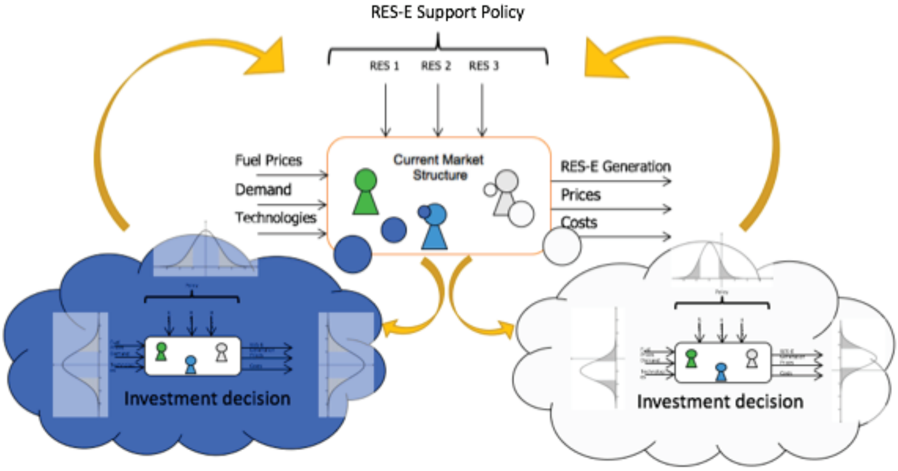


Figure 4.1: High level diagram of behaviour of agents and their interaction with environment in EMLab. Adapted from Richstein (2015)

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 3.2, and with flowchart in 3.3, and is represented in Figure 4.1. The design elements, and consequently the RES-E policies, that have been modelled as part of the current work, are described in Section 3.4.

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 with 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 pinpoint which micro decisions lead to which macro outcomes in the model. Thirdly, unlike optimization 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 (Richstein, 2015; Richstein *et al.*, 2014; Bhagwat *et al.*, 2014).

4.2. EXPERIMENT DESIGN

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 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 4.1.

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 4.1.

Table 4.1: 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

Sensitivity Analysis The impact 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 current[3] 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%.

Experiment Setup: Randomness and Repetitions Agent-based modelling in general, and this model in particular, require multiple runs to arrive at statistically significant

---

[3] June, 2016

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.

4.2.1. 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 Green (2015), and equivocal opinions on nuclear technology, refer Association (2016), 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 3.1. The intermittent nature of renewable generation sources is represented by hourly availability factors, which are then aggregated to segment-based[4] availability factors. The data for hourly availability for the renewable technologies is obtained from Pfenninger and Staffell (2016). 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 Lako (2010) and Ragwitz *et al.* (2003), and extrapolated, as described in A.1.3. 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 summarized in Table A.1. The initial load duration function is based on 2014 ENTSO-E data for Netherlands. A value of lost load of 2000 Eur/MWh has been used for this work (Anderson and Taylor, 1986; Linares and Rey, 2013; Nooij *et al.*, 2007).

4.2.2. 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[5]. 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 benefits might

---

[4] 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.

[5] Greater amounts of renewable energy will be generated when there is insufficient demand for it

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.

4.3. RESULTS

This section comprises of two subsections: the first consists of the results as per the performance indicators mentioned in the introduction to this chapter. The performance indicators are effectiveness of policy, and social welfare and distributional implications. The second consists of a discussion and interpretation in subsection 4.3.2, 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.

4.3.1. RESULTS AND DISCUSSION

EFFECTIVENESS OF POLICY

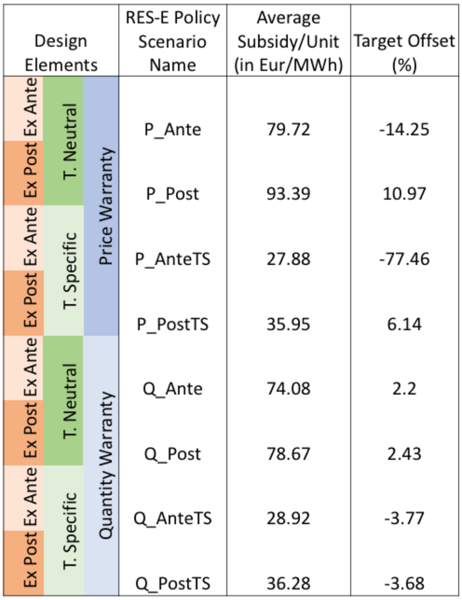
Effectiveness of policy is measured using two indicators: *cost effectiveness* and *target offset*. *Cost effectiveness* is defined as total subsidy cost per MWh of renewable electricity generated[6], summed across all 40 years, in Eur/MWh. It is then averaged across all 40 repetitions of the scenario. *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 years and 40 repetitions per scenario.

$$targetOffset = \frac{\sum_{rep}\sum_{t}\frac{(rGen_{t,rep}-target_{t,rep})\times 100}{target_{t,rep}}}{n_{rep}\times n_{tick}} \tag{4.1}$$

Figure 4.2 indicates these values for each scenario. The evolution of capacity in each of the scenarios is shown in Figure 4.3.

---

[6] All renewable energy technologies are considered



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

Figure 4.2: 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 a consequence of the regulator agent's short-sightedness with respect to expectations of future electricity prices[7]. 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 normalized 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 spillage [8] and lower the generation. Therefore, unless there is an interconnector

---

[7] 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 year, 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 year. 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.

[8] Spillage can be defined as renewable capacity generating more than the demand at a certain hour

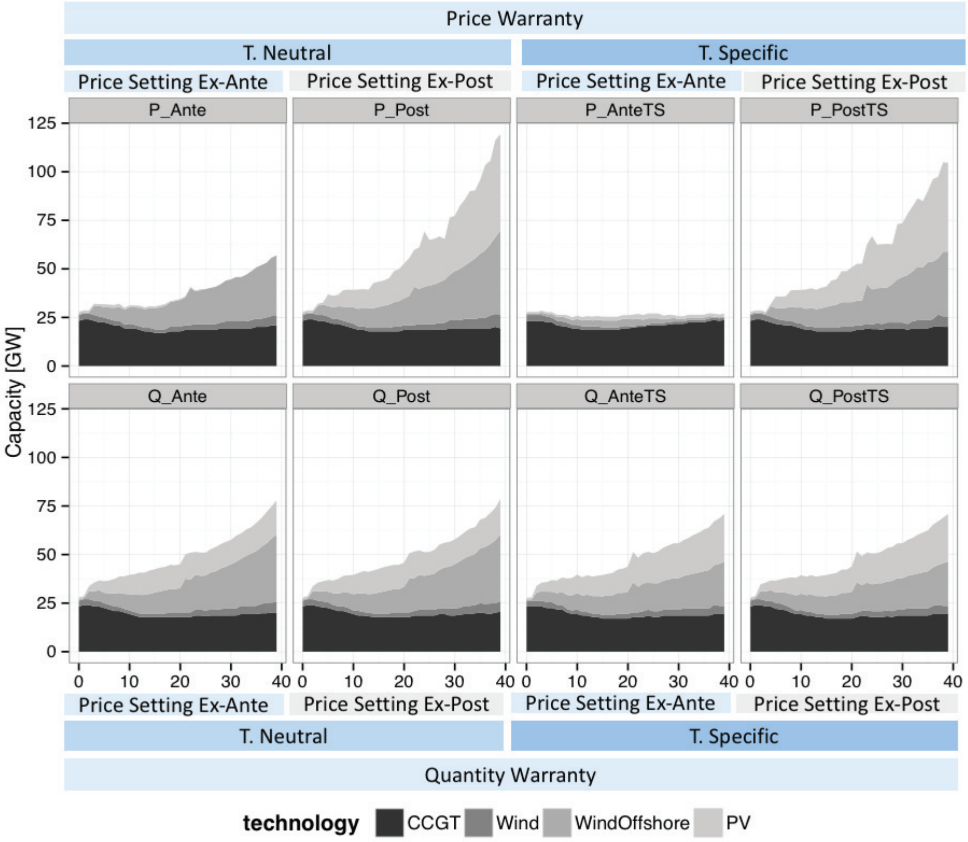


Figure 4.3: Capacity growth in GW per policy scenario with time (in years) on x-axis

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 Figures B.1a and B.1b.

SOCIAL WELFARE AND DISTRIBUTIONAL IMPLICATIONS

The distributional implications are presented in Figure 4.4, indicating the change in surpluses for the consumer, producer, government, and total social surplus, for each scenario. The change is computed by comparing each scenario with a base case, where no policy is implemented. Change in consumer expenditure[9], change in producer costs, and change in government expenditure are used as proxies for calculating the changes in consumer, producer, and government surpluses.

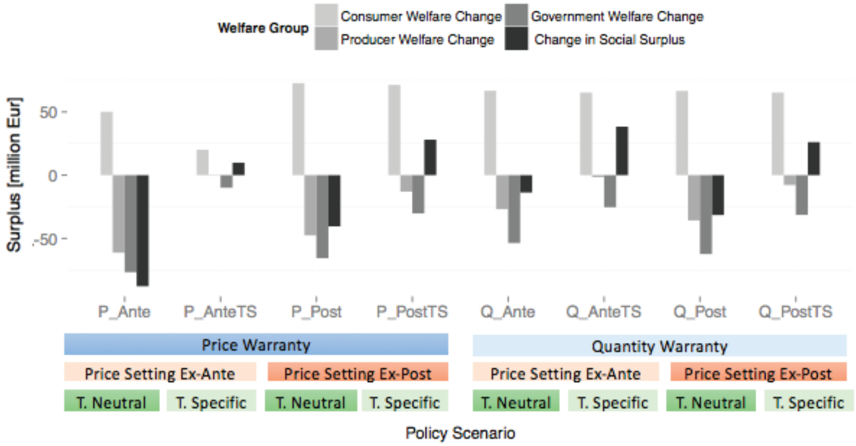


Figure 4.4: Change in Surplus for producer, consumer, government, and society (total) in 40 years

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 group. In all scenarios, consumer surplus increases; this is primarily caused by a fall in the average electricity prices due to the merit order effect. Government surplus is only affected by the amount of subsidy spent. The main design element affecting government welfare is therefore technology specificity. Surplus is more negative in technology neutral scenarios, compared to their corresponding technology-specific counterparts due to the windfall profits mentioned earlier.

---

[9] 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.

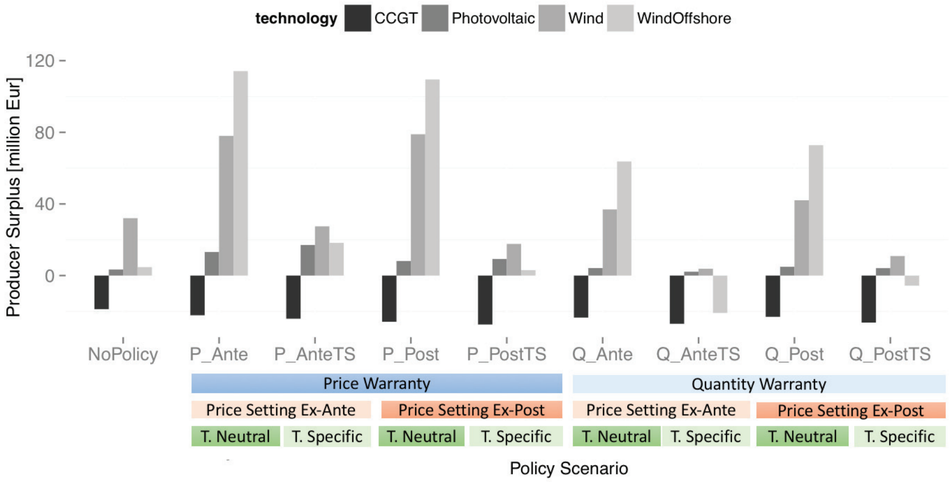


Figure 4.5: Producer Suplus per Technology and Policy Scenario

Producer surplus is affected by costs (fixed and variable) and revenues (electricity spot market revenue and RES-E subsidies) for various technologies. Figure 4.5 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[10].

The cost-benefit impacts of each policy scenario on a single technology, such as for instance Wind Offshore, is illustrated in figure 4.6.

---

[10] 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.

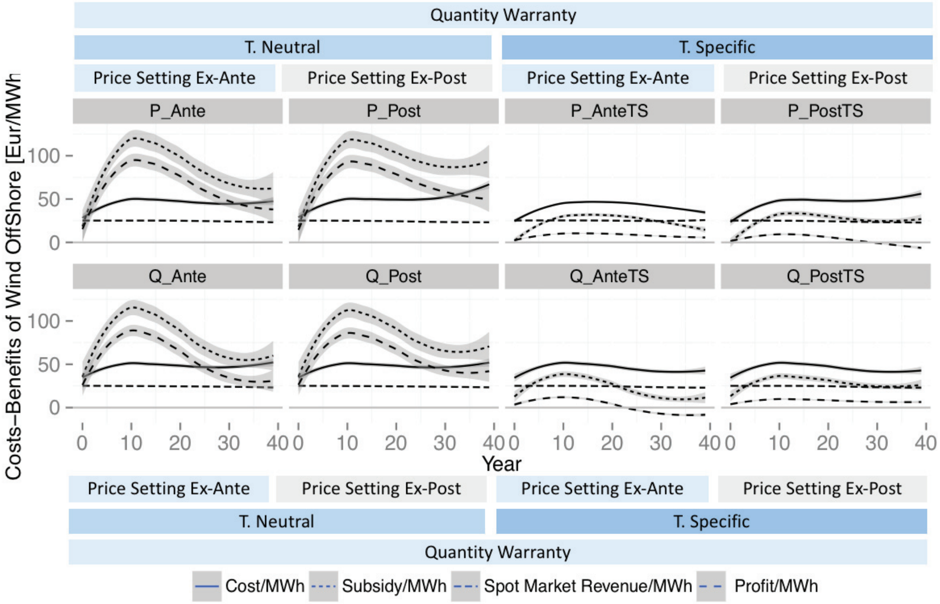


Figure 4.6: Cost, Revenue, Subsidy, and Profit for WindOffshore per MWh over 40 years

4.3.2. 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.

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.

Technology-specificity vs technology-neutrality Theoretically as pointed out by Fais *et al.* (2014), 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 Fais *et al.* (2014), 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[11]. Another factor which could impact this result is if technology cost reductions are different than assumed.

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 Figure B.2a. In this scenario set, the same risk aversion of 11% is 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 B.2.

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.

4.3.3. APPLICABILITY OF THE DESIGN ELEMENT APPROACH

By quantitatively demonstrating that mere design elements, irrespective of the RES-E policy they belong to, have significant 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 of late in academic literature (Winkler *et al.*, 2016), it remains distant from ongoing policy discussions, as is elucidated below.

The 2014 State Aid Guidelines proposed that competitive bidding, or auctions, should be the main form of support Commission (2014) 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 caus-

---

[11] See Figure B.2b to observe results for a scenario set where the RES-E generation target remains constant at 10% of total consumption throughout the time-period

ing increasing concern (Glachant and Ruester, 2013). Among the primary concerns of the European Commission now, is to be able to promote renewable electricity without causing unintended cross border impacts (Commission, 2015). 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.

4.4. CONCLUSIONS

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 organized 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 specificty 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 upto 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 co-ordinated at the European level.

REFERENCES

K. K. Iychettira, R. A. Hakvoort, P. Linares, and R. d. Jeu, *Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare,* Applied Energy **187**, 228 (2017).

D. M. Newbery, *Towards a green energy economy? The EU Energy Union's transition to a low-carbon zero subsidy electricity system – Lessons from the UK's Electricity Market Reform,* Applied Energy **179**, 1321 (2016).

European Commission and Directorate-General for Economic and Financial Affairs, *Energy economic developments: investment perspectives in electricity markets.* (Publications Office, Luxembourg, 2015) oCLC: 948760359.

C. Batlle, I. J. Pérez-Arriaga, and P. Zambrano-Barragán, *Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing,* Energy Policy Modeling Transport (Energy) Demand and Policies, **41**, 212 (2012a).

T. Couture and Y. Gagnon, *An analysis of feed-in tariff remuneration models: Implications for renewable energy investment,* Energy Policy **38**, 955 (2010).

Schmalensee, *Evaluating Policies to Increase Electricity Generation from Renewable Energy,* Review of Environmental Economics and Policy **6**, 45 (2012).

K. Neuhoff, J. Barquin, J. W. Bialek, R. Boyd, C. J. Dent, F. Echavarren, T. Grau, C. von Hirschhausen, B. F. Hobbs, F. Kunz, C. Nabe, G. Papaefthymiou, C. Weber, and H. Weigt, *Renewable electric energy integration: Quantifying the value of design of markets for international transmission capacity,* Energy Economics **40**, 760 (2013).

I. E. A. (IEA), *Deploying Renewables: principles for effective policies*, Tech. Rep. (Paris, 2008).

P. del Rio and P. Linares, *Back to the future? Rethinking auctions for renewable electricity support,* Renewable and Sustainable Energy Reviews **35**, 42 (2014).

P. del Rio and P. Mir-Artigues, *Combinations of support instruments for renewable electricity in Europe: A review,* Renewable and Sustainable Energy Reviews **40**, 287 (2014).

R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, and A. Held, *A historical review of promotion strategies for electricity from renewable energy sources in EU countries,* Renewable and Sustainable Energy Reviews **15**, 1003 (2011).

B. Fais, M. Blesl, U. Fahl, and A. Voß, *Comparing different support schemes for renewable electricity in the scope of an energy systems analysis,* Applied Energy **131**, 479 (2014).

L. Dressler, *Support Schemes for Renewable Electricity in the European Union: Producer Strategies and Competition,* Energy Economics , (2016).

J. Winkler, A. Gaio, B. Pfluger, and M. Ragwitz, *Impact of renewables on electricity markets – Do support schemes matter?* Energy Policy **93**, 157 (2016).

W. H. Reuter, J. Szolgayová, S. Fuss, and M. Obersteiner, *Renewable energy investment: Policy and market impacts,* Applied Energy **97**, 249 (2012), energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy.

A. Held, M. Ragwitz, M. Gephart, F. ISI, M. Gephart, E. de Visser, C. Klessmann, and Ecofys, *Design features of support schemes for renewable electricity*, Tech. Rep. (2014).

C. Batlle, P. Linares, M. Klobasa, J. Winkler, F. Isi, A. Ortner, and T. U. W. Eeg, *Interactions between RES-E support instruments and electricity markets*, Tech. Rep. October (Beyond 2020, 2012).

P. Capros, L. Paroussos, P. Fragkos, S. Tsani, B. Boitier, F. Wagner, S. Busch, G. Resch, M. Blesl, and J. Bollen, *Description of models and scenarios used to assess European decarbonisation pathways,* Sustainable Energy System Changes **2**, 220 (2014).

C. Huber, T. Faber, R. Haas, G. Resch, J. Green, S. Olz, and S. White, *Deriving optimal promotion strategied for increasing hte share of RES-E in a dynamic European electricity market*, Tech. Rep. (2004).

M. H. Voogt, M. A. Uyterlinde, K. Skytte, M. Leonardi, and M. H. Whiteley, *Renewable energy burden sharing. REBUS. Requirements and expectations of utilities and consumer organisations in the European energy sector*, Tech. Rep. (Energy research Centre of the Netherlands ECN, Petten (Netherlands), 2001).

D. Most and W. Fichtner, *Renewable energy sources in European energy supply and interactions with emission trading,* The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers **38**, 2898 (2010).

M. Ventosa, Baıllo, A. Ramos, and M. Rivier, *Electricity market modeling trends,* Energy Policy **33**, 897 (2005).

F. Olsina, F. Garcés, and H.-J. Haubrich, *Modeling long-term dynamics of electricity markets,* Energy Policy **34**, 1411 (2006).

J. M. Epstein, *Generative Social Science: Studies in Agent-Based Computational Modeling* (Princeton University Press, 2007).

S. Manson, *Bounded rationality in agent-based models: Experiments with evolutionary programs,* International Journal of Geographical Information Science **20**, 991 (2006), cited By 40.

M. J. North, N. T. Collier, J. Ozik, E. R. Tatara, C. M. Macal, M. Bragen, and P. Sydelko, *Complex adaptive systems modeling with Repast Simphony,* Complex Adaptive Systems Modeling **1**, 1 (2013).

J. Richstein, *Interactions between carbon and power markets in transition* (Delft University of Technology, Netherlands, 2015).

J. C. Richstein, E. J. L. Chappin, and L. J. de Vries, *Cross-border electricity market effects due to price caps in an emission trading system: An agent-based approach,* Energy Policy **71**, 139 (2014).

P. Bhagwat, K. K. Iychettira, and L. J. De Vries, *A modelling Approach to Analyze the Implementation of Capacity markets in Germany,* (Dusseldorf, 2014).

B. Green, *Dutch lawmakers back coal phase-out,* (2015).

W.-N. Association, *Nuclear Power in the Netherlands,* (2016).

S. Pfenninger and I. Staffell, *Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data,* Energy (in review) (2016).

P. Lako, *Technical and economic features of renewable electricity technologies*, Tech. Rep. ECN-E–10-034 (ECN, 2010).

M. Ragwitz, G. Resch, C. Huber, and S. White, *Dynamic Cost Resource Curves*, Tech. Rep. ENG2-CT-2002-00607 (Energy Economics Group, Vienna University of Technology, 2003).

R. Anderson and L. Taylor, *The social cost of unsupplied electricity: A critical review,* Energy Economics **8**, 139 (1986).

P. Linares and L. Rey, *The costs of electricity interruptions in Spain. Are we sending the right signals?* Energy Policy **39** (2013).

M. d. Nooij, C. Koopmans, and C. Bijvoet, *The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks,* Energy Economics **29**, 277 (2007).

E. Commission, *Guidelines on State aid for environmental protection and energy 2014-2020* (2014).

J.-M. Glachant and S. Ruester, *The EU internal electricity market : done forever?*, Working Paper (2013).

E. Commission, *Launching the public consultation process on a new energy market design*, Tech. Rep. COM(2015) 340 final (Brussels, 2015).

5

CONGRUENCY BETWEEN NATIONAL SUPPORT SCHEMES AND AN INTERNATIONAL ELECTRICITY MARKET

5.1. INTRODUCTION

The European Union's Renewable Energy Source (RES) Directive (2009/28/EC) introduced legally binding national targets to meet 20% of final energy consumption from renewable sources (Commission, 2009). The implementation of the directive seems to be largely on track to realizing the targets, and electricity from renewable sources flourished in many countries. However, the lack of harmonisation between individual Member States to achieve targets led to concerns about fragmentation of the electricity market (Glachant and Ruester, 2013). There were also concerns about cost-effectiveness of a nationally determined strategy from a pan-European perspective (Commission, 2016).

The latest package of measures released by the European Commission proposes a single Europe-wide target of 27% renewables by 2030, without translating them into national-level targets. In addition, it proposes that support of renewables is opened to other Member States to ensure cross-border tradability and address fragmentation of the internal market. In this regard, it makes bold strides by specifying that support for at least 10% of the newly supported capacity in each year between 2021 and 2025, and 15% between 2026 and 2030, should be open to installations in other member states (Commission, 2016). This is a major departure from its earlier strategy, which paid much importance to nationally-determined policies.

Significant amounts of intermittent RES-E in the energy mix have led to unintended impacts. One of the most significant consequences is the so-called merit-order effect, where the spot market electricity price reduces to the extent by which the renewable electricity generation displaces demand along the merit order curve (Sensfuss *et al.*, 2008). It has been empirically demonstrated by a number of studies (Cludius *et al.*, 2014; Ederer, 2015; Gelabert *et al.*, 2011; O'Mahoney and Denny, 2013; Traber and Kemfert, 2009, 2011; Weigt, 2009). It is also possible that the presence of a huge share of renewable electricity will lead to substantial changes in import and export, leading to the spreading of the merit order effect across national borders (Sensfuss *et al.*, 2008). The problem addressed in this research is to understand such cross-border impacts between the Netherlands and Germany. We also seek to understand the role that design elements of RES-E support could play in such cross-border effects.

Relatedly, the future of nuclear and coal-fired power plants appears bleak in the Netherlands and Germany. In 2011 it was mandated that nuclear power was to be phased out by 2022 in Germany. The German Climate Action Plan 2050 mentions that ”the federal German government in its development cooperation does not lend support to new coal power plants”, and includes a commission for ”Growth, Structural Change, and Regional Development” (Federal Ministry for the Environment, 2016). Similarly, the Dutch parliament voted for a 55% cut in CO 2 emissions by 2030, which would require the closure of all of the country's coal-fired power plants (Neslen, 2016). In Germany and the Netherlands, such a trend limits the options of flexibility primarily to gas-fired power generation. Biomass and hydro-power are other options, but less prevalent in these two countries

The objective of this work is to analyse the long-term, cross-border welfare impacts of different renewable support schemes in Germany and the Netherlands, while taking into account the proposed phase-out of nuclear and coal power. The performance indicators for the assessment are average wholesale electricity price trends, the costs of subsidies, and the income transfer between the producers and consumers under various schemes, and different interconnection capacities. As outlined in the previous chapters, the RES-E schemes are identified by their constituent design elements: price or quantity warranty, technology specificity or neutrality and ex-post vs. ex-ante price setting.

5.1.1. LITERATURE REVIEW

ON HARMONISATION OF RES-E SUPPORT

During the early stages after the liberalisation of the electricity market, when the first RES-E Directive was released in 2001, there was a vibrant academic discussion on the most effective way to support renewable electricity in Europe. The objective of these works, briefly described below, was to assess which RES-E support design for EU would provide the most cost effective way of attaining RES-E targets.

Much of the quantitative work in comparing RES-E schemes was done from a purely neoclassical economics perspective, with equilibrium models. Qualitative assessments of RES-E support schemes however, such as from the policy analysis field, tend to be broader in their theoretical foundations. For instance, Finon and Perez (2007) use a transaction cost perspective to compare RES-E support instruments, and Jacobsson and Lauber (2006) combine an ‘economics of innovation’ analysis (linking diffusion patterns to actual policies) with a ‘politics of policy’ analysis (explaining the choice of policies in the larger political context) to explain diffusion of renewable electricity technologies in Germany. Others use empirical methods to perform assessments Johnstone *et al.* (2010); Lewis and Wiser (2007); Haas *et al.* (2011).

Harmonisation can be defined as a top down implementation of common, binding provisions concerning the support of RES-E throughout the EU (Bergmann *et al.*, 2008). The greatest merit of harmonisation of renewable support schemes, from an economist’s perspective, is greater cost effectiveness from better resource allocation. And indeed this was demonstrated by researchers who have conducted static theoretical analysis with equilibrium models (del Rıo, 2005). Such results were corroborated by simulations that indicate significant cost reductions in a harmonised scenario, as compared to a business as usual (BAU) scenario. Huber *et al.* (2004) simulated the electricity market with the Green-X model, and RES-E policies, by deriving endogenously changing supply and demand curves, to generate market equilibriums, for every year (tick) in the model. Voogt *et al.* (2001), using the REBUS model, indicated a 15% cost reduction in the harmonised RES-E support scenario as compared to business as usual. The REBUS model is an Excel spreadsheet calculation tool which, given individual cost curves, and potentials of renewable electricity options, computes the effects of an international burden sharing tool.

In a recent work del Rio *et al.* (2017), the aspect of differences between support schemes of neighbouring countries is analyzed. The authors model two main dimensions: the degree of harmonisation of policies, and the RES-E support instruments. They find that the differences in policy costs can be attributed more to the instruments rather than the degrees of harmonisation. This result holds special relevance given that the recent package of measures announced by the EC proposes strong measures towards "opening of support schemes" to other Member States. [1] While the authors employ a detailed

---

[1] While "opening of support schemes" does not amount to harmonisation, it does force MSs to invest in coun-

representation of the costs and benefits of RES-E technologies in all EU countries, to the knowledge of this author, they do not specifically model the electricity market separately, and the ensuing cross-border price effects that occur due to the addition of RES-E capacity in one country. These cross-border price impacts are important as they indicate possible consequence on the costs of subsidy in the neighbouring country.

Others (Bruninx *et al.*, 2013) model the impact of the German nuclear phase out on Europe's electricity generation via an optimisation model. In their results, nuclear energy is replaced by coal and lignite. Since the publication however, most Central Western European countries have announced a lignite phase out, and the future of coal seems bleak. This work focuses solely on the Netherlands and Germany, and includes detailed representations of their coal and nuclear phase out plans, and studies the impact of different capacities of interconnection in the system.

5.2. EXPERIMENT DESIGN AND DATA

5.2.1. EXPERIMENT DESIGN

In order to study the cross border impacts, experiments were conducted using an agent – based model of the electricity market with an endogenous investment algorithm, described in Chapter 3. The impact of different renewable support schemes in one country on the neighbouring country, under different levels of interconnection capacity between them were tested. The renewable support scheme designs are characterised in term of three main features, that are referred to as 'design elements': price vs. quantity warranty, technology neutrality vs. specificity, and price setting ex-ante vs. ex-post. Each renewable support scheme is composed by a combination of the three design elements, leading to a total of 2 power 3 or 8 unique support schemes. In this experiment design, for a certain interconnection capacity which remains constant throughout the simulation, 8 scenarios are simulated: with each scenario testing a different support scheme in Germany, while the support scheme in the Netherlands remains the same. This experiment is run at three levels of interconnection capacity: 0MW, the current capacity of 3950MW, and a high value of 10000MW. The interconnection capacities remain the same throughout the simulation period which runs for 40 ticks, each tick representing one year. The investments in any scenario are determined by decisions of the agents involving cost benefit analysis incorporating the costs of the technology, the expected revenue from the electricity market, and applicable subsidies. The following sections outline the main results of the experiments.

5.2.2. DATA

This section complements the data presented in Chapter 3. The data below is exclusive to the experiments performed for this chapter.

Fuel costs For the purpose of the experiments here, the fuel costs are assumed to remain constant at an average of the 2015 levels, through the length of the simulation. The data sources and assumptions are listed in Table 5.1.

Technology targets and potentials At the official European level, targets for renewable electricity have not been set for individual member states beyond 2020. However

---

tries outside of their own in a bid to improve cost-effectiveness of investments.

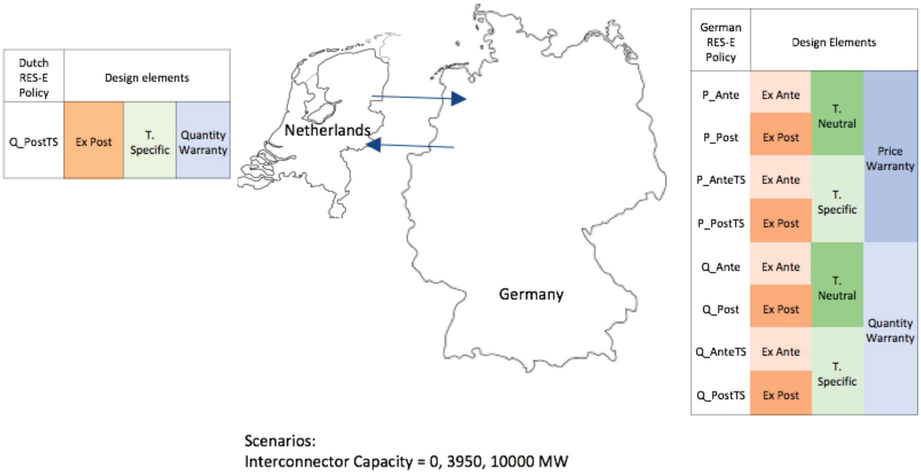


Figure 5.1: Experiment design for analysis of cross border effects

Table 5.1: Assumptions for fuel costs, and corresponding data sources

Fuel name	Average Price in 2015	In Unit	Average Price in 2015 (converted to Eur/GJ)	Source
Coal	61.619	US Dollars per Metric Ton	1.896	(IMF) (2017)
Lignite	22.360	USD per short ton	1.460	Administration (2016)
Uranium	0.005	US Dollars per KWh	1.303	Association (2017)
Natural Gas	7.441	US Dollars per MMBTU	6.361	(IMF) (2017)

the European Union has set itself "a long-term goal of reducing greenhouse gas emissions by 80-95%, when compared to 1990 levels, by 2050" (Commission, 2017). In view of this, the targets have been set at a linearly increasing rate from 2015 levels in both countries to 70% at 2050. The targets are shown pictorially in Figure A.4 and A.5 in the appendix. The 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 Table A.2.

Phasing out technologies As mentioned in the introduction, Germany announced plans to phase out their nuclear power plants in 2022. Similarly, in 2015, Germany's economic ministry and energy companies agreed to take lignite fired power plants offline (Environment, 2015). In the Netherlands too, a closure of all of the country's coal-fired power plants is expected to take place before 2030 (Neslen, 2016). The intial portfolio in the simulation resembles the generation portfolios of the Netherlands and Germany in 2015 closely. The planned phasing out of coal and lignite is implemented in the model, even if exact years for the decommissioning have not been proposed for all technologies. Nuclear power plants in Germany are phased out in 2 stages of 5.GW each in 2018, and 2022. Lignite power plants are phased out in three stages: 8.18GW in 2020, 7.52GW in 2025, and 3.97GW in 2030. In the Netherlands, 1.1 GW of Lignite is assumed to be shut down in 2020 (Maasvlakte 1 and 2), another 1.02 GW is assumed to be shut down in 2026, representing the closure of Centraale Maasvlakte 3. Furthermore, the model assumes that there will be no additional investment in either Coal PSC, Lignite, or Nuclear technologies in either country.

5.3. RESULTS

5.3.1. IMPACTS OF INTERCONNECTION ON ELECTRICITY PRICES

The primary 'medium' so to say, by which electricity spot markets and renewable support schemes interact is through the electricity spot market price. The fundamental mechanism behind the interaction is as follows: the production of cheap variable renewable electricity (VRE) causes a reduction in the average electricity prices. This has been documented and analysed by several studies (Sensfuss *et al.*, 2008; Hirth, 2013). Depending on the amount of interconnection with the neighbouring market, the relative size (capacity in MW) of the neighbouring price zone, and the design of the support scheme, the reduction in electricity prices spread. That is to say, the average electricity price in the neighbouring country also changes. And since subsidies are a difference between cost of the technology and revenue from the electricity market, they are directly linked to the electricity price, due to which, costs of renewable support schemes are also affected.

The spreading of the merit order effect between Germany and the Netherlands is indicated in Figure 5.2. The figure shows the progression of average (annual) electricity price in Germany and the Netherlands across time for each of the eight RES-E support schemes, at different interconnection capacities. At the outset, as one may expect, the electricity prices in both price zones converge as the interconnection capacity increases, irrespective of support scheme design. At an interconnection capacity of 10GW, the prices have almost entirely converged under all scenarios of renewable support schemes.

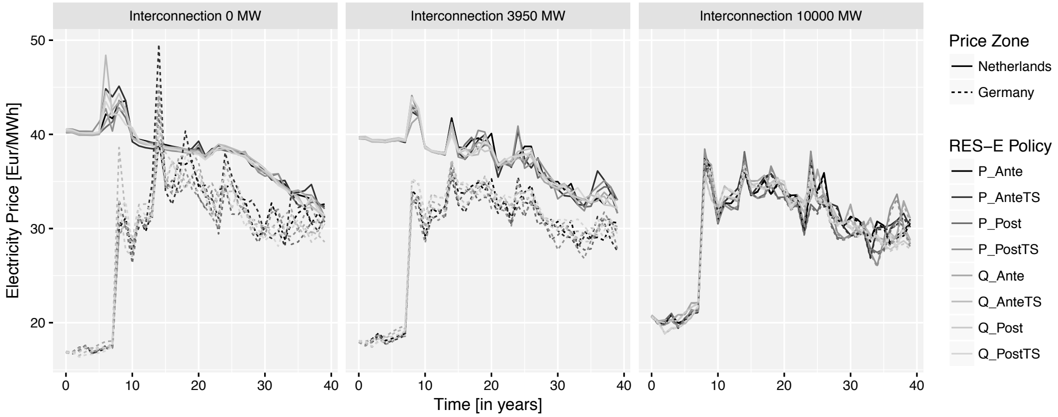


Figure 5.2: Average electricity price plot across different interconnection capacities, for each RES-E policy scenario, in both the Netherlands and Germany

Since European guidelines indicate that support schemes have to be ‘market-based’, subsidies are designed to cover only the part of renewable electricity costs that is not covered by the electricity market. Therefore, as the revenue from the electricity market decreases due to the spreading of the merit order effect, the cost of subsidies in the neighbouring country increases. This is explained in detail in the following section.

5.3.2. EFFECTS ON COSTS TO CONSUMER

In this model, the costs to the consumer are driven primarily by two factors: the price of electricity and the cost of subsidy. In Figure 5.2, we observe that costs of electricity decrease in the Netherlands as interconnection capacity increases. This effect is particularly evident when the scenarios of medium (3950 MW) and high (10000 MW) interconnection capacities are compared. For Germany however, the electricity price level remains more similar across interconnection levels, with the exception of certain peak prices being absent as interconnection capacities increase.

The cost of the subsidy as mentioned above, is subject to the revenue that producers earn from the electricity market, and to the costs of the technology. Figure 5.2 demonstrates that the electricity prices decrease in the Netherlands as interconnection capacity with Germany increases. Correspondingly, during the first 30 years, the subsidy costs in the Netherlands increase in scenarios with highest interconnection. This trend can be observed in Figure 5.3. The question that follows is why these trends appear, and how these trends impact the overall welfare of the consumers, that is, how total costs of electricity, subsidy, and both together affect the consumer over the entire period of the simulation, under different scenarios. These results are explained in the following sections in detail.

COSTS OF SUBSIDY IN THE NETHERLANDS

In Figure 5.3, a contradiction is apparent and deserves explanation. On the one hand subsidy costs in the Netherlands increase as interconnection increases upto year 30 (appr.),

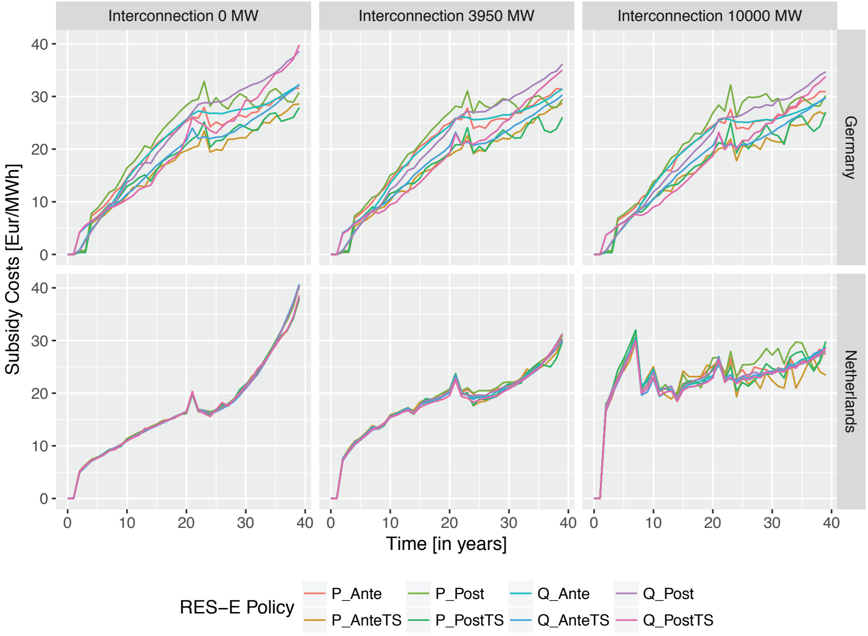


Figure 5.3: Subsidy costs per MWh electricity generated in the Netherlands and Germany across time

however beyond year 30, subsidy costs decrease as interconnection capacity increases. This is explained by the fact that beyond year 30, at low interconnection levels there is substantial spillage in the system, i.e., the intermittent electricity production surpasses demand frequently. This leads to an increase in costs per unit of production, thereby increasing the subsidy costs. This is also corroborated by Figure B.5, and Figure B.6 in the appendix, which show the spillage of RES-E production with time, per technology. In the first phase of the simulation before year 30, where spillage does not play too great a role, the following results are observed. In ‘Interconnection 10000’ scenarios, the subsidy costs in the Netherlands are higher by a range of 10 - 2 Eur/MWh as compared to the ‘Interconnection 3950 MW’ scenarios (current levels), and by 18 - 2 Eur/MWh as compared to the ‘Interconnection 0 MW’ scenarios. Since spillage substantially affects the costs of subsidies beyond year 30, it is useful to see results separately until year 30, as in Table 5.2, and for the full simulation as in Table 5.3.

The results demonstrate that greater interconnection capacities with Germany lead to higher subsidy costs in the Netherlands, due to lowering of electricity prices, as long as shares of RES-E production in the Netherlands remain lower than approximately 60%, which is approximately the share of renewable electricity at year 30. As shares increase, the level of interconnection plays a progressively higher role in the subsidy costs, due to spillage.

The questions that follow are what factors these figures are sensitive to and why. The amount of spillage is sensitive to the technology, the interconnection capacity, and the

Table 5.2: Costs of electricity and subsidy, summed for the first 30 years [ticks], averaged across different RES-E policy scenarios, in bn euros.

Country	Interconnection Capacity [in MW]	Cost of electricity in DE [in bn Eur]	Cost of electricity, SD, in DE [in bn Eur]	Cost of Subsidy in NL [in bn Eur]	Cost of Subsidy, SD, in NL [in bn Eur]
Netherlands	0	159.95	2.46	54.60	1.26
Netherlands	3950	156.29	2.53	55.14	1.15
Netherlands	10000	124.17	1.92	63.72	2.27
Germany	0	537.03	9.94	316.65	37.53
Germany	3950	539.66	7.19	310.01	39.54
Germany	10000	551.04	4.81	308.46	37.94

Table 5.3: Costs of electricity and subsidy, summed for the full simulation period [40 years], averaged across different RES-E policy scenarios, in bn euros.

Country	Interconnection Capacity [in MW]	Cost of electricity in DE [in bn Eur]	Cost of electricity, SD, in DE [in bn Eur]	Cost of Subsidy in NL [in bn Eur]	Cost of Subsidy, SD, in NL [in bn Eur]
Netherlands	0	209.46	5.11	99.12	2.75
Netherlands	3950	205.39	5.06	92.32	2.36
Netherlands	10000	168.50	5.14	101.16	3.77
Germany	0	730.38	15.99	508.29	51.90
Germany	3950	732.43	7.17	494.42	51.35
Germany	10000	741.72	6.62	488.87	49.52

absence of storage in the system. The dependence of spillage on technology types in each of the countries is indicated in Figures B.5 and B.6 . The type of support scheme, and its design would also impact the results, as demonstrated in the previous chapter[2] and explained further in the sections below. Other factors that could impact subsidy costs, but whose sensitivity has not been modelled, due to resource constraints, are the costs of technologies, their capacity factors, and geographical distribution of power plants.

COSTS OF SUBSIDY IN GERMANY

The subsidy costs in Germany in this experiment depend primarily on the type of support scheme implemented in Germany. The impacts of design elements on subsidy costs follow from the explanations provided in Chapter 4, and are briefly described below:

---

[2] The type of support scheme here refers to the country's own support scheme, and not that of the neighbouring country's.

- Price warranty schemes vs Quantity warranty schemes: Price warranty schemes lead to an investment up to the potential of the technology, rather than their targets, if no budget limit or quantity limits are exogenously set, and assuming the regulator has perfect knowledge of future electricity prices. In this case, if the fraction of VRE generation is higher than appr. 60% then spillage occurs, leading to higher subsidy costs than their corresponding quantity warranty schemes. Quantity warranty schemes lead to an investment up to the targets set by the regulator. If the targets are set in a manner that there is no spillage in the system, then costs of subsidy remain lower than their price-warranty counter parts. In this experiment, both targets and potentials set for Germany across the 40 years are similar, see Figure A.4 in the appendix. Therefore the difference in spillage between both types of schemes is marginal.
- Technology specificity vs. technology neutrality: Technology neutral schemes are more expensive than their technology specific counter-parts due to wind-fall profits obtained by non-marginal technologies in the technology neutral schemes.
- Ex-post vs. ex-ante price setting: Ex post schemes are more expensive to the consumer, as the regulator underestimate the reduction in electricity prices due to the merit order effect.

Aside from impacts of support scheme design, other factors that impact subsidy costs in Germany are i. the amount of interconnection and ii. the amount of spillage. When capacity of interconnection increases the electricity price in the exporting zone increases. An increase in the revenue from electricity prices implies a reduction in the costs of the subsidy. On average, across all RES-E policy scenarios, as interconnection increases, subsidy costs in Germany decrease, as is shown in both Tables 5.2 and 5.3. The standard deviation of the costs of subsidy are quite high for Germany, primarily because the technology neutral support schemes require much more subsidy than the technology specific ones[3]. This is evident in Figure B.4 which shows the sum of subsidy and electricity costs through the full simulation for both countries.

TOTAL COSTS TO CONSUMER

The total costs to consumers; across the full period of the simulation, i.e., the sum of electricity and subsidy costs through 40 years are indicated in Figure 5.4. Although for the Netherlands the costs of subsidy increase and the costs of electricity decrease, the reduction in costs of electricity is higher than the increase in cost of subsidy. This implies that the total cost for the Netherlands reduces as interconnection increases. This corroborates with results that have been found by authors who studied the merit order effect, for an uncongested region. In addition it is also evident from Figure 5.4 that the type of design of the RES-E schemes in Germany does not directly affect costs in the Netherlands. Nonetheless, it can be expected that the quantity of RES-E generation in Germany, determined by its target, has an impact on the electricity prices in the Netherlands and consequently on its subsidy costs.

The results are not as straightforward for Germany, where the cost trend depends not only on the interconnection capacities, but also on the type of renewable support

---

[3] Due to high infra-marginal subsidy costs, i.e., high windfall profits for non-marginal technologies

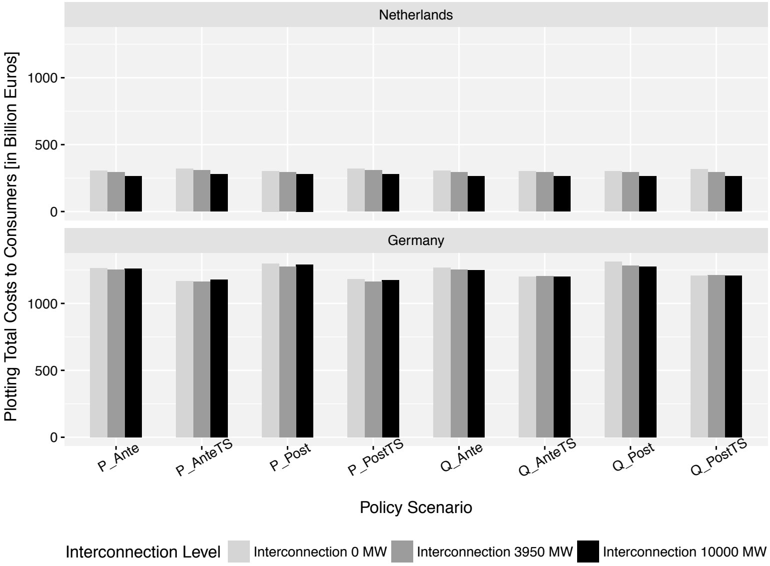


Figure 5.4: Total cost to consumer including costs of electricity as well as subsidy over 40 years

scheme active in each scenario. As explained in the above sections, factors such as technology neutrality of support scheme, spillage, have an impact on the costs of subsidy and electricity; the costs are reflected in Figure 5.4.

5.3.3. COSTS AND REVENUES TO PRODUCER

In this section the impacts of the various policy scenarios on the costs and revenues of the producer are discussed. Under perfect competition, and long-term equilibrium, theory predicts that profits are zero. However, in this model, neither is perfect information assumed, nor is economic decommissioning implemented, and infra-marginal profits play a significant role. In Figure 5.5, the profits of the producers summed across the length of the simulation (40 years) are indicated per technology, per country, per RES-E policy in Germany, and for different scenarios of interconnection capacity.

As mentioned in Chapter 3, economic decommissioning of power plants has not been modelled; the plants are operational through out their technical lifetimes, irrespective of whether their long run marginal profits are negative. This has an impact on CCGT plants as they are largely the marginal generating technology; their long-run profits are negative. For pulverised super-critical coal based power plants (CoalPSC), their low marginal costs lead to high infra-marginal rents, and positive profits. Since Germany is the larger, exporting country, the profits of German CoalPSC plants increase, as interconnection capacities increase, while the trend is opposite for the Dutch CoalPSC plants. Nuclear and lignite plants, with their low short-run marginal costs, and flexible nature, make higher infra-marginal profits as interconnection capacities increase. Un-

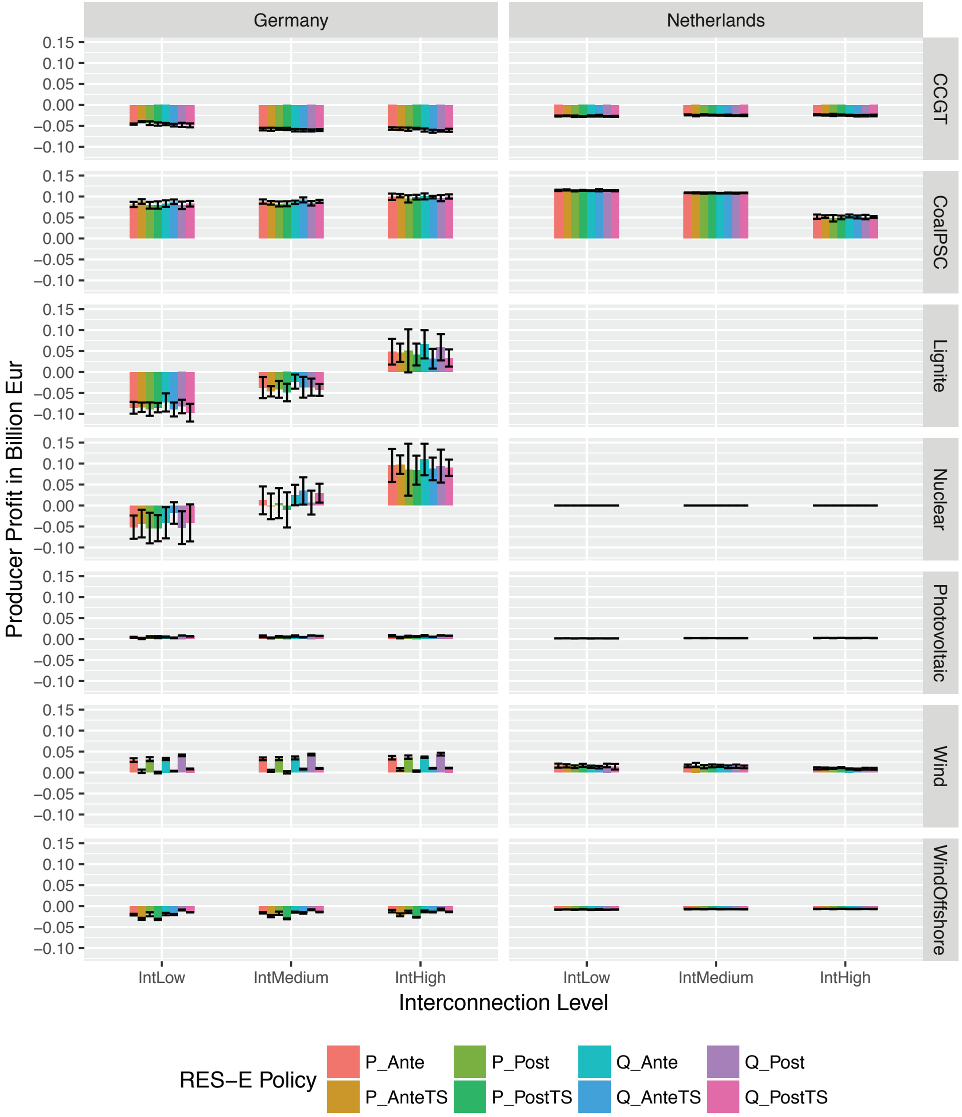


Figure 5.5: Total profit to producer per policy scenario and per technology across 40 years

forseen[4] decommissioning by the German government, also exacerbate their low overall profits at low interconnection capacities.

As for renewable technologies, the subsidies are designed to just cover costs, and the regulator is assumed to have the same cost information as the energy producer. This is reflected in near-zero profits for Solar PV. Since it is the marginal renewable technology due to its higher costs, the technology neutral and technology specific RES-E policies both result in near-zero profits. Wind power plants (on-shore) earn-infra marginal profits under technology neutral policy scenarios.

5.4. DISCUSSION

5.4.1. MERITS AND LIMITATIONS OF THE MODEL

The popular aphorism, "All models are wrong, but some are useful" seems especially pertinent when models seek to simulate the next several decades. The uncertainties in modelling such a timescale are innumerable. While a few of them have been taken into account, such as bounded rationality of agents regarding future electricity prices, and uncertainty in demand growth, assumptions have been made regarding many other parameters. For instance, if costs of variable renewable electricity technologies were to drop at a faster rate than assumed in this study, the costs of subsidy would be even lower, strengthening the idea that decrease in electricity costs will be greater than the increase in subsidy costs to the consumer in the neighbouring country. Costs of gas, coal, and uranium are impacted by global trends and difficult to predict in the long-term. In this work they have been assumed to be constant at 2015 levels. While this assumption helps the analyst focus solely on the variables of interest, such as levels of interconnection and renewable support scheme designs, in reality fuel costs might have an impact on the results.

Despite its many limitations the model provides several insights on cross-border effects caused due to national support schemes alongside an international electricity market. Results show that given a certain interconnection capacity, the designs of renewable support schemes and their targets do lead to unintended effects on subsidy costs in a neighbouring country. However, these effects are primarily caused by virtue of the installed capacity of intermittent renewable electricity that a support scheme design incentivizes, as against the design elements themselves.

The results also indicate that at high shares of RES-E production, interconnections play an important but ultimately limited role in lending flexibility to the system, and consequently in ensuring that each unit of intermittent electricity is consumed in an efficient manner. They indicate that the presence of flexibility has strong implications on the targets of intermittent renewable generation the European Union or individual countries can set for themselves, without having to suffer costs of spillage in the form of increased subsidies. The targets to be set each country must take into account, ceteris paribus, firstly its interconnection capacities with neighbouring countries. At a later point in time when spillage of intermittent renewable generation becomes inevitable in the absence of storage, countries must also take into account the amount of storage available to them while setting their targets. An ex-ante price setting scheme ameliorates

---

[4] at the time of investment

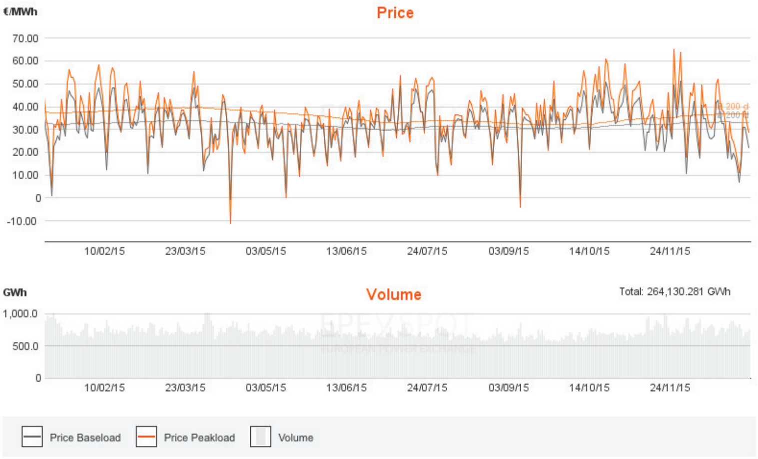


Figure 5.6: EPEX-SPOT Data showing day ahead electricity prices and volume for 2015, for base load (grey) and peak load (orange) in the DE/AT price zone. It also shows the 200 day average prices. (SPOT, 2015)

the impact of the merit order effect on subsidy costs, at the risk of renewable energy producers incorporating their price risks into the cost of capital.

5.4.2. VALIDATION: COMPARISON TO OBSERVED DATA

Validity, as described in section 3.6, is an investigation of the model's adequacy for purpose. One strategy to validate models is to check whether the simulation output fits closely with observational data, while treating the simulation as a black box. Although comparing output from the model for the next 30 years to actual observational data is impractical, it is possible to use historical data as input and observe the outputs while accounting for assumptions made.

In this chapter, data such as fuel prices, the expected decommissioning of plants (nuclear and lignite) are inputs. Since cross border effects were the main purpose of the model, we used constant fuel prices of 2015 levels, to reduce the variability due to less important factors in the experiment. If the model works as expected, the outputs or electricity prices should match the prices that were observed in Germany and the Netherlands in 2015. The range of price levels under existing interconnection levels between simulated and observed data are comparable. EPEX-SPOT data in Figure 5.6 shows that the 200 day average price ranges lie between 30 and 40 Eur/MWh, whereas the actual day-ahead prices vary from less than 0Eur/MWh upto 60 Eur/MWh (SPOT, 2015).

The simulation indicates comparable price ranges after year 7, at which point Lignite power plants are phased out in Germany. Upto year 7 however, we see average prices of between 16 Eur/MWh at zero interconnection capacity, upto 23 Eur/MWh at 10 GW interconnection capacity. The reason for much lower prices in Germany before year 7 could be attributed to the fact that all interconnection capacities between Germany and surrounding countries have not been modelled. The export to the Netherlands accounts for only a fraction of its total export. This is corroborrated by data from the ENTSO-E, which indicated that during 2015, the export to the Netherlands from Germany accounted for an average of 29% [ranging between 16% and 45%] of its total exports (ENTSO-E, 2015).

5.4.3. DISTORTION OF THE INTERNAL ENERGY MARKET

One could wonder whether the unintended effects are indeed a “distortion” of the internal energy market, as has been described in some key documents of the European Commission (Commission, 2016) and (Commission, 2015). Similarly, some researchers have termed such effects a “fragmentation” of the internal market due to national level policies (Glachant and Ruester, 2013). As far as national RES-E schemes are concerned, these cross-border effects, while unintended, are but a fiercer manifestation of the merit order effect, which affects VRE importing countries whose sizes are relatively smaller. This is not necessarily an adverse effect, as the effect would have persisted even if countries were isolated import of VRE, as shown above also brings with it a significant reduction in electricity prices, whose benefits to the consumer outweigh the increase in subsidy costs. As far as the simultaneous goals of consuming greater amounts of VRE, and having a single internal electricity market are concerned, such a result is only reasonable, and should be welcome!

The question of consistency or distortion then lies in whether the current institutions ensure that the investment signal, and not just the “consumption (or production) signal” is also commensurate with the principle of “low-hanging fruit”. RES-E support schemes as they operate today predominantly incentivize cost-effective investments within national boundaries. While this arrangement has proved to be effective in inducing large amounts of RES-E generation, from a pan-European perspective concentration of efforts in certain member states has proved to be expensive. A popular example is Germany’s expensive investment in electricity from photovoltaic panels in Germany itself, while the same investment in Southern Europe could have gained from much higher capacity factors. The recently proposed RES-E directive (Commission, 2016) includes an article which mandates that member states open support for RES-E to generators located in other member states. The article specifies capacities as well: "*Member States shall ensure that support for at least 10% of the newly-supported capacity in each year between 2021 and 2025 and at least 15% of the newly-supported capacity in each year between 2026 and 2030 is open to installations located in other Member States.*" The new proposed scheme would help ameliorate large differences in cost effectiveness. The efficiency gains of such a tactic to members of the country investing in another country however is constrained by interconnection capacities. Even sufficient interconnection will only be useful up to an extent, beyond which having storage will become a necessity to include greater amounts of RES. That limit, for the Netherlands and Germany put together seems to lie at 60% annual generation from variable renewable electricity in both countries.

5.5. CONCLUSIONS

The primary objective of this chapter was to investigate cross-border effects due to national RES-E support schemes, operating in an international electricity market. In order to carry out this research, EMLab Generation, a model comprising of both an electricity market clearing module, and an endogenous investment algorithm was used. Price zones based on Germany and the Netherlands were simulated, to test the effects of different support scheme designs in each country, and the common electricity market, on distributional implications under diffrenent scenarios of interconnector capacities, over a long term period of 40 years, starting from 2015.

As economic theory would predict it is found that subsidy costs increase in the smaller country, due to spreading of the merit order effect from the larger neighbouring country. Increasing the interconnection capacity between Germany and the Netherlands from the current 3950 MW to 10000MW would lead to an increase of Eur 8.58 billion[5] in Dutch subsidy costs, under assumed cost structures until 2045. However, the increase in subsidy costs remains lower than the reduction in costs of electricity (Eur 32.12 billion), corroborrating earlier, single country analyses on the topic. Therefore, total cost in the neighbouring country reduces as interconnection increases, as the invisible hand works its magic. Another important insight is that as share of RES-E increases, interconnection has limited impact on reducing spillage of RES-E while storage becomes increasingly important. The results show that targets for RES-E, depend not only on the targets of the neighbouring countries, but also the capacity of storage that exists in the system.

Several policy recommendations follow from the results and analyses. The results show that it is necessary that policy makers and researchers ponder over questions about how subsidy costs should be allocated between countries over the long term when they are so intricately connected with the electricity markets they operate in. This should be part of the European Commission's research agenda. Futher, it is evident that while setting RES-E targets either for individual member states, or for several together, the capacity of flexible sources available to them should be explicitly taken into account. The targets that can be set in a cost efficient manner are limited by the amount of interconnection and storage available to that system.

This research also opens up several avenues for future work. The results indicate that shares of RES-E greater than 60%, is not a cost efficient proposition without storage. However this figure is accompanied by disclaimers of limited temporal resolution in the model. In order to deduce a precise estimate of the point at which storage becomes essential, models with greater temporal resolution are necessary. Since costs of RES-E technologies have been dramatically dropping over the last few years, a large sensitivity analysis could help answer the question, "At what costs do subsidies become redundant". Another interesting question is to evaluate cross border effects under other institutional arrangements such as bilateral contracts, capacity markets, and perhaps the EU-ETS.

---

[5] At 2015 levels, without accounting for inflation

REFERENCES

E. Commission, *Directive 2009/28/EC,* Official Journal of the European Union **52** (2009), 10.3000.

J.-M. Glachant and S. Ruester, *The EU internal electricity market : done forever?*, Working Paper (2013).

E. Commission, *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast)*, Tech. Rep. COM(2016) 767 final (European Commission, Brussels, 2016).

F. Sensfuss, M. Ragwitz, and M. Genoese, *The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany,* Energy Policy **36**, 3086 (2008).

J. Cludius, H. Hermann, F. C. Matthes, and V. Graichen, *The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications,* Energy Economics **44**, 302 (2014).

N. Ederer, *The market value and impact of offshore wind on the electricity spot market: Evidence from Germany,* Applied Energy **154**, 805 (2015).

L. Gelabert, X. Labandeira, and P. Linares, *An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices,* Energy Economics **33**, S59 (2011).

A. O'Mahoney and E. Denny, *Electricity prices and generator behaviour in gross pool electricity markets,* Energy Policy **63**, 628 (2013).

T. Traber and C. Kemfert, *Impacts of the German Support for Renewable Energy on Electricity Prices, Emissions, and Firms,* The Energy Journal **30**, 155 (2009).

T. Traber and C. Kemfert, *Gone with the wind? — Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply,* Energy Economics **33**, 249 (2011).

H. Weigt, *Germany's wind energy: The potential for fossil capacity replacement and cost saving,* Applied Energy **86**, 1857 (2009).

B. a. N. S. Federal Ministry for the Environment, nature Conservation, *Climate Action Plan 2050: Principles and goals of the German government's climate policy,* (2016).

A. Neslen, *Dutch parliament votes to close down country's coal industry,* (2016).

D. Finon and Y. Perez, *The social efficiency of instruments of promotion of renewable energies: A transaction-cost perspective,* Ecological Economics **62**, 77 (2007).

S. Jacobsson and V. Lauber, *The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology,* Energy Policy **34**, 256 (2006).

N. Johnstone, I. Haščič, and D. Popp, *Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts,* Environmental and Resource Economics **45**, 133 (2010).

J. I. Lewis and R. H. Wiser, *Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms,* Energy Policy **35**, 1844 (2007).

R. Haas, C. Panzer, G. Resch, M. Ragwitz, G. Reece, and A. Held, *A historical review of promotion strategies for electricity from renewable energy sources in EU countries,* Renewable and Sustainable Energy Reviews **15**, 1003 (2011).

J. Bergmann, C. Bitsch, V. Behlau, and S. Jensen, *A European harmonised policy to promote RES-electricity - sharing costs and benefits*, Tech. Rep. D17 (Vienna University of Technology, 2008).

P. del Rıo, *A European-wide harmonised tradable green certificate scheme for renewable electricity: is it really so beneficial?* Energy Policy **33**, 1239 (2005).

5

C. Huber, T. Faber, R. Haas, G. Resch, J. Green, S. Olz, and S. White, *Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market*, Tech. Rep. (2004).

M. H. Voogt, M. A. Uyterlinde, K. Skytte, M. Leonardi, and M. H. Whiteley, *Renewable energy burden sharing. REBUS. Requirements and expectations of utilities and consumer organisations in the European energy sector*, Tech. Rep. (Energy research Centre of the Netherlands ECN, Petten (Netherlands), 2001).

P. del Rio, G. Resch, A. Ortner, L. Liebmann, S. Busch, and C. Panzer, *A techno-economic analysis of {EU} renewable electricity policy pathways in 2030,* Energy Policy , (2017).

K. Bruninx, D. Madzharov, E. Delarue, and W. D'haeseleer, *Impact of the German nuclear phase-out on Europe's electricity generation—A comprehensive study,* Energy Policy **60**, 251 (2013).

I. M. F. (IMF), *IMF Cross Country Macroeconomic Statistics,* (2017).

U. E. I. Administration, *Annual Coal Report 2015*, Tech. Rep. (US Department of Energy, 2016).

W. N. Association, *Nuclear Power Economics | Nuclear Energy Costs,* (2017).

E. Commission, *2050 Energy strategy - European Commission,* (2017).

D. Environment, *The end of lignite coal for power in Germany,* (2015).

L. Hirth, *The market value of variable renewables: The effect of solar wind power variability on their relative price,* Energy Economics **38**, 218 (2013).

E. SPOT, *EPEX SPOT SE: Day-Ahead Auction,* (2015).

ENTSO-E, *Country Data Packages,* (2015).

E. Commission, *Launching the public consultation process on a new energy market design*, Tech. Rep. COM(2015) 340 final (Brussels, 2015).

6

RES-E POLICY DESIGN IN PERSPECTIVE OF THE ENERGY TRANSITION

6.1. INTRODUCTION

In auctions for wind offshore projects organised in Germany in April 2017, three of the four winning projects bid at zero subsidy. In such auctions, we see mounting evidence of dramatic reductions in technology costs, caused in part (for wind offshore) by advancements in turbine technologies, standardization and optimisation of designs. At the same time, governments have become increasingly optimistic that zero subsidy becomes the norm; for instance, the Dutch government announced plans to organise subsidy-free auctions in 2026, and the UK is not too far behind (Wind, 2017). Despite this optimism from the wind offshore industry and governments, the question we ask is whether such optimism is justified - not just in 2026, but also in the longer-term perspective of three to four decades in the future, given the current institutional settings that we operate in.

In Europe, the energy transition comprises a multitude of policies and strategies as multiple objectives simultaneously compete for attention: the EU ETS, demand response measures, capacity mechanisms etc are a few. The recent package of measures released by the European Commission, ‘Clean Energy for All Europeans’, further promotes the objective of decarbonisation by proposing strict measures to ensure that at least 27% of all energy consumed comes from renewable sources by 2030, while steadily moving towards reducing emissions by 80-95% in Europe by 2050.Dramatically decreasing costs of solar and wind generation technologies have aided the transition further, not just in Europe, but the world over: costs of solar PV are half as much as they were in 2010, and are expected to fall by a further 60% over the next decade (IRENA, 2016).

As has been a recurring theme in the preceding chapters, there have been unintended effects caused by the huge influx of intermittent renewable electricity into the electricity market. The first of these unintended effects is the "merit-order" effect, due to which renewable electricity generation has a strong price reduction effect on wholesale electricity spot prices (Sensfuss *et al.*, 2008). A second effect, which directly relates the presence of variable renewable electricity (VRE) to its economic value, is the idea of the "market value of VRE", as defined and quantified by Hirth (2013). Due to the simple fact that VRE[1] is inherently variable with time and has limited predictability, its economic value in the spot market is heavily influenced by its own existence. As the share of VRE increases, its economic value reduces. Due to this reason, it is questionable whether support for renewables can be phased out as their share increases.

Three elementary aspects of the energy transition are especially important: the electricity spot market, the EU ETS, and finally, flexible resources. The electricity spot market represents a set of institutions which form the essence of a well-functioning, liberalized market for electricity. They signal the value of electricity as a commodity, and in principle, incentivize investment in the most cost-efficient generation sources. The relationship of the cost of subsidies to VRE with the price of electricity is therefore, fundamental to the assessment of the economic viability of VRE. The EU-ETS is a pillar of the European Union’s energy strategy. It was envisioned as a tool to price carbon-dioxide emissions, and therefore incentivize low-carbon sources of electricity generation in the power sector as well. It is, therefore, imperative to assess how this ETS mechanism will impact the costs of subsidies as the share of RES-E in the system increases. Finally, tem-

---

[1] For the purposes of this chapter, VRE and RES-E are used interchangeably

porally flexible resources such as storage, and locational-based flexible resources such as interconnection are resources essential for controlling the variability, and consequently the market value of VRE. The need for flexibility, and its impact on the possible cost of subsidy is discussed.

The aim of this chapter is therefore to touch upon these three aspects of the energy transition. In light of the intricate relationship between the subsidy designs and the internal electricity market, the first section comprises a discussion on the components that drive RES-E subsidies. The second section of this chapter is a deliberation on the role the EU-ETS could play in the interaction between subsidy costs and electricity price. The third section reviews scientific literature regarding the role of flexible resources, such as interconnection and storage, on the market value VRE, and juxtaposes it with results obtained from the preceding chapters. Finally, the chapter culminates with a comparison between factors which could influence subsidy costs over the short term versus the long term.

6.2. SUBSIDY COSTS AND ELECTRICITY PRICES

6.2.1. DRIVERS OF RES-E SUBSIDY

The standard method to make an investment decision is to carry out a cost-benefit analysis, which culminates in a net present value (NPV) calculation. An NPV calculation takes into account all cashflows during each year of the project operation, and discounts it to the present value. The subsidy, similarly, is calculated as the difference between the costs and revenues for a given project. As long as the costs are greater than the revenue from the electricity market, subsidy programmes will be necessary to incentivize investment. Through the course of this PhD project, technology costs have dropped significantly in the industry, and there have been interesting analyses on factors influencing revenues from the spot market price. These issues have been discussed in this subsection.

COSTS

The cost comprises three quantities: the technology costs, the operation and maintenance costs, and the cost of capital. Technology costs have seen a rapid decline over the last few years for solar, wind, and wind-offshore technologies.

In the case of solar, global utility-scale PV system costs have reduced by 62% between 2009 and 2015 (IRENA, 2016). The potential for further cost reduction is expected to be large: the global average of installed-costs could reduce by 57% in 10 years from 2015 to 2025 (ire, 2016). The utility scale cost trends for solar are presented in Figure A.6.

Multiple sources report a similar cost decline in the wind industry: in the order of 60% between 2009 and 2016. For instance, Bloomberg New Energy Finance finds that in Europe, the costs of building an offshore wind farm has fallen by 22% solely over 2016-17 (Finance, 2017a). They expect levelized costs of offshore wind to fall by a further 71% by 2040 (Finance, 2017b). A report from the Lawrence Berkeley National Laboratory finds that wind turbine prices in the USA have fallen between 20% and 40% from 2008 until 2016 (Wiser *et al.*, 2016).

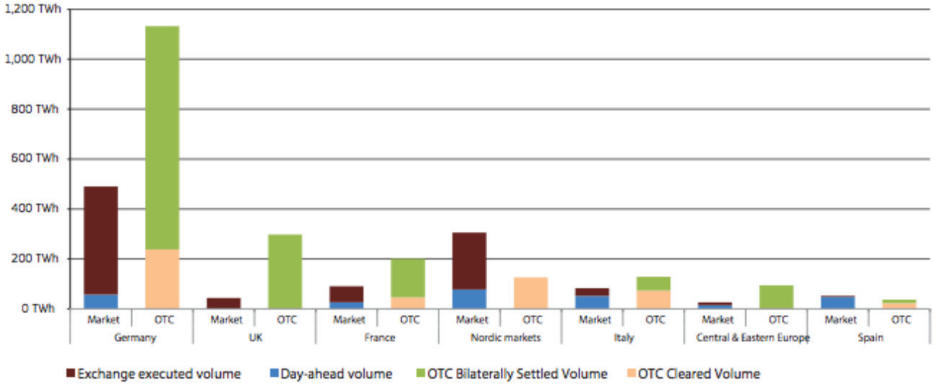


Figure 6.1: Comparison of electricity traded volumes in day-ahead, forward, OTC markets in the third quarter of 2016. Source for Energy (2016)

REVENUES

In western Europe, substantial shares of electricity are either traded on organised trading platforms such as the spot market or bilaterally on the so-called over-the-counter (OTC) markets. In different countries the shares traded in each market might be different. For an indication, see Figure 6.1. The day-ahead markets such as the EPEX-Spot in the central western Europe region are transparent with data, and therefore provide a useful source for analysing revenues from the electricity market. In this section, we seek to understand what the current drivers of spot market electricity prices are.

In the body of literature on electricity price drivers, most existing studies are empirical, and focus exclusively on the merit order effect of renewables; for instance Sensfuss *et al.* (2008); Cludius *et al.* (2014); Ederer (2015); Gelabert *et al.* (2011); O'Mahoney and Denny (2013); Traber and Kemfert (2009, 2011); Weigt (2009); Würzburg *et al.* (2013). Bublitz *et al.* (2017) provide a concise and insightful literature review of such studies. In addition, unlike the aforementioned studies, they determine and compare price drivers with the objective of ascertaining whether the merit order effect is indeed the biggest cause of the price drop in the German electricity market (Bublitz *et al.*, 2017). They use two methods: a linear regression model and an agent-based model to test price effects from different factors on the spot market price. Contrary to popular opinion, they find that between 2011 and 2015 the impact of carbon and coal prices was twice as high as the impact of renewable expansion. Other studies look at effects of other factors such as the influence of neighbouring countries (Dehler *et al.*, 2016), coal and gas prices (O'Mahoney and Denny, 2013; Dehler *et al.*, 2016), the nuclear moratorium (Thoenes, 2014), and of demand and fuel prices (Hirth, 2016a).

All the above studies are ex-post analyses and use empirical data. They have little to say about future price trends or determinants of electricity prices in the presence of high shares of renewable electricity generation. To gain insight into the drivers of electricity prices decades into the future, long-term energy models are commonly employed. Given the uncertainties involved in such modelling, it is worth remembering Hamming's argument on computation: the purpose of computation is insight, not numbers (Hamming, 1962). As a strategy to gain insight under uncertainty, scenario analysis has gained immense importance since Rand Corporation first used it in the 1940s. For this dissertation, scenarios with at least 70% renewable electricity generation by 2055 are considered. There are few studies modelling such scenarios specifically for Germany and the Netherlands which account for factors such as uncertainties in carbon prices, coal and gas prices, demand growth, etc. on the electricity prices.

Simulations conducted for this dissertation provide some useful insights. In the following section, we look at results from the model to understand what could be major electricity price drivers in the long-term period of 20-30 years, as the share of intermittent renewable energy increases in the energy mix.

6.2.2. MODEL RESULTS ON THE RELATIONSHIP BETWEEN SUBSIDY COSTS AND ELECTRICITY PRICES

In Chapter 4 of this dissertation, a simple representation of the Netherlands is modelled with only four technologies: Solar PV, wind, wind offshore, and CCGT (Combined Cycle Gas Turbine). The results presented in Chapter 4 were mainly concerned with the effects of different RES-E support designs on social welfare. In this chapter, we focus on the part of the results that shows the relationship between electricity prices and subsidy costs under different gas price trends. We use the RES-E support scheme with the following configuration: *quantity warranty, technology specificity,* and *ex-post price setting.* This configuration most closely represents the support scheme currently implemented in the Netherlands, as shown in Chapter 4. In particular, we study three trends: a) *Constant*, where the gas price remains constant at 4 Eur/GJ through the entire period of the simulation, b) *High*, where, starting from 4 Eur/GJ, the gas price increases at a mode of 4 % percent at each tick, and c) *Low*, where, starting from 4 Eur/GJ, the gas price decreases at a mode of 2 % at each tick. The progression of the trends in gas prices for each of the above cases is indicated in figure 6.2.

OBSERVATIONS

Trends in electricity prices (averaged per year) and subsidy costs per year, both expressed in Eur/MWh, across the length of the simulation period - 0 to 40 years - are shown in Figure 6.3. The electricity price trends are, as expected, primarily impacted by gas prices. However, interestingly, they are not impacted as much by the amount of renewable electricity generation in the mix. Figure 6.3 also demonstrates that the subsidy cost for solar PV reduces over time, with the rate of reduction differing between scenarios depending on the electricity price trends. The scenarios differ only in their gas trends, which are indicated in figure 6.2 as mentioned above. The corresponding fractions of renewable electricity generated are indicated in figure 6.5. At the outset, the following major observations can be made with regard to the relationship between electricity price and subsidy costs under different gas price trend scenarios:

- In the *gas price trend: Constant* scenario, a clear pattern does not emerge. There is no direct relationship between electricity price and subsidy cost.
- In the *gas price trend: High* scenario, as electricity prices increase, subsidy costs decrease for all technologies. This can be seen in figures 6.3 and 6.4. This relationship is maintained as the share of renewable electricity in the mix increases.

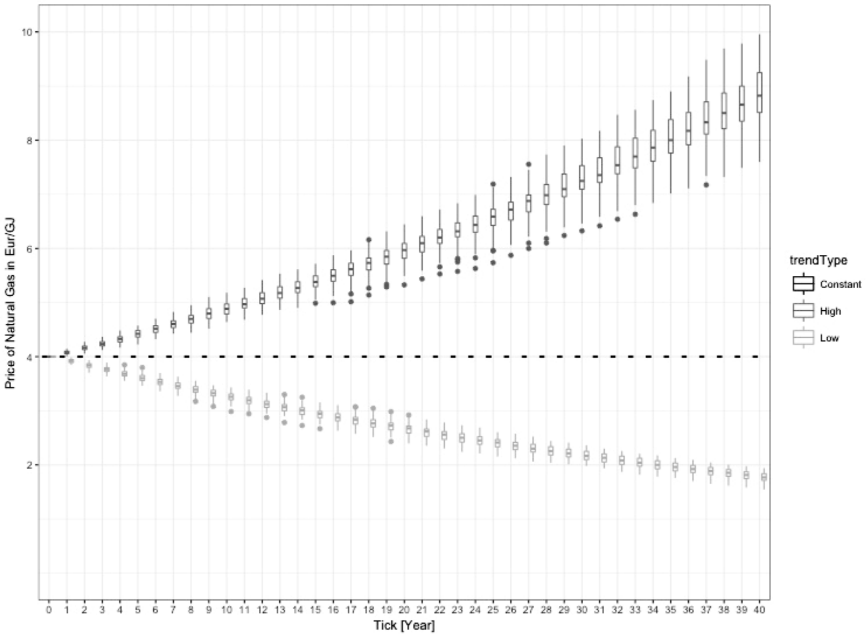


Figure 6.2: Assumptions of gas prices made for Constant, Low, High scenarios.

- In the *gas price trend: Low* scenario, as electricity prices decrease and as the share of renewable electricity increases, the subsidy costs do increase, but only slightly more than in the *gas price trend: Constant* scenario. This increase is more clearly visible in Figure 6.3 than in Figure 6.4. In addition, it is also evident that when electricity prices fall, they cause modest increases in subsidy costs; but that rising electricity prices cause larger reductions in subsidy costs.

Factors other than gas prices also impact the electricity price and subsidy cost within the model. The subsidy costs are influenced by fixed costs of the technology, their capacity factors, and the absence of storage or interconnection in the system. This last factor leads to spillage of intermittent renewable electricity production. As the share of VRE generation increases, there are more frequent instances of VRE generation being higher than the demand, which leads to curtailment of RES-E or spillage. Increased spillage manifests itself as an increase in the per unit (MWh) fixed operation and maintenance cost of the technology.

The electricity prices in the model are also influenced by low granularity of time periods within a tick: all 8760 hours in a year are modelled in terms of 20 load segments as described in Chapter 3 of this dissertation.

INTERPRETATION

The main effects observed in each of the three scenarios investigated above are explained here.

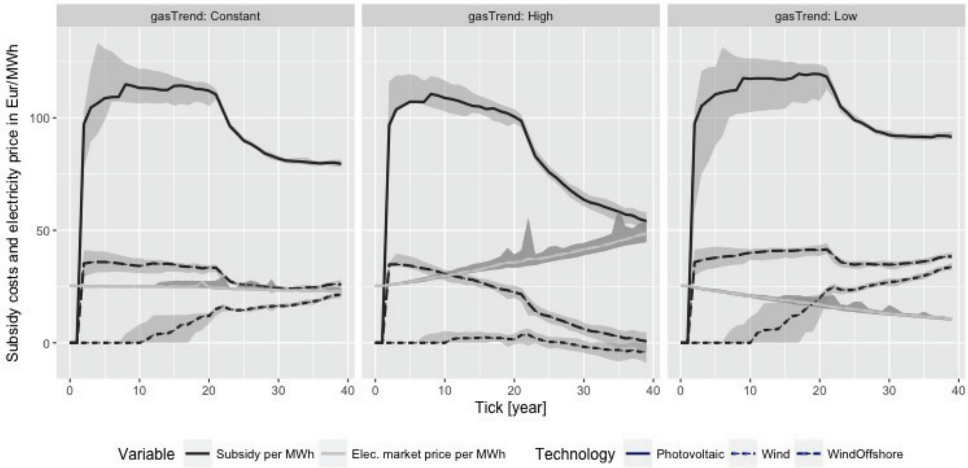


Figure 6.3: Electricity price and subsidy cost trends [in Eur/MWh] across time. The shaded region indicates the 95% confidence interval. Source: Own illustration.

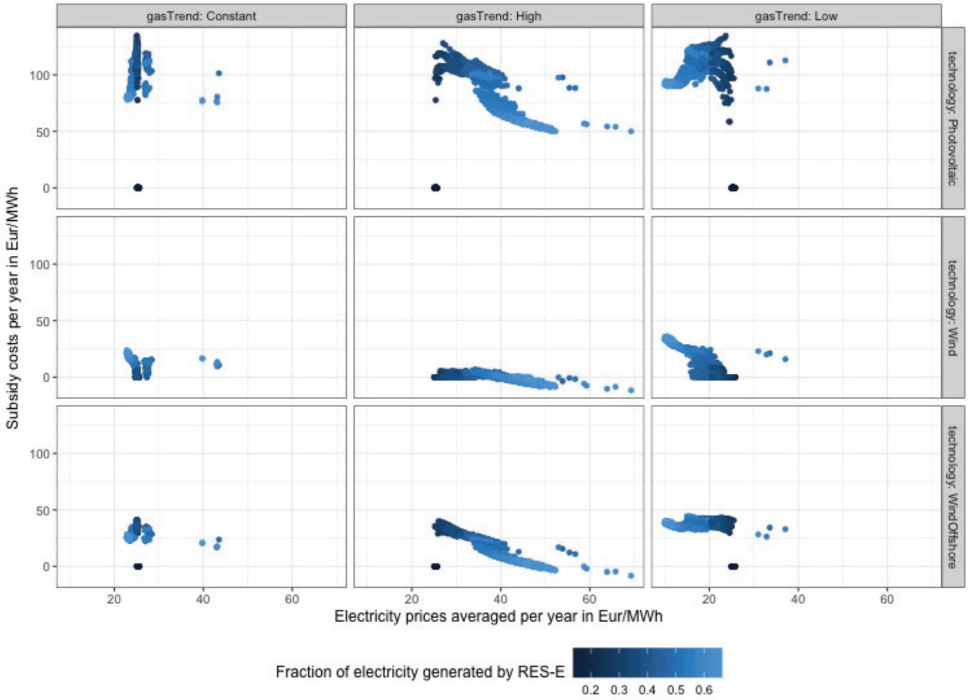


Figure 6.4: Electricity price (yearly average) versus subsidy costs [in Eur/MWh] under different gas price trend scenarios for different technologies. Source: Own illustration.

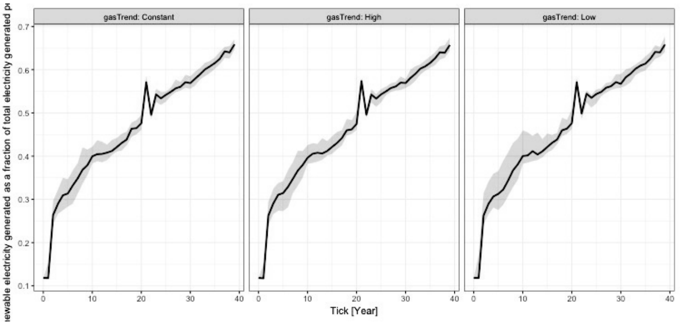


Figure 6.5: Fraction of electricity generated by renewables per tick, and under the three gas price scenarios

Gas price trend: Constant We observe that *when the gas price is constant, there is little impact on the electricity prices,* despite an increase in the share of renewables. The implication of this observation is that the merit order effect is not apparent in the electricity price trends of these runs. One reason for this is that, for these runs, the Netherlands is modelled as an isolated system with no interconnections or storage. The absence of spatial or temporal flexibility in the system from these sources means that there are very few instances in the model when the demand can be met entirely by intermittent renewable electricity, and since CCGT is the only flexible technology in the model, all flexibility is derived from the CCGT. This in turn ensures that the marginal cost of those plants remain a prominent component in the electricity prices, even as the share of VRE increases.

Gas price trend: High In the gas price high scenarios, *under all conditions, the subsidy costs reduce with increasing electricity prices, for all technologies.* Even in the gas price constant scenarios, when the electricity prices remain almost constant, after the first 7-8 years, the per-unit subsidy costs for solar and wind offshore reduce with time, albeit at different rates. This is shown in Figure 6.3. This reduction is almost entirely a function of the reducing cost curves of the technologies, combined with their capacity factors. The cost curves are presented in Figures A.2 and A.3. For wind onshore, the reduction in fixed costs takes place at a far slower rate than for PV and wind offshore. Furthermore, the assumed average capacity factor for wind onshore is half as much as that of wind offshore. This means that, as the share of renewables increases, curtailment for wind onshore is much higher than that of wind offshore. This curtailment manifests itself as increasing per-unit subsidy costs for wind onshore technology in the gas trend constant scenarios. Interestingly enough, even this effect is trumped for wind offshore by the relatively high electricity price in the gas trend high scenarios.

The observations suggest that high electricity prices have a significant and direct role to play in reducing subsidy costs, especially in scenarios where fixed costs of technologies do not reduce with time, or when the absence of transmission and storage lead to high amounts of curtailment.

Gas price trend: Low Conversely, observations from Figure 6.3 indicate that *low electricity prices do not directly translate to high subsidy costs* as the share of renewables increase. Instead, in the gas trend low scenario, when the electricity prices are relatively low, the subsidy costs depend far more on the rate of reduction in the costs of technology, relative to electricity prices. Therefore, if the rate of reduction in technology costs is lower than the rate of reduction in electricity prices, as in the case of wind onshore, then subsidy costs increase with time. The increase in per-unit costs are also bolstered by the curtailment of wind onshore production as the share of VRE increases. In contrast, if the rate of reduction of fixed technology costs is greater than the rate of reduction in electricity prices, subsidy costs reduce.

6.2.3. INSIGHTS

There are large uncertainties associated with cost developments of renewable technologies, amounts of interconnection, advancements in storage technologies, and their impact on electricity prices. Therefore, the results above are not predictive, but rather provide insights on the relationship between electricity prices and subsidy costs under various conditions.

Despite the fact that the merit-order effect was not apparent in the results, the observations still provide interesting insights on different factors impacting subsidy costs under various electricity price scenarios. The most interesting outcome, to the author, is the difference between the factors affecting subsidy costs under low or high electricity prices. Crucially, over a long-term period of 40 years, high electricity prices [appr. 30-50 Eur/MWh] have a more substantial role to play in reducing subsidy costs, than low electricity prices have in increasing it. Another important insight is that decreasing average electricity prices is only a problem for the attractiveness to invest in RES-E if the technology costs do not reduce at a rate faster than the electricity prices.

6.3. EU-ETS IN RELATION TO SUBSIDY COSTS

In the previous section, model results demonstrated that when average electricity prices are low, the impact on subsidy costs depends more on the cost curves of the technologies themselves. The objective of this section is to understand how (a) the EU-ETS and RES support interact in the presence of an electricity market and (b) the EU-ETS could influence the phasing out of subsidy costs for RES-E technologies, especially under low average electricity prices.

The European Union's Emissions Trading Scheme (EU-ETS) has been one of the primary policy instruments in the Union's transition towards a low carbon economy. The electricity sector has been the largest sector of the economy contributing to emissions within the EU-ETS framework. While the share of EU emissions from the electricity sector has been gradually reducing since 1990, the total amount of electricity consumed is set to increase, as other sectors such as transport and heating tend towards electrification (European Commission and Direction générale de la mobilité et des transports, 2014). Therefore, policies in the electricity sector and the ETS framework are intricately interrelated and the interactions between them have been justifiably analysed and debated in the literature.

This section comprises a brief discussion highlighting the major points in the aforementioned debate. It further situates the results obtained in this dissertation within the context of this debate. One notable discussion is the efficiency versus cost-effectiveness debate, which is addressed in the first sub-section. There have been vigorous debates on the economic logic behind simultaneously implementing renewable electricity support schemes as well as the emission trading scheme. Another discussion, more directly relevant to this thesis, is regarding the price effects of renewable support schemes on ETS prices, and conversely, the effect of ETS prices on RES-E subsidy costs. This is addressed in the second subsection.

6.3.1. EFFICIENCY AND COST-EFFECTIVENESS OF THE EU-ETS AND RES-E?

If the sole objective of the many policy instruments was to reduce carbon emissions, then, from the perspective of theoretical neoclassical economics, a combination of RES-E subsidies and the EU-ETS system is inefficient. Central to the argument is the idea that RES-E support policies do not have any impact on altering the CO_2 emissions cap, and hence do not result in emissions reductions. Further, such policies would contribute to reductions in the European Emission Allowances (EUA) price, and shift emissions to other sectors and other European countries instead (Böhringer and Rosendahl, 2010; del Río and Labandeira, 2009; Fischer and Preonas, 2010; Frondel *et al.*, 2010, 2008; Sijm, 2005). Such arguments have been demonstrated with analytical models, many of which use partial equilibrium modelling (Amundsen and Mortensen, 2001; De Jonghe *et al.*, 2009; Fankhauser *et al.*, 2010; Morthorst, 2003). Computational general equilibrium models have also demonstrated similar results (Paltsev *et al.*, 2009; Morris, 2009; Böhringer *et al.*, 2009), as have simulations and numerical methods (Traber and Kemfert, 2009; De Jonghe *et al.*, 2009; Linares *et al.*, 2008).

Others, such as Lehmann and Gawel (2013), argue that such a thesis assumes that the only market failure which exists is that the true cost of carbon emissions is not reflected in the prices of commodities. They argue that this assumption does not account for several market failures, and factors such as lock-in and path-dependencies. They contend that due to such reasons, some of which are elaborated below, the ETS alone is not a cost-effective solution in the long run. The following points have been extracted from Lehmann and Gawel (2013); Sonnenschein (2016)

- Positive externalities which arise from knowledge spillovers are not captured in the above argument. Several authors demonstrate that the presence of both policies simultaneously is justified when learning spillovers are accounted for (van Benthem *et al.*, 2008; Fischer and Newell, 2008; Kalkuhl *et al.*, 2012; Kverndokk and Rosendahl, 2007).
- The true social costs of non-renewable energy sources cannot be completely internalised. From an economic perspective the cost of marginal damages from one tonne of CO_2 is subject to considerable uncertainty. Estimates range from zero to €300 per tonne of CO_2. Furthermore, the emissions gap is the result of political negotiation rather than efficiency considerations.
- Participants in the EU ETS are subject to policy-induced uncertainties caused by

price fluctuations and the political nature of setting of the cap. Such uncertainties are detrimental to investments, which are characterised by high initial costs and long life-times.
- The path-dependent nature of investments in the electricity sector mean that sub-optimal decisions taken today could render infrastructure changes towards a low emission system much, much more expensive in the future. This is known as the carbon lock-in.

In the policy-setting arena of the European Commission, the debate seems to have been decisively resolved. Both the EU-ETS and the renewable electricity support schemes coexist and are periodically revised in order to account for developments in abatement technologies and related costs.

6.3.2. INTERACTING PRICE EFFECTS

Renewable electricity support schemes and the EU-ETS, as currently instituted in several countries in Europe, are interdependent. On the one hand, subsidies which lead to expansions in RES-E generation could reduce demand for allowances, and consequently reduce the emissions allowance (EUA) price over the long term (Hintermann *et al.*, 2016). On the other hand, the emissions allowance (EUA) price or a carbon tax would increase electricity prices, which consequently reduce subsidy costs. As Linares *et al.* (2008) explain, the final cost to society depends on the interactions between these instruments. In this section, literature which provide quantitative estimates of such interactive effects have been reviewed. From this brief literature review, it is found that most "interaction" literature is primarily focussed on quantifying the extra costs due to the introduction of RES-E support along with the EU-ETS. Fewer studies discuss results in a manner in which the converse effect, that is, the effect of EU-ETS on reducing RES-E subsidy costs are clear.

In Table 6.1, papers which quantify impacts of renewable electricity on EUA prices using numerical models, simulation models or empirical methods are presented. Most papers on the topic use numerical models to quantify effects. The results of these numerical models are also not immediately comparable, as some of them present a drop in EUA prices, while others present a reduction in the demand for EUA allowances, and in many cases all assumptions are not clearly indicated. The scopes of the papers also differ in terms of location and time period. One interesting insight is the substantial difference between the estimations of numerical models and that of econometric analysis. While the numerical models present results ranging from -1.32 Eur/tCO_2 to -100 Eur/tCO_2, or at least a -22% change in the EUA price, the econometric analysis attributes a much more modest -0.11 to -0.14% drop in ETS prices to the presence of renewable electricity. Interestingly, the paper using econometrics Koch *et al.* (2014) finds that dummy variables employed to simulate selected policy events, including the ban on using certain CERs and the announcement of an energy efficiency directive amongst others explain 44% of the price variation.

In Table 6.2, papers which quantify the impact of EUA prices on reducing subsidy costs are presented. Both papers presented here are based on numerical modelling. To the knowledge of this author there are no papers analysing this effect based solely on empirical data. In the first paper Linares *et al.* (2008), a scenario which has an increasing

Table 6.1: Influence of renewable electricity on carbon price

Study	*Methodology*	*Regional and Temporal Scope*	*Objective*	*Key Findings*	*Reference case*
Linares *et al.* (2008)	Analytical and simulation research	Spain, 2004 to 2020	Impact of renewable support policy (Tradable Green Certificate) on EUA price	Reduction in EUA price per ton of CO_2: 2008 to 2012: 1.32 Eur/tCO2 (22%) 2013 to 2017: 5.28 Eur/tCO2 (42%) 2018 to 2020: 7.34 Eur/tCO2 (33%)	No RES-E Support
Weigt *et al.* (2012)	Unit commitment model	Germany, 2006 to 2010	Reduction in demand for EUA allowances due to RE deployment in German electricity sector	Reduction by 33-57 Mton (10-16%) between 2006 and 2010	No RE Policy
Van den Bergh *et al.* (2013)	Partial equilibrium model	2 EU Member States in Southern and Western Europe, 2007 to 2010	The impact of RES-E deployment on the EUA price and the CO2emissions in the European electricity sector	Reduction in EUA price per ton of CO_2: 15 EUR/tCO2 in 2007, 46 EUR/tCO2 in 2008, 100 EUR/tCO2 in 2010	No RE Policy
Koch *et al.* (2014)	Econometric ex-post analysis	EU, 2008-2013	To what extent can EUA price drop be attributed to renewable policies	0.11% to 0.14% (5% significance level)	No RES-E support

quota for renewables is compared with a similar scenario which has the EU ETS system added to the RES quota. Here, the reduction in subsidy costs ranges from 0 to appr. 12%. However, since assumptions regarding the progression of renewables quota and of the ETS caps through time are not clearly specified, it is difficult to assess the impact of ETS prices on the subsidy costs as the quota increases. In the second paper De Jonghe *et al.* (2009) however, the lowering of subsidy costs is clearly indicated at various assumptions of RES-E quota as well as ETS allowance caps. All in all, it is evident from the analysis that *as the share of renewables increase, the EUA price itself, and the impact of EUA prices on subsidy costs reduce.* This is clearly indicated in Figure 6.6, from De Jonghe *et al.* (2009). Of course, it is possible that if the cap were set to be increasingly stringent to ensure a high CO_2 price, the price could have an impact on the subsidy costs. However, such an approach would defeat the purpose of a quantity-based instrument, while employing a CO_2 tax could achieve the same goal in a direct manner.

6.3.3. IMPLICATIONS FOR MODEL RESULTS

In the previous section, model results demonstrated that when average electricity prices are low, the impact on subsidy costs depends more on the cost curves of the technologies themselves. The objective of this section was to understand how the EU-ETS could influence the phasing out of subsidy costs for RES-E technologies, especially under low average electricity prices. Findings from the literature reviewed indicate that, while EUA prices could indeed reduce subsidy costs in the short term (0-5 years), they are far less likely to help phase out RES-E subsidies in the longer term (20-30 years) as the share of RES-E significantly increases. Of course, this is true if the electricity sector still forms a significant share of the sectors included in the ETS in the long-term. If other carbon intensive sectors drive the marginal CO_2 price, this implication might not hold.

Table 6.2: Influence of carbon price on renewable electricity subsidy

Study	*Methodology*	*Regional and Temporal Scope*	*Objective*	*Key Findings*	*Reference case*
Linares *et al.* (2008)	Analytical and simulation research	Spain, 2020	Impact of EUA price for emissions cap of 80Mt on VRE subsidy	Subsidy costs reduce from 56.59 Eur/MWh to 50.82 Eur/MWh (by 10%) when ETS is introduced	No EU ETS
De Jonghe *et al.* (2009)	Simulation model	France, Germany, and Benelux	Impact of CO2 quota on RES-E subsidy cost	For a relatively high quota on renewables (>40%), the certificate price is only dependent on this quota, and is independent from the restriction on CO2 emissions.	No EU ETS

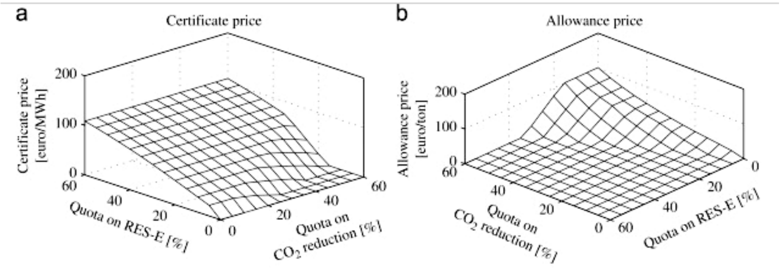


Figure 6.6: (a) Tradable Geeen Certificate price as a proxy for subsidy cost and (b) allowance price for combinations of TGC and CO2 allowances. Note that the X-axis has a reversed direction in panel (b). Source: De Jonghe *et al.* (2009)

Nonetheless, even if the quota on CO_2 reduction were to be increased as the share of RES-E increased, the impact of a marginal increase in the quota on EUA prices and RES-E subsidy costs would be far less at higher RES-E shares than at lower shares. This is because carbon-intensive generation technologies themselves will set the marginal price less often in a system with greater RES-E. If the main objective were to phase out subsidy costs based on spot market prices, a tax on CO_2 would be a more effective and straightforward means to achieve it at high shares of RES-E in the generation mix.

6.4. IMPACT OF FLEXIBILITY ON THE ECONOMIC VALUE OF VRE

In the previous chapter it became apparent that both interconnection and storage, or the lack of it, have significant implications on the per-unit costs of intermittent RES-E generated. In particular, the lack of storage, or temporal flexibility in the system, manifested itself as a large amount of curtailment of intermittent RES-E, which led to greater proportions of the costs having to be recovered in shorter periods, thereby increasing the per-unit costs of intermittent electricity generated. In this section, we juxtapose this outcome with comparable literature dealing with the impacts of flexibility on the subsidy costs of renewables.

Several works on flexibility focus on system cost minimisation under high penetration of renewables or a completely decarbonised system, with different options for flexibility (Brouwer *et al.*, 2016; Budischak *et al.*, 2013; De Jonghe *et al.*, 2011; Jacobson *et al.*, 2015; Steinke *et al.*, 2013). Other papers discuss the "integration costs of RES-E", where they estimate, for instance, “an increase in power system operating costs” due to the presence of VRE (Milligan and Kirby, 2009). While these are important questions in themselves, they answer questions related to the ’ideal’ costs, or describe the changes possible to system costs when renewables are integrated into the system and more flexibility is required. They do not, however, provide insights on the effects of flexibility on the economic value of variable renewables electricity itself. In the researcher’s effort to assess the possibilities of phasing out of RES-E subsidy, this aspect is key, as it evaluates the role of flexibility in the economic viability of VRE.

In a landmark paper, Hirth (2013), defined and quantified the concept of "market value of VRE". Central to this concept is the idea that the availability of the primary energy source, wind or solar irradiation, fluctuates over time in a manner that has limited predictability. This, as Hirth describes, "affects the economics of power generation either by increasing costs, for instance of balancing, or more significantly, reducing the value of the power generated on the spot market." Several papers have quantified this reduction in market value of renewables with an increase in their share. To the knowledge of the author, only two papers however, clearly quantify the impact of flexibility stemming this reduction of the economic value of intermittent renewable electricity. Their results are presented below.

The first paper is a work from the Lawrence Berkeley National Laboratory (Mills and Wiser, 2015), which evaluates options to stem the reduction in the value of wind and PV using a long-run equilibrium investment and dispatch model and simulating a region loosely based on California in 2030. Interestingly, for this specific case, the authors find that the largest increase in the value of wind comes from geographical diversity, while the largest increase in the value of solar PV comes from low cost bulk storage.

The second paper, again by Hirth (2016b) comprises both empirical and numerical analyses, to quantify how the flexibility provided by hydropower mitigates the reduction in market value of wind energy in Sweden and Germany. He finds that, as the share of wind increased from 0% to 30%, hydropower mitigates the value drop by a third. As a consequence, a unit of wind energy (in MWh) is 12%-29% more valuable in Sweden than in Germany. The use of low wind speed turbines, carbon pricing, and greater hydropower capacity are found to be able to accentuate the value added by flexible hydropower. The author also finds that the positive impact of hydro-flexibility on the value of wind tapers off as wind penetration increases beyond 20%.

It follows from the above literature that the specific features of a system play a significant role in determining which source of flexibility might work the most to increase the value of VRE. In conclusion, as the share of VRE increases in any electricity system, the decision to invest in a VRE plant will depend on benefits accrued not just from the primary resource itself, but also from the types and sources of flexibility in the system.

6.5. DISCUSSION

In this section, insights from the three strands of literature discussed in this chapter are brought together to expound on factors that influence RES-E subsidy costs. The time scales that are analysed in this dissertation are spread over the long term (appr. 30 years), whereas a lot of the literature is focussed on past, current, or shorter future time scales. The discussion therefore culminates in a comparison between factors which could influence subsidy costs over the short term versus the long term, when the share of RES-E is expected to be substantially higher. An indicative representation is shown in Figure 6.7.

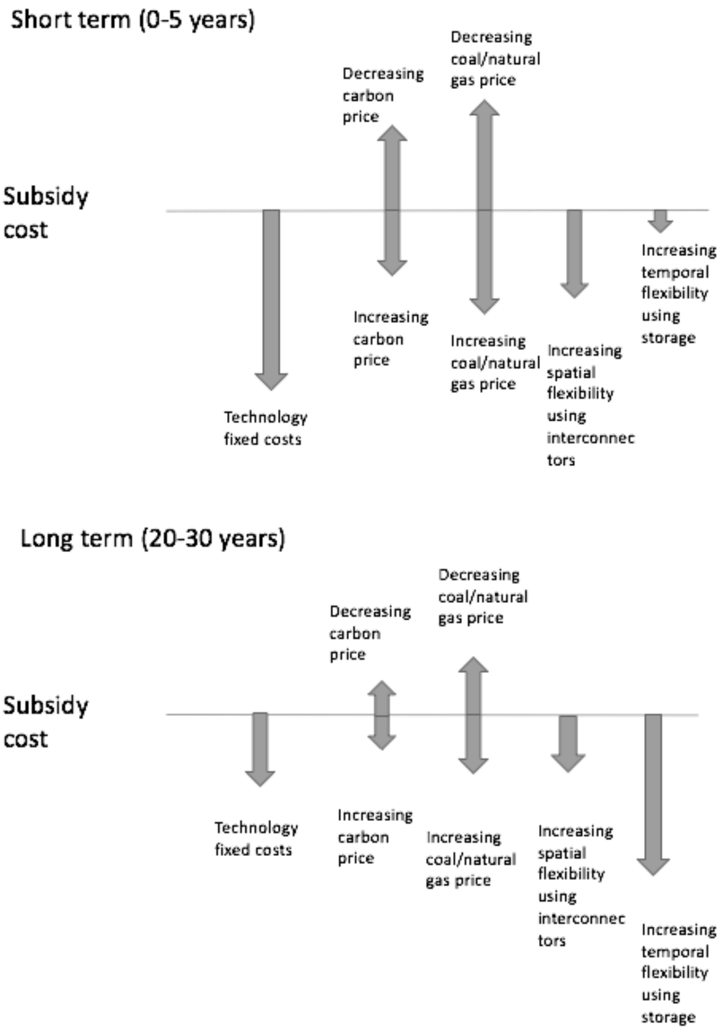
Costs have reduced dramatically over the last decade and are expected to reduce in the near future, as explained in section 6.2. Learning curves or experience curves are commonly used to forecast cost projections for new technologies. This is based on the notion that the more times a task is performed, the less investment in effort is required for each subsequent iteration[2]. A common formulation of this effect is that unit costs decrease by a constant percentage for each doubling of experience or production. Therefore, as technologies mature, cost reductions are also expected to decrease with every extra unit of production (McDonald and Schrattenholzer, 2001). Based on this theory it is reasonable to predict that further cost reductions will be far lesser in about 30 years from now for technologies such as PV and wind.

Given the merit order effect, revenue from electricity spot prices would be lower in a system with more RES-E generation than less. In a system with substantially higher RES-E generation, the time during which coal/gas would set the marginal price would reduce, as compared to a system with lower shares of RES-E generation. Therefore, a unit change in fuel prices such as those of coal or gas, will have a lower impact on the revenue from the electricity spot market for RES-E technologies, than it does today. This is true under the assumption that coal and gas will still be part of the merit-order that far into the future. A similar argument holds for the role of carbon prices in reducing subsidy costs in the future. As the share of RES-E increases, and carbon-based generation decreases, the influence of carbon prices on the spot market decreases.

Interconnection, as we know, provides spatial flexibility, while storage provides temporal flexibility. At high shares of RES-E, weather conditions and consequently primary energy supply across different locations should be diverse enough to supply demand. In large parts of Europe, where seasonal weather and demand changes are drastic and simultaneous, for instance, the supply of solar energy reduces substantially during the winter, while demand remains the same or increases. Therefore, while interconnection does help provide flexibility at low shares of RES-E and in the near future, it is unlikely that it will be sufficient to increase the market value of VRE at high shares (>60%) of RES-E in the long term. This was also a key finding in section 5.3.2, where we found that interconnection plays a limited role in lending flexibility to the system, whereas storage will play an increasingly important role as RES-E shares increase. These findings are pictorially represented in Figure 6.7.

---

[2] The concept is commonly referred to as the learning curve effect.



Short term (0-5 years)

Long term (20-30 years)

Figure 6.7: Impacts of various factors on subsidy costs in the short and long terms

6.6. CONCLUSION

The main research objective for this chapter was to identify the conditions under which RES-E subsidies can be phased out. Given that some European countries are considering a system in which subsidies will no longer be offered to RES-E technologies, this is a topical question. This is also a vital topic in the context of the objective of this dissertation, which is to help understand design of RES-E subsidies in the European institutional setting. The objective was accomplished primarily by a literature review which examined three major aspects of the energy transition in Europe: the cost and revenue drivers of RES-E technologies, the EU ETS, and finally, the role of flexibility. In the course of this literature review, work from the earlier chapters on designing RES-E subsidies was put in perspective of the larger energy transition in Europe.

We find that at relatively high average electricity prices, the impact of electricity prices on subsidy costs is direct and clear; as prices increase, subsidy costs decrease. However, as electricity prices on the spot market reduce, the change in subsidy cost trends depends far more on the cost curves of each RES-E technology. With respect to the EU-ETS, it is clear that, even if EUA prices play a significant role on the electricity prices today, their influence on the electricity prices, and the RES-E subsidy costs will reduce as the share of RES-E generation increases with time. From Sections 6.4 and 5.3.2, it is clear that at high shares of RES-E, interconnection will play a limited role in providing flexibility while storage (long-term, seasonal) will play a pivotal role. Consequently, the costs of subsidy for RES-E at high shares are substantially dependant on the presence of storage in the system. The chapter concludes with a discussion on which factors impact subsidy costs the most in the short term, versus the long term, under certain institutional settings.

The analysis is largely qualitative, and opens up several avenues for future research. One interesting path is to analyze the costs at which auctions for long-term contracts are better than the spot market at creating competition in RES-E and low-carbon flexibility technologies. Another path for future research could be to use a high-resolution model to compute the point at which the extra costs of subsidy due to spillage could be higher than the cost of a certain amount of (large-scale)storage.

REFERENCES

O. Wind, *UK to Set Sail to Subsidy-Free Offshore Wind Farms,* (2017).

IRENA, *Solar PV in Africa: Costs and Markets*, Tech. Rep. (2016).

F. Sensfuss, M. Ragwitz, and M. Genoese, *The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany,* Energy Policy **36**, 3086 (2008).

L. Hirth, *The market value of variable renewables: The effect of solar wind power variability on their relative price,* Energy Economics **38**, 218 (2013).

REmap: Roadmap for a Renewable Energy Future., Tech. Rep. (IRENA, Abu Dhabi, 2016).

B. N. E. Finance, *Wind Power Blows Through Nuclear, Coal as Costs Drop at Sea,* Bloomberg.com (2017a).

B. N. E. Finance, *New Energy Outlook 2017*, Tech. Rep. (Bloomberg Finance L.P., 2017).

R. Wiser, M. Bolinger, G. Barbose, N. Darghouth, B. Hoen, A. Mills, J. Rand, D. Millstein, K. Porter, and R. Widiss, *2015 Wind Technologies Market Report*, Tech. Rep. LBNL-1005951 (Lawrence Berkeley National Laboratory, 2016).

M. O. for Energy, *Quarterly report on European electricity markets*, Tech. Rep. (Directorate-General for Energy, European Commission, Brussels, 2016).

J. Cludius, H. Hermann, F. C. Matthes, and V. Graichen, *The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications,* Energy Economics **44**, 302 (2014).

N. Ederer, *The market value and impact of offshore wind on the electricity spot market: Evidence from Germany,* Applied Energy **154**, 805 (2015).

L. Gelabert, X. Labandeira, and P. Linares, *An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices,* Energy Economics **33**, S59 (2011).

A. O'Mahoney and E. Denny, *Electricity prices and generator behaviour in gross pool electricity markets,* Energy Policy **63**, 628 (2013).

T. Traber and C. Kemfert, *Impacts of the German Support for Renewable Energy on Electricity Prices, Emissions, and Firms,* The Energy Journal **30**, 155 (2009).

T. Traber and C. Kemfert, *Gone with the wind? — Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply,* Energy Economics **33**, 249 (2011).

H. Weigt, *Germany's wind energy: The potential for fossil capacity replacement and cost saving,* Applied Energy **86**, 1857 (2009).

K. Würzburg, X. Labandeira, and P. Linares, *Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria,* Energy Economics Supplement Issue: Fifth Atlantic Workshop in Energy and Environmental Economics, **40, Supplement 1**, S159 (2013).

A. Bublitz, D. Keles, and W. Fichtner, *An analysis of the decline of electricity spot prices in Europe: Who is to blame?* Energy Policy **107**, 323 (2017).

J. Dehler, F. Zimmermann, D. Keles, and W. Fichtner, *Der Einfluss der Nachbarländer auf den Schweizer Strommarkt,* (Graz, Austria, 2016).

S. Thoenes, *Understanding the Determinants of Electricity Prices and the Impact of the German Nuclear Moratorium in 2011,* The Energy Journal **35** (2014), 10.5547/01956574.35.4.3.

L. Hirth, *What Caused the Drop in European Electricity Prices?*, SSRN Scholarly Paper ID 2874841 (Social Science Research Network, Rochester, NY, 2016).

R. Hamming, *Numerical methods for scientists and engineers* (McGraw-Hill, New York, 1962).

European Commission and Direction générale de la mobilité et des transports, *EU energy, transport and GHG emmissions trends to 2030: reference scenario 2013* (Office for official publications of the european communities, Luxembourg, 2014) oCLC: 889309007.

C. Böhringer and K. Rosendahl, *Green promotes the dirtiest: On the interaction between black and green quotas in energy markets,* Journal of Regulatory Economics **37**, 316 (2010).

P. del Río and X. Labandeira, *Barriers to the introduction of market-based instruments in climate policies: an integrated theoretical framework,* Environmental Economics and Policy Studies **10**, 41 (2009).

C. Fischer and L. Preonas, *Combining Policies for Renewable Energy: Is the Whole Less than the Sum of its Parts?* SSRN Electronic Journal (2010), 10.2139/ssrn.1569634.

M. Frondel, N. Ritter, C. M. Schmidt, and C. Vance, *Economic impacts from the promotion of renewable energy technologies: The German experience,* Energy Policy **38**, 4048 (2010).

M. Frondel, N. Ritter, and C. M. Schmidt, *Germany's solar cell promotion: Dark clouds on the horizon,* Energy Policy **36**, 4198 (2008).

J. Sijm, *The interaction between the EU emissions trading scheme and national energy policies,* Climate Policy **5**, 79 (2005).

E. S. Amundsen and J. B. Mortensen, *The Danish Green Certificate System: some simple analytical results,* Energy Economics **23**, 489 (2001).

C. De Jonghe, E. Delarue, R. Belmans, and W. D'haeseleer, *Interactions between measures for the support of electricity from renewable energy sources and CO2 mitigation,* Energy Policy **37**, 4743 (2009).

S. Fankhauser, C. Hepburn, and J. Park, *COMBINING MULTIPLE CLIMATE POLICY INSTRUMENTS: HOW NOT TO DO IT,* Climate Change Economics **01**, 209 (2010).

P. Morthorst, *National environmental targets and international emission reduction instruments,* Energy Policy **31**, 73 (2003).

S. Paltsev, J. Reilly, H. Jacoby, and J. Morris, *The cost of climate policy in the United States*, Tech. Rep. 173 (2009).

J. F. Morris, *Combining a renewable portfolio standard with a cap-and-trade policy : a general equilibrium analysis*, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts (2009).

C. Böhringer, A. Löschel, U. Moslener, and T. F. Rutherford, *EU climate policy up to 2020: An economic impact assessment,* Energy Economics **31**, S295 (2009).

P. Linares, F. J. Santos, and M. Ventosa, *Coordination of carbon reduction and renewable energy support policies,* Climate Policy **8**, 377 (2008).

P. Lehmann and E. Gawel, *Why should support schemes for renewable electricity complement the EU emissions trading scheme?* Energy Policy Special Section: Transition Pathways to a Low Carbon Economy, **52**, 597 (2013).

J. Sonnenschein, *Conditions for the Cost Effective Combination of Emissions Trading and Renewable Energy Support Policies,* Energy Procedia **88**, 133 (2016).

A. van Benthem, K. Gillingham, and J. Sweeney, *Learning-by-Doing and the Optimal Solar Policy in California,* The Energy Journal **Volume 29**, 131 (2008).

C. Fischer and R. G. Newell, *Environmental and technology policies for climate mitigation,* Journal of Environmental Economics and Management **55**, 142 (2008).

M. Kalkuhl, O. Edenhofer, and K. Lessmann, *Learning or lock-in: Optimal technology policies to support mitigation,* Resource and Energy Economics **34**, 1 (2012).

S. Kverndokk and K. E. Rosendahl, *Climate policies and learning by doing: Impacts and timing of technology subsidies,* Resource and Energy Economics **29**, 58 (2007).

B. Hintermann, S. Peterson, and W. Rickels, *Price and Market Behavior in Phase II of the EU ETS: A Review of the Literature: Appendix Table 1,* Review of Environmental Economics and Policy **10**, 108 (2016).

H. Weigt, E. Delarue, and D. Ellerman, *CO2 Abatement from Renewable Energy Injections in the German Electricity Sector: Does a CO2 Price Help?*, Tech. Rep. CEEPR 2012-003 (MIT Center for Energy and Environmental Policy Research, 2012).

K. Van den Bergh, E. Delarue, and W. D'haeseleer, *Impact of renewables deployment on the CO2 price and the CO2 emissions in the European electricity sector,* Energy Policy **63**, 1021 (2013).

N. Koch, S. Fuss, G. Grosjean, and O. Edenhofer, *Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything?—New evidence,* Energy Policy **73**, 676 (2014).

A. S. Brouwer, M. van den Broek, W. Zappa, W. C. Turkenburg, and A. Faaij, *Least-cost options for integrating intermittent renewables in low-carbon power systems,* Applied Energy **161**, 48 (2016).

C. Budischak, D. Sewell, H. Thomson, L. Mach, D. E. Veron, and W. Kempton, *Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time,* Journal of Power Sources **225**, 60 (2013).

C. De Jonghe, E. Delarue, R. Belmans, and W. D'haeseleer, *Determining optimal electricity technology mix with high level of wind power penetration,* Applied Energy **88**, 2231 (2011).

M. Z. Jacobson, M. A. Delucchi, M. A. Cameron, and B. A. Frew, *Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes,* Proceedings of the National Academy of Sciences **112**, 15060 (2015).

F. Steinke, P. Wolfrum, and C. Hoffmann, *Grid vs. storage in a 100% renewable Europe,* Renewable Energy **50**, 826 (2013).

M. R. Milligan and B. Kirby, *Calculating wind integration costs: Separating wind energy value from integration cost impacts*, Tech. Rep. (National Renewable Energy Laboratory Colorado, 2009).

A. D. Mills and R. H. Wiser, *Strategies to mitigate declines in the economic value of wind and solar at high penetration in California,* Applied Energy **147**, 269 (2015).

L. Hirth, *The benefits of flexibility: The value of wind energy with hydropower,* Applied Energy **181**, 210 (2016b).

A. McDonald and L. Schrattenholzer, *Learning rates for energy technologies,* Energy Policy **29**, 255 (2001).

7

CONCLUSIONS AND REFLECTIONS

In this chapter, key findings of the thesis are summarised, and the findings are reflected upon. In Section 7.1, answers to research questions are presented. The following section 7.2 presents a reflection on the usefulness and limitations of the approach, the model, and the results presented. Section 7.3 then describes avenues for future work.

7.1. ANSWERS TO RESEARCH QUESTIONS

As the energy transition in Europe gathers steam, policy makers grapple with questions regarding the most appropriate designs of the institutions that drive the transition. Policy makers confront inter-alia, multiple objectives, multiple stakeholders, dynamically changing costs, and advancements in technology. As the share of renewable electricity from solar PV and wind increases in the system, impacts such as the merit-order effect, reducing market value of intermittent generations, decrease the wholesale market-based revenues for power plants. Such effects question the design of current institutions such as the electricity spot market as well as renewable support schemes over the long term. In this context, the main research question posed in Chapter 1 of the thesis is the following:

How do national renewable electricity support schemes interact with the electricity market over the long term (20-30 years) as the European Union transitions to a decarbonized energy system?

Using an approach based on theoretical foundations of institutional analysis, and design theory, in this dissertation RES-E support schemes are broken down into their design elements from a welfare economics perspective. A modelling framework is then introduced, using the modelling paradigm of agent-based modelling, by which RES-E schemes are modelled in EMLab Generation. EMLab Generation mainly comprises an electricity market clearing algorithm and an endogenous investment algorithm, and allows the researcher to study long-term dynamics in the electricity sector. Most literature tackling similar questions and using quantitative models, employ optimization tools which assume perfect foresight or known probabilities of imperfect foresight [1], or operate under the assumption of a long-term equilibrium. In contrast, this approach incorporates true uncertainty to model regulatory and investment decisions. This way the long-term model is a step closer to reality.

The model shows that the way electricity prices are taken into account while designing subsidies makes a substantial difference to welfare distributions. When multiple countries are considered, the spreading of the merit order effect from a larger country to a smaller one, would cause the smaller country's subsidy costs to increase. This indicates that even if RES-E support can be designed to be "market-based" at the operational level, designing them to be "market based" at the investment level is far more complicated. It indicates that RES-E targets of countries should take into account the targets of neighbouring countries, the amount of flexibility in terms of interconnection and storage in the sytem. Finally, the impact of flexibility on costs of RES-E subsidies is also discussed. These issues have been explored through the various research questions that follow.

How can policy design options for RES-E support in Europe be systematically and comprehensively explored and modelled?

Using a combination of design theory, institutional analysis, and agent-based modelling (ABM), we provide a method to systematically explore policy design options for RES-E support in Europe. This is done firstly by identification of the design elements[2] of a policy or set of policies, and secondly by evaluating the impact of each design element on the socio-technical system using an agent-based model.

Given a certain frame of analysis, we propose that it is theoretically possible to identify the complete policy design space. Crucially, this aspect potentially opens up to the policy analyst new avenues for intervention, and allows her explore, given a range of uncertainties, which element(s) of intervention is(are) the most vital to achieve the goals of the community. The applicability of the approach is demonstrated by representing and differentiating between six renewable electricity support schemes from Western Europe in terms of the design elements. The applicability of the modelling framework using ABM, and consequently of the Design Element Approach, is demonstrated by evaluating the long-term, dynamic impact of three design elements: *price warranty versus quantity warranty, technology neutrality versus specificity,* and accounting for the electricity market price *ex-ante versus ex-post* on the Dutch electricity sector.

It is important to note here that claims of completeness of the design space come with limitations. For instance, if the energy producer agent were to assume multiple identities, such as being politically active and strongly pushing for local autarky, the design elements would be different. The design framework published here therefore pertains mainly to an analysis which lies within the scope of welfare economics, although founded firmly within an institutional framework and empirical experience. Other limitations of the approach include its computationally intensive nature, and the need to prudently select the most important design elements necessary for the analysis.

---

[1] As in stochastic optimisation

[2] Design elements of renewable electricity support policies are defined as a closed set of components which a renewable electricity policy is comprised of, such that each component now forms the smallest level of analysis.

How do RES-E support policy design elements interact with a single isolated electricity market and what social welfare implications do they actualise?

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 to which they belong, 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 upto 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 co-ordinated at the European level.

How do RES-E support policy design elements interact with an interconnected, congested electricity market? The primary objective of chapter 5 is to investigate cross-border effects due to national RES-E support schemes, operating in an international electricity market. Using EMLab Generation, regions based on Germany and the Netherlands were simulated, to test the effects of different support scheme designs in each country, and the common electricity market, on distributional implications under different scenarios of interconnector capacities.

As theory would predict, it is found that subsidy costs increase in the smaller country, as electricity prices decrease, as the merit order effect spreads from the larger neighbouring country. However, the increase in subsidy costs remains lower than the reduction in costs of electricity, corroborating earlier, single country analyses on the topic. Therefore, total costs in both countries reduce as interconnection increases, and the invisible hand works its magic. As the share of RES-E increases, interconnection has limited impact on reducing spillage of RES-E while storage becomes increasingly important.

The results show that setting targets for RES-E, should not only take into account the targets of the neighbouring countries, but also the capacity of storage that exists in the system. The results also raise interesting questions about how subsidy costs should be allocated between countries over the long-term, especially when subsidy costs are so intricately connected with the electricity markets they operate in.

How could major developments in the energy transition such as RES-E technology cost trends, the EU ETS, and flexibility influence RES-E support?

The objective was accomplished primarily by a literature review which examined three major aspects of the energy transition in Europe: the cost and revenue drivers of RES-E technologies, the EU ETS, and finally, the role of flexibility. In the course of this literature review, work from the earlier chapters on designing RES-E subsidies was put in perspective of the larger energy transition in Europe.

We find that the impact of high average electricity prices on subsidy costs is direct and clear; i.e., as prices increase subsidy costs decrease. However, as electricity prices on the spot market reduce on average, the change in subsidy cost trends depend far more on the cost curves of each RES-E technology. With respect to the EU-ETS, it is clear that, even if EUA prices play a significant role on the electricity prices today, their influence on the electricity prices, and the RES-E subsidy costs will reduce as the share of RES-E generation increases with time. From Sections 6.4 and 5.3.2, it is evident that at high shares of RES-E, interconnection will play a limited role in providing flexibility while storage (long-term, seasonal) will play a pivotal role. Consequently the costs of subsidy for RES-E at high shares are substantially dependent on the presence of storage in the system.

7.2. REFLECTIONS

As computer simulation methods are gaining more and more prominence across disciplines, ideas about their trustworthiness for generating new knowledge are being discussed in works on philosophy of science (Gilbert and Troitzsch, 2005; Parker, 2008; Winsberg, 1999, 2001; Epstein, 1999). The reader's confidence in a computer simulation is instilled by evaluating the claim that a simulation is indeed fit for its purpose. The science that deals with such evaluations is called the Epistemology of Computer Simulations (EOCS) Winsberg (2015). The idea of external validation of a simulation is explored in the subsequent paragraphs. The stage is set by a note on the role of simulations in science. The uncertainties and assumptions involved in the model (EMLab) and how they relate to the real world are explored in the following subsection. Finally, the usefulness of the framework, model, and results are reflected upon.

7.2.1. ROLE OF SIMULATION IN SCIENCE

The study of epistemology of (computer) simulations concerns itself with questions related to the nature and purpose of simulations. How are experiments different from simulation models? How should their reliability and validity be evaluated? What is the role of simplifying assumptions in simulations? In relation to evaluating a simulation against its fitness of purpose, a widely popular approach is to verify and validate. While it is a pragmatically useful approach, certain philosophers question whether verification and validation are indeed entirely independent of each other, and whether such a distinction could misrepresent the messiness of simulationists' practice.

Winsberg, who has written extensively on the topic, suggests that the idea that simulation is a new mode of science, methodologically lying in between theory and experiment, is a good place to start (Winsberg, 2010). Deb Dowling, a sociologist of science, characterises simulation as being similar to theory because it involves "manipulating equations" and "developing ideas". However, she also suggests that it is like an experiment given that it involves "fiddling with machines", "trying things out", and "watching to see what happens" (Dowling, 1999). The idea that there are more activities between experiment and theory has been introduced several decades ago in 1983 by (Hacking, 1983). Hacking repudiates the traditional dichotomy of theory and experiment. He urges that it is replaced by the following characterizations: speculation, calculation, and experiment. By speculation he refers to the activity of laying out basic theoretical principles such as Maxwell's equations, or Newton's laws of motion to name a few. The activity he calls 'calculation' refers to making theoretical principles apply to the local, concrete systems that make up the real world. Winsberg suggests that simulation is most similar to the second activity, one which often takes the researcher beyond merely theoretical principles themselves.

Describing theories as Hacking does is a refreshing point of view to any researcher who has had to explain the value of agent-based models to firm believers of the neoclassical school of economic theory. It is a reminder that the idea of a long-term equilibrium in energy markets is merely speculation, and never a truth. One that must be scrutinised time and again, in order to either confirm or deny its credibility. To the author of this work, agent based models are a powerful method for performing such evaluations, and in creating and testing new speculations.

Even so, how does one evaluate the credibility or validity of such a method? Winsberg is of the opinion that the credibility of simulations "comes not only from the credentials supplied to it by the governing theory, but also from the antecedentally established credentials of the model-building techniques used to make it." This is because if it is successful in making a variety of predictions or interventions, it means that there is something about it that is "in some way latching on to the real structure of the world". Furthermore, Parker suggests that for model evaluation to have rigour and structure, it is necessary that there is explicit argumentation about the capacity of a model to provide evidence for the concerned scientific hypotheses, and not simply superficial comparisons of simulation results and empirical data.

Following from this discussion, in the sections below we explore how the model presented relates to the real world, how the assumptions made in the model affect results and under what conditions. We then discuss the usefulness of the scientific framework used, the model itself, and the results.

7.2.2. HOW DOES THE MODEL RELATE TO THE REAL WORLD?

One of the challenges that are commonly faced by researchers of long term electricity market models is ensuring a "suitable" tradeoff between fine temporal resolution and computational tractability. For EMLab, although the input is hourly data, during the market clearing process, the data is aggregated to 20 segments on both the demand and supply side. At high shares of intermittent RES-E generation, it becomes is important to represent the market clearing with a fine resolution, as otherwise the impact of renewables on the market price will be under-represented.

Interconnections are represented in a limted manner in the model. In Chapter 4, The Netherlands is represented as an isolated system, and in Chapter 5, only the interconnection between Germany and the Netherlands is represented. In reality the transmission network is far more complex. As spatial heterogeneity in supply and demand contributes to balancing, its absence in Chapter 4 leads to an inflated presence of CCGT in the merit-order, increasing average electricity prices. Similarly in Chapter 5, if the interconnections had been represented with greater accuracy, while taking into account the electricity markets of the neighbouring countries, the effect of Germany's electricity prices on the Dutch RES-E subsidy costs would be lower than what has been presented. The subsidy costs to the Netherlands would depend more on the interconnection capacities and the supply curves of the other neighbouring zones.

Market mechanisms outside of the day-ahead market have not ben analyzed: for instance, intra-day markets, or balancing markets. Interviews with officials from the EPEX-SPOT indicates that the volumes traded in the intra day markets have been rapidly increasing over the last few years, as shares of intermittent RES-E electricity increase. This trend can be expected to continue, as the shares RES-E increase even further. Since the subsidy costs are currently only tied to the spot market (day ahead) prices, the analysis in the dissertation holds. However, as the intra-day and balancing markets will play a greater role, it is imperative that their impact on revenues for RES-E technologies are evaluated while setting RES-E targets in the future. Such an evaluation would be intricately tied with the role such markets play in attracting options for flexibility in the system as well.

Investor behaviour in EMLab is represented by incorporating bounded rationality - a distinctive feature of the model. The advantages of such a modelling feature is that it allows us to analyse and represent observed phenomenon such as investment cycles. Through the model-building process, after many rounds of trial and error, it was evident that the magnitude and period of the cycles were largely dependent on the "future-time-period" of the investing agent, i.e., the future time step for which an agent evaluates an investment decision vis-a-vis the current time period. The longer into the future an agent looks to make an investment, the more mistakes he is bound to make, as there are more unknowns, thus increasing the amplitude and period of the cycles. If different technologies are given different permit times and construction times, this impacts the features of cycles correspondingly.

7.2.3. REFLECTION ON APPROACH, MODEL

The framework introduced in Chapter 2 brings together two separate strands of literature: the institutional analysis framework and design theory. The combination is shown to also be coherent with and complementary to the modelling paradigm of agent based modelling and simulation. The framework does not provide causal relationships which provide insight on why a certain actor behaves in a certain manner under certain conditions. Nonetheless, it makes for a strong fundamental basis to simulate a test-bench on which the real world can be represented, and theories or "speculations" tested. Although this framework was applied and demonstrated using renewable support schemes in Europe, its fundamental nature makes it eminently employable to other domains. The claim is supported by the fact that each of the foundational concepts that make up the framework have been applied in thousands of publications and are being actively used across sectors, geographies, communities.

One aspect of the modelling framework presented that needs further attention however is the fact that choosing a limited number of design elements for analysis is, to say the least, challenging. How does a researcher tell whether a certain element is important or not? While this dissertation sheds little light on the topic, others such as Taeihagh *et al.* (2014) have proposed and demonstrated some interesting ways to reduce the policy design element set. One such method uses a combination of interviews with stakeholders, combinatorics, and network theory, to design policies and aid decision making.

A major advantage of the model is that it is open source. Most models that are used to inform the European Commission's policy documents are black box simulations. The assumptions, data, systems used to set policy are not publicly available. Making models open source allows for replicability, transparency, and for debating their validity, which are all basic tenets of the scientific method.

The model has provided interesting insights on impacts of design elements of RES-E support and on the nature of cross border interactions. The results pave the way towards new questions that need to be resolved as the shares of RES-E increase in the elecricity system. For instance, they raise pressing questions about the need to further develop a methodology for sharing the paying the investment costs behind the subsidies between countries. These are explained in greater detail in the following section on future work.

7.3. FUTURE WORK

The framework presented in this work can be extended in several ways. Its reliability and usefulness could be tested by applying it to other socio-technical systems. It could be extended methodologically by incorporating endogenous policy emergence and evolution using policy process theories.

For modellers of long term energy systems, it is paramount that models employ high temporal resolution at high shares of intermittent RES-E generation. Creative techniques to accomplish this while having endogenous investment in the model need to be invented. One way of accomplishing this, without compromising on the constraints of computational resources, is to run high resolution optimization algorithms to compute hourly market clearing at intervals of 3 or 5 years (ticks), given a certain generation mix.

In Chapter 5 it was evident that the costs of RES-E electricity will rise due to high spillage, if adequate temporal flexibility is not provided. An interesting point of departure is to compute the tradeoff between marginal storage and the marginal unit of RES-E generation: at what point does an extra unit of storage cost lesser than an extra unit of intermittent RES-E without storage? This would be interesting to policy makers as it signals whether, and at what point, storage technologies might need regulatory support to be able to increase the share of RES-E in the system.

Given that electricity markets are intricately connected across national borders, questions regarding burden sharing of subsidy costs are complex, as merit order effects spread across border. They should also depend on the neighbouring countries' targets, generation mixes, and flexibilty sources. These questions need to be explored in greater detail, and possible mechanisms to cope with the complexities should be evaluated.

REFERENCES

G. N. Gilbert and K. G. Troitzsch, *Simulation for the social scientist*, 2nd ed. (Open University Press, Maidenhead, England ; New York, NY, 2005).

W. S. Parker, *Franklin, Holmes, and the Epistemology of Computer Simulation,* International Studies in the Philosophy of Science **22**, 165 (2008).

E. Winsberg, *Sanctioning Models: The Epistemology of Simulation,* Science in Context **12** (1999), 10.1017/S0269889700003422.

E. Winsberg, *Simulations, Models, and Theories: Complex Physical Systems and Their Representations,* Philosophy of Science **68**, S442 (2001).

J. M. Epstein, *Agent-based computational models and generative social science,* Complexity **4**, 41 (1999).

E. Winsberg, *Computer simulations in science,* in *The Stanford Encyclopedia of Philosophy,* edited by E. N. Zalta (Metaphysics Research Lab, Stanford University, 2015) summer 2015 ed.

E. B. Winsberg, *Science in the age of computer simulation* (University of Chicago Press, Chicago, 2010) oCLC: 676697492.

D. Dowling, *Experimenting on Theories,* Science in Context **12** (1999), 10.1017/S0269889700003410.

I. Hacking, *Representing and intervening: introductory topics in the philosophy of natural science* (Cambridge University Press, Cambridge [Cambridgeshire] ; New York, 1983).

A. Taeihagh, R. Bañares-Alcántara, and M. Givoni, *A virtual environment for the formulation of policy packages,* Transportation Research Part A: Policy and Practice **60**, 53 (2014).

A

DATA AND ASSUMPTIONS

A.1. DATA

A.1.1. DEMAND AND FUEL PRICE TRENDS

Table A.1: Demand and Fuel Price Trends

		Growth Rate		
	Start value	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

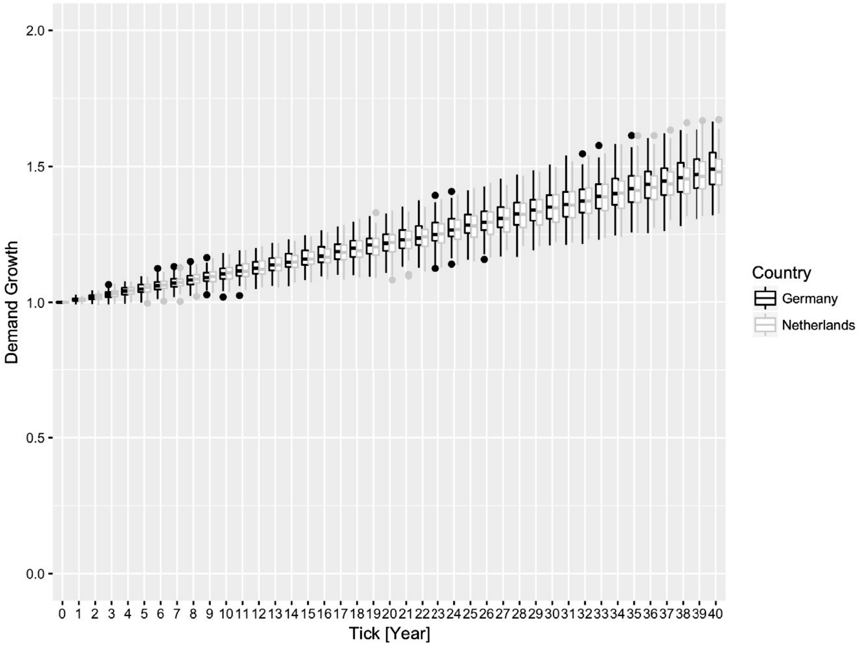


Figure A.1: Stochastic, annual demand growth factor trends for both Netherlands and Germany.

A.1.2. RENEWABLE TECHNOLOGY COST CURVE ASSUMPTIONS

The assumptions for cost trends are based on data from IRENA reports and are in 2014 prices. The Solar PV investment costs are based on IRENA (2016), while cost trends for wind offshore and onshore are based on IRENA and IEA-ETSAP (2016).

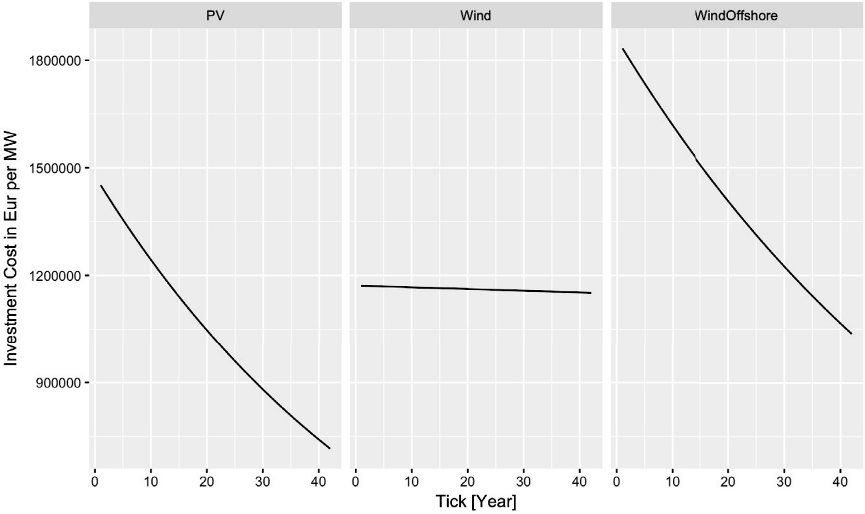


Figure A.2: Assumed Investment cost trends per technology across the time period of the simulation

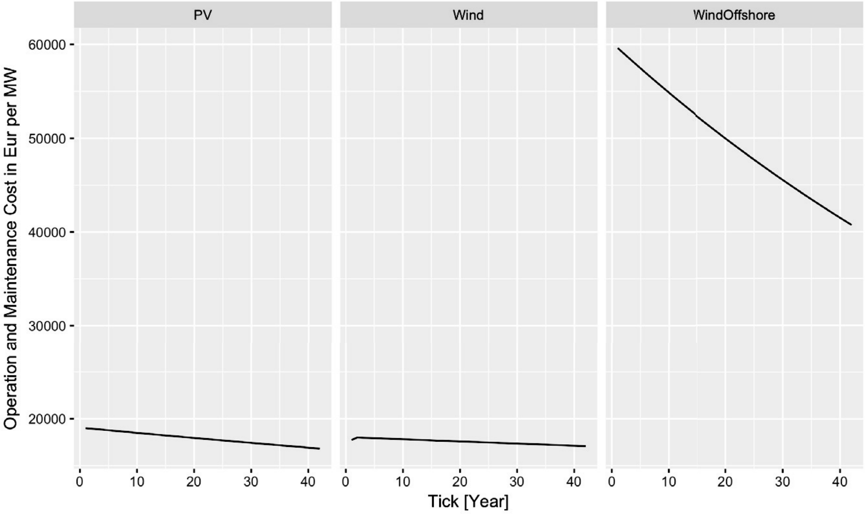


Figure A.3: Assumed operation and maintenance cost trends across the time period of the simulation

A.1.3. 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; of Economic Affairs Agriculture and Innovation (2010).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.

Table A.2: Realistic Technology Potentials

Technology	Year	Country	Potential (in GWh)	Source
Wind Onshore	(2010, 2040)	NL	(2151.62,9032)	Lako (2010)
Wind Offshore	(2010, 2040)	NL	(837.27,58756)	Lako (2010)
Photovoltaic	(2013, 2020)	NL	(1065.19,10839.8)	Ragwitz *et al.* (2003)
Wind Onshore	(2014,2050)	DE	(49290.1596,123000)	Scholz (2012)
Wind Offshore	(2014,2050)	DE	(2053.17112,310000)	Scholz (2012)
Photovoltaic	(2014,2050)	DE	(34916,107000)	Scholz (2012)

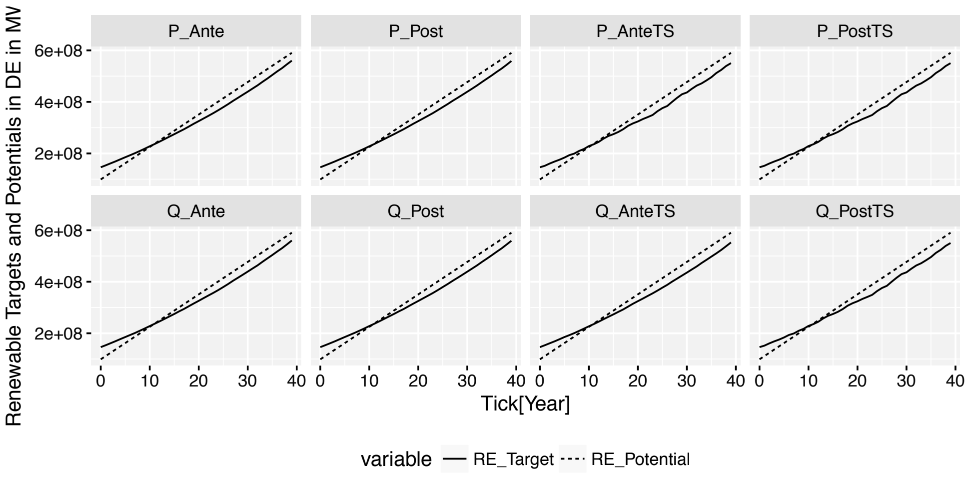


Figure A.4: Assumed targets and potentials of renewable electricity technologies (all) in Germany in MWh.

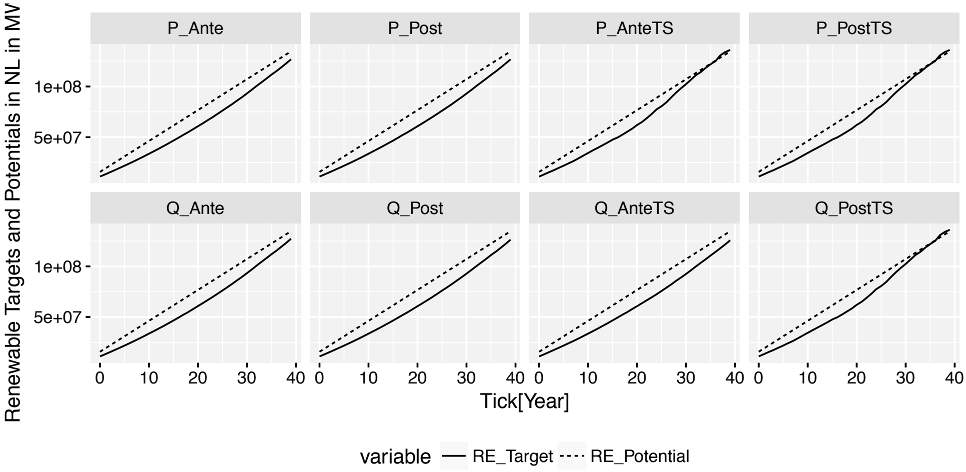


Figure A.5: Assumed targets and potentials of renewable electricity technologies (all) in Netherlands in MWh.

A.1.4. ASSUMPTIONS: TECHNOLOGY CHARACTERISTICS

Table A.3: Assumptions regarding fixed costs of conventional technologies

Technology	Investment Costs		Fixed O & M Costs		Efficiency	
	Start [in Eur]	Growth rate	Start [in Eur]	Growth rate	Start	Growth rate
Coal Pulverised SC	1365530	0	40970	0	0.44	0.00327
Lignite	1700000	0	41545	0	0.37	0.00500
Nuclear	2874800	0	71870	0	0.33	0.00001
CCGT	646830	-0.008	29470	0	0.59	0.00207

A.2. CURRENT TECHNOLOGY COST DATA TRENDS

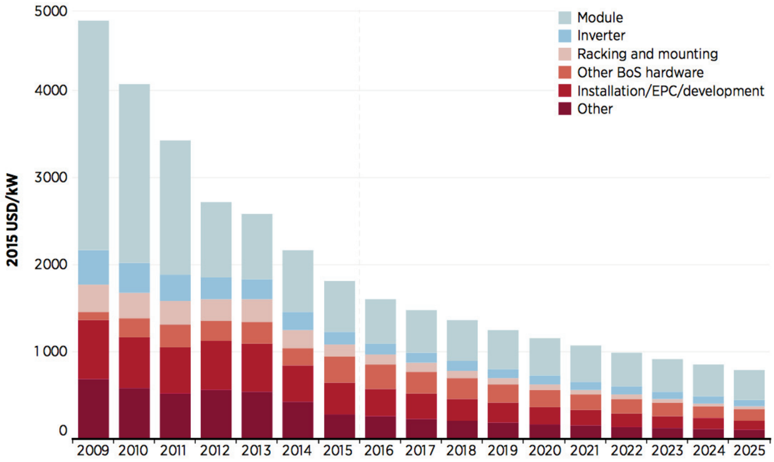


Figure A.6: Global weighted average utility-scale installed solar pv system costs and breakdown, 2009-2025, Source: IRENA (2016)

REFERENCES

IRENA, *Solar PV in Africa: Costs and Markets*, Tech. Rep. (2016).

IRENA and IEA-ETSAP, *Wind Power Technology Brief*, Tech. Rep. E07 (2016).

M. of Economic Affairs Agriculture and Innovation, *National Renewable Energy Action Plan of the Netherlands: Directive 2009/28/EC*, Submitted to European Commission (2010).

P. Lako, *Technical and economic features of renewable electricity technologies*, Tech. Rep. ECN-E–10-034 (ECN, 2010).

M. Ragwitz, G. Resch, C. Huber, and S. White, *Dynamic Cost Resource Curves*, Tech. Rep. ENG2-CT-2002-00607 (Energy Economics Group, Vienna University of Technology, 2003).

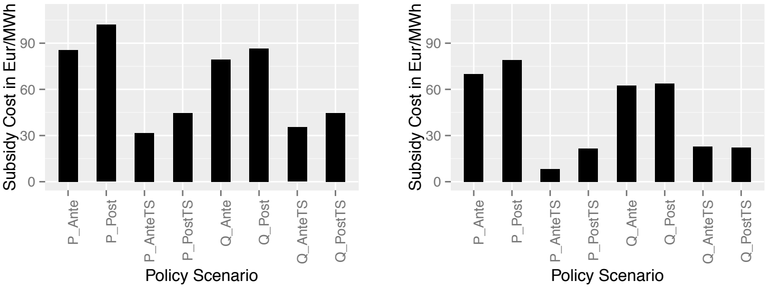
Y. Scholz, *Renewable energy based electricity supply at low costs - development of the REMix model and application for Europe*, Ph.D. thesis, German Aerospace Institute, Stuttgart (2012).

B

RESULTS

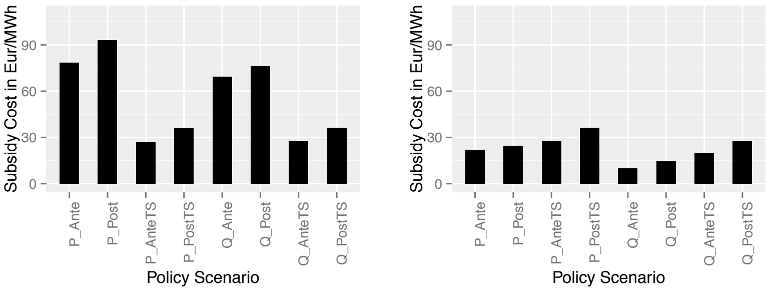
B.1. CHAPTER 4: RESULTS AND SENSITIVITY ANALYSIS

B.1.1. FIGURES



(a) Subsidy costs in Gas Low scenario (b) Subsidy costs in Gas High scenario

Figure B.1: 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

Figure B.2: Subsidy costs of scenarios addressing each effect on price setting individually

B.1.2. TABLES

Table B.1: 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 B.2: Comparison of Average Subsidy Between Base Case Set and Same Risk Scenario Set

	Base Case Scenario	Same Risk Scenario	
Scenario Name	Avg Subsidy/Unit (Eur/MWh)	Avg Subsidy/Unit (Eur/MWh)	Difference
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

B.2. CHAPTER 5: RESULTS

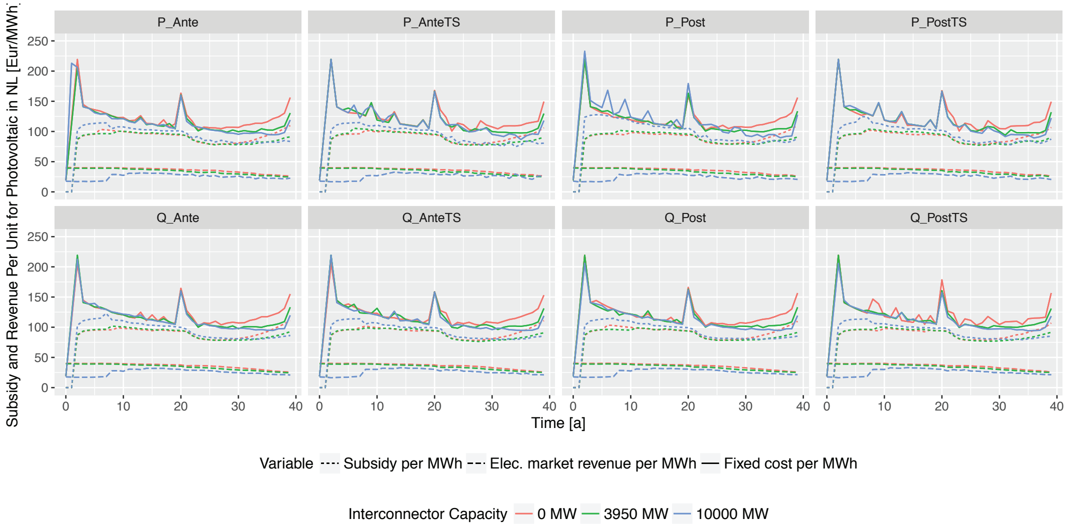


Figure B.3: Fixed costs, revenue from subsidy, revenue from spot market shown per MWh electricity generated, across time.

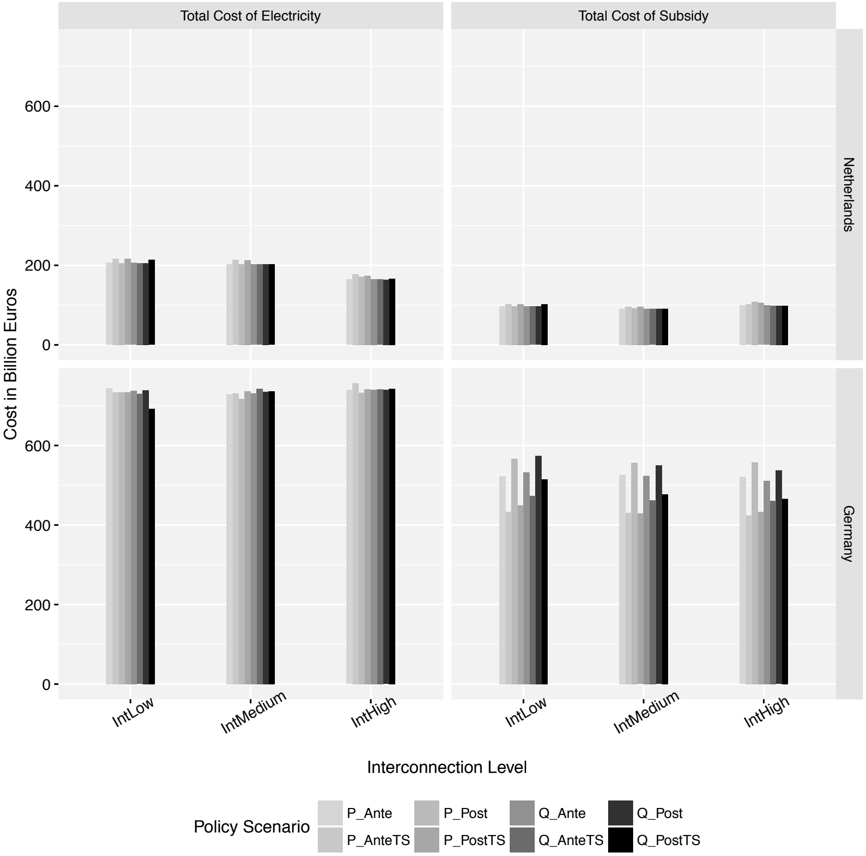


Figure B.4: Electricity and subsidy costs summed across 40 ticks, per country, and per RES-E policy

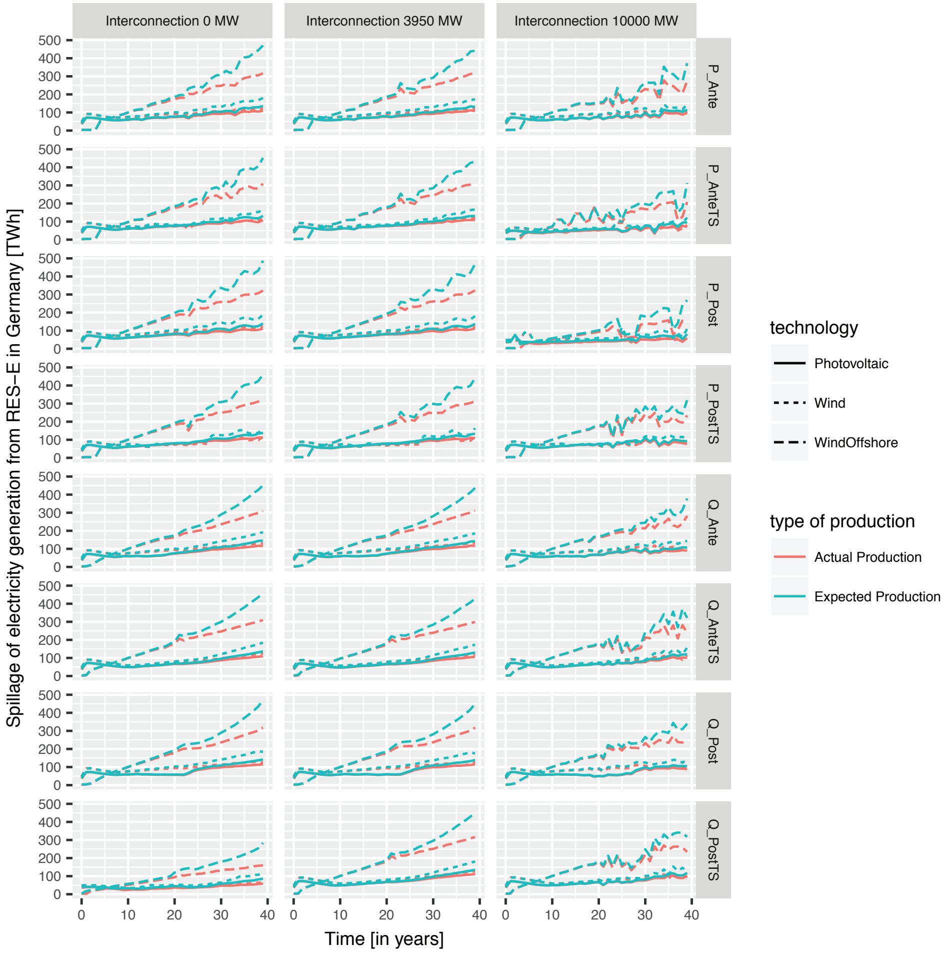


Figure B.5: Expected versus actual production of RES-E due to spillage across time in Germany in TWh

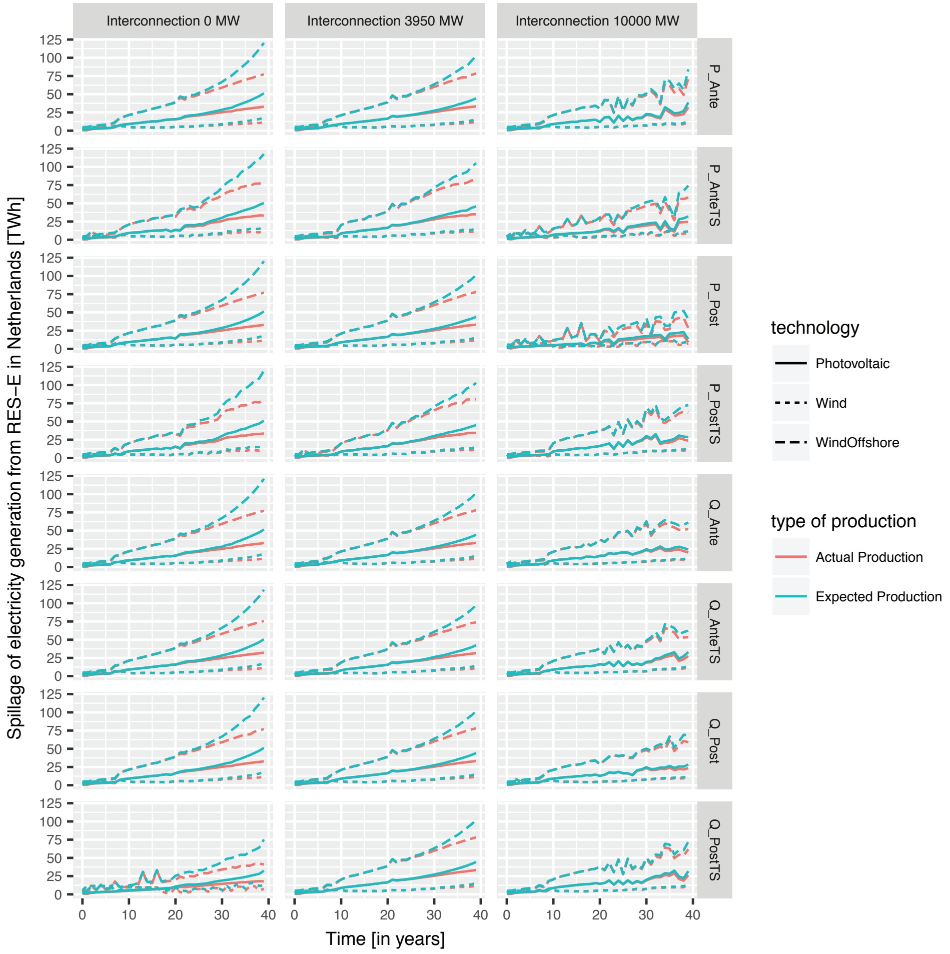


Figure B.6: Expected versus actual production of RES-E due to spillage across time in the Netherlands in TWh

LIST OF PUBLICATIONS

PEER-REVIEWED JOURNAL ARTICLES

- **K. Iychettira**, R. Hakvoort, P. Linares, *Towards a comprehensive policy for electricity from renewable energy: An approach for policy design*, Energy Policy **106**, 169-182 (2017).
- **K. Iychettira**, R. Hakvoort, R. de Jeu, P. Linares, *Towards a comprehensive policy for electricity from renewable energy: Designing for Social Welfare.*, Applied Energy **187**, 228-242 (2017).
- E. J. L. Chappin, L. J. de Vries, J. C. Richstein, P. Bhagwat, **K. Iychettira**, S. Khan *Simulating climate and energy policy with agent-based modelling: The Energy Modelling Laboratory (EMLab)*, Environmental Modelling and Software **96**, 421-431 (2017).
- P. C. Bhagwat, **K. Iychettira**, J. C. Richstein,E. J. L. Chappin, L. J. de Vries, *The effectiveness of capacity markets in the presence of a high portfolio share of renewable energy sources*, Utilities Policy **48**, 76-91 (2017).
- P. C. Bhagwat, J. C. Richstein,E. J. L. Chappin, **K. Iychettira**, L. J. de Vries, *Cross-border effects of capacity mechanisms in interconnected power systems*, Utilities Policy **46**, 33-47 (2017).

UNDER REVIEW

- **K. Iychettira**, M. Klein, R. Hakvoort, *Can subsidies be phased out under high shares of RES-E? Evaluating primary influencing factors*, Working paper submitted for publication, (2017).
- **K. Iychettira**, R. Hakvoort, P. Linares, *Congruency between national support schemes and an international electricity market: A case of The Netherlands and Germany*, Working paper to be submitted for publication, (2018).

CONFERENCE PROCEEDINGS

- **K. Iychettira**, *Towards a comprehensive policy for electricity from renewable energy: A Structured Design Approach*, 3rd International Conference on Public Policy, Singapore, 28-30 June 2017.
- **K. Iychettira**, R. Hakvoort, R. de Jeu, P. Linares, *Modelling long term impacts of renewable electricity support designs on Social Welfare*, 40th Annual IAEE International Conference, Singapore, 18-21 June 2017.
- **K. Iychettira**, R. Hakvoort, R. de Jeu, P. Linares, *Designing the Right RES-E Support Schemes: assessing impacts of design elements using an agent-based model.*, WholeSEM Annual Conference 2016, Cambridge, UK, 4-5 July 2016.
- **K. Iychettira**, P. Linares, R. Hakvoort, *Harmonising RES-E support schemes using design elements*, 12th International Conference on the European Energy Market, Lisbon, Portugal, 19-22 May 2015.

- **K. Iychettira**, P. C. Bhagwat, J. C. Richstein, L. J. de Vries, *Interaction between Capacity Markets and Investment into Renewable Energy in the Netherlands and Germany*, 37th Annual IAEE International Conference, New York, USA, 15-18 June 2014.

CURRICULUM VITÆ

Kaveri Kariappa IYCHETTIRA

Kaveri was born on the 30th of December 1989. She spent her early years in Mysore, and later moved to Bangalore where she completed her secondary education and bachelor degree. Through school and early college, she showed a penchant for writing; she wrote for and edited several community magazines and newsletters. In 2007 she graduated from pre-university college, and in 2011, obtained a Bachelor in Engineering, with a specialization in Electrical and Electronics, from RV College of Engineering in Bangalore. During 2010-11 she also interned at the Centre for Science Technology and Policy in Bangalore, where she worked on analysing the impact of India's National Solar Mission.

She went to the Netherlands in 2011, to pursue a Masters in Engineering and Policy Analysis at Delft University of Technology. She was awarded the Justus van Effenfond Scholarship, a full funding of her Masters education, granted to only 8 students in 2011 across the University. During her Masters, she specialized in the disciplines of Modelling and Economics. She wrote a dissertation analysing the impact of capacity markets in the electricity sector in The Netherlands and Germany. She was awarded the "Best Graduate Award" for the Faculty of TPM at the Delft University of Technology for the year 2013.

In October 2013, she began an Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS) at Delft University of Technology. As part of the SETS programme, she spent 11 months at Comillas Pontifical University in Madrid, Spain, and 6 months at KTH Royal Institute of Technology in Stockholm, Sweden. During her doctoral programme, she published several peer-reviewed journal publications, supervised 4 master thesis projects, and presented at 5 international conferences. She also served as the student representative for the 32 students across the three universities during 2015-16. She began working as a post-doctoral fellow at the Belfer Centre of the Harvard Kennedy School since September 2017.