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The influence of multi-target policies on the ranking of technologies

A bottom-up approach using OPERA optimisation model

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Universiteit Utrecht
Faculty of Geosciences

George Antonopoulos
Student number: 4191609
Email: g.antonopoulos@students.uu.nl

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ECN Supervisors: Dr. Bert Daniels
Jamilja van der Meulen

Utrecht University Supervisor: Dr. Robert Harmsen

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Abstract

The increasing trends in GHG emissions over the last 40 years due to the economic growth are aggravating the effects of Climate Change. A way to stabilise and reverse these effects is through the decarbonisation of energy systems and the transition to a low carbon economy; however, this requires time and involves costly investments. The gradual transition to a low carbon economy demands the development and implementation of new technologies as well as policies that will exploit the potential of the technology mix in the least cost for society. Cost effectiveness has been used as an indicator for giving such insights to decision and policy makers. In planning such futures, models are being widely used providing input to assess the developments need to be undertaken taking into account policy and technology interactions. In this study we used OPERA optimisation model in order to study the Dutch energy system regarding the cost effectiveness of technologies under different policy pathways for 2030. Four scenarios were studied representing possible pathways with regard to the climate and energy targets. In particular renewable energy, primary energy savings and final energy savings targets were investigated along with the non-ETS emission reduction targets. Aim of the research was to provide a method to examine how the interactions among the scenario objectives and the assessed technologies affect the ranking of the latter using as indicator their cost effectiveness. The shadow prices of the assessed targets were used as a proxy to estimate the cost effectiveness of technologies as well as the interactions among the objectives of each scenario. The analysis suggests that the scoring of each technology is highly dependent on its influence on the scenario objectives. Providing such ranking can be proved really useful for policy makers because the alignment or misalignment of technologies with the policy objectives can be predicted. Hence, technological lock-ins can be avoided and more efficient and effective policies to be planned in the longer term time horizon.

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Abbreviations

AIMMS	Advanced Interactive Multidimensional Modeling System
ATsp	Additional target shadow price
CCS	Carbon capture and storage
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
C_{spec}	Specific costs
EC	European Commission
ECN	Energy Research Centre of the Netherlands
EE	Energy efficiency in final terms
EE prim	Energy efficiency in primary terms
ETS	Emission Trading System
ETsp	Emission target shadow price
ETsp (MT)	Emission target shadow price for the MT scenario
ETsp (ST)	Emission target shadow price for the ST scenario
EU	European Union
GHG	Greenhouse gas
GJ	Giga-Joule
GUI	Graphical User interface
H.P.	Heat pump
IPCC	Intergovernmental Panel on Climate Change
M€	Million Euros
MACC	Marginal abatement cost curve
MS	Member State
MT	Multi target
N_2O	Nitrous oxide
O&M	Operation and maintenance
OPERA	Options Portfolio Emission Reduction Analysis
PJ	Peta-Joule
RE	Renewable energy
RES	Renewable energy sources
SDE	Stimulering Duurzame Energieproductie
Solar PVs	Solar photovoltaic
ST	Single target
Tsc	Total system costs
UI	User interface

UKERC	UK Energy Research Centre
WAM	With additional measures
WEM	With existing measures

1 Chapter: Introduction

1.1 Context

One of the biggest environmental threats that post-industrial world is facing, is climate change and its consequences. Global climate change exerts pressure to earth and its livelihood due to the risks and effects posed towards weather patterns, global warming, natural ecosystems, biodiversity and the natural environment (IPCC, 2014). Anthropogenic activities such as energy generation, industrial processes (cement and steel production), transportation etc. have increased dramatically the emissions of greenhouse gases (GHG) (UNEP, 2014)(Dinica, 2002); reaching at a point that half of them were attributed only to the last 40 years (period 1970-2010) (IPCC, 2014). This increase in emissions is being driven mainly by economic and population growth (Dinica, 2002). However, as being argued in Intergovernmental Panel's report on Climate Change (2014), the contribution of economic growth to the rise of GHGs concentrations in the atmosphere is by far higher than that of population growth. The economic growth is characterized by all activities in the system-wide energy system. Zooming in the last decade (2000-2010) of the aforementioned period, the observed increase in GHG emissions (around 10 GtonCO$_{2eq}$) is decomposed to the economic sectors, where energy supply is attributed with 47% share in the increase of emissions, industry with 30%, transport with 11%, and the built environment with 3% [1], while the total GHG emissions in 2010 are decomposed as shown in Figure 1 (IPCC, 2014).

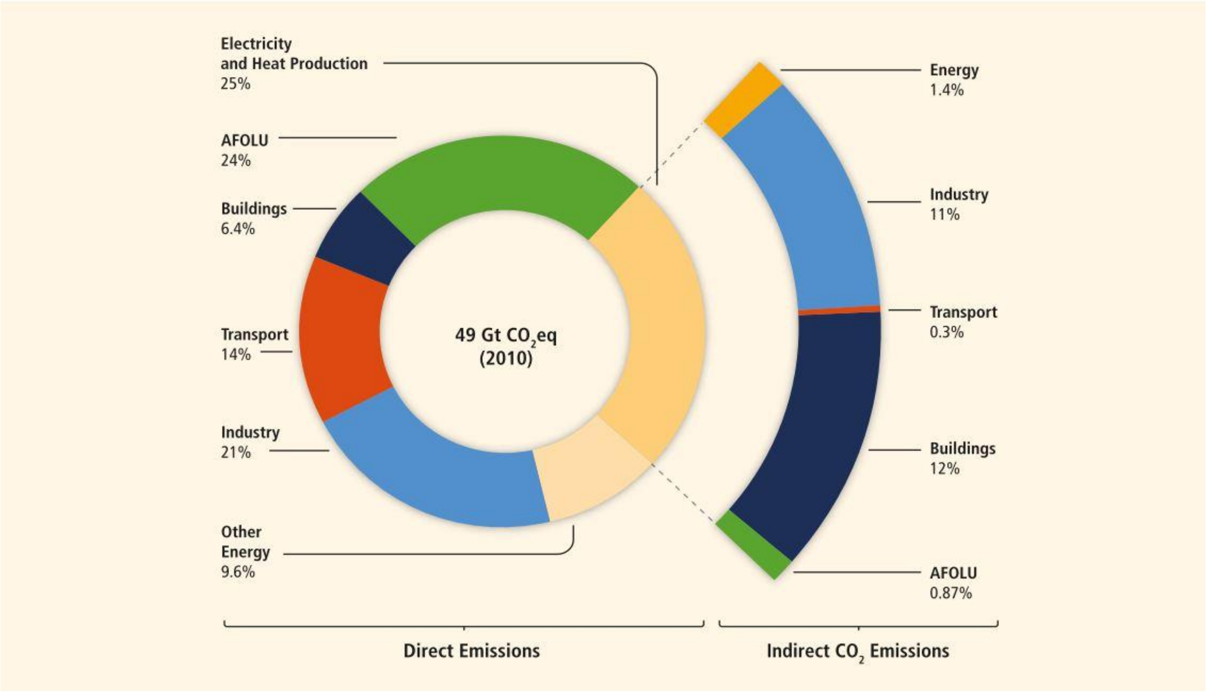

Figure 1: GHG emissions by economic sector in 2010 (source: IPCC, 2014)

Therefore, decarbonisation of energy systems has attracted the focus of scientists, world leaders and policy makers in order to stabilize the rise of global average temperature at 2°C by 2100 (Grübler & Nakićenović, 1996) (Dagoumas & Barker, 2010).

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[1] These percentages do not include indirect emissions. When taken into account, the percentages of industry and of built environment are much bigger.

To that end, European Union (EU) in an attempt to increase its commitment on the energy and climate change targets, invited European Commission to come up with proposals regarding the targets set (European Commission, 2008):

- 20% GHGs reduction by 2020 compared to 1990 levels
- 20% increase in share of renewable energy by 2020, including a 10% share of RES in transport target.
- 20% increase in energy efficiency by 2020.

However, these targets went through revision and update by the European Commission for the year 2030 in order to be in accordance with 2050 targets (Sijm et al., 2014). The main drivers behind this initiative were the recognition that Member States (MS) have lost a large share of their investment capacity in low carbon technologies and policies due to the recession started in 2008 (ibid); the rising energy prices which have increased the dependency on fuels coming outside the EU (mainly USA) (ibid); the market failure of EU's Emission Trading System (EU ETS)[2] (European Commission, 2014c). Although the European Commission considers a governance regime, however its implications and its (non) binding character are yet to become clear (Daniels et al., 2014). The so far non-binding character of the 2030 policy framework of climate and energy gives the opportunity to each MS to explore the national targets which they will be used to shape the energy agreement[3]. Therefore the targets of 2030 for GHG emission reduction have been set at 40% as compared to 1990 levels. This target is split into targets in emission reduction regulated by EU ETS, and by the effort sharing decision[4]. The renewable energy penetration targets for EU as a whole were set at 27%, while the energy efficiency[5] target has been set at 30%. An overview of the proposed objectives in EU-wide level for 2030, as well as the possible objectives for the Netherlands, is presented in Table 1.

Table 1: Overview of 2030 objectives for EU and potential objectives for the Netherlands [(European Commission, 2014b), (European Commission, 2014c), (European Commission, 2011) (Daniels et al., 2014)].

	2030 objectives
Goals for EU as a whole	
Emission reduction	40% relative to 1990
Emission reduction, ETS	43% relative to 2005
Emission reduction, non - ETS	30% relative to 2005
Renewable energy	27%
Energy saving	30%
EU goals for Netherlands	
Emission reduction, non - ETS	possible 28% to 48% relative to 2005
Renewable energy	possible 19%-26%
Energy saving	Unknown

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[2] EU-ETS is the European trading system for greenhouse gas emissions including especially power plants and large industrial companies. Other sectors, such as agriculture, transport and the built environment are not covered by the ETS.

[3] In the agreement for the 2020 targets the Netherlands had set: a) final energy consumption savings averaging 1.5% annually; b) 100PJ final energy savings by 2020; c) increase in the share of energy generated from renewable energy sources from 4.4% (2013) to 14% (2020) to 16% (2023) and to 20% by 2030; and d) 897Mton CO_2eq in cumulative emissions not regulated by the European Emissions Trading Scheme (EU-ETS) for the period 2013-2020 (SER, 2013).

[4] The effort sharing decision is based on the attribution of national commitments towards the overall target by taking into account the wealth (GDP/cap) of each country (Carbon Market Watch, 2015).

[5] This includes saving compared to the (in 2007) estimated energy use for the years 2020 and 2030 (ibid).

1.2 Related scientific work and problem definition

Our society is structured in a way that is dependent on fossil fuels. To alter this dependence, changes need to be made in the energy system, which require time and involves costly investments. For the gradual transition towards a renewable energy system it is necessary to develop and implement new technologies and infrastructures as well as policies in an international, national and even regional level (DESA, 2013). Decision makers need to allocate funds in order to apply the relevant measures in the most optimal way (Rossi, Lipsey, & Freeman, 1998). Since cost-effectiveness has drawn the attention of scientists and institutions, it has been chosen as an indicator to assess the outcomes of models that analyse the climate change mitigation measures, as well as their effects. Such kind of models can be classified into two categories:

- Top-down models: they perform a cost/benefit analysis dealing with cost efficiency purely from an (macro)economic perspective; taking into account market driven interactions within the system (Chicco & Stephenson, 2012).
- Bottom-up models: their origins are lying in technical and engineering models; they deal with cost minimization or profit maximization given a specific target (e.g. emissions) taking into account different technology options in the context of energy demand and supply (ibid).

Several studies were dedicated in the comparison of those two approaches when assessing GHG mitigation potentials. In the study by van Vuuren et al. (2009), the authors have compared a number of top down and bottom up models by using similar approach with the 4th Assessment Report of IPCC in estimating global, regional and sectoral GHG emission reduction potentials. They concluded that there are no systematic variations among the approaches, especially in global scale estimates, and they highlighted that the incorporated technology depth in bottom up models makes them more suitable to address policy measures other than CO_2 prices. In a similar study, Blok et al.(2001), have compared Primes top down model with a bottom up approach using GENESIS database. They addressed the cost effective technology mix and GHG emission distribution among sectors, and they deducted that bottom-up models are bounded in incorporating energy with economy interactions.

Furthermore, a number of studies were involved in identifying the role of technologies under decarbonisation objectives. Lehtila & Pirilä (1996), in their supporting study regarding the Finnish policy planning, they have used a bottom up model (EFOM) to arrive with a cost optimal technology mix and how these technologies can be coordinated in planning CO_2 emission reductions through effective policy. Tavoni et al. (2012) using a model comparison exercise with integrated assessment models, they have examined the role of technologies in abatement strategies. The exercise was based on foregone costs of specific technologies to derive with their value for the system in mitigation processes. CCS and wind have shown the largest impact on the system when their implementation was omitted. Furthermore, they highlighted the importance of having a diverse portfolio of abatement technologies. Dagoumas & Barker (2010), in their study for the UKERC, they explored a range of low carbon pathways for the UK in 2050. Using a version of MARKAL (MED), which accounts for demand elasticity, they assessed all the sectors of the British energy system deriving with the technologies that would perform better with respect to their marginal abatement costs and marginal investment costs under different scenarios. Furthermore they identified trade-offs between technologies that compete with each other when having the same functionality. In the Netherlands, Daniels et al. (2012) performed a cost-benefit analysis on the Dutch energy system identifying the options that are cost effective in achieving 80% GHG emission reduction by 2050 in the Netherlands, as well as the total social costs of such a reduction. For the purpose of the research they used a bottom up optimization model. Their findings suggest that the results are accompanied by high uncertainty;

however, similarly to the study by Dagoumas & Barker (2010), they also conclude that the achievement of such target in a cost effective way requires the implementation of a broad range of technologies. A similar type of study has performed by Chen (2005); using MARKAL-MACRO to generate a reference scenario for China's energy system in 2050, he addressed primary energy conservation and GHG mitigation by evaluating the marginal abatement costs and carbon intensity. He concluded that deep reductions in China come at high costs due to the limitation of the system to ease coal's domination.

Another type of studies addresses the merit order of technologies in low carbon economies based on their cost effectiveness using MAC curves. Vogt-Schilb & Hallegatte (2014) in their study, they used an inter-temporal optimization model to criticise the way MACCs are being constructed using only the cost and the emission reduction potential of a technology. They argue that the driver of technology implementation should be the longer term targets because the exploitation of the cheapest potential would make the ambitious long term targets too expensive. In the same mentality, Taylor S. (2012) identifies a flaw in the cost effectiveness in MACCs. The ranking of technology options in a MACC gives an advantage to technologies that may have low mitigation potential, while more expensive options can deliver more benefits. He suggests a ranking method based on Pareto optimization where cost effectiveness is omitted, instead of using MAC curves.

In the Netherlands, the literature on ranking technologies under the influence of different policy measures seems to be limited. However, Harmsen R. (2014) examined the performance of different renewable energy technologies under different target definitions and policy objectives, wanting to indicate the penalization that occurs towards several renewable energy technologies when competing to get support from the Dutch subsidy scheme (SDE). The criteria he used to provide the ranking were: the cost effectiveness under the RES target, the cost effectiveness under the amount of fossil fuel avoided, and the cost effectiveness under the GHG emission target.

Through the study of the relevant scientific work is quite evident that the decarbonisation of the energy system has attracted the interest of scientists. Technological pathways towards a low carbon economy are important to be studied from different perspectives in a mid-term and long-term time horizon. By understanding how individual technologies interact with each other as well as with different targets can provide policy and decision makers the input required in granting political acceptability of policy measures, identify market imperfections and implementation barriers, and avoid technological lock-ins towards the transition to low carbon economies. The alignment or misalignment of technologies to the targets set can determine the pathway that needs to be followed in order to stabilize climate change without compromising energy security. The scoring of technologies based on cost effectiveness can serve this end by providing a tool under which such insights can be extracted. Policies with respect to energy demand and supply, as well as to GHG emissions, play an important role and are crucial to be evaluated for their effectiveness at the lowest cost for society.

1.3 Research aim

Costs for reducing emissions are an important factor in policy and decision making either from a national or an international point of view. After politicians agree on targets with regard to energy and emissions, there has to follow a step which makes the targets measurable and specific (not that they always adhere to this order of events) (Konidari & Mavrakis, 2007). The aim of this research is to develop a method to approximate the effects, costs and cost-effectiveness of individual measures and to apply this method in comparing the influence of various alternative targets (next to the emission target), in their impact on the scoring of these measures.

Thereafter, the approximation will be run, using OPERA (Options Portfolio Emission Reduction Analysis) linear optimization tool, on various target specific scenarios for the Netherlands in 2030. This study is restricted within the Netherlands since the data and the energy system representation reflect only the Dutch energy system. The outcomes will hold a basis for further explorations of the optimal energy system and on how well or bad do specific technologies perform in terms of cost-effectiveness concerning different targets. For example, by having an energy savings target in primary terms rather than final, the resulting technology mix and the contribution of the same technologies to the target will differ. The following research question has been identified as relevant to give insights on the influence of different targets on the cost effectiveness of measures towards the targets' fulfilment.

Research question

- To what extent the scoring of individual measures in achieving certain emission targets can be influenced by additional energy targets?

Sub-questions

- What is the effect of the different targets on the shadow prices and how they interact with emission targets?
- What are the main substitutions within the scenarios, and how different technologies contribute to the objectives of the various scenarios?
- How do shadow prices determine the cost effective technology mix?
- What is the ranking of the core technologies based on their cost effectiveness among the different targets?

1.4 Research set up

This research is conducted for, and in cooperation with ECN Policy Studies. ECN Policy Studies has developed the OPERA which allows for a wide range of analyses on the future energy system of the Netherlands. It is a bottom-up technology model that assesses a mix of technologies which are satisfying multiple requirements/restrictions usually in terms of GHG emissions, energy use and implementation of renewable energy sources; either due to a push or a pull effect[6]. For this study four (4) scenarios were constructed and run:

- Single target scenario (ST) - only non-ETS emission reduction targets.
- Renewable energy scenario (RE) - renewable energy targets along with non-ETS emission targets.
- Final savings scenario (EE) - final energy savings targets along with non-ETS emission targets.
- Primary savings scenario (EE prim) - primary energy savings targets along with non-ETS emission targets.

The model performs an optimization of the aforementioned scenarios deriving with the optimal solution at the least cost for society, using as a reference a fixed baseline scenario grounded on the National Energy Outlook 2014. The cost calculation is based on the national cost methodology using a 4% discount rate.

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[6] Push and pull effect refers to policy imposed and market driven strategies respectively. OPERA does not include policies, unless it is as exogenous assumptions with regard to policy effects.

1.5 Outline of the report

The remainder of this report is structured in a way that the reader can follow all the steps undertaken during the conduction of this study. To this end, in chapter 2 the theoretical concepts that were perceived necessary for the reader to feel more familiar with the topic are introduced. First, several elements of importance in the design of targets, such as the accounting methods, are addressed. Next, background information on cost effectiveness and shadow prices, along with the norms that are subjected to are concisely described. Moreover, the characteristics of OPERA model are introduced in order to give a complete picture on the functions and boundaries that adheres to. Finally, this chapter ends by providing the research framework which links the research questions to the concepts discussed and to the methods.

Chapter 3 deals with the analysis of the followed methods in order to reach the answering of the research questions. The chapter starts with the description of the process developed with the intention to be added in the model. Next, it provides all the methodological steps as designed for the purpose of the research. In the end of the chapter, the limitations that emerged during the conduction of the study, along with its original ideas are presented.

Chapter 4 proceeds with the presentation of the main findings of the study as well as with the discussion on the interpretation of the outcomes. Thereafter, this chapter is followed by the concluding remarks and the answering of the research questions (Chapter 5).

2 Chapter: Theoretical background

In this section, several theoretical concepts are introduced, which will help the reader to feel more familiar with the methods followed in this study. First, this section deals with the elements that are of importance when designing a target. Next, it provides a concise background on the cost effectiveness as an indicator, along with the norms that adheres to. In addition, the concept of shadow prices and marginal costs is addressed, both with respect to linear programming and to policy studies. Furthermore, the characteristics of the model such as the objective function, the constraints it subjects to, the energy system representation and the baseline scenario are also concisely described in this part. In the end, the research framework bridges the concepts described with the methodology.

2.1 Design of targets

In climate and energy policy making, the target's design can provide a stage for discussion over the GHG targets, the energy conservation objectives and pave the steps needed towards the desired end state (Rietbergen & Blok, 2010). During this process someone has to keep in mind the steps of implementation and evaluation that a policy must undergo. According to Rietbergen and Blok (2010), a target must guide and motivate the stakeholders to take action by being realistic and specific. Moreover, it must be easy to evaluate its functionality by applying monitoring processes, in order to identify the distance that should be covered to reach the targets (ibid).

For that reason a target should be S.M.A.R.T. (specific, measurable, appropriate, realistic, timed) (Harmsen, 2014). These ingredients indicate the points that need attention from policy makers when planning a new policy. However, when setting multiple targets, the landscape becomes more complex, where interactions between targets must be taken into account (ibid). Policy makers, when it comes to interactions between measures and targets, are not always able to recognise the contribution of each target to another one (Harmsen, Wesselink, Eichhammer, & Worrell, 2011). This is more explained in the study by Harmsen et al. (2011), where the contribution of renewable energy to primary energy savings is positive. This might lead to underestimation by MS of the energy saving target and turn their focus on the renewable energy one, as it is binding for MS. Such a case could have been avoided if the savings target reflects final savings.

2.1.1 Accounting of targets

In the evaluation of targets and in measuring the progress towards their achievement it is crucial to be transparent on the way they are accounted in statistics. Hence, for the targets assessed in this study, the following methods apply.

Renewable energy

Renewable energy was being measured in the Netherlands using the substitution method, which is based on the fossil primary energy avoided when the renewable output is juxtaposed with the respective output produced by conventional fossil energy sources (Buck, Keulen, Bosselaar, & Gerlagh, 2010). Adopting the EU's methodology, it is now measured in terms of the share of renewable energy on the gross final consumption (ibid). Renewable Energy monitoring Protocol categorizes under renewable energy sources the six following: solar, wind, hydropower, environmental heat (geothermal and hypothermal energy), ground heat (geothermal energy and energy stored in the ground), and biomass.

Energy savings

At the moment the Netherlands express the energy savings target in terms of final consumption compared to a fixed reference year (static) (Buck et al., 2010). However, since the European Commission includes in the proposal a target in primary energy use, this possibility was also explored.

In final terms: The gross final consumption includes the direct supply of electricity and heat to end users, and the supply of fuels for heating (e.g. in boilers) and for transport including biofuels and biomass. The fuel consumption by combined heat and power (CHP) is not part of the gross final consumption; however, the production of heat and electricity by CHP, when it is not sold to other users, is considered part of the gross final consumption (Daniels et al., 2014). In addition, gross final consumption calculations include: the gross production of RES; the own electricity consumption of power plants; and the distribution losses of various energy carriers.

In primary terms: The primary consumption calculation includes the gross final consumption plus the conversion losses at supply sectors (refineries, power plants) and CHPs (Daniëls, Koelemeijer, & Smekens, 2014).For renewable sources such as wind, solar and hydropower the electricity produced counts as a primary energy input (ibid).

2.2 Cost effectiveness

In the evaluation of policy goals and policy instruments one criterion that is widely used, is cost-effectiveness (Gorlach, 2013;Harmsen, 2014). When aiming towards a target, the question that comes naturally is: What measures/options are needed and at what costs? Cost effectiveness bridges this twofold question by providing a relation among the costs and the effects of the measures available in the portfolio of the decision maker (Gorlach, 2013). Thus, it provides insights on how the desired target can be achieved in the least cost for society[7] (Del Río & Cerdá, 2014). Furthermore, cost effectiveness of a technology is often linked to a target definition. Hence, targets should be linked to the overarching policy objectives, since otherwise wrong incentives could be sent when policy makers focus on cost effective target achievement (Broc, 2014).

The indicator used to express cost-effectiveness into something tangible is the specific costs that derive from the implementation of the measure in relation to the objective of the policy. In CO_2 abatement studies, the Specific costs (C_{spec}) can be described as the costs per unit of CO_2 emissions saved and they are defined by the following formula (Blok, 2007):

$$\text{Cspec} = \frac{a \times I + C - B}{\Delta CO_2}$$

, where:

- $\alpha = \frac{r}{1-(1+r)^{-L}}$ is the capital recovery factor or annuity factor; r is the discount rate and L the lifetime of the technology or the project
- I represent the annual investment costs
- C represents the annual operational and maintenance costs
- B represents the annual benefits
- and ΔCO_2 represent the amount of emission avoided

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[7] Cost effectiveness can be used to address the evaluation of a target from a private perspective (i.e. firms), but this case is out of the scope of this study.

In case specific costs are referring to energy savings the aforementioned formula is altered by using in the denominator ΔE instead of ΔCO_2, which reflects the energy saved.

When cost-effectiveness is used to define a policy measure, can be further described by two variants, namely static and dynamic efficiency (Gorlach, 2013). Static efficiency translates the term cost effectiveness as the fulfilment of the policy objective in the least cost by taking into account emission reductions through the economy. Given that, it is assumed that policy instruments are applied for all emission sources, and polluters are treated uniformly with regard to the motivation they get to further reduce their emissions (e.g. through a carbon price, a carbon tax, etc.). Dynamic efficiency[8] also aims in minimizing the costs of reducing emissions; however, it is assessed for a period of time and not a specific target year. The interaction among agents is considered as a dynamic process of trade-offs. The main goal of dynamic efficiency approach is to identify and promote ways that incentivize the innovation and diffusion of low carbon technologies (ibid).

2.3 Shadow prices – Marginal costs

In linear optimization shadow prices reflect the rate of change of the objective function if the right hand side value of a constraint is changed by 1 unit. Thus, a positive shadow price implies an increase in the objective function's value, while a negative shadow price suggests a decrease of the objective function. When constraints are not binding, this results in shadow prices equal to zero (Bisschop, 2012b).

In environmental studies, a shadow price when it is linked with abatement strategies reflects the marginal willingness of society to pay in order to avoid 1 unit (e.g. CO_{2eq}) of the target substance being released in the atmosphere (Sathaye, Norgaard, & Howarth, 1993). Similarly, when it refers to energy related objectives, it reflects societies' willingness to pay in order to achieve something desirable (e.g. costs per 1 unit (e.g. GJ) of additional renewable output or energy savings) (ibid).

Policies' objectives are associated with shadow prices when the former are binding for the system (Mandell, 2013). For example, when an emission cap is applied it will result to a shadow price derived by the calculation of the Lagrange multiplier in the linear program (Pfulger, 2013).Those shadow prices therefore can be regarded as the marginal costs to achieve the objective set. It is argued that cost effective policy is in need to equally spread the marginal costs of its objective across the overarching economy ("equinarginality principle") (Del Río & Cerdá, 2014; Söderholm, 2012) However, this would be most likely, the case in a well functioning market setting (i.e. competitive markets) (Dreze & Stern, 1990). Nevertheless, marginal costs can act as "price signals" for the assistance to achieve the targets set in the least cost for society. These signals could be a carbon tax of a CO_2 price in a cap and trade scheme (e.g. a strong price signal in carbon price can incentivise the development and deployment of low carbon technologies) (World Economic Forum, 2015); or a support mechanism for energy objectives (e.g. like the tradable white and green certificates which support energy efficiency and renewable sources in electricity generation sector) (Del Río & Cerdá, 2014). Thus, the way marginal costs are strongly linked with static efficiency as described earlier in the text.

2.4 Model description

2.4.1 AIMMS

OPERA is a complex optimisation model, which was built within the mathematical optimization platform "AIMMS" (Advanced Interactive Multidimensional Modeling System). AIMMS is a

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[8] Dynamic efficiency is briefly described although is out of the scope of this study.

mathematical modeling tool consisting of a programming language, a graphical user interface (GUI) for better communication of the outcomes, and links to numerical solvers such as Gurobi, CPLEX etc. (Bisschop, 2012a).

In brief, AIMMS adheres to the basic guidelines of mathematical optimization, meaning that it uses parameters, variables, constraints and the objective function. For enabling the easier and coherent implementation of the above, as well as the data customization and update, it includes features such as sets, subsets, and indices, which allow interconnections between the elements of the model. The user can modify all the elements consisted in the model through the software's user friendly interface by using the "Model Explorer" tool option (Roelofs & Bisschop, 2013).

2.4.2 OPERA tool

The model applies an integral optimization algorithm to arrive at the cost-effective mix of technical measures-options, and takes into account the many ways in which different parts of the energy system interact. The selection of the optimum technology mix, is realized based upon an elaborate database which includes technology factsheets, as well as data on energy and resource prices, demand for energy services, emission factors of energy carriers, emission constraints, and resource availability (Welle et al., 2014). Applied to the Dutch energy system, OPERA obtains a variety of scenario data from the Dutch Reference Outlook and National Energy Outlook where the baseline scenario[9] is based on (ibid). Provided the baseline scenario, OPERA accounts for the demand in terms of energy (e.g. electricity, space heating, transport, resource availability etc.) as well as in terms of activity (e.g. passenger kilometres, ammonia production etc.), that must be fulfilled. In addition, the baseline is used to compare its results with alternative scenarios. For example, the results account for the impact of increasing shares of intermittent renewable energy source on infrastructure, energy storage and other ways to match demand and supply at each moment. A flowchart of the general function of the model is shown in Figure 2. The model starts with a background (baseline) scenario. For this baseline the model has a complete description of the energy system including activity (i.e. output), capacities and operation hours of technologies. A run with the model will result in an alternative configuration of the energy system, with other capacities and operational characteristics of technologies, and possibly including technologies that do not play a role at all in the baseline scenario. Costs, energy use and emissions will also be different. The extent to which the alternative configuration differs from the baseline depends on -among others- the constraints applied with regard to for example emission ceilings, maximum energy use, and/or the required amount of renewable energy. Thus, the provided solution includes the cost optimal package of options with the respective emissions, which meet the targets and the boundary conditions of the system.

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[9] The baseline scenario is represented by a technology portfolio based on the National Energy Outlook Modelling System as well as on the complete energy balances of the Netherlands as reported in MONIT (www.monitweb.nl) (Daniëls, Seebregts, et al., 2014).

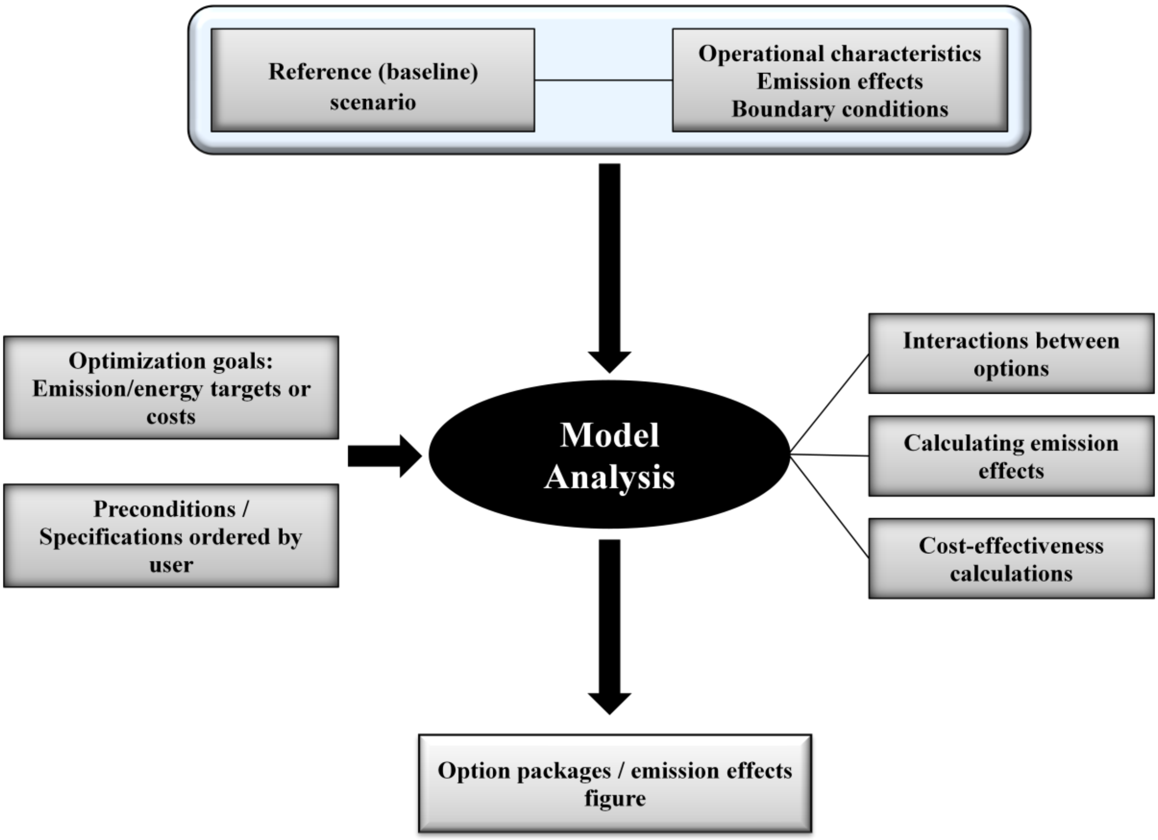

Figure 2: Overview of the general functions of the model

2.4.3 Objective function

The optimization algorithm is based on the minimization of the objective function which is the calculation of total system costs according to the equation:

$$\begin{aligned}
&\textbf{\textit{Total System Costs}}\\
&= \sum_{cj,d}\Bigg[\textbf{\textit{Emission charges}}\\
&\times \Bigg(\sum_{o,v,cj}\sum_{e}\textbf{\textit{Energy carrier Activity}} \times \textbf{\textit{E.F}}_{\textbf{\textit{national}}} \times (\mathbf{1} - \textbf{\textit{Emission Correction}})\\
&- \sum_{o,v,cj}\Big(\textbf{\textit{Activity}}_{\textbf{\textit{target year}}} \times (\textbf{\textit{Non Energy Emission factor}} + \textbf{\textit{E.F.}})\Big)\Bigg)\\
&+ \sum_{rg,o,v,cj}\textbf{\textit{Activity}} \times \textbf{\textit{Total variable costs}}\\
&+ \sum_{o,v,e,cj}\textbf{\textit{Energy carrier Activity}} \times \textbf{\textit{Energy prices}}\\
&+ \sum_{rg,o,v,cj}\textbf{\textit{Capacity}}_{\textbf{\textit{target year}}} \times \textbf{\textit{Capital costs}} + \sum_{rg,o,v,cj}\textbf{\textit{Capacity}}_{\textbf{\textit{target year}}} \times \boldsymbol{O}\&M\ \textit{fixed costs}\\
&- \sum_{d,cj}\textbf{\textit{Free Allowances}} \times \textbf{\textit{Emission charges}}\Bigg]
\end{aligned}$$

Several parameters and indices are introduced in the equation above, which are explained in the following table (Table 2).

Table 2: Explanation of elements included in the objective function

Element	Explanation
cj	Target year
d	Target substance (e.g. CO_2, CH_4, etc.)
o	Options/technologies
v	Variants of options
rg	Regions (parts of the energy system that share similar characteristics)
Emission charges	Price of target substance (e.g. CO_2 price in EU-ETS)
Free Allowances	Emission credits under EU-ETS for the Netherlands which are not been auctioned
$E.F._{national}$	Emission factor
Emission Correction	Emission correction factor due to unoxidised carbon in fuel combustion

The objective function subjects to a number of constraints which may apply differently according to user's preferences. The main constraints are:

- Energy demand must not exceed energy supply
- GHG emissions must meet the user's defined boundaries
- The resource consumption (e.g. biomass) must respect the levels defined by the user
- Solar, wind, nuclear energy must not exceed the maximum production defined by the user, and by the characteristics of the system
- The system always must have adequate capacity to satisfy peak demands for heat and electricity; adequate electricity generation capacity for flexibility in meeting varying demand; and enough electricity capacity to meet demand when intermittent electricity is scarce.
- Must satisfy all the constraints defined by the user through the scenario specifications (e.g. primary/final energy ceilings, renewable energy penetration etc.).

Determinants of costs

The determinants of costs as determined by the objective function can be divided into three categories:

- Technology characteristics (e.g. capital costs, O&M costs etc.),
- Fuel characteristics (e.g. energy prices, emission factors)
- The control variables calculated in the model solution in order to meet the requirements imposed by the user (e.g. activity, energy carrier activity, capacity).

The cost calculation follows the national cost methodology in accordance with the environmental costs (Daniels et al., 2014). This is the balance of direct costs and benefits from a social cost perspective. The costs include investments, which at a social discount rate (4%) are translated into annual costs; operating and maintenance costs (O&M); and benefits from the avoided energy use at world market prices. In addition, the net purchase or sale of rights in the European Emission Trading System (EU ETS) is being part of the costs and the benefits respectively.

2.4.4 Energy system representation

In OPERA the energy system of the Netherlands is represented by both the supply and demand side, embracing the energy system's infrastructure and networks as well. Below, the energy supply sectors that are included in OPERA are presented (Daniëls, Seebregts, et al., 2014) (see also Figure 3):

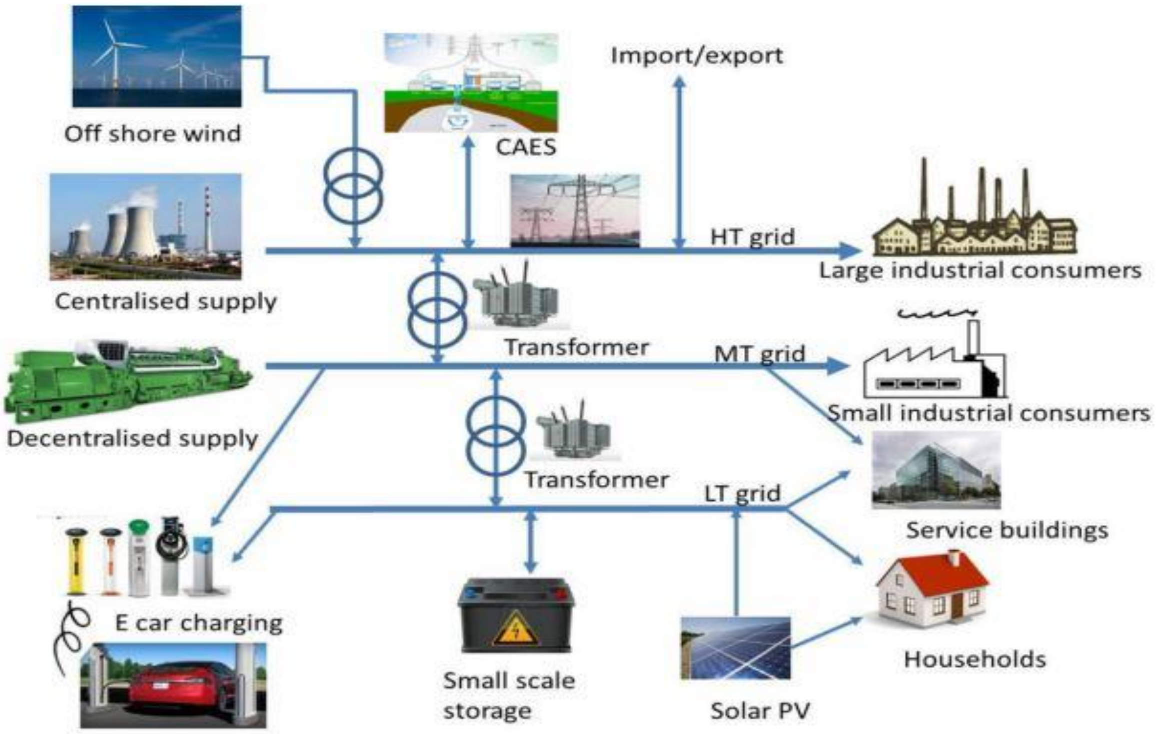

Figure 3: Schematic representation of energy system as included in OPERA (Welle et al., 2014)**.**

- Electricity: both centralised and decentralised technology are represented, either fossil fuel or renewable-based;
- Gas: both natural gas as well as biomass-based gas are included, both potentially[10] combined with Carbon Capture and Storage (CCS);
- Heat : both centralised and decentralised technology, by both fossil fuel and renewable energy sources;
- Hydrogen: centralised and decentralised based on fossil fuels (either with or without CCS), renewables and electricity;
- Grids: including various levels (i.e. high/medium/low voltage grids, high/medium/low pressure gas grids etc.) and storage options;
- Energy conversion: refineries, liquid fuels from fossil and biomass (without and with CCS) (Daniëls, Seebregts, et al., 2014).

2.4.5 Technology Representation

The model database that corresponds to energy related technologies describes the actual energy system on the supply and the demand side, as well as alternative, current and future, scenarios. The tighter the emission targets get, the more the alternative technologies are favoured in future scenarios (Daniëls, Seebregts, et al., 2014). Substitutions of technologies are depending on the limiting constraints (e.g. emission cap, renewable energy targets etc.); meaning that technologies which fulfil the same function, will compete each other in the context of cost-effectiveness in meeting the targets. However, they could favour each other as well. For example, implementation of a lot of intermittent renewable energy in order to meet renewable energy targets, may favour the use of storage and peak load technologies (ibid). For the demand side, the model database contains at least one alternative

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[10] CCS can be applied –for example- in the process of hydrogen production from natural gas or biogas.

technology for each function. However, in most of the cases a small package of options is present to fulfil the demand side functionalities, calling into play different primary energy carriers (e.g. fossil, biomass, solar, etc.). Thus, possible biases towards primary energy carriers are avoided, since the model can choose from a variety of options the most optimal solution (Welle et al., 2014). Regarding the system needs, several technologies can come with a number of variants, which represent different intensities at which an option can be applied. For example, when the system requirements demand so, technologies can be present in the technology mix with 1, 2, 3 or 4 variants (ibid).

Emission reduction technologies in the non-ETS sectors

Decarbonisation of the non-ETS part of the energy system has to be realized by 2030 supported by the various sectors of the energy system; built environment (residential and services), energy, industry, agriculture, and transport sector. Within these sectors a broad selection of technology options can be assessed by the model in order to satisfy the increasing emission constraints of the non-ETS part of the system (Welle et al., 2014).

In the built environment and the non-ETS industry sectors energy demand is driven by the heat demand[11], mainly for space heating; and the electricity demand mainly for lighting and appliances (Tigchelaar, Daniels, & Menkveld, 2011). The available pathways, deriving from these sectors, to reduce emissions in the non-ETS sub-system include (Smekens, Kroon, & Plomp, 2011):

- Insulation in order to reduce heat demand (wall/roof/floor insulation etc.)
- More efficient heating systems[12]
- Bio-based gas (green gas)
- Heat storage
- Renewable heating (heat pumps, geothermal energy, etc.)
- Heat networks improvement

In the agriculture sector, energy consumption is driven mainly by the demand for heating in greenhouses as well as by the electricity demand for lighting absorption. In agriculture and especially in greenhouses, CHPs (using natural gas) are of high importance since they are responsible of providing the required heat and electricity. Under the emission reduction pathways there are options that can substitute or restrict the use of CHPs (Smekens et al., 2011):

- Insulation to reduce heat demand
- Deep geothermal energy
- Bio-based gas (green gas)
- Heat storage in aquifers[13]

In the transport sector, the energy demand is driven by the need of transportation of people or goods. Oil is the dominant energy carrier to meet the demand of this sector. Several pathways aim in reducing its significance by lesser demand (either due to structure effect or activity effect)[14], and by substitution of oil with:

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[11] Heat demand is provided mostly by natural gas oriented systems.

[12] Hybrid configurations (e.g. hybrid heat pumps with a back-up boiler for peak demand) are also an option in reducing emissions.

[13] It is usually combined with heat pumps.

[14] Structural effect refers to the substitution of current vehicles with more efficient ones; Activity effect refers to the reduction of the demand.

- Biofuels
- Natural gas or green gas
- Electricity (plug in cars, all electric vehicles)
- Hydrogen (fuel cell vehicles)

2.4.6 Baseline scenario

The baseline scenario that is included in the model is based on a fixed reference year projection grounded on the National Energy Outlook[15] (NEV) 2014. The NEV analyzes the current state as well as the future developments of the Dutch energy system for the period 2013-2030 using as a basis two "policy variants" (Hekkenberg & Verdonk, 2015); those in effect as of May 2014 (i.e. referred as "with existing measures" (WEM)) and those announced to be implemented in the future and were considered specific enough to process (i.e. referred as "with additional measures" (WAM)) (Hekkenberg & Verdonk, 2015). For this period economy demonstrates a growth at around 30%, while energy consumption appears to be constant, and GHG emissions to have been reduced by 17%. An overview of the baseline scenario is presented in Table 3.

Table 3: Overview of National Energy Outlook for the Netherlands for the period 2000-2030 (Hekkenberg & Verdonk, 2015).

	2000	2020		2030	
		WEM	WAM	WEM	WAM
Oil price (2013US$/barrel)	37	127		143	
Gas price (€cent/m^3)	15	30		32	
Coal price (€/tonne)	50	89		94	
CO_2 price (Euro/tonne)	n.a	9	12	15	21
Final energy consumption (PJ)	2245	2163	2132	2193	2161
Annual rate of energy efficiency improvement	n.a.	1.0	1.2	0.7	0.7
Share of RE in final consumption (%)	1.4	10.6	12.4	20	20
GHG emissions (MtonCO$_{2eq}$)	213	183	176	161	158

2.5 Research Framework

The research was structured based on four sub-questions, which facilitate the answering of the main research question. The order and the nature of the sub-questions can be regarded as a step by step procedure to reach to that end; starting from a broader picture of the interactions among targets, and reaching to more specific technology-target interactions. Before starting connecting the pieces, the set up of the analysis needs to be established.

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[15] National Energy Outlook is conducted every year by ECN together with PBL, CBS and RVO.nl in request of the Ministry of Economic Affairs and projects future developments in the Dutch energy system.

The procedure to be followed involves modelling of the energy system of the Netherlands. For this purpose, the OPERA optimisation tool was used. The understanding of the model features and its functionality is a crucial part of the research in order to be able to evaluate the model outcomes, the system interactions as well as to interfere in the code if needed. The initial approach to answer the research questions involved the development and testing of a generic and automated method, in order to approximate the effects[16], the costs and the cost effectiveness[17] of individual measures towards the relevant energy and emissions targets, as compared to a baseline. The development of the process to be added in the original code of the model was performed in the AIMMS code. Unfortunately, the testing of this method failed to provide with reliable results, while further extensive testing aiming to identify where exactly the weaknesses of the code were lying, would pose a threat in completing this research on time. However, the whole process developed will be provided to the reader in the start of the methods section mainly because it gives insights on the subject of the research and justifies, to a certain extent, the format of the research as it is at the moment. Furthermore, in the "limitations of the research" section, a brief reference on the original ideas of the research will be provided, as well as what did go wrong on the validation of the process.

Therefore, the methods presented in the next section are based on the analysis of the data derived by the main version of the model. The preparation of the model starts with the development of the scenarios to be used in this study. Determining the assumptions and boundaries of the scenarios is an essential part of the study. The scenarios must be consisted regarding characteristics and the availability of different technologies as well as policy measures in both energy use and emission targets (Lehtilä & Pirilä, 1996). The scenarios included in this study represent different non-ETS emission reduction targets, as well as energy targets with respect to renewable energy use, primary energy use and final energy use. Defining the accounting methods for the main elements of each target is what makes a target measurable and easier to be monitored and evaluated. It also enhances the transparency of the outcomes. After establishing the scenarios, they are applied in the model runs in order to provide us with the necessary data for the answering of the research questions. The procedure that just described -from scenario development to model runs- can be regarded as the set up of the approach. Thereafter, four steps (one for each research sub question) follow, which lead to the main results.

Step 1: *"What is the effect of the different targets on the shadow prices and how they interact with emission targets?"*

The answering of this question provides us with an overview of the different scenarios, and how the different targets interact with each other. Targets are perceived by the model as constraints (e.g. non-ETS emission constraint), which limit the degrees of freedom of the system. This relation results in shadow prices for each constraint imposed to the system; reflecting the increase in costs when the new optimal solution is reached. The way how shadow prices develop when additional energy targets are applied to the system gives insights on the interactions occurring with the non-ETS targets, as well as with the system in total. The total system costs are calculated by the objective function after optimizing all the determinants of the equation based on a least cost calculation.

Step 2: *"What are the main substitutions within the scenarios, and how different technologies contribute to the objectives of the various scenarios?"*

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[16] As effects of a measure are considered to be the upshots that can be directly attributed to its implementation (e.g. emission effects, energy effects) (Chicco & Stephenson, 2012).

[17] Cost effectiveness calculations made use of the formula provided in section 2.2

The answering of the second sub-question gives an overview of the technologies assessed and how they interact with the different targets. This step consists of two parts. In the first part we examine the expected influence that the technologies have towards the targets, based on the technology representation of non-ETS sectors in the model, the functionality they fulfil, and their characteristics. Our main focus was on the non-ETS sectors since the targets are explicitly dealing with the non-ETS emission reductions. The counteracting technologies that fulfill a particular functionality within a sector are usually predefined in the model. The second part consists of the evaluation of the influence that technologies pose to the targets based on the model results. Then, the analysis is divided in expected and unexpected outcomes. Through this comparison, the additional information obtained by the model outcomes will be evaluated in order to give insights on both the interactions of technologies with the underlying targets, as well as on whether possible flaws in the model exist.

Step 3: "*How do shadow prices determine the cost effective technology mix?"*

The answering of the third sub-question arrives by using shadow prices of emission constraints as a proxy to draw an approximation of the cost effectiveness of the technologies under different targets. The shadow prices derived by the energy targets of each scenario are expected to play a role on the development of emission shadow prices as well. Thus, the assessment of the development of the shadow prices under the different scenarios will determine to what extent cost effectiveness is changing regarding each technology. The outcomes of this step will give insights on how the technology mix can be determined.

Step 4: *"What is the ranking of the core technologies based on their cost effectiveness among the different targets?"*

The final sub-question is reflecting all the results of the preceding steps. Using shadow prices as a proxy for cost effectiveness, the ranking of technologies is provided showing their scoring under the different scenarios.

The integration of the outcomes of these steps aims to provide us with insights on what extent the interactions noticed affect the scoring of technologies in each scenario, and thus answering the main research question.

All the aforementioned steps provide the framework that was followed for the conduction of this research. All the model results derive after the evaluation of the conditions imposed to the system by the user, as compared to a baseline. The baseline scenario is to a great extent the determinant of the outcomes, as with a different baseline the results would be completely different.

3 Chapter: Methods

In this section, the methods followed in order to provide answers to the main research question and the sub-questions will be analysed. As mentioned in the previous section, first, the process developed will be described. Thereafter the methods of the steps followed will be presented.

3.1 Process development

The general purpose of the process described in this section is to establish the contribution of individual technologies to emission reductions, reduction of energy use and so on. At this point, an illustration of the process is presented (Figure 4). Next, a concise description of the code will follow, aiming to give an impression to the reader of the functions undertaken in the code.

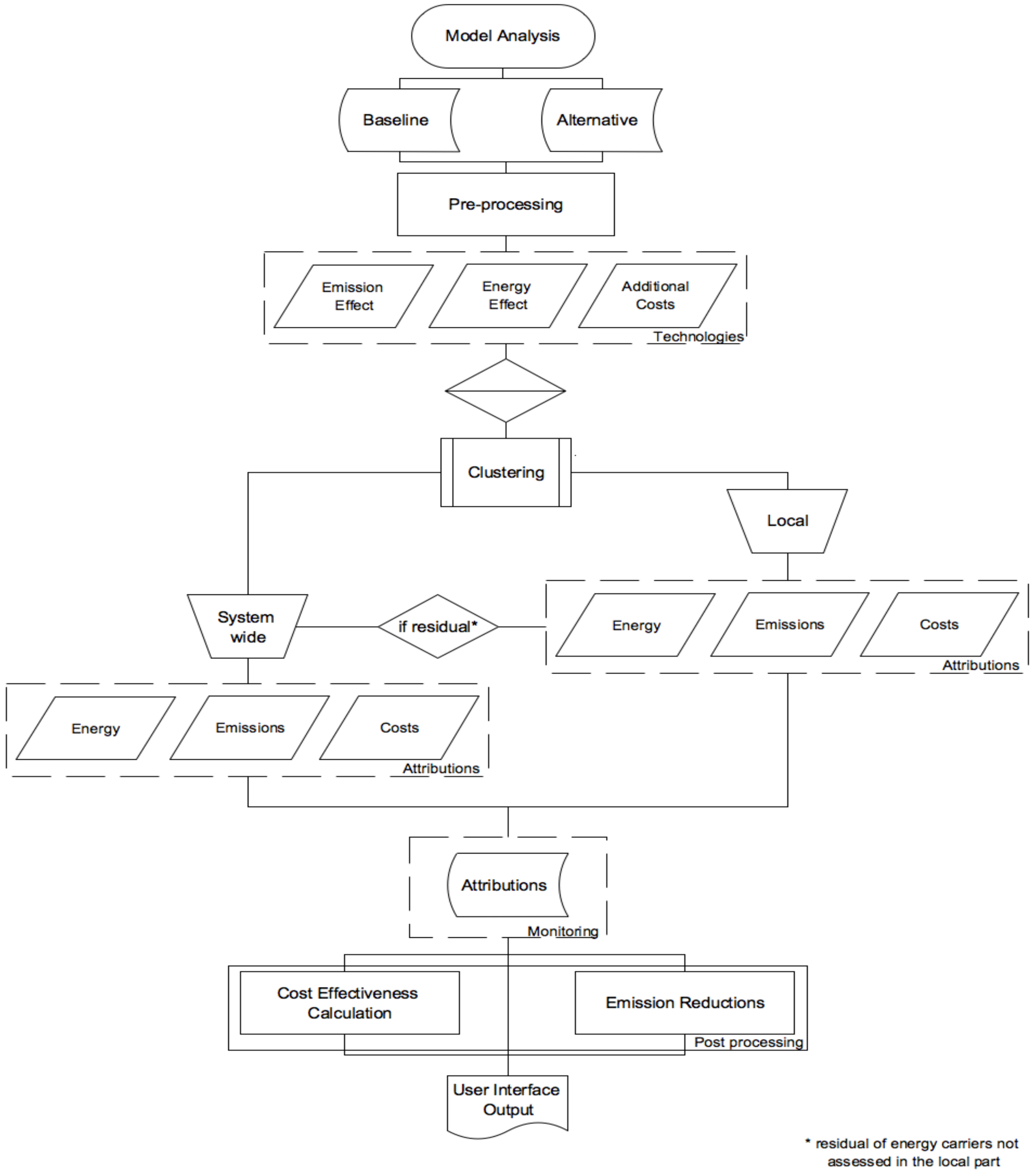

Figure 4: Flowchart of the process developed [for the explanation of the symbols used, see Appendix B]

Basic principle of the process

All the basic model results only comprise the activity of all kinds of technologies including their energy use and emissions, but not the reduction of emissions. The process to be described applies a specific algorithm that attributes the avoided emissions, energy use and costs of (conventional) reference technologies in the baseline to their alternative counterparts in the model results. The concept behind the algorithm is that such effects can be attributed to options by comparing them with the (reference) technologies that are involved in the same activity, including the production of secondary energy carriers. Table 4 contains a list of the activities and the units that are used for comparison. For example, if in the baseline a conventional boiler meets the demand for heat in households, and in the model results this is (partly) substituted by solar boiler, the emission effects that can be attributed to the latter are based on this particular substitution. Some of the relevant substitutions are mainly local affairs, or otherwise confined to specific subsystems of the energy system. An example is meeting the demand for heat, in which substitutions within a sector are dominant. But other substitutions have a system wide scope, such as those in electricity production.

Table 4: List of activities included in the model along with their units

Activities	Units
Ammonia (NH_3) production	*Mton*
Ethane (C_2H_6) production	*Mton*
Passenger transport	*Billion (bn) passenger km*
Freight transport	*Billion (bn) freight km*
Passenger transport (Electric)	*Billion (bn) passenger km*
Passenger transport (Plug In)	*Billion (bn) passenger km*
Non-road mobile machinery (MWT)	*PJ*
Other GHGs CH_4	*Mton*
Other GHGs N_2O	*Mton*
Other GHGs F-gasses	*Mton*
Other GHGs F-gasses under ETS	*Mton*
Other GHGs F-gasses non-ETS	*Mton*
Other GHGs CH_4 under ETS	*Mton*
Other GHGs CH_4 non-ETS	*Mton*
Other GHGs N_2O under ETS	*Mton*
Other GHGs N_2O non-ETS	*Mton*
Biofuels	*PJ*
Biofuels Feedstock	*PJ*
Biogas	*PJ*
Heat	*PJ*
Hydrogen	*PJ*
Electricity	*PJ*
CO_2 flow	*Mton*

The process developed to support the purpose of this research can be divided in four parts for reasons of better illustration of its function. Those parts include:

- a) the pre-processing part before the “for” loop which contains the initial calculations of parameters
- a “for” loop which runs through all the relevant activities (both primary and secondary) calculating the energy, emission and cost effects, including a

    - b) a local focused “for” loop which calculates the relevant parameters for several sub systems of the Dutch energy system
    - c) a system-wide part which deals with system-wide substitutions of technologies
- d) The post processing calculations which generates parameters for illustration and analysis purposes.

a) *Pre-processing*

The process starts by defining which technology options are active in the model solution. This is determined by creating a set[18] which includes those technology options that demonstrate an increase or a decrease in their activity as compared to the baseline scenario. The pre-processing part of the approximation is responsible to perform the initial calculations based on the basic model results. These necessary calculations include: the determination of the emission effect of individual options by taking into account the activity they demonstrate multiplied by the emission factors of each target substance (i.e. CO_2, CH_4, N_2O etc.); the calculation of the energy effect of individual options by taking into account the change in activity of energy carriers throughout the set of the active options; and the estimation of the direct additional costs, accounting for the variable costs per unit of additional activity, the energy prices per unit of additional energy carrier’s activity, and the capital and O&M costs per unit of additional capacity of the options in the solution.

Before entering the loop section of the process, a new element is introduced which links sectors with the relevant options and the respective energy carriers by sorting them into clusters. The options belonging in each cluster can be either competitive or complementary with each other.

The “for” loop over the activities/energy carriers

The loop over the activities and energy carriers is introduced to the body of the procedure in order to assess the process specific effects. More specifically, there are two kinds of specific effects, namely: the local (sub-system) effects and the system-wide (generic) effects. Demand and supply of heat as well as of hydrogen for example, are treated by the model locally because substitutions usually take place within the same sector. Thus, energy carriers involved in such processes of the energy system, they first being assessed in the context of their energy, emission and cost effects inside the local part of the loop. Next, if a residual of another energy carrier exists, then it is being treated by the generic part of the loop. Such activities for example are the electricity demand and supply related ones. The loop runs several calculations through all the elements of the “**activity**” set[19].

b) *Sub-system (local) Loop*

After the first round of calculations within the system’s boundaries, a shift towards a more local approach is needed in order to attribute energy, emission, and cost effects first to the options that are linked for having the same functionality within a sector. For this purpose the set “***clusters***” is modified to account all the local based processes along with the relevant options and the respective carriers. For example, the heat demand of households can be considered as functionality of a sector; and the options that can fulfil this demand of heat are linked/coupled within the *cluster = heat demand of households.* Usually, options that are linked to a specific cluster are mutually exclusive and

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[18] This set of the active options is divided in sub-sets throughout the process, where options with similar characteristics are grouped together for more specific calculations. In this set all kinds of technologies are included both renewable and fossil based.

[19] In this set carriers and activities such as NH_3, C_2H_6, passenger km, freight km, biogas, Hydrogen, electricity, heat, etc. are included as shown in Table 4.

those that provide the same function, are competitors (e.g. increase in activity of heat pumps or thermal insulation, leads to decrease in the activity of boilers). Thereafter, the local loop runs through all the discussed elements, calculating the attribution of the energy, emission, and cost effects to the options of the optimal technology mix.

Take for example an amount of heat that needs to be met in a household. In the baseline the heat demand was being fulfilled by a gas boiler. After the model run, the resulted solution indicated that the same heat demand will be met by an electric heat pump. Running this procedure, both these technologies are assessed within the cluster "heat demand for households" and the amount of heat is eliminated since both technologies produce the same heat. However, the inputs in these technologies are not the same. Initially there was gas, while afterwards there was electricity. Running these facts through the local loop the process results the amount of gas that was saved along the emission reduction that can be attributed to the heat pump because of the saved fossil fuel. On the other hand, the electricity increase cannot be attributed in the local system since it is not generated within the local boundaries. Thus, it is being transferred for assessment to the generic part of the loop.

c) ***System-wide (generic) substitutions***

In this part of the loop, all the system wide substitutions are being evaluated and assessed concerning their energy, emission and cost effects. Initially, the reference supply options which are not demonstrating an increase in activity compared to their baseline values will be assessed regarding their energy effects. Since these options have less (or at least the same) activity as in the baseline, there is the need to attribute this reduction to alternative options that substituted this amount of activity in the alternative scenario. Then, the attribution of emissions and costs will be done based on the energy effect as in the pre-processing part of the procedure.

At this point, a new set is created within the process which includes all the options that were not assessed within the local part as well as the options which have unattributed effects remaining in the local section. Having calculated the share of energy for the baseline supply options, similar approach as in the local loop is followed for the attribution of the energy, emissions, and cost effects to the rest options being part of the optimal technology mix (i.e. the new set). The calculations used are attributing the respective effects to the options and energy carriers of the new set by deducting the amount of the effects corresponding to the baseline supply options from the residual part (as derived from the last step in the local part of the loop).

To give an example on how the generic part of the loop works, imagine the case that more electricity is generated by wind energy in the alternative scenario. As a consequence there is less electricity generation by the baseline options (i.e. coal based, gas based, etc.). The generic part of the loop calculates the overall emission decrease and then attributes it onto the alternative electricity generation carriers and options (such as wind farms).

Furthermore, several parameters are introduced to the code for balancing and monitoring purposes. The reason is that this procedure is designed for attributing the changes to individual technologies and not altering the total change (i.e. under no circumstances the total amount of energy use, emissions, and costs should change). Therefore, these parameters allow for monitoring the proper functionality of the procedure. Mind that, the attribution of changes is based on the functionality of technologies, i.e. physical quantities produced or consumed, including secondary energy carriers (electricity, heat, hydrogen). In the end of the procedure all functionalities should be eliminated, by translating them into the effects on primary energy carriers.

d) ***Post processing***

The post processing part constitutes the part where a set of algorithms is introduced mainly for monitoring purposes of the whole process, as well as for presenting very specific results that are of interest to visualise them through the graphical user interface feature of AIMMS. The reason that these monitoring actions were put outside the loop is for getting the overall results deriving from the generation of each step of the loop. Such algorithms store results for cost effectiveness of options, emission reduction per option, energy flux and net energy effect etc. For monitoring purposes, two kinds of algorithms were created. Regarding energy, emissions, and costs they calculate the effects per sector[20] and category[21] of options. This introduction is straight forward and it is based on the results of the loop but it concentrates the results in groups (sectors, categories) by complying with the respective restrictions posed by the user. Namely, the restrictions are simply two binary parameters that correlate options to sectors and categories respectively, in order each time the results to be stored to the associated sectors and categories.

3.2 Methodology flowchart

The course of the methodological steps followed is presented in the following flowchart Figure 5. First, the set up of the conditions under which the required data were retrieved by the model consists of the development of the scenarios based on several assumptions regarding their objectives. Thereafter, the scenarios are incorporated in the model runs providing the required data. Step 1-4 consist the followed methodological steps in order to reach in answering the research questions.

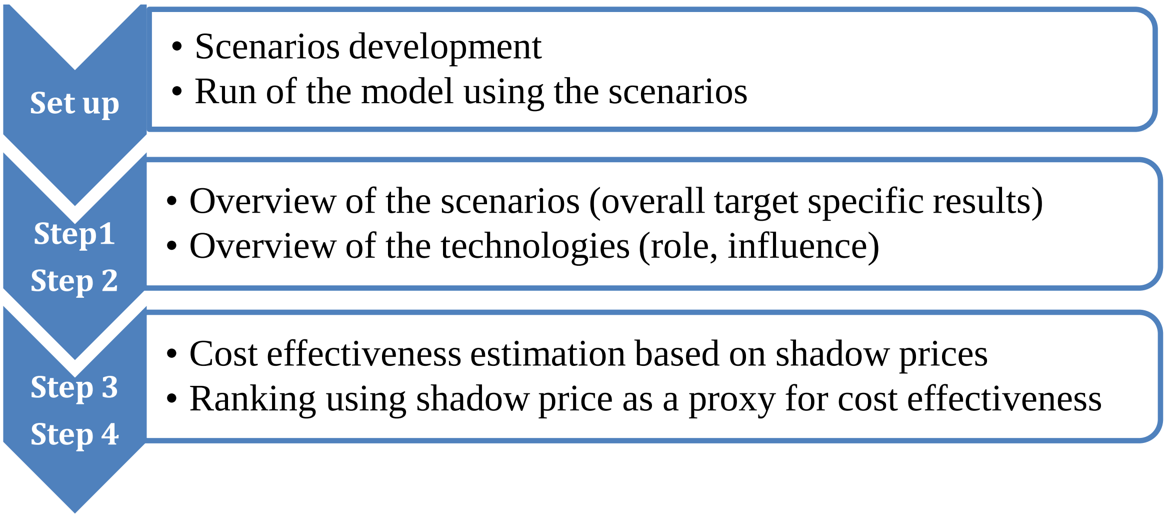

Figure 5: Methodology flow chart

3.3 Development of scenarios

In this section, the characteristics and the concept behind the scenarios developed will be presented. Two types of scenarios were constructed: a single target (ST) scenario, where only non-ETS emission reduction targets are imposed to the system; and three multi-target (MT) scenarios consisted of both non-ETS targets and additional targets with regard the energy use (the various additional targets existing in each MT scenario represent different objectives/cases).

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[20] Sector refers to the energy system's sectors such as industry, agriculture, residential, etc.

[21] Category refers to options with similar service fulfilled or of the same characteristics (e.g. final electricity saving options, final heat saving options, fossil power plants, etc.).

Single target scenario (ST)

The single target scenario represents the case where only non-ETS CO_2 emission targets are imposed to the system. The way it is constructed, it takes into account emission levels defined by the user. For the purpose of this research we grounded the emission targets on the study by Daniels et al. (2014), where they explored possible non-ETS emission targets for the Netherlands in 2030 based on the European Commission's communication documents. Therefore, the selected range of non-ETS reductions starts from 28% and goes until 45% as compared to 2005 levels. The less ambitious emission ceiling corresponds to 89.1 Mton CO_{2eq}, while the most ambitious corresponds to 68.1 Mton CO_{2eq}. The ETS CO_2 price was set at 40 €/ton CO_2.

Renewable energy scenario (RE)

In the same study, conducted by Daniels et al., (2014) the potential renewable energy targets for the Netherlands beyond the 20% reached in the baseline scenario, were explored. In addition, according to the Impact Assessment of the EU, the Netherlands would come out with a share on renewable energy between 19% to 24% in order to lead to 40% GHG emission reductions (European Commission, 2014a). Furthermore, a 35% EU-wide target for the share of renewable was examined and the resulted share for the Netherlands ended up at 26% share on renewable energy. The renewable energy scenarios in this report consist of different shares based on the above arguments plus a more ambitious one. We end up with four different renewable energy scenarios with renewables share of respectively 22%, 24%, 26% and 28% (hereafter, referred as RE 22, 24, 26, 28). The RE scenario is a multi-target scenario where along with the renewable objectives also the same as in the ST scenario non-ETS emission reduction targets are applied. Again the ETS CO_2 price was set at 40 €/ton CO_2 for all respective targets.

Final consumption scenario (EE)

In the reference year projection that is used by the Commission in the Impact Assessment (2014), the projected gross final energy consumption for the Netherlands is 2500 PJ in 2030 (excluding non-energy consumption). Taking into account a reduction of 25%-30%, as proposed in the Communication document, the respective reduction would result in a range from 1875-1750 PJ final consumption. However, these goals proved to be out of range (Daniels et al., 2014). The gross final energy consumption in the National Energy Outlook 2014 was projected at 2193 PJ. In this study a reduction from that point was evaluated resulting in final energy consumption equal to 2125 PJ, 2075 PJ, and 2025 PJ. This values when compared to the European Commission's baseline correspond to 15%, 17%, and 19%. Hereafter, the final energy consumption savings will be referred to as EE 15, 17, 19. EE scenario is a multi-target scenario where along with the final energy saving objectives also the non-ETS targets are applied. Again, the ETS CO_2 price was set at 40 €/ton CO_2.

Primary energy scenario (EE prim)

According to the Primes 2013 reference projection on primary energy consumption for the Netherlands in 2030, the respective amount is 3361 PJ excluding non-energy consumption. Taking into account Commission's approximation on energy savings target (either in final or in primary terms) of 25-30%, results in consumption ceilings of: 2521 PJ, 2487 PJ, 2453 PJ, 2420 PJ, 2386 PJ, and 2353 PJ. Those ceilings were used in the construction of the EE prim scenario. Hereafter, the respective targets will be referred as EEprim 25, 26, 27, 28, 29, 30. EEprim scenario is a multi-target scenario where along with the primary energy objectives also CO_2 targets are applied. ETS CO_2 price was set at 40 €/ton CO_2.

Summing up, each MT scenario case is characterized by a series of non-ETS emission reduction targets that follow the same pathway as in the ST scenario, and one additional target. In the following table (Table 5), an overview of the targets RE, EE, and EEprim along with the energy prices used in the calculations and the ETS CO_2 price, are presented.

Table 5: Overview of scenarios' characteristics [Note: CO_2 prices for the ETS sector are common in all scenarios and based on the Impact Assessment of the European Commission for the targets of 2030 roadmap (European Commission, 2014a)].

		Energy Prices (€/GJ)			**CO_2 price (€/ton)**
Scenarios		Natural gas	Coal	Oil	
	Share of Renewables (%)				
RE 22	22	7.38	2.79	13.20	40
RE 24	24	7.38	2.79	13.20	40
RE 26	26	7.38	2.79	13.20	40
RE 28	28	7.38	2.79	13.20	40
	Ceiling on consumption (PJ)				
	Final				
EE 15	2125	7.38	2.79	13.20	40
EE 17	2075	7.38	2.79	13.20	40
EE 19	2025	7.38	2.79	13.20	40
	Primary				
EE25 prim	2521	7.38	2.79	13.20	40
EE26 prim	2487	7.38	2.79	13.20	40
EE27 prim	2453	7.38	2.79	13.20	40
EE28 prim	2420	7.38	2.79	13.20	40
EE29 prim	2386	7.38	2.79	13.20	40
EE30 prim	2353	7.38	2.79	13.20	40

3.4 Model runs

The developed scenarios are therefore ready to be used in the model runs. In this respect, we chose to address non-ETS targets alone using the single target scenario (ST), and the additional targets along with the non-ETS emission targets using the multi-target scenarios (MT). Hence, the model runs were planned as follows:

- Each scenario was run separately (i.e. ST, RE, EE, EE prim) for all the respective objectives.
- For the MT scenarios, the same format in non-ETS emission reductions, as in the ST scenario, was used; meaning the same 1Mton step by step process under the same upper and lower limits (i.e. 89.1 Mton CO_2 - 68.1 Mton CO_2).

3.4.1 Data collection

The data that were retrieved from the model in order to facilitate the analysis and eventually the answering of the research question are presented in this section. Willing to provide a method of evaluation of different targets we assessed the shadow prices. Next to the non-ETS emission target shadow prices, we introduced three new parameters which are being calculated by the model. These parameters represent the shadow prices deriving by the constraints imposed to the system as additional targets; meaning, by the energy conservation targets (i.e. the cost to the system if the energy savings in final or primary terms would increase by 1GJ), and by the renewable energy targets (i.e. the cost to the system if the renewable energy consumption would increase by 1GJ)[22]. Hereafter, these shadow prices will be referred as additional targets' shadow prices (ATsp), and the non-ETS emission shadow prices will be referred as emission targets' shadow prices (ETsp). In this way, each MT scenario case is characterized by two series of shadow prices; the additional target's shadow price developing throughout the different non-ETS targets; and the non-ETS emission target's shadow price deriving by the respective target. Likewise, the ST scenario is characterized only by ETsp for each emission target.

Additionally, total system costs for each scenario and objective were retrieved to complement the overall scenario related data. Next, the activity (i.e. output) of each technology present in the solution was drawn for each scenario and target. Activity is one of the main control variables of the model, which determines in a great extent the total system costs, especially in relation with the baseline activity of each particular technology. The outcomes of each scenario model run were assessed in the following way in order to provide the basis in answering the research questions.

3.5 Overview of the scenarios

In Table 6 the parameters used to address the interactions among the additional targets and the non-ETS emission reduction targets are demonstrated. Table 6 provides a short description on how these parameters can determine the relation among the non-ETS targets, and the additional ones of each scenario. Based on these interactions we formulated specific criteria, which determine the interactions occurring in the scenarios. Depending on the values of the ETsp and the ATsp, we ended up with five different criteria which are presented in section 4 and facilitate the analysis of the interactions within the scenarios. For better illustration, the collected data were plotted into graphs, as well as presented in a concentrated table. Furthermore, the non-binding mitigation potential was identified. For each scenario case, the highest non-ETS reduction target which corresponded in zero emission target shadow price, was characterized as the non-binding mitigation potential. The level of reductions as compared to the ST scenario assisted in getting a holistic view of the interactions. This part therefore, is used as basis for comparison between the different scenarios, and an introduction on the shadow price functionality.

Table 6: Parameters' effects used to draw specific criteria to assess the relation of emission and additional targets among the different scenarios

Total system costs (Tsc)	Emission target shadow price (ETsp)	Additional target shadow price (ATsp)
Total system costs are used in determining whether a scenario is more challenging than another. They reflect the change in the system's degrees of freedom to minimize costs.	Emission target's shadow price comparison among the ST and MT scenarios can determine the convergence or divergence of the additional target with the emission target (i.e. synergy or antagonism).	Additional target's shadow price development in relation with the ETsp throughout the ambitions of the emission targets can determine whether a multi-target scenario gets assisted by the emission targets to achieve the additional objective, or the additional objective ensures the achievement of the

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[22] The energy related shadow prices are expressed in €/GJ.

		emission target.

3.6 Overview of the technologies

Aim of this step of the analysis is to provide with an answer to the second sub-question, indicating the influence that the technologies under study pose to the different objectives of the MT scenarios. The identification of the technologies that were present in the solution of each scenario and they were associated with partial or complete substitutions in a sector suggested the option package which was examined. Thereafter, the methodology followed was divided in two parts. In the first part we formulated the expected influence of the options in the package towards the targets of each scenario, based on the functionality they serve and their characteristics. In particular, the influence on the non-ETS targets was examined; on the ETS targets (if applicable); on the renewable energy targets; on the final energy savings targets; and on the primary energy targets. This led to obtain an overview on the expected effects that the technologies demonstrate towards the targets.

In the second part, we determined the influence of the technologies towards the same targets as before, based on the model results. We retrieved data on the activity demonstrated by the technologies in each solution and plotted over the non-ETS emission reduction steps along with the activity showed in the ST scenario. This led to graphs, where the set of targets of a MT scenario was directly compared to the ST scenario. Having as point of comparison the point that the technology showed an increase in activity, the positive, negative or no effect of the technology to the additional targets was defined (hereafter for reasons of simplicity we will refer to this point as “introduction point” of the technology). If a technology was observed to have moved its introduction point towards the less ambitious non-ETS targets under the influence of a MT scenario, then it was associated with positive effect to the additional target. If the introduction point remained stable, then it had neutral effect, and if it moved towards the more ambitious non-ETS emission targets then the technology was associated with adverse effects to the additional target and its application was being driven by its contribution in emission reductions. Note that the activity of each technology consists of the aggregation of the output of the variants of an option (when applicable) in order to get the overall picture on the behavior of technologies.

These two parts provided a basis to juxtapose the expected behavior of technologies towards the targets, with the observed behavior of technologies based on the model outcomes. Next to the options package identified in the start, possible interactions with some technologies from the energy sector (under ETS) such as wind off shore and green gas from co-digestion were also identified.

3.7 Cost effectiveness estimation

This step aims to provide an answer to the third sub-question. We used the concept of shadow price to draw an approximation of the cost effectiveness of technologies. The advantage that we exploited in this step is that shadow prices do incorporate every change that was performed in the system with respect to costs (i.e. network, infrastructure, interactions within and among sectors etc.) and thus, it is being calculated by the model in a very detailed and precise way. For this step we assessed the variants of the technologies in order to add more detail in the analysis. Using the same model runs, we estimated the cost ranges of each technology as derived from the CO_2 calculations (the marginal abatement costs for different emission ceiling) and the changes in the deployment (i.e. activity) of options at two consecutive ceilings. For example, if at shadow prices between 50 euro/ton and 200 €/ton, an increase in the use of a specific option occurred, this increase corresponds with that range in marginal costs. An increase in activity might occur for more than two consecutive levels. Therefore, the associated increase in costs will represent a range of non-ETS targets. The range was determined by the level of the introduction point of a technology and the emission level that the technology reached its maximum activity and no further increase was noticed. The same approach was used to estimate the ranges of the energy costs as derived by the shadow prices of the additional targets. Thereafter, we calculated the averages of these cost ranges and examined their development, in order to show how shadow prices can determine under the respective assumptions the cost effectiveness of a technology.

3.8 Ranking of technologies

The answering of the fourth sub-question is being dealt by this step. A ranking of the assessed technologies is provided based on the calculated averages of the cost effectiveness ranges. After we have showed how the shadow prices approximate cost effectiveness of technologies, the results of the previous step were ranked using the rank function in excel, in order how technologies perform under different targets as compared to the rest technologies of the assessed set.

3.9 Limitations of the research

During the conduction of this research, several limitations factors were emerged, which bounded the outcomes of the study to a certain extent. The main limitations were related to the following subjects:

- The coarseness of time slices[23]. Four (4) time slices were selected for the model runs. Supply and demand patterns were filled by dividing the 8760 hours in four time slices which share similar characteristics. The main reason of choosing that number of time slices over a higher one was to limit the computational time of the model runs. The more the tome slices, the more the resolution of the model, the more the time needed to execute the optimization.
- Biomass availability has been limited to 300 PJ in the model. Biomass being a common resource with limited availability raises the competition of option over its use. This competition defines to a certain extent the technology mix regarding the biomass based options.
- Nuclear energy has a strict maximum output limitation at 42 PJ in the model assumptions. Therefore, its role in future energy systems cannot be studied adequately.
- In the cost calculations, no regulatory costs of policy were taken into account; no structural effects on the economy; no damage costs; and no income from less import dependence. Thus, the results of model runs cannot be correlated with those of a cost benefit analysis, where such costs play a role.
- International cooperation is out of the scope of the model. Having a Dutch focus entails that only domestic mitigation opportunities for non-ETS emission reductions are calculated. With international cooperation, costs may be brought down by, for example, import and export of energy.
- The 1Mton CO_{2eq} step by step emission reduction used in the model runs might be too small in relation with the additional targets' intervals. Thus, resulting in overlapping results in the less ambitious additional targets.

3.9.1 Original ideas of the research and limitations of the process

In this section, the original ideas of the research and the limiting factors that came on surface through the validation of the process leading to the withdrawal of its use are clarified. In the original planning of the research, the development of the process would have been followed by three different methods of validation in order to test the consistency and the accuracy of the outcomes. The first method

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[23] The time representation of the model is briefly explained in Appendix A3.

involved a simulation of the procedure using case studies. As case studies, several technologies fulfilling the same functionality within the same cluster are considered. The simulation would replicate the calculations undertaken by the code using an excel exercise; aiming to derive with the same attribution of energy use, emissions and costs as in the model. For example, a case study would involve the substitution of gas boilers by heat pumps in meeting the heat demand in households. The second method included the assessment of shadow costs in a similar way as it is being performed in the current approach. Using high resolution in emission reduction steps (e.g. 1 Mton), we would identify at which levels of emissions a substitution between two technologies occurred. Then, by defining the cost increase at those particular levels of emissions, we should have ended up with a value close to the cost effectiveness in the model outcomes. The third method was aiming to compare the results of the process with the overall results when specific options were excluded from the available options in the system. In this way we would estimate the value of that particular technology for the system by subtracting the total system costs when the technology was not available from those when it was available. Then, by dividing that amount with the attributed emission reductions to that technology, we would expect the outcome to be approximately the same with the calculated cost effectiveness in the approximation. Thereafter, if the validation turned out to be successful, the approximation would be run under scenarios of alternative target definitions in order to show their impact on the cost effective technology mix; deriving with a ranking of technologies based on their cost effectiveness for each target.

However, since the first stages of the evaluation of the outcomes, it became clear that the results of the approximation were overruled by great uncertainty. First, the third method was used to validate the outcomes. Two separate trials were attempted by excluding two technologies from the assessment of the model. Both cases resulted in unrealistic values regarding the foregone costs of their exclusion, indicating the unreliability of the approximation at that point. The testing was taken one step further by initiating the second method, where again the results were not as expected. In particular, the values deducted by the shadow costs were deviating significantly from the calculations of cost effectiveness of several technologies especially those that were dealt by the system-wide part of the code. Furthermore, at a particular non-ETS emission reduction target the approximation demonstrated significant deviation on the cost effectiveness of the most expensive technology entering the optimal mix, as compared to the shadow price of that emission level. These indications suggested that the results were unreliable enough to make us continue the study without using the approximation. Extensive testing and debugging of the code would be a laborious procedure which was not feasible at that point. Therefore, it was decided to continue the research using the methods as they have been described above.

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4 Chapter: Results and Discussion

This chapter substantiates the preceding concepts following the methodological steps described in chapter3. The presentation of the results is incorporated with the discussion on the main findings in order to provide to the reader a logical flow of the course of this study. The subjects that are presented here are following the same order with the steps needed for answering the questions addressed. First, the overview of scenarios will indicate the interactions identified within the objectives of the scenarios. Next, the overview of the technologies will give insights on the interactions of the technologies with the objectives of the scenarios as well as on the added value of the model along with possible weaknesses that might be observed. Finally, the estimation of the cost increase of each technology in each scenario can provide useful insights on the cost effectiveness and the cost effective technology mix. The study ends up by providing a ranking of the technologies using as input the outcomes of the previous step.

4.1 Overview of scenarios

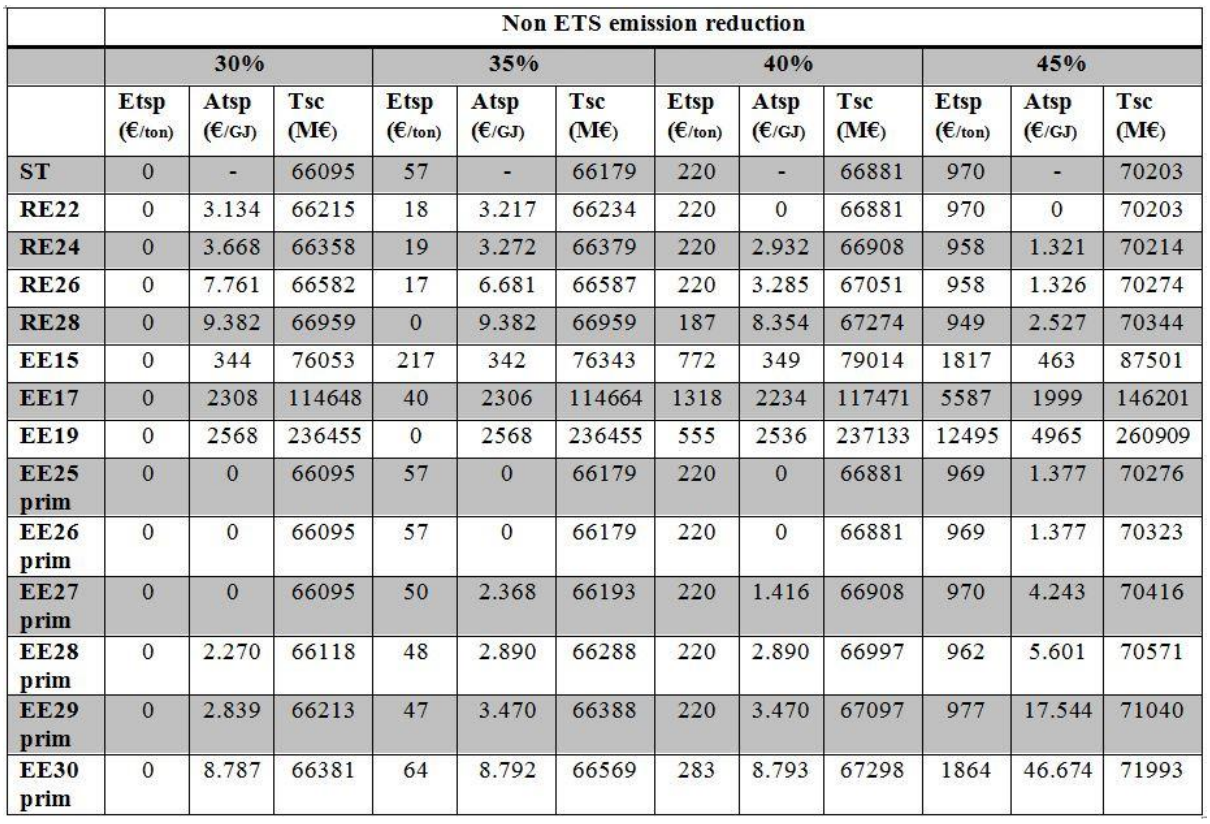
This section includes the main findings as derived from the followed methods aiming to address the first sub-question. The parameters stated in Table 6 (see section 3.5) led to the formulation of the criteria shown in Table 7. The latter will hold as a basis for the discussion on the targets' interactions as can be drawn by the overall results. The first two columns of Table 7 refer to the preconditions that need to be satisfied in order to lead to the effects mentioned in column 3.

Table 7: Criteria on assessing the interaction of the additional target with the emission targets using shadow prices

IF	Non-ETS emission target shadow price (ETsp) for ST and MT scenarios	Additional target shadow price (ATsp) for MT scenarios only	Effects
1	ETsp (ST) = 0, or ETsp (MT) =0	ATsp = 0	There are no binding targets for the system.
2	ETsp (ST) ≠0, ETsp (MT) =0	ATsp ≠ 0	The additional target ensures that the emission target is met.
3	ETsp (ST) ≠ 0, ETsp (MT) ≠ 0	ATsp = 0	The emission target ensures that the additional target is met.
4	ETsp (ST) ≠ 0, ETsp (MT) ≠ 0 and ETsp (ST) > ETsp (MT)	ATsp ≠ 0	There is a net partial synergy among the targets.
5	ETsp (ST) ≠ 0, ETsp (MT) ≠ 0 and ETsp (ST) < ETsp (MT)	ATsp ≠ 0	There is more antagonism than synergy among the targets.

In Table 8 below, three elements are presented for each scenario target; namely, the non-ETS emission target shadow price (ETsp), the additional target shadow price (ATsp), and the total system costs (Tsc). Four different non-ETS emission targets were chosen to be illustrated out of the series of the 1 Mton step by step reductions. The depiction of only four non-ETS targets was chosen mainly because of lack of space. Nevertheless, the progression of these targets can show the development of shadow prices and total system costs as the non-ETS targets become more ambitious.

Table 8: Concentrated values of ETsp, ATsp, and Tsc for 4 different non-ETS targets for all scenarios



	Non ETS emission reduction											
	30%			35%			40%			45%		
	Etsp (€/ton)	Atsp (€/GJ)	Tsc (M€)	Etsp (€/ton)	Atsp (€/GJ)	Tsc (M€)	Etsp (€/ton)	Atsp (€/GJ)	Tsc (M€)	Etsp (€/ton)	Atsp (€/GJ)	Tsc (M€)
ST	0	-	66095	57	-	66179	220	-	66881	970	-	70203
RE22	0	3.134	66215	18	3.217	66234	220	0	66881	970	0	70203
RE24	0	3.668	66358	19	3.272	66379	220	2.932	66908	958	1.321	70214
RE26	0	7.761	66582	17	6.681	66587	220	3.285	67051	958	1.326	70274
RE28	0	9.382	66959	0	9.382	66959	187	8.354	67274	949	2.527	70344
EE15	0	344	76053	217	342	76343	772	349	79014	1817	463	87501
EE17	0	2308	114648	40	2306	114664	1318	2234	117471	5587	1999	146201
EE19	0	2568	236455	0	2568	236455	555	2536	237133	12495	4965	260909
EE25 prim	0	0	66095	57	0	66179	220	0	66881	969	1.377	70276
EE26 prim	0	0	66095	57	0	66179	220	0	66881	969	1.377	70323
EE27 prim	0	0	66095	50	2.368	66193	220	1.416	66908	970	4.243	70416
EE28 prim	0	2.270	66118	48	2.890	66288	220	2.890	66997	962	5.601	70571
EE29 prim	0	2.839	66213	47	3.470	66388	220	3.470	67097	977	17.544	71040
EE30 prim	0	8.787	66381	64	8.792	66569	283	8.793	67298	1864	46.674	71993

In order to show a more complete picture of the scenarios the aforementioned tables are accompanied with several graphs which complement with additional information what might be missing from Table 8. These data will hold as a basis for the analysis on how additional targets interact with the non-ETS ones, and what is the effect on the shadow prices and total system costs (Tsc). In particular, Figure 6 presents the emission reductions achieved by the system for each scenario, whilst having a non binding non-ETS emission constraint; meaning that non-ETS targets' shadow price is zero for the illustrated percentage.

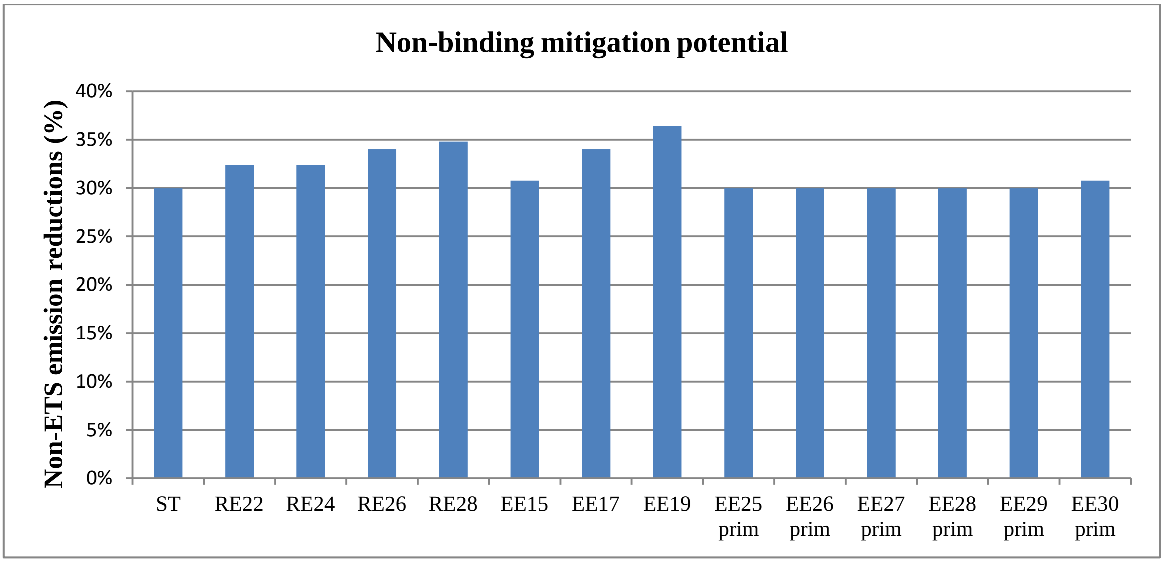


Figure 6: Mitigation potential while having a non-binding non-ETS emission constraint

Moreover, to further illustrate these interactions, we depicted as examples three graphs. Figure 7 to Figure 9 are shown the development of shadow prices of different targets in the MT scenario, for 3 cases, as well as their comparison with the ST scenario. The shadow prices that were used to construct these graphs correspond to each non-ETS emission target which derived from the step by step emission reduction. The green line reflects the development of the non-ETS emission reduction target shadow price in the ST scenario, while the blue line shows the non-ETS emission reduction target shadow price in the MT scenarios. In the red line the development of the additional target shadow price is demonstrated. Similar graphs for all the multi target scenarios can be found in the Appendix C.

4.1.1 RE 22%-28%

In this section the interactions among the different targets of the renewable energy scenario and the ST scenario are assessed. Figure 7 illustrates how the interactions can be observed for the case of a 22% renewable energy target.

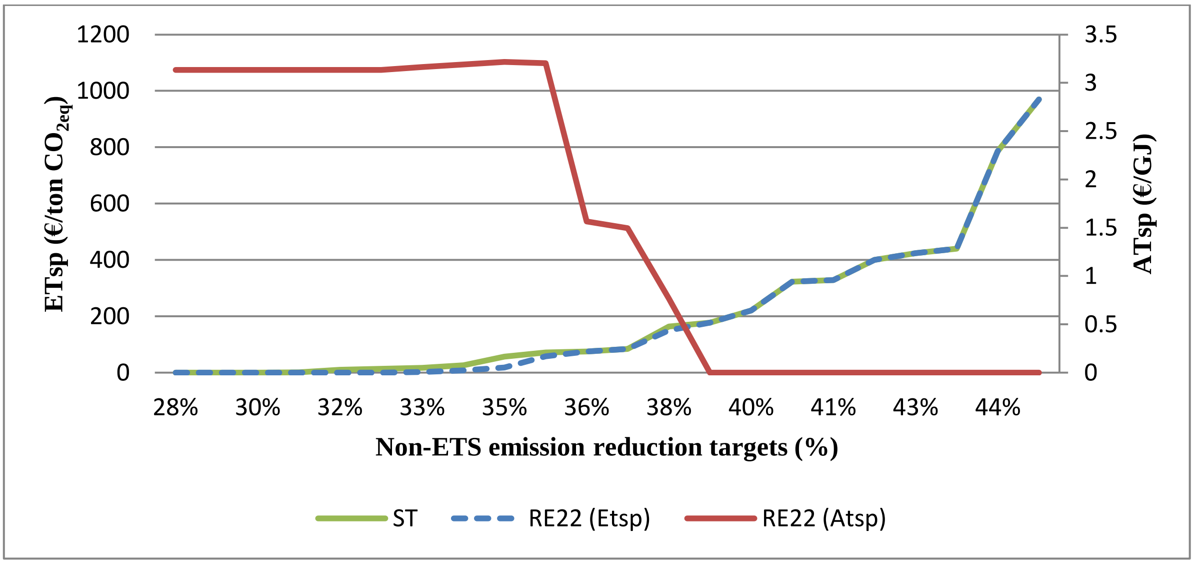


Figure 7: Shadow prices trend over the non-ETS emission targets of ST scenario and RE 22% multi target scenario

From Table 8 and Figure 6 it is shown that all the possible targets under the RE scenario have a non-binding CO_2 constraint for a range of emission targets. In particular, RE 22% shows an ETsp (MT) = 0 up until 32% emission reduction, while having an ATsp ≠ 0 (Figure 7); indicating -using criterion 2 from Table 7-that up to this point the additional target of 22% renewable energy ensures the achievement of 32% emission reductions in non-ETS sectors. For more ambitious non-ETS emission targets, the CO_2 shadow price of the single target scenario (ETsp (ST)) is slightly greater than the multi target CO_2 shadow price (ETsp (MT)) until a target of 38% pointing out a net partial synergy among the targets according to criterion 4 in Table 7. Thereafter both ETsp become equal and the ATsp becomes zero until the most ambitious non-ETS target (45%). These facts indicate that the non-ETS emission targets are ensuring the fulfilment of the 22% additional target (using criterion 3). RE 24% shows similar behaviour as the 22% target. Again the additional target ensures a 32% emission reduction target. From that point after the two targets act with synergy as the non-ETS emission targets become more ambitious; however, ATsp never reaches zero, which points out that solely the emission targets cannot guarantee the achievement of the additional target. Likewise, a 26% renewable energy target, based on criterion 2, ensures 34% emission reductions. As non-ETS targets become more ambitious there is a net partial synergy in the system as the shadow price of non-ETS targets in ST scenario is slightly higher than in the RE 26. Similarly, a renewable energy target at 28% shows to ensure the achievement of a 35% emission reductions in non-ETS sectors by having zero ETsp and ATsp≠0 (criterion 2). Thereafter, as shown in Table 8, the ETsp (MT) is smaller than the ETsp (ST) indicating that there is again a net partial synergy among the targets. (For the graphs describing the interactions of RE 24, 26, and 28 with the ST see Figure 23 in Appendix C).

Looking at the total system costs (Tsc) through Table 8 for each RE target, it is clear that always they are greater as compared to those in the ST scenario at each level of emission reduction. This indicates that the multi target scenario is more challenging than the single target; decreasing the degrees of freedom of the system by having one more constraint that must be met. However, the overall picture of the RE scenario shows that non-ETS targets work with synergy with the renewable energy objectives towards the transition to a low carbon economy.

4.1.2 EE 15%-19%

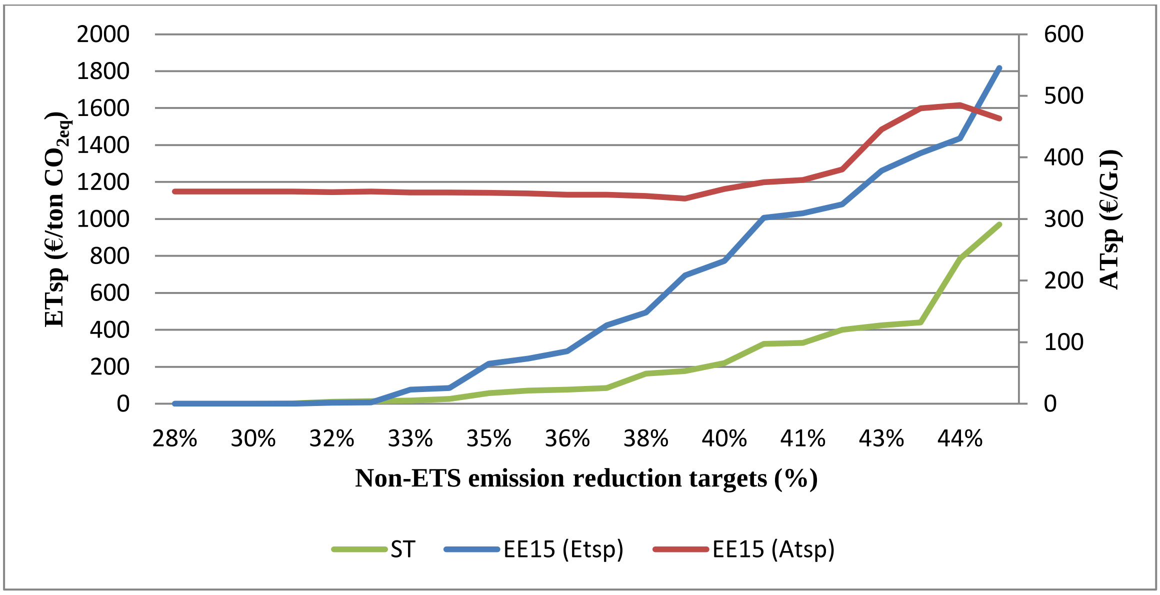


Figure 8: Shadow prices trend over the non-ETS emission targets of ST scenario and EE 15% multi target scenario

Table 8 and Figure 6 give the necessary information to assess the final energy savings scenario and its respective targets. The shadow price of non-ETS targets is zero for all three EE targets (15%, 17%, 19%), while the corresponding ATsp for each target is a lot higher than zero; indicating that the additional targets ensure the non-ETS emission reductions of 31%, 34%, and 36% respectively (criterion 2). Thus, the measures that the system chooses to implement in order to meet the final energy savings targets are helping as well the system to meet the aforementioned emission targets. However, as the emission targets become more ambitious, the ETsp (MT) for each target increases sharply becoming dominant over the ETsp (ST). This is illustrated in Figure 8 where for the case of 15% final savings target; ETsp (MT) is greater than ETsp (ST) for non-ETS targets more ambitious than 32%. Such case is characterized by antagonism between the emission and additional target (criterion 5). As the final saving targets and the emission targets become more ambitious the antagonism is more profound as the system reaches at extremely high ETsp (MT) levels as compared to the ST ones. This can be further confirmed by looking at the table where the respective values at non-ETS targets 35%, 40%, and 45% are presented (see also, Figure 25 in Appendix C the graphs depicting the shadow price development in EE 17, 19). A possible explanation for such high shadow prices could be the fact that under EE scenario, the system has exploited almost all the potential[24] for energy savings due to the policies in place already in the baseline. In order to be able to exploit further the untapped potential, it needs to proceed to high investments.

When viewing at the Tsc such thing is further confirmed. Tsc are a lot higher since the less ambitious emission targets. Hence, the EE targets are exerting a lot of pressure to the system by decreasing significantly its degrees of freedom when they are applied. As the emission targets become more ambitious along with the EE targets, the degrees of freedom are becoming even more limited, increasing the total system costs by a factor of 3.5 for the far reached emission and savings levels. In other words EE scenario appears to be very constraining for the system leaving too little space for manoeuvring regarding the optimal technology mix.

4.1.3 EE prim 25%-30%

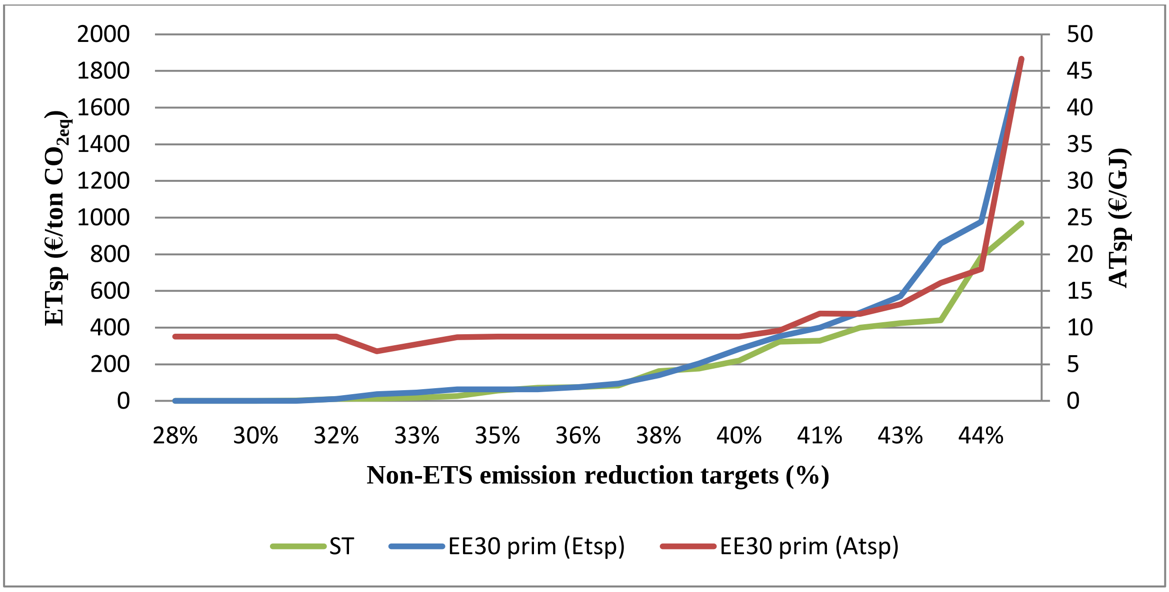


Figure 9: Shadow prices trend over the non-ETS emission targets of ST scenario and EE prim 30% multi target scenario

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[24] A lot of the potential of energy savings is included in the intended policy package, as EED has already a lot of regulations in energy efficiency.

Table 8 and Figure 6 indicate that primary energy savings targets of 25%, 26% and 27% as well as emission targets until 30% are not binding for the system; both ETsp (MT) and ATsp are zero (criterion 1).Hence, the system does not need to proceed to investments in technology deployment to achieve the aforementioned targets, since this potential is already unlocked in the baseline. From that level of non-ETS emissions targets and on, ETsp (MT) of the EE prim 25, 26, and 27% are developing almost identical as non-ETS emission targets are getting more ambitious, whilst the ATsp are remaining zero up to a certain emission target. In particular, based on criterion 3, a non-ETS emission target of 42% ensures 25% primary energy savings; a 40% emission reduction ensures 26% primary savings, while 32% emission reduction is driving the achievement of 27% primary savings. Deployment of options that serve the non-ETS sectors' decarbonisation, also serve the achievement of the additional target. At the point that the additional target becomes binding for the system (ATsp ≠ 0); meaning that the primary energy constraint becomes binding for the system, the aforementioned primary targets are demonstrating a net partial synergy with the objectives of the emission targets by showing equal or less non-ETS emission target shadow price as compared to the ST scenario (see also Figure 24 in Appendix C). When a 28% primary energy savings is applied the system achieves 30% emission reductions only by the implementation of measures driven by the additional target (criterion 2). Thereafter, the ETsp (MT) starts increasing throughout the more ambitious non-ETS targets, ending up at a slightly lower level as compared to the ETsp (ST). This development implies that the additional target cooperates with the emission target (criterion 4) (see Figure 24 in Appendix C). However, this picture is altered when moving to more ambitious EE prim targets. A primary energy savings target of 29% and 30% can facilitate an emission target of 30% and 31% respectively as discussed with respect the EE prim 28% target (criterion 2). Thereafter, both ATsp and ETsp are demonstrating increasing trends. ETsp (MT) becomes greater than ETsp (ST) as non-ETS emission targets are reaching at ambitious levels indicating that there is antagonism among the additional and emission target especially in deep emission cuts (criterion 5). In Figure 9, where the development of the shadow prices for EE prim 30% is illustrated, the aforementioned relation is visible. At non-ETS emission targets beyond 39% the targets in EE prim 30 are characterized by antagonism; the ETsp (MT) becomes greater than the ETsp (ST).

Total system cost overview of the EE prim scenario confirms, at first, the high convergence of 25% and 26% targets with the emission targets. The non binding constraints are translated in identical Tsc for as long this applies. Furthermore, targets at 27% and 28% are becoming more challenging for the system as the emission targets aim in deep cuts. However, the antagonism of the targets is clearer when assessing EE prim 29% and 30% from the Tsc perspective. The higher costs as compared to the single target scenario indicate the challenges that are posed to the system as it is pushed to the limits. The degrees of freedom are again lesser leading to relative high system costs.

Summarizing the overview of the scenarios and the relationship that additional targets share with the non-ETS ones, we can draw the following remarks presented in Table 9.

Table 9: Overall observed relationship among additional target and non-ETS emission target based on the scenario review.

	General Remarks
RE	• Up to a certain emission target the RE targets are driving the reduction targets; thereafter synergy exists among emission and additional target. • Total system costs are always greater in the MT rather than in the ST, indicating that RE scenario is more challenging and has fewer degrees of freedom.

<table>
<tr><td>EE</td><td>• EE targets are ensuring a certain mid-range (31%-36%) level of emission reductions; thereafter the non-ETS and the final energy targets are antagonistic to each other.
• Total system costs indicate that the EE targets are extremely challenging for the system; in combination with the emission targets the degrees of freedom of the system become very limited.</td></tr>
<tr><td>EE prim</td><td>• 25%, 26% and 27% are driven in certain extent by emission targets; 28% ensures a 30% emission reduction and thereafter acts complementary to the non-ETS targets; 29% and 30% ensure 30% and 31% emission reduction; however they progress antagonistically as targets become more ambitious.
• Total system costs confirm the relations among the targets. Most important is the obvious challenges that are posed by the far reached savings and emission cuts to the system by decreasing its degrees of freedom.</td></tr>
<tr><td colspan="2">• When an additional target demonstrates synergy with the emission target means that the two objectives can be satisfied by technologies which serve in a similar extent the achievement of the targets. With respect to the shadow price levels; a synergistic profile among the additional and the non-ETS target leads to less additional costs in MT scenarios as compared to the ST.
• When there is antagonism between the additional and the emission target, this is translated to implementation of technologies that exert pressure to the objectives of the one of the two targets by trying to satisfy the other. In this case higher CO_2 shadow prices are noticed for the MT than in the ST. The extent that the two targets are diverging defines the height of the shadow prices. This is obvious in the EE scenario. As long as targets become more ambitious shadow prices and TSC are reaching very high levels. However, exactly because of those high levels we need to handle with care EE scenario's targets as demonstrated by the model.</td></tr>
</table>

4.2 Overview of technologies

This section provides the technology overview regarding the influence that the assessed technologies pose to the objectives of each scenario. The analysis is based on a comparison among the expected behaviour of the technologies towards the targets according their functionality, and the behaviour observed from the model solution. First, in Table 10 the main substitutions as identified through the model runs for the non-ETS sectors are presented. The options observed in Table 10 represent the technologies that demonstrated a change in their activity as compared to the baseline. Hence, these technologies were included in the solution to satisfy the imposed targets. However, expected substitutions in several sectors might be absent from the table (e.g. in transport sector no electric cars seem to replace part of ICE cars), as they do not demonstrate any change in their activity output; indicating that the respective substitution already happened in the baseline.

Table 10: Substitutions of technologies in the non-ETS sectors as identified in the model results

Sector	Baseline Technology	Substitute technologies
Built environment	Natural gas boilers	Electric boiler
	High efficient (107%) boilers	Ground Heat pump
		Groundwater Heat pump
		Hybrid Heat pump with boiler
		Micro CHP
		Geothermal heat
		Solar water heater

Agriculture	Gas CHP	Geothermal heat
	Natural gas boilers	Biomass boilers
		Seasonal heat storage with heat pumps
		Ground based solar PVs
Transport	ICE passenger cars	E20/B20 biofuels car
	High duty vehicles (HDV)	CNG HDV freight
Industry non-ETS	Gas Boilers	Green Gas
	Gas CHP	Gas heat pumps
		Electric heat pumps
		Heat from electricity
		Hydrogen boilers

4.2.1 Expected influence of technologies on the different objectives of targets

The technologies derived from the substitutions were aggregated in categories including as well some technologies of the generic part of the system. In particular, renewable electricity and green gas production from co-digestion were chosen, as they are important parts of the energy system when addressing decarbonisation along with energy savings and renewable energy. In Table 11, the expected influence of the technologies on the objectives of the targets is presented using the following symbolism: positive (**+**) if the technology helps towards the achievement of the target, indirect (**i**) if the technology indirectly affects the target, negative (**-**) when the technology exert pressure to that target, and neutral (**~**) when a technology has no effect on a target.

Table 11: Expected effect of technologies on the objectives of the targets based on the substitutions

	Non-ETS emissions	**ETS emissions**	**Renewable Energy**	**Reducing energy use**	
				Final	Primary
Energy savings					
• **Saving on heat in non-ETS sectors**	+		i	+	+
• **Saving on electricity, all sectors**		+	i	+	+
Electrification - Hydrogen					
• **Electric boilers**	+	-			
• **Resistance heating**	+	-			
• **Electric heat pumps**	+	-	+		
• **Geothermal**	+	-	+		
• **Seasonal heat storage with heat pumps**	i	-	+		
• **Ground/groundwater heat pumps**	+	-	+		
• **Hybrid heat pumps with boilers**	+	-	+		
• **Hydrogen boilers**	+				
Small-scale gas heat pumps	+		+		
Small-scale CHP and micro-CHP	-	+			+
Renewable electricity					

• Wind off shore		+	+		+
• Ground based solar PVs		+	+		+
Biomass-Green gas					
• Green gas in industry non-ETS	+		+		-
• Green gas from co-digestion	+		+		-
• Biomass boilers	+		+		-

Energy saving

Energy saving not only reduces the need for energy directly, but also leads to derived savings because of the avoided conversion losses in the production of electricity, heat and transport fuels. Examples include building insulation, more efficient appliances, efficient lighting and lighter and more streamlined cars. In non-ETS sectors, heat savings are contributing to non-ETS emission reductions, as well as to both final and primary savings. Renewable energy is affected indirectly through the denominator effect. Given that renewable output (nominator) remains constant, a decrease in final energy use (denominator) will lead to an increase in the share of renewable energy in the system. Electricity savings in non-ETS are resulting to emission reductions in ETS sector. Energy savings performed in sectors under ETS, result in the same effects as in the non-ETS, however emission reductions are only associated with the ETS.

Electrification and use of hydrogen

Electricity and hydrogen can be used in cases where fossil fuels are used now. So, on site they come with no associated emissions and can contribute directly in emission reductions (non-ETS). Electrification options substitute fuels by electricity. Many renewable heat options also include an electrification component, as they use electricity as an auxiliary energy source for harvesting renewable energy. Examples of the latter include electric heat pumps, geothermal energy, seasonal heat storage with heat pumps, hybrid heat pumps with boilers[25], ground and groundwater heat pumps. Pure electrification includes resistance heating and electric boilers. Next to the emission reduction in non-ETS, an increase in the ETS emissions is expected by the use of these technologies as they require more electricity generation which falls under the ETS. The use of hydrogen generally requires extensive and expensive techniques at the relevant end use sectors. It is mostly applied in transport and in the built environment providing with emission reductions in the non-ETS levels. Depending on the production pathway of H_2, negative or positive effects on ETS emissions can be observed.

Gas heat pumps

Gas heat pumps are providing part of the heat demand by using fossil fuel to harvest renewable heat. As such, they have direct positive effect on renewable energy objectives. In addition as compared to their counterparts in heat provision (gas boilers), they result in reduction in non-ETS emissions. However, they are considered to have a 100% primary efficiency so they hardly result in positive primary energy effects, as gas boilers also operate in ~100% efficiency.

Small scale CHPs - micro CHPs

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[25] Hybrid heat pumps use boiler for back up to meet peak demand when needed.

Small-scale CHPs in non-ETS sectors work for achieving the overall system wide emission reduction targets; emissions in non-ETS are increasing as compared to the gas boilers while the counterproductive electricity in non-ETS will have positive effects on ETS emission reductions (by less large-scale electricity production). Micro-CHPs in end use sectors affect positively primary energy savings as in the calculations of primary energy only the input of CHP is taken into account without accounting for conversion losses. In total, there is a net decrease in emissions, but when looking at non-ETS reductions, the decrease in the deployment of small-scale CHP is an obvious way to positively affect non-ETS emissions, despite this being at the expense of the efficiency. To prevent this kind of effects it may be more sensible to move small-scale CHPs in the ETS.

Renewable electricity

Renewable electricity includes the generation of electricity mainly from wind energy and solar energy. Electricity generation is not part of the non-ETS sectors, and hence it has no effect on direct emission reductions in these sectors. On the other hand, as part of the ETS, it helps in the decarbonisation of the power sector. Wind energy is limited to the supply sector, but solar PVs can also be applied to the demand side in small-scale applications especially in built environment and in agriculture. Renewable electricity is associated in statistics with 100% primary efficiency; this results in positive effects towards primary consumption as no conversion losses can be attributed to the relevant options. Thus, when compared to their fossil counterparts in electricity generation they come with a strong advantage in primary energy savings.

Biomass-Green gas

Biomass can be converted into electricity and/or heat, green gas, hydrogen, raw materials and transport fuels providing a clear contribution in renewable output. It is one of the most versatile options, also because derivative products such as green gas and biofuels can be used virtually anywhere without expensive and significant adjustments on the spot of installations and vehicles. The use of primary (raw) biomass is mainly limited to large-scale applications (industry and energy sector), but derived fuels (green gas and biofuels) usually have the same applicability as their fossil counterparts, so also on a small scale. Biomass can be used for the production of heat in boilers or CHP installations; non-ETS emissions are reduced by the use of biomass as compared to its fossil counterparts. Green gas conversion returns are usually similar to the conventional heat sources, resulting in almost no effect on final consumption, however primary energy is often shown an increase due to the conversion of biomass to the second order energy carrier.

4.3 Observed influence based on model results

Table 12 has been completed after the evaluation of the data as described in section 3. The symbolism follows the same sign order as in Table 11. The difference though, is on the additional information granted, as compared to the expected effects discussed earlier. Thus, the observed effects that give new insights about the technologies are represented in ***red fonts***, while the expected effects in ***black fonts***. Comparing Table 12 with Table 11, we discerned two categories of technologies regarding their behaviour: i) those that behave in the model as expected initially and whichever deviation is explained easily concerning the underlying substitution, and ii) those that are in need to be handled with care because the analysis suggests that they have deviations from what was expected and is more complex to be explained mainly because the reasons may lay on various causes.

An illustration of the analysis can be found on Figure 10 - Figure 12 later on the analysis, which will serve as an indicative example of the process followed to fill in Table 12. Further explanation though will be provided under the section that the figures are referring to. More figures are provided in Appendix D.

Table 12: Observed interaction of the technologies with the objectives of the targets based on the model results

	Non-ETS emissions	ETS emissions	Renewable Energy	Reducing energy use	
				Final	Primary
Energy savings					
- **Saving on heat in non-ETS sectors**	+		i	+	+
- **Saving on electricity, all sectors**		+	i	+	+
Electrification - Hydrogen					
- **Electric boilers**	+	-	+	**n.a.**	-
- **Resistance heating**	+	-	-	-	-
- **Electric heat pumps**	+	-	+	-	~
- **Geothermal**	+	-	+	-	+
- **Seasonal heat storage with heat pumps**	i	-	+	-	-
- **Ground/groundwater heat pumps**	+	-	+	+	~
- **Hybrid heat pumps with boilers**	+	-	+	+	~
- **Hydrogen boilers**	+			**n.a.**	
Small-scale gas heat pumps	+		+	+	~
Small-scale CHP and micro-CHP	-	+	-	+	+
Renewable electricity					
- **Wind off shore**		+	+		+
- **Ground based solar PVs**		+	+	+	+
Biomass-Green gas					
- **Green gas in industry non-ETS**	+		+	-	~
- **Green gas from co-digestion**	+		+	-	~
- **Biomass boilers**	+		+		~

4.3.1 Technologies behaving as expected

Saving options are demonstrating an expected behaviour contributing to all objectives of different targets in a positive way. The indirect effect on renewable targets comes as a result of the denominator effect, where the less final consumption increases the amount of the share in renewables. The policy in place in the baseline drives the implementation of such technologies in all scenarios (usually with negative costs). The little untapped potential is only optimal in deep non-ETS emission cuts and comes at a very high cost.

Renewable electricity is present with two options in this assessment; wind off shore and ground based solar PVs. Both these technologies are following the expected route, having positive effects on RE and EE prim targets, as well as in ETS emission levels. The functionality they serve (i.e. provision of electricity) has no direct effect on non-ETS targets, since electricity generation falls under ETS sectors. ***Ground based solar PVs*** are restricted in providing electricity in agriculture sector and they are not present in the solution of the ST scenario; however, they demonstrate a strong positive influence on EE targets when these are applied along with the non-ETS ones. Taking into account CHP's electricity generation though, we could argue that is replaced by the renewable electricity generated by PVs. Thus, the positive effect on EE targets could be explained by the fact that in gross final consumption calculations CHPs are accounted by their combined output[26] instead of electricity only. In general, renewable electricity options show to have an indirect contribution on non-ETS targets as well.

Geothermal energy demonstrates the expected outcomes regarding its contribution to renewable energy targets and non-ETS emission targets. In addition, in the model results is being part of the cost optimal technology mix, having negative costs. However, the additional information that the model gives, in this respect, is on the contribution of geothermal heat on final and primary savings, where the latter is influenced positively and the former negatively. These effects might imply that geothermal energy substituted part of the heat generated by the CHPs. Another possible explanation is the final consumption increase due to the ancillary devices facilitating the harvesting of geothermal energy (e.g. gas turbine). In this way final energy in statistics is greater, and hence a negative effect on EE targets occurs, removing the technology from the cost negative mix; the 100% conversion efficiency of geothermal energy leads to primary savings[27] keeping the technology part of the optimal mix.

Hydrogen boilers' implementation is mainly driven by the non-ETS emission reductions. Their operation becomes optimum in very strict non-ETS emission levels and this entails that are followed by high costs. In all scenarios that are present, they appear at the same level of non-ETS emission reductions, implying that their effect on the other targets is neutral. However, in EE scenario hydrogen boilers are completely absent from the technology mix. This might be explained either because hydrogen boilers have adverse effects on the additional target (i.e. final savings), or emission cuts are achieved in another non-ETS sector where the chosen technology favours the final savings target.

Resistance heating is a pure electrification option which facilitates the transfer of non-ETS emissions to ETS sectors. From the model results its operation is associated with negative effects on: renewable targets (most likely through the denominator effect), EE targets (possibly because of the use of electricity; more than the use of gas in a boiler), and EE prim (again maybe due to the conversion losses on electricity generation).

Micro-CHP is implemented in all scenarios at the less ambitious non-ETS emission targets and it is being phased out in moderate emission targets as the negative effect on non-ETS emission reductions counteracts with deep emission cuts. Exception to that are EE targets, where the phasing out of the technology is happening in more ambitious non-ETS emission targets for the 15%; and not at all for 17% and 19%. This positive effect might be explained by the accounting method for gross final consumption, where for CHP their production of heat and electricity counts. RE targets are negatively affected as the technology has no contribution to renewable objectives. The negative effect comes indirectly through the denominator effect. Micro-CHPs are neutral to EE prim targets opposite to what was expected. However, taking into account that micro-CHPs are operating in end use sectors, the net

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[26] Unless it is sold to other users; then it counts as supply.

[27] In case the underlying substitution was among geothermal heat and boilers then hardly a positive effect or negative effect on EE prim and EE respectively would occur.

primary consumption is balanced (avoided conversion losses from the electricity generation on site are counteracted by heat conversion losses occurred as compared to a boiler).

4.3.2 Technologies need to be handled with care

Under this section the technologies that demonstrate a non-typical behaviour will be discussed. However, some of these technologies do demonstrate expected outcomes as can be seen in Table 12 (in black fonts). Thus, in the following paragraphs there will be a distinction on the expected and unexpected effects under each technology, followed by a list of generalised possible explanations (see section 4.6).

Green gas and ***green gas from co-digestion***[28] showed the expected behaviour for non-ETS emissions and renewable energy contribution, while surprisingly they showed a negative effect on final savings and neutral effect on primary savings instead of being vice versa (see Figure 26 and Figure 27 in Appendix D). These effects, however, might have their explanation on the fact that green gas is modelled to be very versatile and applicable in all sectors, making difficult to identify exactly the substitutions that have been undergone. In particular, green gas is pumped in the gas network and thereby its destination is unknown. A compromise on the way green gas is modelled is that per PJ of green gas 0.8 PJ of joint heat and electricity are produced. In addition, it is a technology that derives from biomass where competition over its use is prevailing.

Seasonal heat storage with heat pumps is an option that facilitates intermittent electricity production and as such contributes to increase renewable energy consumption along with the use of heat pumps that are considered as a renewable heat option. The effect on non-ETS targets therefore, is indirect. Care is needed for the negative effects that are showed with respect to the final and primary savings targets (see Figure 28 in Appendix D). Given that their use facilitates intermittent production is rather strange that an increase in primary consumption is noticed as well as final. There might be several possible explanations which will be discussed in the following sections.

Biomass[29] ***boilers*** were expected to show strong renewable energy contribution along with the decrease in non-ETS emissions. In addition, a slight increase in primary consumption was expected as well. However, positive influence on RE targets is only clear for the 28% share on renewable energy, and EE prim seem not to be affected by the conversion losses of biomass (see Figure 29 in Appendix D). These effects however, may have to do with the fact that biomass is a common resource with limited availability and there are many applications that compete with each other in different sectors.

Electric boilers behave as expected with regard to their positive contribution to the non-ETS targets by burdening the ETS sectors with CO_2 emissions. However, they demonstrate a negative effect on primary energy targets which can be explained possibly by the conversion losses during the generation of the required extra electricity. Moreover, they show a slightly positive influence on RE targets, where for 26% and 28% a small shift of their deployment towards the less ambitious non-ETS targets is observed (see Figure 30 in Appendix D). One possible reason for this outcome could be that electric boilers partially facilitate the absorption of intermittent electricity generated by renewable sources.

Hybrid heat pumps with boilers are intermediate applications that facilitate the transition from gas boilers to full time heat pumps especially for far reached non-ETS emission targets. Beside the

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[28] In gross final consumption calculations, the output of green gas from co-digestion is accounted.

[29] Biomass input counts the consumption of biomass as renewable production. Examples where this applies are: biomass boilers, biofuels in transport sector, and biomass for feedstock.

expected positive influence on non-ETS and renewable target, they also demonstrate a positive effect on final energy savings (see Figure 31 in Appendix D). Similar effects are demonstrated by ***ground/groundwater heat pumps*** as well, where positive effects on EE prim 29% and 30% are observed. This may have various causes; from interactions with other parts of the energy system to direct competition with other technologies, or better operational characteristics as compared to other heat pumps such as better coefficient of performance (COP).

Gas heat pumps (limited optimal levels of operation) facilitate the moderate non-ETS CO_2 targets and the transition from high temperature boilers to electric heat pumps. For far reached non-ETS emission targets the technology has adverse effects on non-ETS emission reductions and is being phased out eventually. Furthermore, until that point it shows a positive influence on RE targets, while being neutral to EE prim ones (except for the 30% primary energy savings). The striking outcome of its implementation however, is that it seems to favour significantly EE targets before being abandoned due to the ambitious non-ETS targets (see Figure 32 in Appendix D). A possible explanation could lie in the COP but also due to other kind of interactions in the system as gas heat pumps facilitate a transition to more carbon free heating technologies. Again is difficult to end up with a solid explanation, however in the following parts we provide with a series of possible reasons for all the doubtful results of the model.

Electric heat pumps' positive influence on non-ETS targets has been already discussed along with their RE contribution under the electrification options description of the previous part. In addition the latter is visible in Figure 10, where the development of activity over the non-ETS emission reduction targets is shown. Under the influence of the RE additional targets the technology shifts its introduction point to the less ambitious non-ETS targets, indicating that the positive effect towards them drives the deployment of electric heat pumps in order to contribute to the additional target's fulfilment. Figure 12 shows the influence on primary energy savings targets, where the technology demonstrates the same introduction point as in ST scenario, except of the 30% target which seems slightly positively affected. Overall negative effects are demonstrated in final saving targets. In particular, in Figure 11, is observed that under final saving targets of 17% and 19% the technology shows adverse effects on the additional target and its implementation is driven by the strict non-ETS emission levels. However, it shows positive influence on the 15% EE target. This might be a result of the transition from gas heat pumps to the electric ones; for more ambitious EE targets the respective substitution has more adverse effects to the additional target but is needed for the achievement of strict non-ETS targets. Next to that, is ambiguous whether more possible reasons justify this behaviour. Competition among options, interactions within the system, or different technology specifications (e.g. COP) are all possible explanations.

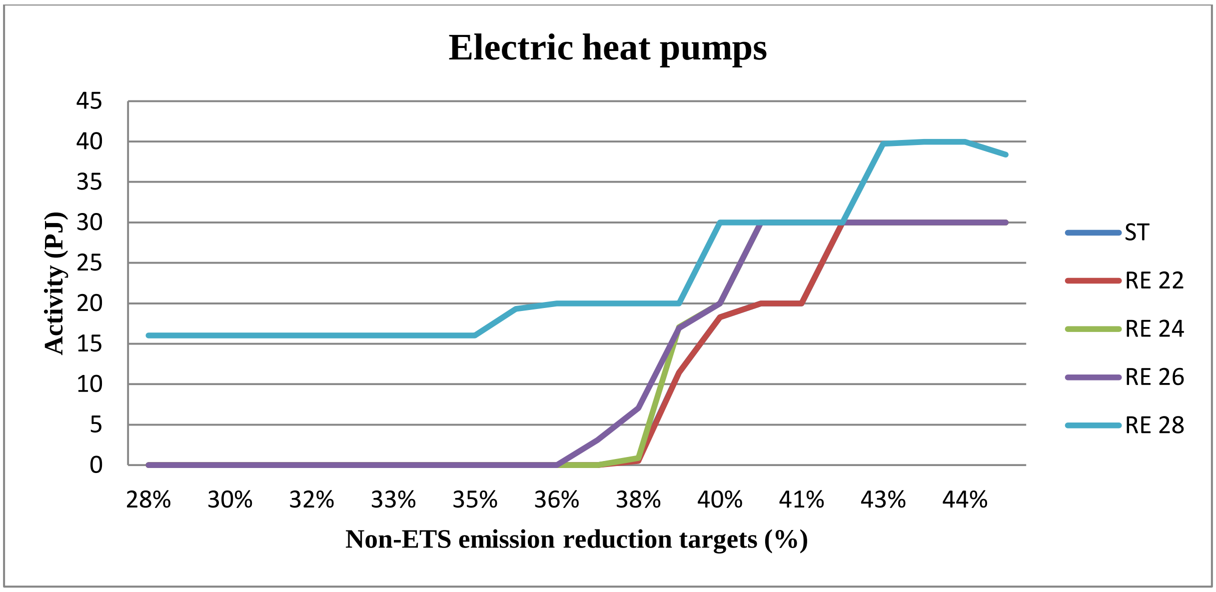

Figure 10: Electric heat pump's activity over various non-ETS emission target under the influence of RE scenario

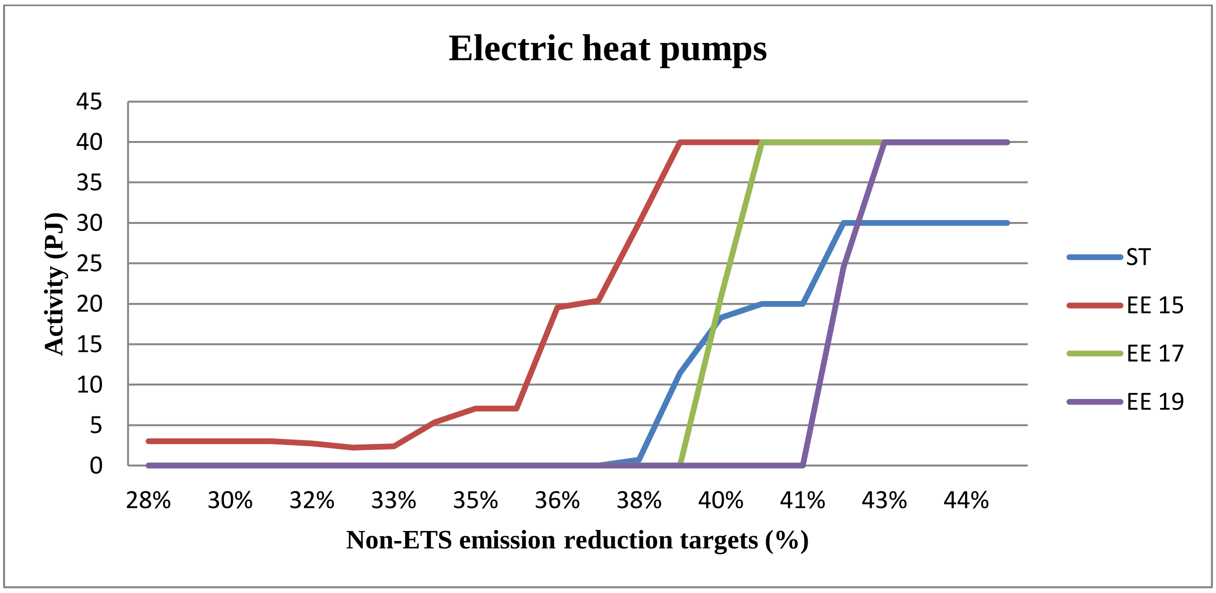

Figure 11: Electric heat pump's activity over various non-ETS emission targets under the influence of EE scenario

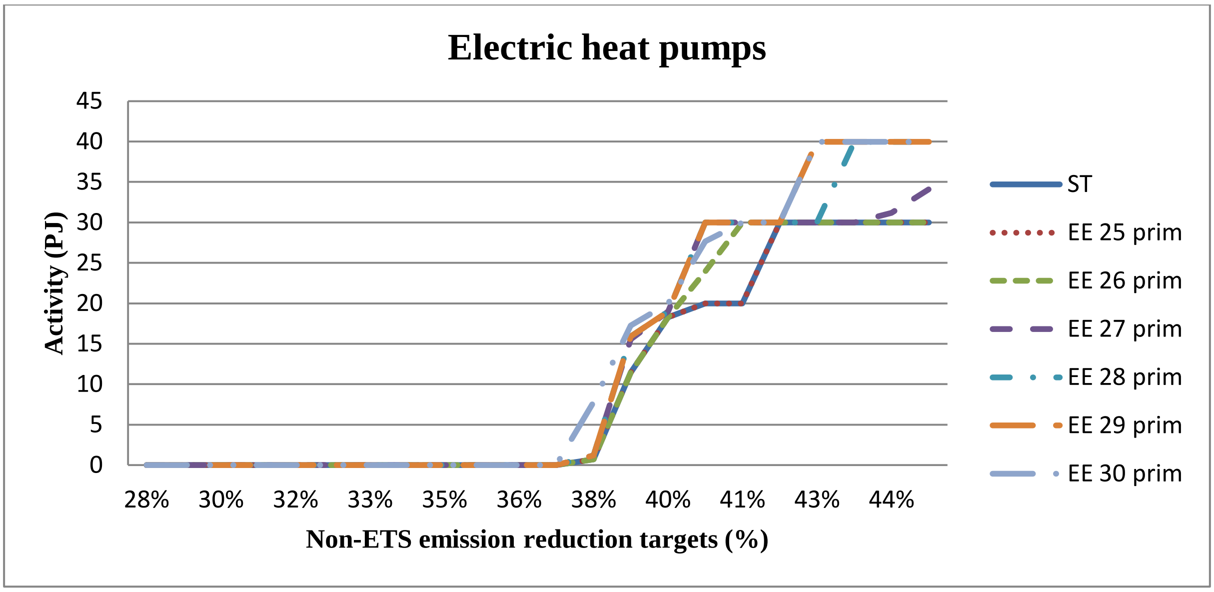

Figure 12: Electric heat pump's activity over various non-ETS emission targets under the influence of EE prim scenario.

4.4 Cost effectiveness estimation

The optimal deployment of a technology with respect to the targets imposed to the system is characterized by a range in cost increase based on the non-ETS targets' shadow prices, for which the technology increased its activity. This cost range includes all the marginal abatement costs for which the technology is cost effective to contribute to the respective non-ETS target achievement, under the different scenarios. Thus, an approximation of the cost effectiveness of the technologies can be drawn from the estimated cost range. The use of the average cost effectiveness adds certain coarseness to the results; however, it is useful to illustrate how shadow prices of different targets can determine the costs at which technologies enter the solution.

Following the data analysis as described in section 3, we present the outcomes in Table 13, where we show for each technology and variant the effect of the additional target on the marginal abatement costs. The symbolism chosen is as follows:

- (S)ynergy reflects the positive effects; meaning a decrease in marginal abatement costs will occur as compared to the ST's marginal abatement costs
- (A)ntagonism reflects the negative effects; meaning the increase of marginal abatement costs as compared to the ST's marginal abatement costs
- (N)eutral reflects the no change in marginal abatement costs as compared to the ST
- Cost optimal reflects the negative abatement costs that the technology is associated with in the ST scenario and keeps the same activity in the MT scenarios.
- N.A. indicates when a technology is not available in the solution for the respective scenario.
- Blank cell appears when the technology does not show any change in activity as compared to the baseline.

Table 13: Effects of the additional targets on the marginal abatement costs of technologies

	RE	**EE**	**EE prim**
Electrification - Hydrogen			
• **Electric boilers**			

○ Variant 1	A	N.A.	A	
○ Variant 2	S	N.A.	A	
○ Variant 3	N	N.A.	A	
○ Variant 4	S	N.A.	A	
• **Resistance heating**	A[30]	A[31]	A[32]	
• **Electric heat pumps**				
○ Variant 1	S	A	A	
○ Variant 2	S	A	A	S at 30%
○ Variant 3	S	A	S	
• **Geothermal**	cost optimal	A	cost optimal	
• **Seasonal heat storage with heat pumps**	S	A[33]	A	
• **Ground/groundwater heat pumps**				
○ Variant 1	S	S	A	
○ Variant 2	S	S	S	
○ Variant 3	N	S	A	
• **Hybrid heat pumps with boiler**				
○ Variant 1	Cost optimal			
○ Variant 2	S	S	N	
○ Variant 3	N	S	N	
○ Variant 4	N	S	N	
• **Hydrogen boilers**	S	N.A.	N	S at 28%&29%
Small-scale gas heat pumps				
• **Variant 1**	S	S	N	S at 30%
• **Variant 2**	S	S	S	
• **Variant 3**	S	S	S at 28% & 30%	A
Renewable electricity				
• **Wind off shore**	S		S	
• **Ground based solar PVs**	S	S	S	
Biomass-Green gas				
• **Green gas in industry non-ETS**	S	A	N	
• **Green gas from co-digestion**	S	A	N	A at 30%
• **Biomass boilers**	N		N	A at 30%[34]

The way the cost effectiveness changes with respect to different targets can be seen in Table 13. Furthermore, through the indicative examples shown in Figure 13 - Figure 20, it is illustrated, in a bubble diagram, the development of the emission target's shadow price (x-axis); the development of the additional target's shadow price (y-axis); and the maximum activity reached as compared to the baseline (size of the bubble). Regarding the results, we distinguish three points for discussion: a) the

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[30] Resistance heating shows less maximum activity under RE 28% target than in ST scenario and the rest RE targets.

[31] All EE targets are showing less maximum activity than ST scenario.

[32] EE prim 29% and 30% demonstrate less maximum activity than ST scenario and the rest of EE prim targets.

[33] Seasonal heat storage with heat pumps are deployed with less activity in the EE 17% than in the 15% and the ST scenario

[34] For the multi target scenario of EE prim 30%, biomass boilers present a higher maximum activity than in the rest targets of the same scenario and the ST scenario.

general trend observed, b) the contribution of the shadow prices of the additional targets, and c) the detail added through the assessment of the variants of certain technologies.

The general trend observed in Table 13 seems to be dictated by the influence exerted on the additional targets by the technologies. Therefore, when a positive influence was observed, an increase in the cost effectiveness is demonstrated. For example, in Figure 13, electric heat pump (variant 3) becomes relatively cheaper as RE targets become more ambitious; following the identified positive influence to those targets. In particular, under the ST scenario it shows to be cost effective at a cost of 364 €/ton CO_{2eq}. In more ambitious RE targets electric heat pump's deployment becomes more attractive with relatively lower costs. More specifically, under a 22% RE target, cost effectiveness is found at around 360 €/ton CO_{2eq}; under a 24% target at 260 €/ton CO_{2eq} and reaches at around 140 €/ton CO_{2eq} for the most ambitious RE target assessed.

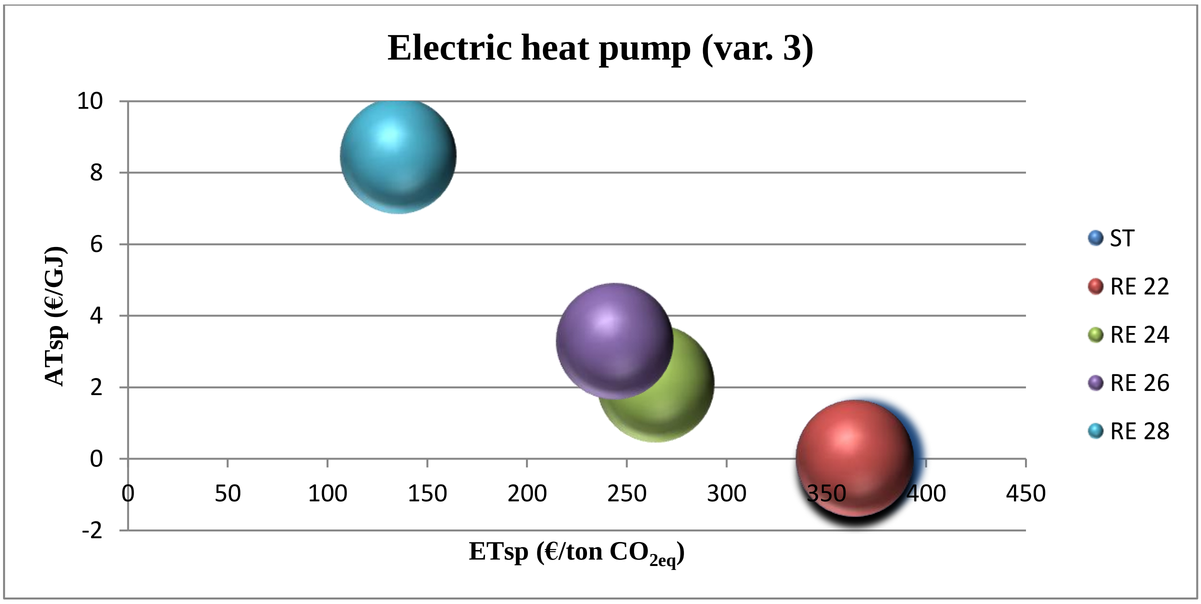

Figure 13: Electric heat pump's (variant 3) shadow price development under RE scenario targets as compared to the ST targets

Similarly, when a negative influence was observed, a decrease in cost effectiveness is associated to the additional target's growth of ambition. Such thing is illustrated in Figure 14, where electric heat pump's cost effectiveness decreases under the influence of a final savings target; starting by being slightly more expensive in the EE 15% and reaching almost 1500 €/ton CO_{2eq} in the most ambitious EE target (19%). The prevailing antagonism among the targets and the technology's effects on them drives the optimal deployment of the technology in far reached non-ETS targets at high costs.

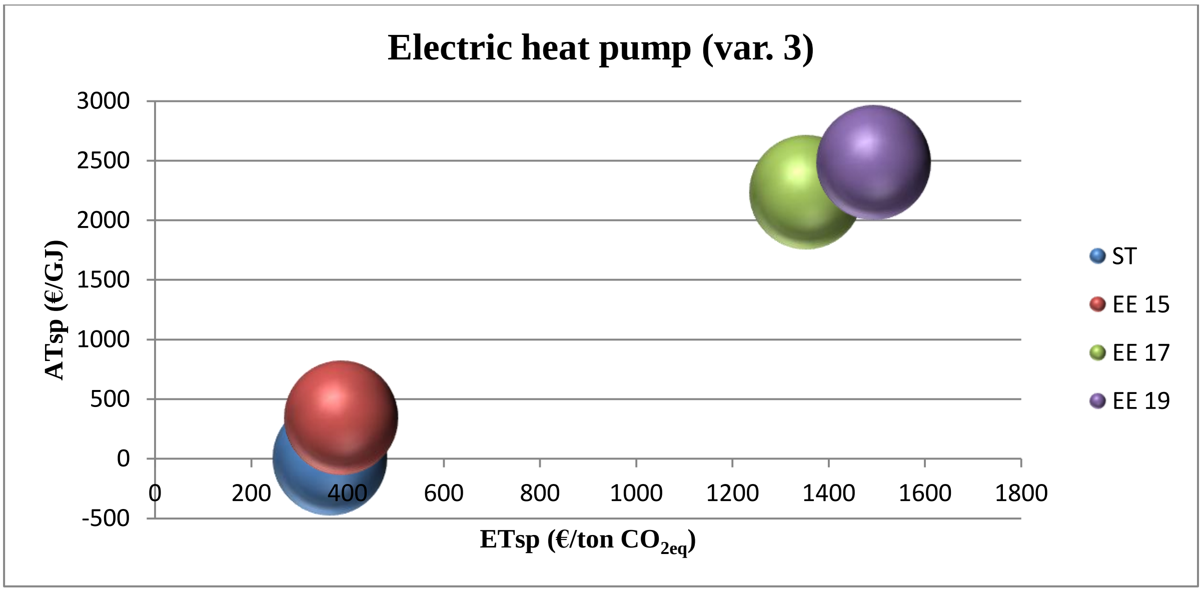

Figure 14: Electric heat pump's (variant 3) shadow price development under EE scenario targets as compared to ST targets

Likewise, the neutral effect of a technology on the additional target is followed by no change in cost effectiveness as can be seen in Figure 15 where biomass boilers' development of cost effectiveness under RE targets is illustrated. Biomass boilers, here, can also act as an example of deviations in model results as compared to the expected ones. Biomass is expected to contribute to the increase in renewable share and thus to have a positive effect on RE targets. However, this is not obvious on the figure. Biomass boilers show no effect on RE targets having almost the same costs as in the ST scenario at around 500 €/ton CO_{2eq} for all the additional targets (i.e.22%, 24%, 26%, 28%). However, this might be a result of the competition over a common resource such as biomass, where at high shadow costs the effects of a technology towards the non-ETS targets, rather than the RE, are more significant in the optimisation. This is quite confirmed by the fact that there is an increase in biomass boilers' maximum output (for 24%, 26%, and 28%) as compared to RE 22% and the ST scenario; indicating that this increase in biomass use has restricted the deployment of other biomass based technologies. The GHG mitigation effects of the technology on non-ETS targets are prevailing, and thus, its cost effectiveness does not show any change as compared to the ST scenario.

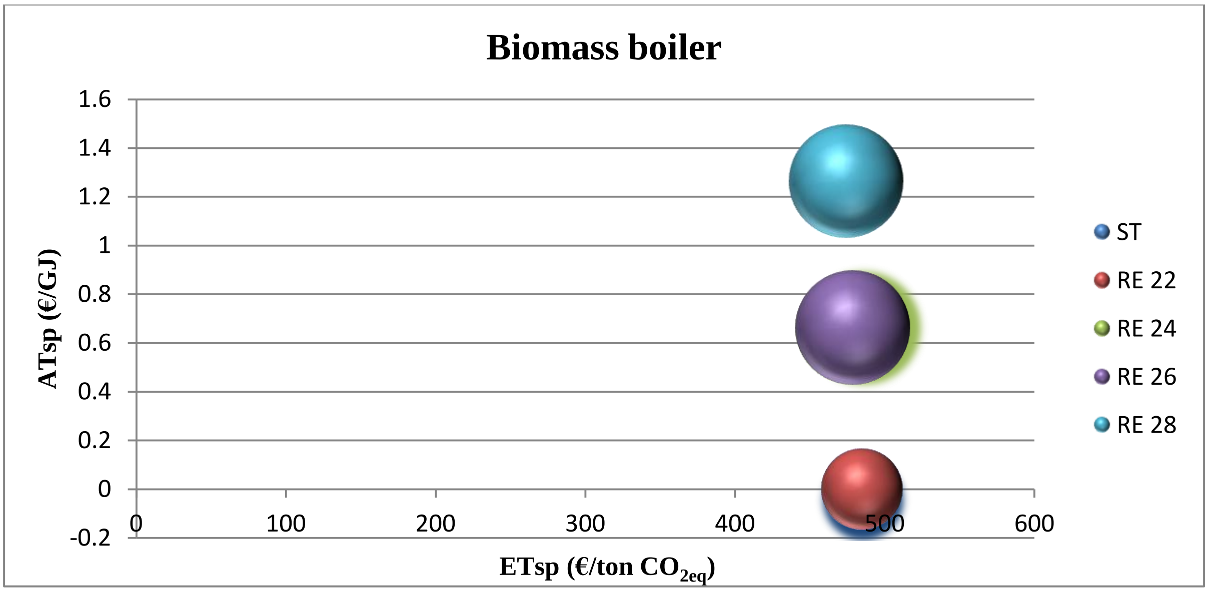

Figure 15: Biomass boiler's shadow price development under RE scenario targets as compared to ST targets

Something that is not visible in Table 13 but can be extracted from the graphs is the contribution of the marginal costs of the additional target for each scenario. Depending on the relation of the additional target and each technology, the former can be associated with the decrease or increase in the cost effectiveness. Since the calculation of the marginal costs of the additional targets follows the same approach, they reflect the same optimal deployment of the technology to achieve the underlying targets. Thus, each combination of marginal costs that characterize the deployment of a technology within a scenario can be assumed to be equivalent to the others, as well as to the marginal abatement costs of the ST targets. Taking for example again electric heat pumps under the RE scenario (Figure 16), we draw a set of marginal costs in the 24% target; namely 100 €/ton CO_{2eq} and 3 €/GJ. This combination is equivalent with the cost effective deployment of the technology in the ST scenario at 130 €/ton CO_{2eq}. This means that the optimal deployment of the technology in achieving both the non-ETS and the renewable energy target in RE scenario comes at these costs. The costs that are associated with the energy target drive down the marginal abatement costs in this case. Moreover, the level of the marginal costs of the additional target can be linked to the financial gap of the substitute technology as compared to its counterpart technology.

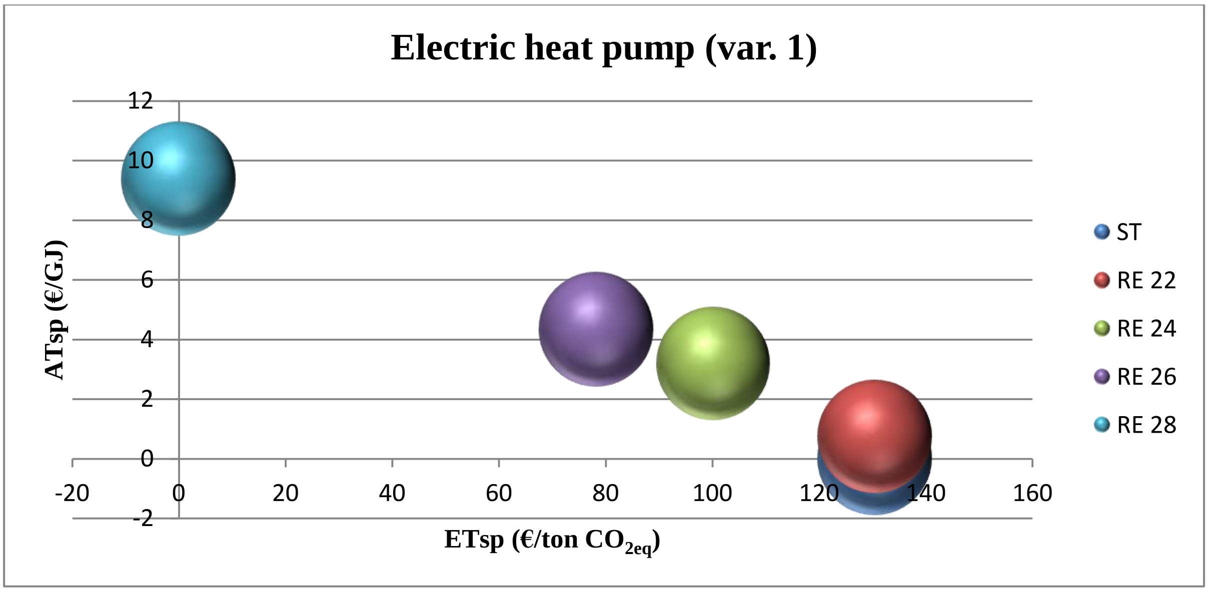

Figure 16: Electric heat pump's (variant 1) shadow price development under RE scenario targets as compared to ST targets

The third point of discussion arises from the assessment of the variants. Variants represent different intensities of technologies and their deployment is driven by the needs of the system. The transition from gas heat pumps to electric heat pumps in non-ETS industry sector will serve as an illustrative example of the use of variants and how shadow prices determine the cost effective technology mix. Both technologies are present in the technology mix with three (3) variants. Starting from gas heat pumps we observe that their deployment comes at different costs under the ST scenario (Figure 17 and Figure 18; indicated by the dark blue bubble)[35].

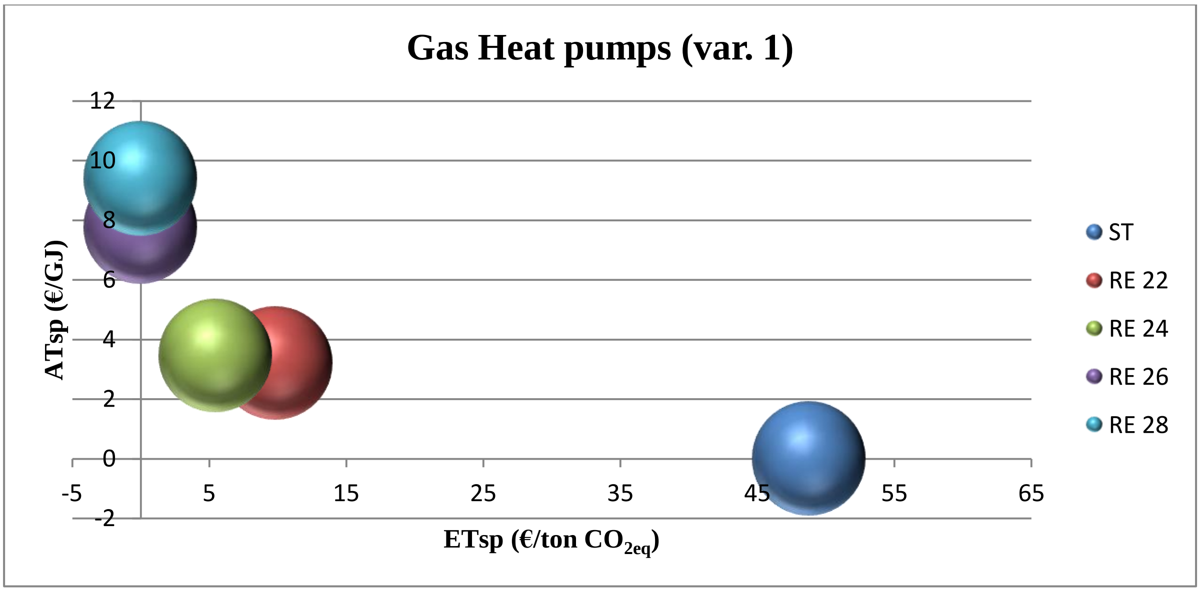

Figure 17: Gas heat pump's (variant 1) shadow price development under RE scenario targets as compared to ST targets

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[35] In order to address all the issues in this section, different scenarios for each variant were used. However, this does not weaken our point since ST scenario includes only CO_2 shadow prices, and hence it is the same for the respective variant.

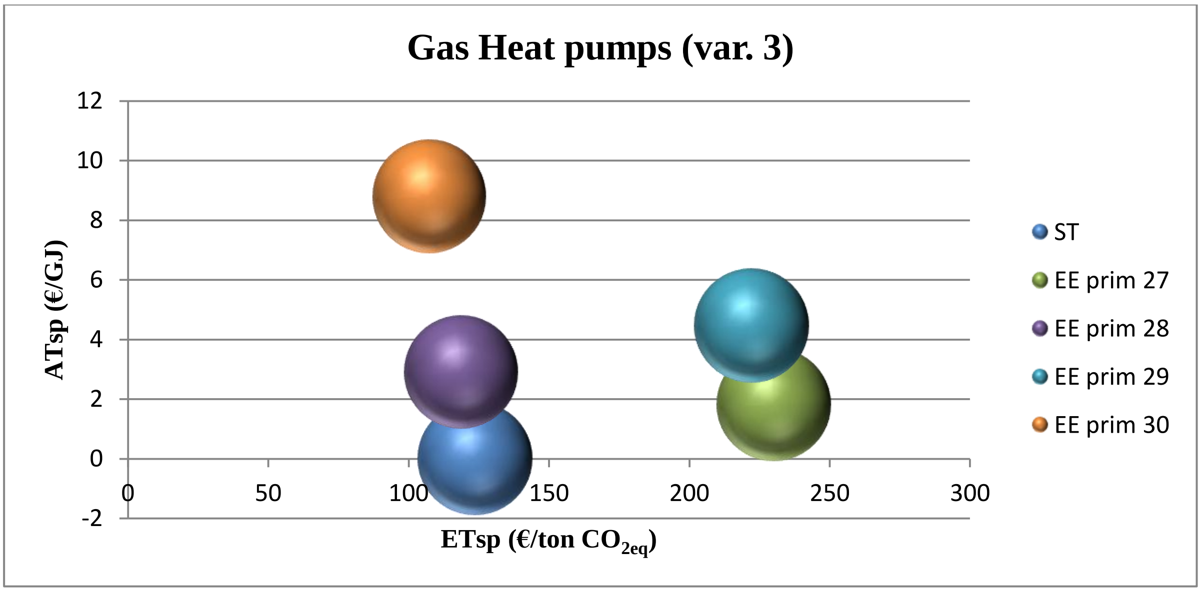

Figure 18: Gas heat pump's (variant 3) shadow price development under EE prim scenario targets as compared to ST targets

As the non-ETS targets become more ambitious the cost effectiveness of gas heat pumps decreases indicating that the variants contribute to different non-ETS targets; starting from 49 €/ton CO_{2eq} for variant 1, and reaching 123 €/ton CO_{2eq} for variant 3 (Figure 17 and Figure 18). As non-ETS targets become more ambitious, the transition[36] starts to be occurring reflected by the cost effectiveness of electric heat pumps' variant 1, which can be found at 130 €/ton CO_{2eq}; reaching 364 €/ton CO_{2eq} for variant 3 (Figure 19and Figure 13). When additional targets are applied on top of the non-ETS targets the deployment of technologies is influenced as described in the previous part. For most of the variants the effect on the additional target (indicated by the combination of shadow prices as described earlier) drives the cost effectiveness accordingly. However, when assessing the variants individually rather than aggregated, certain deviations might appear on the development of cost effectiveness as compared to the overall picture the technologies demonstrate. In particular, gas heat pumps' variant 3 shows diverse effects under different EE prim targets. The 28% and 30% of primary savings drive slightly the costs down while the 27% and 29% increase the marginal abatement costs of the technology. This deviation though, might be a result of the direct competition with electric heat pumps. Looking at the variants of the latter we can deduct the gradual transition being occurred, based on the cost effectiveness observed. More specifically, electric heat pumps' variant 1 (Figure 19) seem to takes over from the point that gas heat pumps' variant 3 left (Figure 18), having a cost effectiveness at 150 €/ton CO_{2eq} for all the additional targets. The decrease in cost effectiveness of gas heat pumps (variant 3), under 27% and 29% EE prim, looks like it is part of the gradual transition to electric heat pumps. Variant 2 of electric heat pumps shows similar marginal abatement costs under the same targets at around 250 €/ton CO_{2eq} (Figure 20); indicating that up to a certain extent the deviation noticed can be associated with that particular substitution.

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[36] The transition from one technology to another does not occur instantaneously but there is a gradual substitution which cannot always be reflected through the average cost effectiveness.

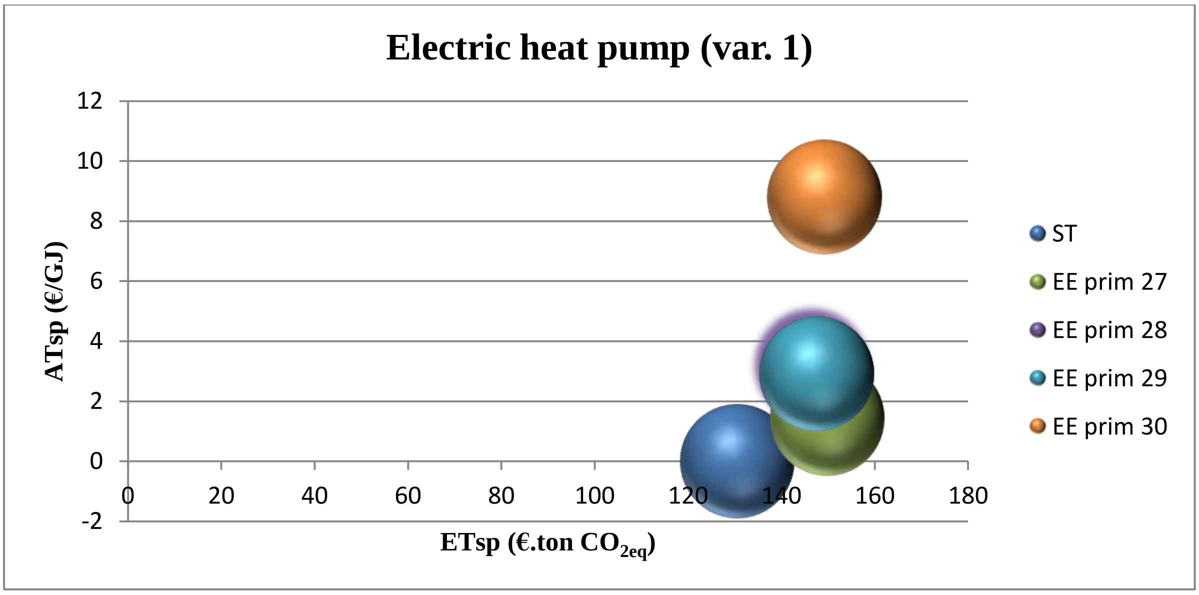

Figure 19: Electric heat pump's (variant 1) shadow price development under EE prim scenario targets as compared to ST targets

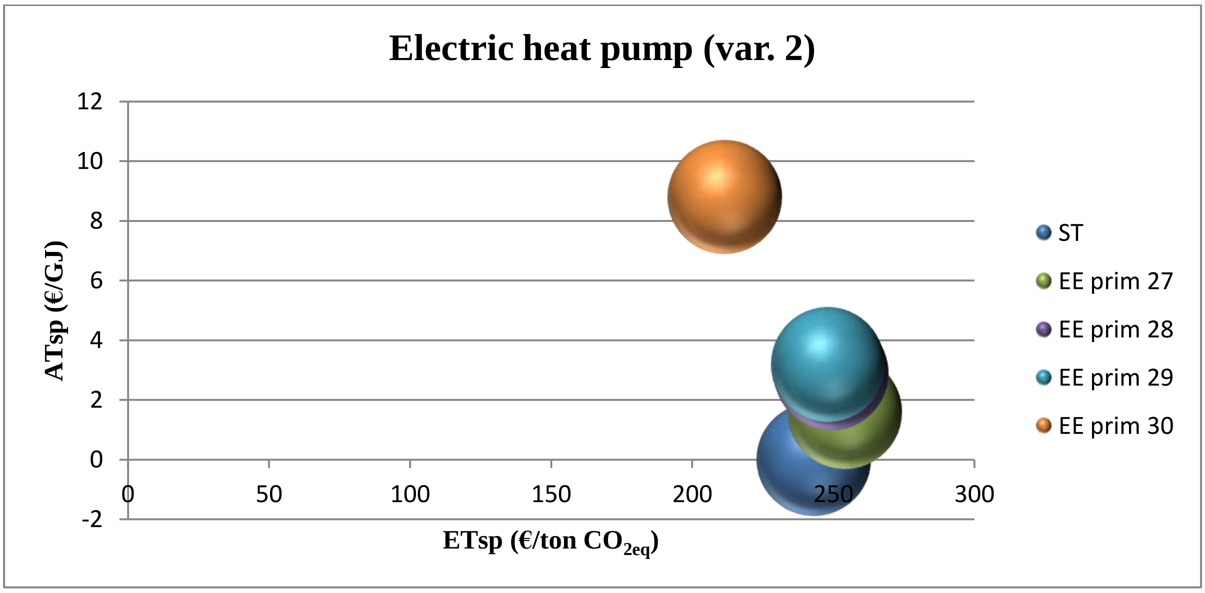

Figure 20: Electric heat pump's (variant 2) shadow price development under EE prim scenario targets as compared to ST targets

Therefore, through this example it is quite clear that shadow prices derived from the set of targets can indicate the cost effective technology mix based on the cost effectiveness where technologies can be found at, with regard to the effects they pose to the additional targets of each scenario. Generally, the most expensive technology that enters the technology mix demonstrates cost effectiveness close to the shadow price associated with that particular target. For example, if a non-ETS target is associated with marginal abatement costs at 500 €/ton CO_{2eq}, then all technologies that demonstrate cost effectiveness less or equal to those costs, should be part of the technology mix in the solution. (Similar graphs for more technologies can be found in Appendix E under Figure 33-Figure 47).

4.5 Ranking of technologies based on cost effectiveness

Based on the average cost effectiveness as derived from the previous step, Table 14 provides the ranking of technologies under the different targets. The ranking was performed for each scenario following an ascending order; meaning that the technology that is most cost effective will occupy the highest position in the ranking. In some cells on the table no ranking is provided; this comes as a result of either the technology not being part of the optimal solution for the respective scenario (hydrogen boiler, electric boiler, ground based solar PVs), or the activity of the technology as compared to the baseline remained unchanged (biomass boiler, wind off shore, and seasonal heat storage with heat pumps).

Table 14: Ranking of technologies under the different scenarios

	ST	RE22 (Etsp)	RE24 (Etsp)	RE26 (Etsp)	RE28 (Etsp)	EE15 (Etsp)	EE17 (Etsp)	EE19 (Etsp)	EE25 prim (Etsp)	EE26 prim (Etsp)	EE27 prim (Etsp)	EE28 prim (Etsp)	EE29 prim (Etsp)	EE30 prim (Etsp)
Green gas from co-digestion	6	7	6	1	1	15	18	18	6	6	6	6	6	6
Ground/groundwater heat pumps (var. 1)	11	13	14	8	1	7	1	1	11	12	13	13	13	13
Ground/groundwater heat pumps (var. 2)	20	21	17	17	17	11	1	1	13	15	17	15	13	14
Ground/groundwater heat pumps (var. 3)	20	21	22	23	24	14	1	1	23	23	22	25	24	19
Hybrid heat pump with boiler (var. 1)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hybrid heat pump with boiler (var. 2)	13	10	10	11	12	7	1	1	13	12	13	13	13	14
Hybrid heat pump with boiler (var. 3)	20	21	22	23	24	12	1	1	23	23	22	22	19	19
Hybrid heat pump with boiler (var. 4)	24	25	26	26	26	18	1	1	26	26	26	25	24	21
Electric boiler (var. 1)	9	10	11	12	15				9	10	9	12	17	22
Electric boiler (var. 2)	14	15	16	15	16				15	16	19	19	22	24
Electric boiler (var. 3)	14	15	18	18	18				15	16	21	20	23	24
Electric boiler (var. 4)	19	20	19	19	18				22	22	22	24	26	
Geothermal heat	1	1	1	1	1	6	13	13	1	1	1	1	1	1
Biomass boiler	16	17	20	20	20				18	18	15	17	16	22
Seasonal heat storage with heat pump	3	1	1	1	1	20	20		3	3	3	3	3	5
Wind off shore		6	12	12	1	1	1	1	18	18	9	10	8	9
Ground based solar PVs			25	20	14	9	1	1	15	14	17	15	12	11
Green gas	18	19	21	22	21	15	17	17	21	21	20	21	20	17
Gas heat pum (var.1)	4	4	4	1	1	1	1	1	4	4	4	4	4	3
Gas heat pum (var.2)	5	5	5	1	1	1	1	1	5	5	5	5	5	4
Gas heat pum (var.3)	7	8	7	10	11	1	1	1	7	8	8	7	9	7
Electric heat pump (var. 1)	8	9	8	7	1	9	14	14	8	7	7	8	7	8
Electric heat pump (var. 2)	10	12	9	9	10	13	14	14	10	9	11	9	10	10
Electric heat pump (var. 3)	11	13	13	14	13	15	16	16	11	11	12	11	11	11
Resistance heating	17	18	24	25	23	19	19	19	20	20	16	23	21	16
Hydrogen boilers	23	24	15	16	22				25	25	25	18	18	18

The scoring indicates the attractiveness of technologies for the system in achieving the non-ETS targets under the influence of the different scenarios. The technologies that were characterized by negative costs (such as geothermal in RE and EE prim scenarios and hybrid heat pumps with boiler) as well as technologies that due to the synergy with the additional target demonstrate zero abatement costs (e.g. gas heat pumps in RE 26, 28 and EE scenarios) are ranked first at the respective scenario. The remaining technologies are completing the ranking for each scenario.

Looking at each scenario separately, we draw information on whether a technology is preferred by the system over another with worse positioning. A technology that gets bad scoring over another, has to do with the fact that does not help towards the specific target, or it can also mean that it performs worse and the system considers attractive to deploy it only when is close to its limits and the effects of technologies regarding non-ETS emission reductions have more significance. However, the vertical assessment gives insights on the order of the deployment of technologies to achieve the respective targets as the marginal abatement costs increase. For example, hybrid heat pumps with boilers (variant 4) will only enter the solution at far reached non-ETS targets where the system reaches its limits and the costs are high, as indicated by the last place in the ranking for the ST scenario. On the other hand, when looking at the rows of the Table 14, we can draw information on how the technology performs under different targets. Having as a starting point the ST scenario where only non-ETS targets are imposed, the extent that each technology becomes cheaper or more expensive for the system can be drawn as an outcome. As discussed earlier, the additional target will drive the costs either up or down based on the influence that the technology poses to the additional target. Electric boilers for instance, get almost always a slightly better scoring in the ST scenario as compared to the multi target ones. However, when very ambitious primary energy savings targets are applied (i.e. 29%, 30%), electric boilers become relatively expensive for the system, which chooses to deploy them when it reaches its limits regarding the non-ETS targets. With this respect, based on how the position deviates among targets we can see how aligned are the technologies towards the different targets. In most of the cases, a technology demonstrates similar positioning (either good or bad) in both RE and EE prim scenario indicating as well the alignment of these additional targets. A technology under EE demonstrates more diverse outcomes.

The technology that shows the best overall ranking among all scenarios and targets is gas heat pump. Facilitating the transition from gas boilers to electric heat pumps is attractive to the system from low to moderate cost ranges under all scenarios; showing the best performance for RE 26, 28 and EE targets. On the contrary, the technology that seems to have overall a bad scoring is hydrogen boiler which only comes at play when non-ETS targets are very constraining.

The provision of such ranking is not meant to compare technologies on their performance rather to give insights on how the different targets can determine the deployment of technologies towards the transition to a low carbon economy.

4.6 Possible reasons of technology deviations

In this section, a list of explanations for the behaviour of technologies towards the different targets that is different from the expected at first sight has been formulated. More than one of the explanations listed here may affect the outcomes, simultaneously. This may render the results of integrated optimization models notoriously difficult to understand.

1. ***Direct competition (local):*** Options may compete with each other for fulfilling the same function (e.g. heat production). An option which is neutral or positive towards a target may be pushed out by an option which is even better. At low shadow prices, the costs of an option are the prevailing factor, while at high shadow prices the effect of an option is. For example the gas heat pump may be present at moderate non-ETS shadow prices, but be replaced by the electric heat pump at high shadow prices. Likewise, resistance heating may contribute to non-ETS emission reduction, but it does not contribute to renewable energy.
2. ***Competition for common resources:*** Options (in different sectors or applications) may compete with each other for a common resource, such as biomass. Thus, biomass will be used by the options that are most attractive to the system. Again, at low shadow prices costs will prevail, while at high shadow prices the effect will. For example, a low efficiency biomass boiler with low costs may be attractive at moderate RE/non-ETS targets, but it will give space to options with higher efficiencies at more ambitious targets, or when other targets (final/primary consumption) become more important.
3. ***No connection to the local demand:*** In some cases there is (hardly) any connection to the local demand. For example, green gas can be applied in any technology or sector that consumes natural gas. So, the exact destination may be quite arbitrary. The destination of green gas may change in a rather random way, or may change due to for example electrification in a particular sector. However, at far reached non-ETS emission reduction

targets combined with a modest ETS CO_2 price it is likely that in non-ETS sectors the demand for green gas will increase.

4. ***System interactions:*** Options may not directly attribute to meeting a target, but may facilitate options that do. For example, all kinds of flexibility options (e.g. electricity storage, heat storage, dispatchable power generation) may help integrating intermittent electricity generation into the system, and to prevent more expensive investments in infrastructure. Partial electrification (e.g. heat pumps combined with conventional boiler) may absorb peak production of solar PV or wind energy, while preventing the heat supply to become completely dependent on sources that are not always available.
5. ***Insignificant differences:*** A common characteristic of optimization models is that the results become increasingly unreliable when the system approaches its technical limits (i.e. when shadow prices are extremely high). In such circumstances, very small differences between technologies – with no significance for all practical purposes – may determine the activity of technologies. The model contains only a limited amount of options, with -for each option-characteristics that are considered representative (e.g. efficiencies, COPs, heat/power ratio in case of CHP's, and so on). In reality, the actual characteristics of a particular technology may vary, and may also be adapted to some extent to actual requirements. This variation or adaptation is usually not represented in the model: the data have certain coarseness. As a result, and especially in case of high shadow prices, the model may prefer a technology instead of another considering the included representative characteristics, while in reality, a variant of the technology with slightly modified characteristics might perfectly meet the demands of the system.

Errors: We cannot rule out that there are errors in the model and its underlying data, for example with regard to the way technologies contribute to specific targets.

4.7 Use for policy planning

The modelling of energy systems gives the opportunity to explore different pathways towards a low carbon economy. When applying a target or a set of targets, the derivative of the model is a shadow price for each target. Shadow prices of both targets (emission and additional) can be used as "price signals" that incorporate externality costs. Carbon tax and EU ETS CO_2 price are such costs. Having the prediction on how targets are affecting each other and moreover how technologies seem to favour or not certain targets, decision makers can set such price signals to stimulate the deployment of low carbon technologies. Moreover, the marginal costs of the additional targets (ATsp) can be used as price signals as well. There is already a market in renewable electricity and energy efficiency in the electricity sector with the tradable green certificates and tradable white certificates respectively. The prediction of ATsp either for specific targets or as a proxy for the marginal operational costs of technologies can help decision makers to decide the level of the price for these marketable intangible goods in order to stimulate the transition more effectively.

The prediction of cost effectiveness of technologies under the influence of combinations of targets (i.e. energy and emission targets) can be proved valuable information for decision makers. By this they can determine the alignment or misalignment of technologies with the targets. Technologies that are misaligned with the target objectives need to be reconsidered as potential options and drive the investment flows to more aligned technologies in order to achieve longer term goals in less cost as well. This means that if for example in the longer term it is planned a more ambitious final savings target, then it may be proved more costly to invest now in a technology, which is misaligned with that particular target, just because it contributes to the CO_2 target set for the midterm. Furthermore, long lifetimes also affect the planning since they can cause lock-in in certain technological pathway that may be in the longer term misaligned with the energy and climate policy objectives. Avoiding technological lock-ins helps in planning with better resolution the transition to low carbon economy at the minimum costs.

4.8 Recommendation for ECN

This research was conducted at ECN Policy Studies using an optimisation tool (Opera) developed completely by ECN. This tool gives the opportunity to the unit of policy studies to study the energy system at a national level and explore various developments that will lead towards the transition to a low carbon economy at the least cost. Examples of projects that Opera was used are: the exploration of the role of power to gas in the Dutch energy system (Daniëls, Seebregts, et al., 2014); the assessment of energy security in Dutch energy transition scenarios (Welle et al., 2014); the study of cost efficient renewable energy deployment towards the 2020 targets and beyond (Dalla Longa & Raimundo, 2012) and many others. My involvement with Opera made me realise that a model is like a "child", which needs "care" and "nurturing" in order to grow. As such, through my engagement with Opera, this study can hold as a first step in assisting ECN to get a better understanding of the model and identify where it needs most their attention. Hereby, some suggestions which could act as a starting point are provided:

- First, documentation file needs to support the model, in order to make it more accessible for more users and help them to be engaged in relevant projects while spending less time in learning the model.
- Regarding the code, there are parts that are not used by the current version of the model but they are present in the "code tree". Maybe they could be organised into libraries and if their use becomes relevant for a project to be summoned again. In this way a better and more efficient structure and operation could be achieved.
- Additionally, often debugging of the existing code is needed in order the perfect functionality of the model to be achieved. Furthermore, reconsideration of the way some technologies are modelled needs to be examined.
- Update the data base and clearing the technologies that were used in older projects and maybe are not reflecting anymore future trends, might be needed.
- The last three points along with other general adjustments in the model might be necessary in order to reduce computational time especially when time slices of high resolution are required for the analysis.
- Finally, ECN is already a key player in a national level with international presence as well. However an opportunity to develop into a key player in international markets would be to include databases (organised into libraries) of other countries' energy system structure, in order to be able to provide its services at a global scale eventually.

5 Chapter: Conclusions

The recognition that the main cause of climate change is anthropogenic activity turned the attention of scientific community and policy makers on searching ways on how the underlying consequences can be reversed. The broad field of the transition to a low carbon economy has a main building block, the decarbonisation of energy systems. Thus, the decarbonisation of energy systems is a crucial field for study in order to reduce CO_2 emissions without compromising the secure provision of energy.

In the scope of this research we provided a method that approximates the effects, the costs and the cost effectiveness of individual technologies under the influence of different scenarios. The scenarios represent different settings of policies regarding climate and energy objectives. A single target scenario represents a system with only non-ETS emission reduction targets. Renewable energy scenarios exploit the combination of renewable energy objectives along with the non-ETS emission targets. Energy savings scenarios represent primary or final energy savings objectives along with non-ETS emission targets. Using a bottom-up optimisation tool (OPERA), we investigated the Dutch energy system under the aforementioned scenarios, in order to derive with answers to our main research question which has as follows:

- *To what extent the scoring of individual measures in achieving certain emission targets can be influenced by additional energy targets?*

The answering process led to the formulation of four sub-questions, which by addressing them was regarded as a step by step approach in reaching to the answers we were seeking. Thus, in the remainder of this section the four sub-questions are dealt.

Sub-question 1: *What is the effect of the different targets on the shadow prices and how they interact with emission targets?*

Regarding the first sub-question we identified that the shadow prices in MT scenarios are determined by the interaction which exist between the additional targets and the non-ETS emission reduction targets. From a general point of view, the analysis suggests that when the additional target and the non-ETS emission target are characterized by synergy, this results in lower shadow prices (ETsp) as compared to a system where only non-ETS targets are imposed. This means that the additional target assists in achieving the emission targets in lower additional costs for the system. Likewise, when the additional target and the non-ETS target, in a MT scenario, are characterised by antagonism this leads to higher ETsp for the MT scenario as compared to the ST scenario. In other words the combination of targets can be achieved with higher additional costs relatively to the ST scenario. When viewing the total system costs the implementation of more than one target leads almost always to higher total system costs indicating the more challenging set up of the system and the decrease of the degrees of freedom of the system. The scenario specific outcomes can be seen in the following table:

RE scenarios	• Up to a certain emission target the RE targets are driving the reduction targets; thereafter synergy exists among emission and additional target. • Total system costs are always greater in the MT rather than in the ST, indicating that RE scenario is more challenging and has fewer degrees of freedom.
EE scenarios	• EE targets are ensuring a certain mid-range (31%-36%) level of emission reductions; thereafter the non-ETS and the final energy targets are antagonistic to each other. • Total system costs indicate that the EE targets are extremely challenging for the system; in combination with the emission targets the degrees of freedom

	of the system become very limited.
EE prim scenarios	• 25%, 26% and 27% are driven in certain extent by emission targets; 28% ensures a 30% emission reduction and thereafter acts complementary to the non-ETS targets; 29% and 30% ensure 30% and 31% emission reduction; however they progress antagonistically as targets become more ambitious. • Total system costs confirm the relations among the targets. Most important is the obvious challenges that are posed by the far reached savings and emission cuts to the system by decreasing its degrees of freedom.

Sub-question 2: *What are the main substitutions within the scenarios, and how different technologies contribute to the objectives of the various scenarios?*

Regarding the second sub-question the model runs indicated the technologies to be assessed based on the substitutions performed in the system in each scenario. Our focus was mainly on the non-ETS sectors since the emission targets were referring to the emissions regulated by the effort sharing decision. The set of the assessed technologies included: electrification options (either partial or pure), biomass based options (e.g. green gas, biomass boilers), gas based options (gas heat pumps, micro-CHP), and renewable electricity options (e.g. wind off shore, ground based solar PVs). The course of the analysis discerned two categories of interest regarding the contribution of technologies towards the targets; namely, options that demonstrated the expected contribution to targets, and those that showed diverse outcomes. The latter category includes several types of heat pumps (gas, hybrid, electric), biomass based technologies and pure electrification options (electric boilers). The identification of the contribution of options was based on a comparison of their deployment between the ST scenario and the MT scenarios. For example electric heat pumps showed a negative effect on final savings targets in contrast to gas heat pumps that a positive influence was observed towards the same targets. The diversity of outcomes as well as the unexpected contribution of options might be explained by factors such as: the direct competition among options; the competition over a common resource (biomass); and the interactions within the system. Additionally, errors in the model and its underlying data should not be ruled out as explanatory factor.

Sub-question 3: *How do shadow prices determine the cost effective technology mix?*

Regarding the third sub-question on how shadow prices determine the cost effective technology mix, we first estimated cost effectiveness of technologies using shadow prices as a proxy. The range of targets that an option showed an increase in its deployment was linked with the range in cost increase portrayed by the shadow prices of the respective targets. The analysis showed that the observed contribution of technologies towards the imposed additional targets dictates as well the development of their cost effectiveness. In other words, a positive contribution resulted in an increase in cost effectiveness as compared to the one showed under the ST scenario. This means that the additional target assists in making the technology cheaper for the system and thus, more attractive. On the other hand, a negative influence of an option towards the additional target is translated by a decrease in cost effectiveness, pushing the technology to be attractive only under stricter and more expensive non-ETS targets. Through this process, we discerned the cost effectiveness for all the assessed technologies. Since shadow prices of non-ETS emission targets are reflecting the marginal abatement costs to achieve that particular target, the estimation of cost effectiveness will determine which technologies are cost effective for each target. Hence, the technologies demonstrating cost effectiveness less or equal to those costs will be part of the technology mix able to achieve the imposed targets.

***Sub-question 4:** What is the ranking of the core technologies based on their cost effectiveness among the different targets?*

The fourth sub-question can be regarded as the final step in answering the main research question. By gathering all the inputs by the previous steps and the data from the cost effectiveness of options estimation, a ranking was provided. Through this ranking we got an overview of technologies based on their scoring with respect to the different scenarios. A technology that gets a bad scoring on the ranking can be interpreted by the fact that it does not help towards the achievement of a specific target, or ceteris paribus, that another technology is more attractive to the system. When assessing the ranking over a specific scenario the latter relation of technologies can be extracted. However, when assessing the scoring of a technology under the different scenarios, more insights can be revealed. The change on the scoring of the technology indicates the alignment or misalignment of the technology to the different scenarios. For example electric boilers demonstrate a misalignment with the very ambitious renewable energy and primary savings targets by getting an overall bad rank. On the other hand, gas heat pumps are shown to be more aligned with the final energy saving targets and the ambitious renewable energy targets, than with the rest of the scenarios.

Summing up, the followed research steps led to the conclusion that the scoring of the technologies is highly dependent on the influence that technologies exert to the additional targets of a scenario. A positive effect will drive the costs of the deployment of a technology down, whilst a negative effect will make the technology relatively expensive to the system. These relations are illustrated through the ranking of technologies.

5.1 Future work

During the conduction of this research, the main limitation that emerged was the not proper function of the developed process (see section 3.9.1). Acknowledging that such a process would add very promising outcomes to the quiver of researchers and policy makers, a study on the identification of the shortcomings and the improvement of its functionality should be performed. Modelling is a constant hand on experience which involves most of the times a trial and error approach accompanied as well by scientific research. Thus, the improvement of the process should start by examining step by step the technologies suggested by this study as the ones needed to be handled with care. Besides examining the functionality of the process on these technologies, also the way they are modelled should be examined with regard to if for example is in accordance with the international statistics.

Furthermore, during the process of this study, we identified the importance of definitions when setting a target. Definitions are able to connect the abstract targets to concrete measures, and allow countries to develop policy plans and monitor their progress. During the process of developing these definitions (e.g. the way renewable energy is calculated), different kinds of considerations have to be taken into account; both with regard to the ease and robustness with which the realised amount can be determined, but also with consequences for contribution of specific technologies. Thus, following a modelling approach such a study can contribute in comparing the outcomes of the use of different definitions of targets with the current ones. The results can assist policy makers in identifying the optimal policy mix.

Finally, one field for future work that has been identified as relevant and useful for granting insights in designing a policy plan is the investigation of the energy system from a dynamic efficiency point of view. This entails a cost optimisation process using dynamic models which can apply different climate and energy targets over a given period of time. In this way, the innovation and diffusion of low carbon or energy efficient technologies can be achieved in least cost in the longer term.

Furthermore, interventions needed in support mechanisms can be identified by using such approach. Thus, a more realistic and complete image of the future can be reached by using such an approach making policy planning more robust.

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Appendix

A. Additional information on OPERA

A1 Data sources

The database of OPERA draws its input data from the results of the National Energy Outlook Modelling System (NEOMS), which consists of various models that are evaluating different aspects of the energy system. Those models determine the energy use and the corresponding emissions for the Dutch energy system as well as for individual sectors. More specifically, the outcomes include energy demand, supply, emissions, technology uptake, investments, costs, prices, and policy impacts taking into account 22 sub-sectors with all relevant technologies and fuels involved. The sectors and the corresponding models are (ECN, 2013):

For energy demand

- Industry and agriculture (SAVE-Production),
- Service sector (SAVE-Services),
- Households (SAWEC and EVA),
- Transport (TEMPO and/or external inputs).

For energy supply

- Combined heat and power (SAVE-Production),
- Electricity supply (Competes),
- Refineries and oil supply (SERUM),
- Renewables (RESolve-E),
- Gas supply (Gas production).

The outputs of all NEOMS models come together in SELPE[37]. Thereafter, OPERA draws those outputs as input data, especially for the baseline scenario. Next to the baseline, the model offers the user the possibility to further interfere to the input data by adding manually several assumptions such as the availability of potentials[38], restrictions on options etc. (Daniels et al., 2014b). Furthermore, as developments abroad are exogenous, the user can customize them manually as well. However, the import and export of electricity is assumed to be constantly balanced in model's calculations; only a change of the import-export balance and of electricity prices can be calculated (ibid). A flowchart of the interconnections of the described modelling system is presented in Figure 21.

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[37] SELPE model is an optimization model of the total energy system which is responsible for validity and consistency checks on the outcomes of the other models (e.g. total electricity demand does not exceed total electricity supply) (ECN, 2013).

[38] Technical potentials of all kinds of measures are included, such as savings, renewable energy, CCS, but also deployment potentials.

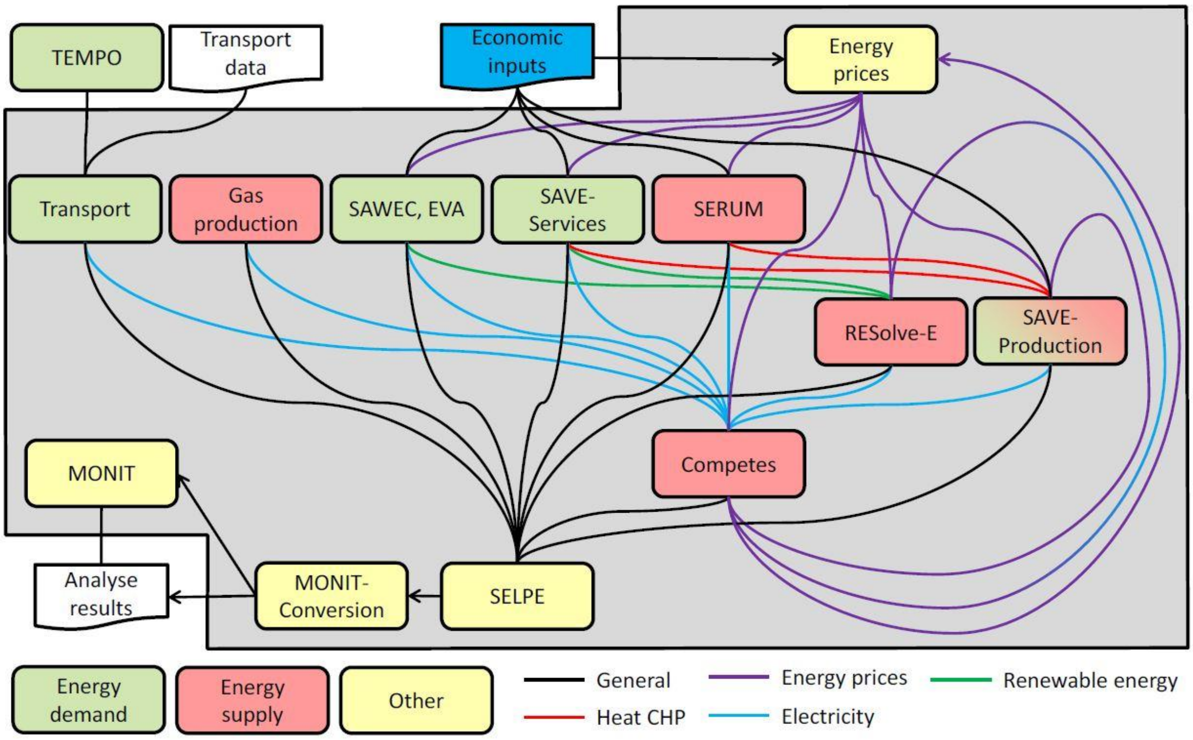


Figure 21: National energy outlook modelling system input data (ECN, 2013)

A2 Infrastructure Representation

Demand can be expressed in different levels throughout the energy system, meaning; for example residential sector consumes low voltage electricity, while industrial sector needs medium or high voltage to operate (Daniëls, Seebregts, et al., 2014). This differentiation among the components of the energy system, highlights the importance to take into account that energy, gas, heat, and electricity are not being consumed on the supply side, but rather they should get transported from supply side to end users through a network which is reliable in transmitting the required energy in order to match the demand at every moment (Daniëls, Seebregts, et al., 2014). To be as much accurate as possible in the representation of the infrastructure, the approach that is followed takes into account energy flows and network capacities.

Electricity network

Electricity network is consisted of three different voltage levels (i.e. high, medium, low). Each level is accompanied with the appropriate supply and demand technologies, as well as with consumption data (based on statistical data). Furthermore, electric transformers were included in the designing of the network so that the electricity to be delivered throughout the system without compromising its security. A limiting factor for the grid is the size of the transformers as it is possible to be lower than needed for the current electricity flow. However, the model can assess this limitation by allowing investments in transformers if the peak demand exceeds existing capacity (ibid).

Gas network

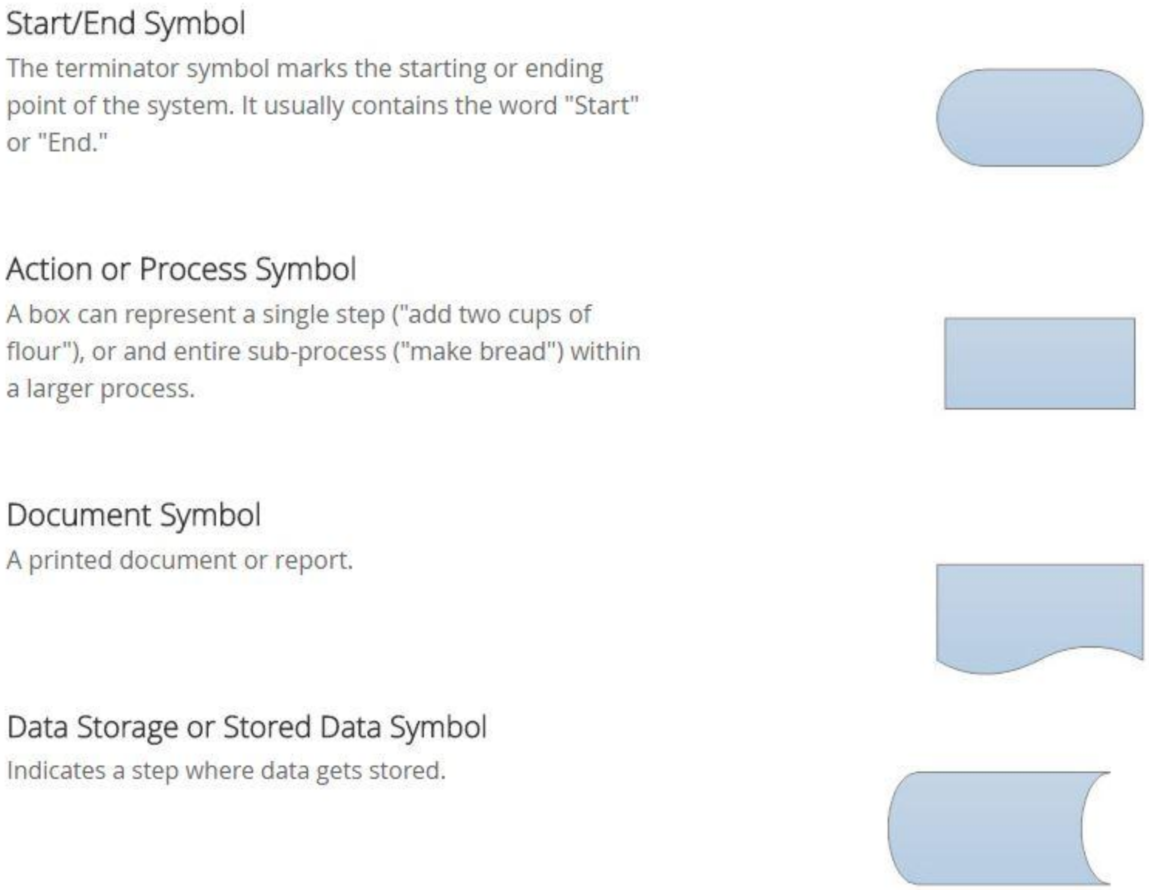
Similarly to the electric network, the natural gas grid is included in the model and is consisted of three different pressure levels (high, medium, low). High pressure grids serve the production facilities, while medium pressure grid and the distribution network (low pressure) serve the end users (Daniëls, Seebregts, et al., 2014). Similar to electric transformers, connectors are included in the design of gas networks, which reduce the pressure from high to low but not the other way around[39]. No additional investment is needed to be taken into account, as higher demand can be met by increased transported quantities of gas. The representation of gas networks compared to the electricity ones is much more straightforward. Any imbalance between demand and supply can be covered by either imports, or domestic supply, or storage (ibid).

A3 Representation of time units and relevant demand and supply profiles

One of the challenges in models like OPERA is to handle supply and demand to match at any moment. The challenge mentioned lies in achieving such thing within computational limits. In OPERA this is done by applying a time slice approach where the 8760 hours of the year are attributed in separate time slices on which certain characteristics are shared (Welle et al., 2014). Briefly, in this approach the hours which share similar characteristics, with respect to the demand and supply of energy, are grouped together formatting a time slice. The more time slices we have, the more detailed resolution the model has.

B. Flowchart symbols

In the following figure (Figure 22), the explanations of the symbols used in the flowchart (in section 3.1), which illustrates the process development are presented.



Start/End Symbol

The terminator symbol marks the starting or ending point of the system. It usually contains the word "Start" or "End."

Action or Process Symbol

A box can represent a single step ("add two cups of flour"), or and entire sub-process ("make bread") within a larger process.

Document Symbol

A printed document or report.

Data Storage or Stored Data Symbol

Indicates a step where data gets stored.

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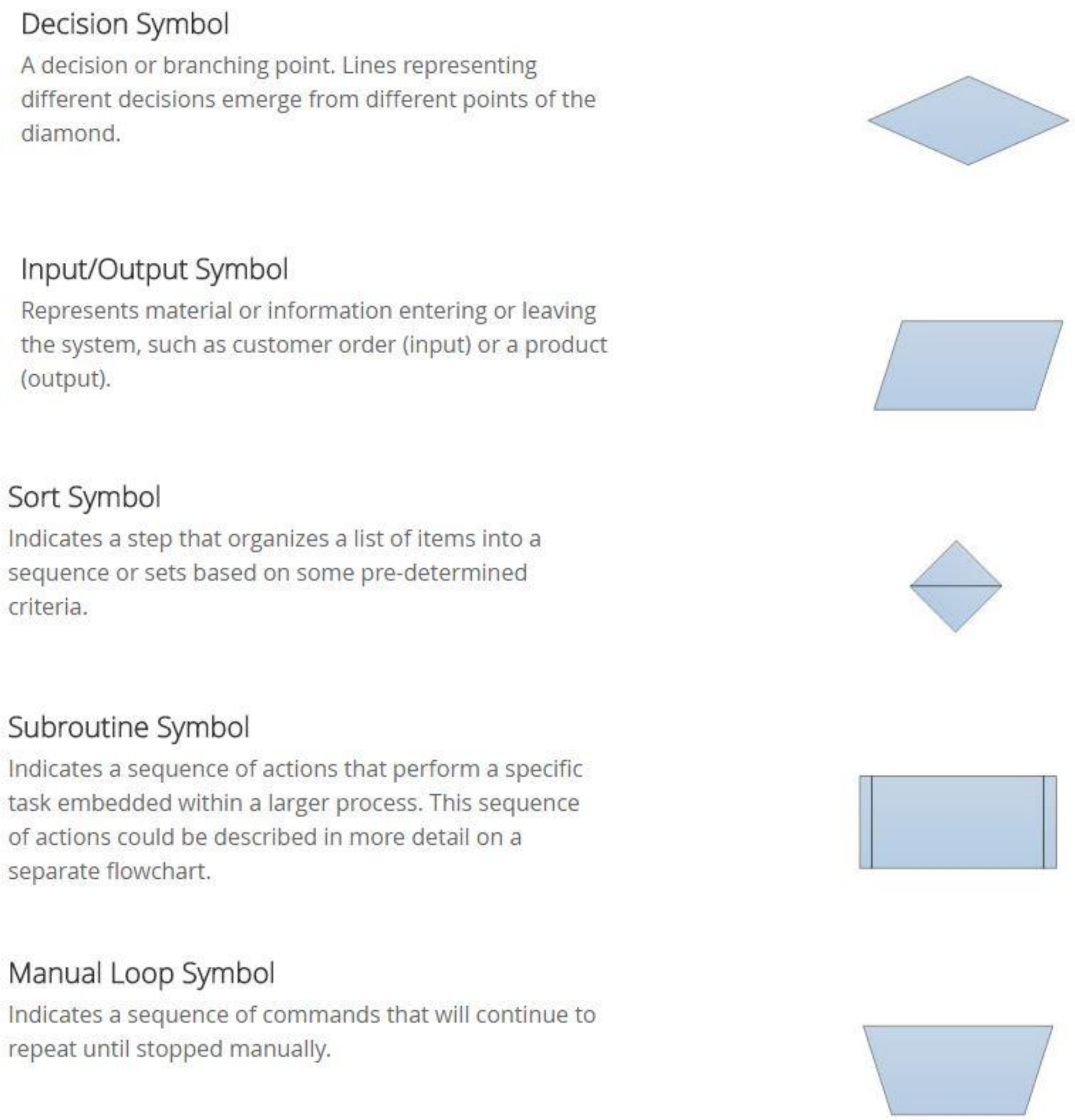
[39] No pressurizing option is modelled as it goes against the quality assurance of gas on the different pressure levels (Welle et al., 2014).



Decision Symbol

A decision or branching point. Lines representing different decisions emerge from different points of the diamond.

Input/Output Symbol

Represents material or information entering or leaving the system, such as customer order (input) or a product (output).

Sort Symbol

Indicates a step that organizes a list of items into a sequence or sets based on some pre-determined criteria.

Subroutine Symbol

Indicates a sequence of actions that perform a specific task embedded within a larger process. This sequence of actions could be described in more detail on a separate flowchart.

Manual Loop Symbol

Indicates a sequence of commands that will continue to repeat until stopped manually.

Figure 22: Flowchart symbols' explanation (Smartdraw, 2016)

C. Complementary graphs of the shadow price development under different scenarios

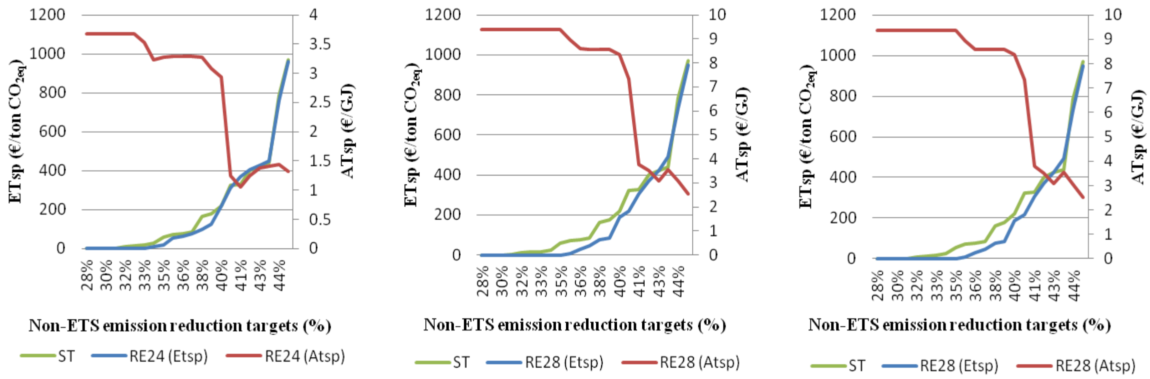


Figure 23: Shadow prices trend over the non-ETS emission targets of ST scenario and RE 24%, 26% and 28% multi target scenarios

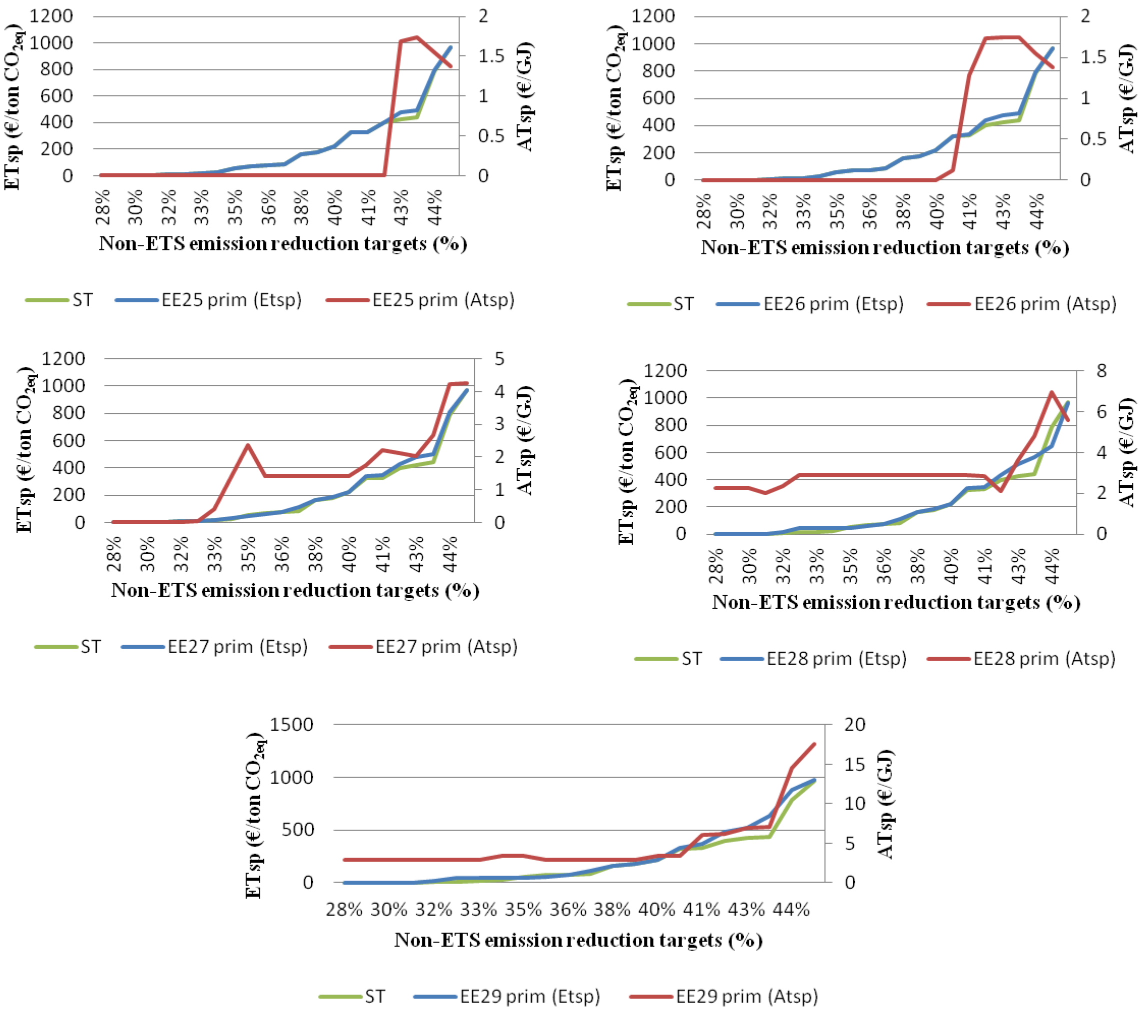


Figure 24: Shadow prices trend over the non-ETS emission targets of ST scenario and EE prim 25%, 26%, 27%, 28%, and 29% (from left to right) multi target scenarios

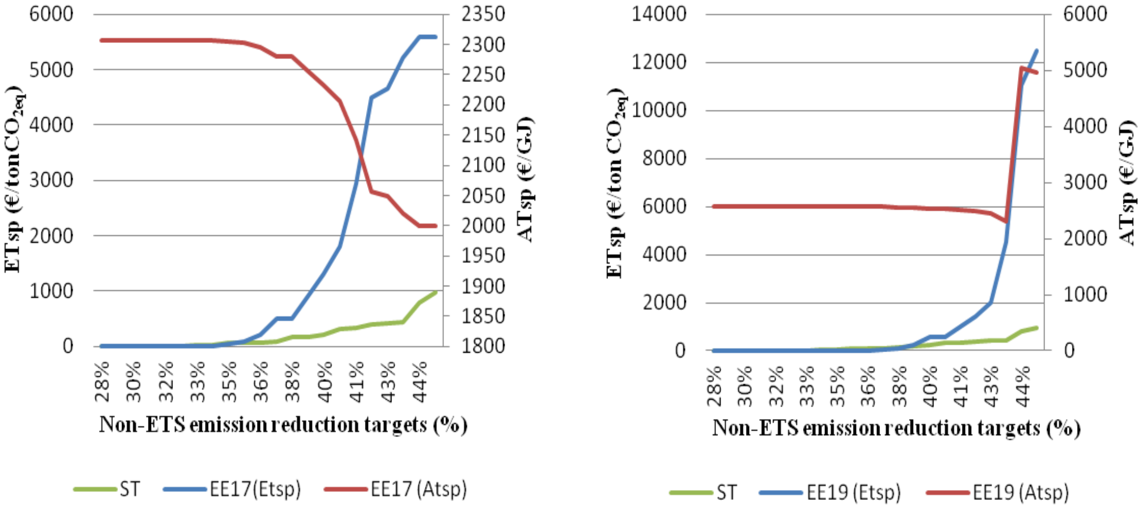


Figure 25: Shadow prices trend over the non-ETS emission targets of ST scenario and EE 17% and 19% multi target scenario

D. Activity development of technologies

In this section we provide all the figures that illustrate the deployment of the technologies that needed to be handled with care for the different scenarios.

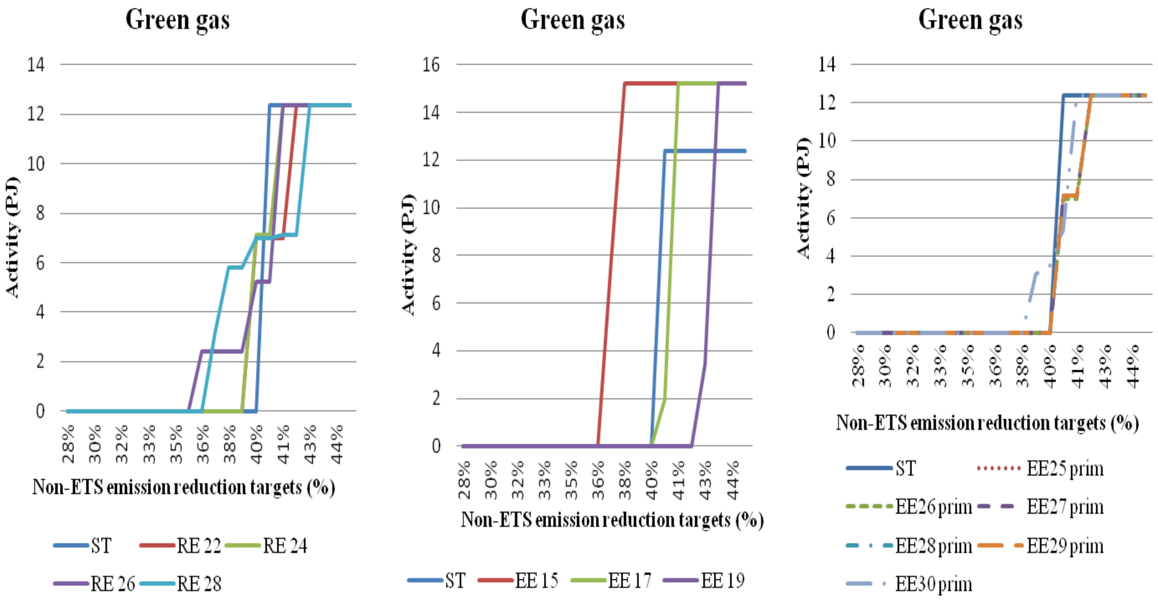


Figure 26: Green gas' activity development over the non-ETS emission reduction targets for the RE, EE, EE prim scenarios (from left to right respectively)

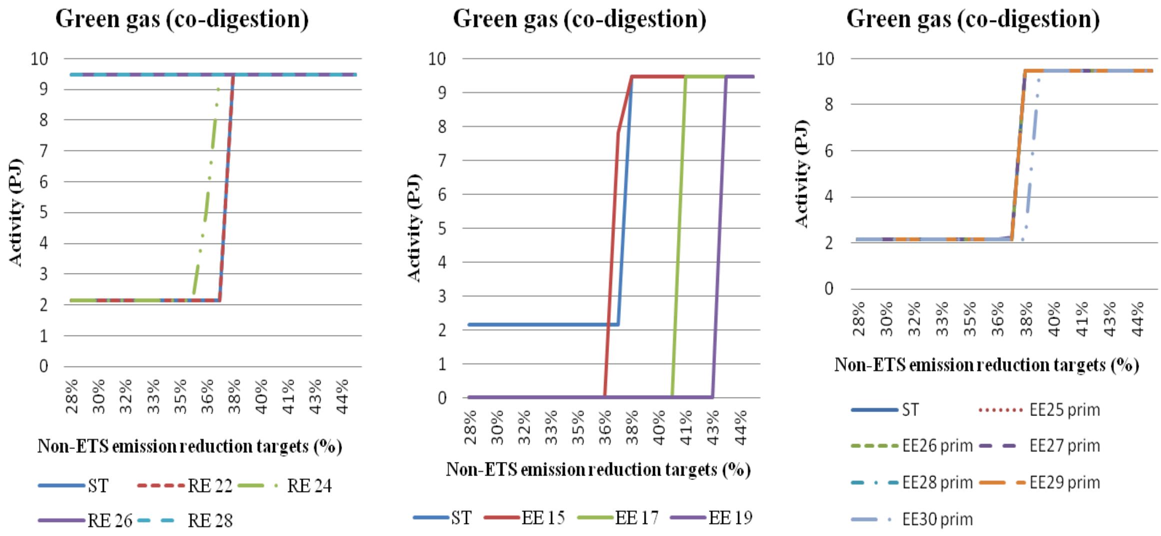


Figure 27: Green gas' (co-digestion) activity development over the non-ETS emission reduction targets for the RE, EE, EE prim scenarios (from left to right respectively)

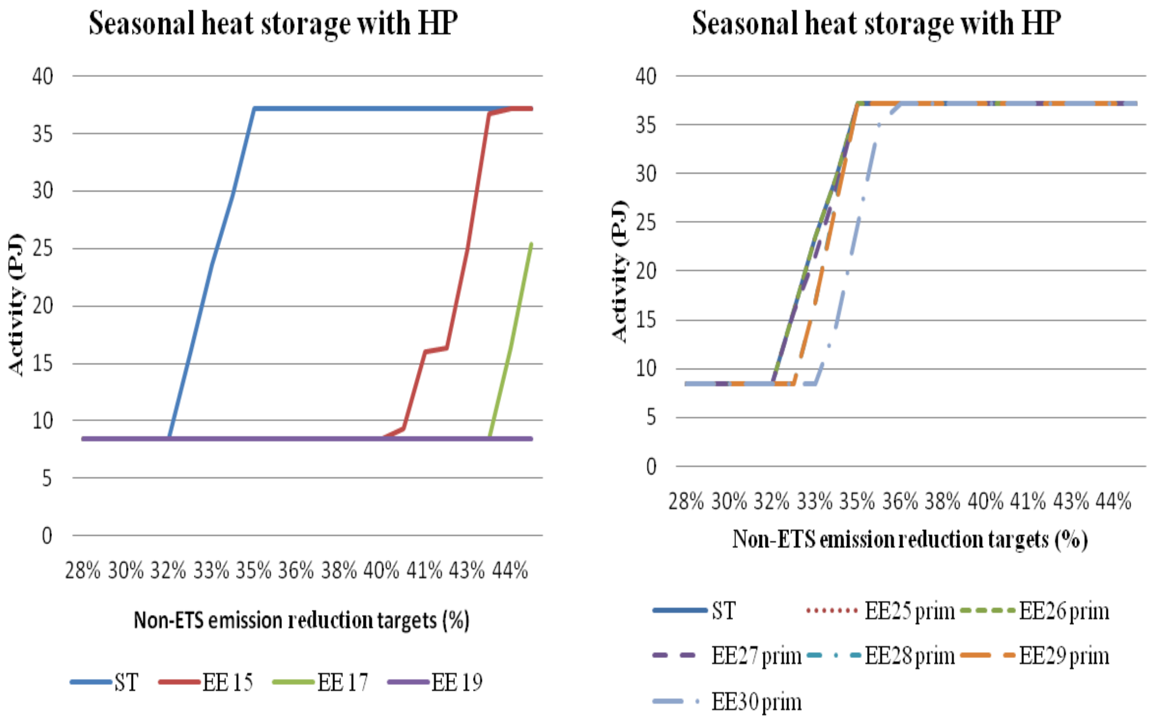


Figure 28: Seasonal heat storage with H.P activity development over the non-ETS emission reduction targets for the EE and EE prim scenarios (from left to right respectively)

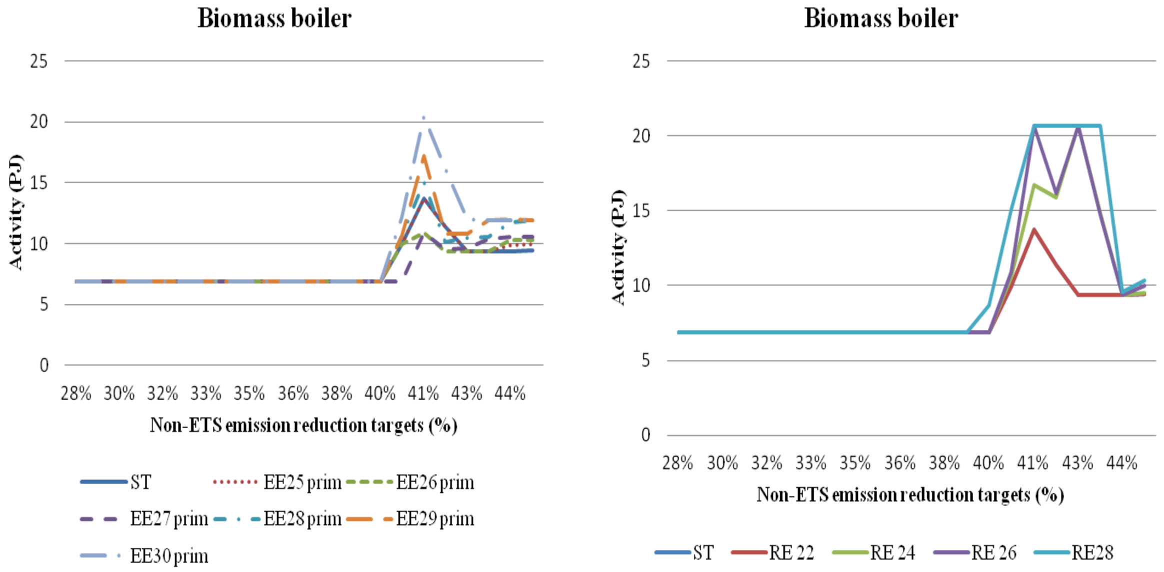


Figure 29: Biomass boiler activity development over the non-ETS emission reduction targets for the EE prim and RE scenarios (from left to right respectively)

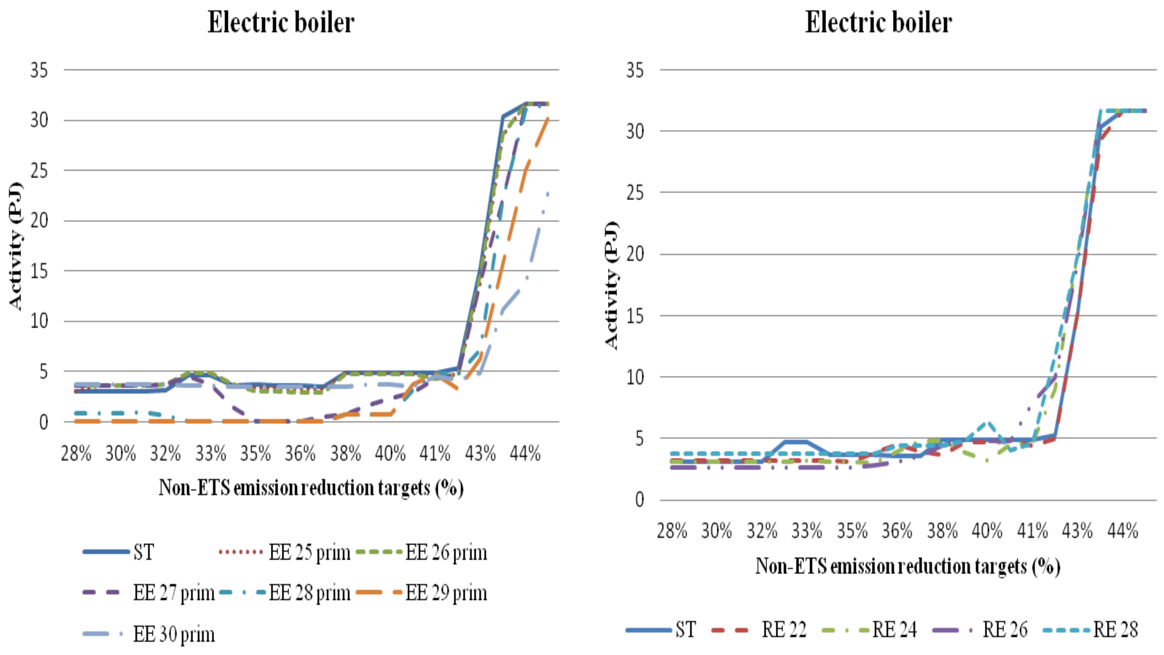


Figure 30: Electric boiler activity development over the non-ETS emission reduction targets for the EE prim and RE scenarios (from left to right respectively)

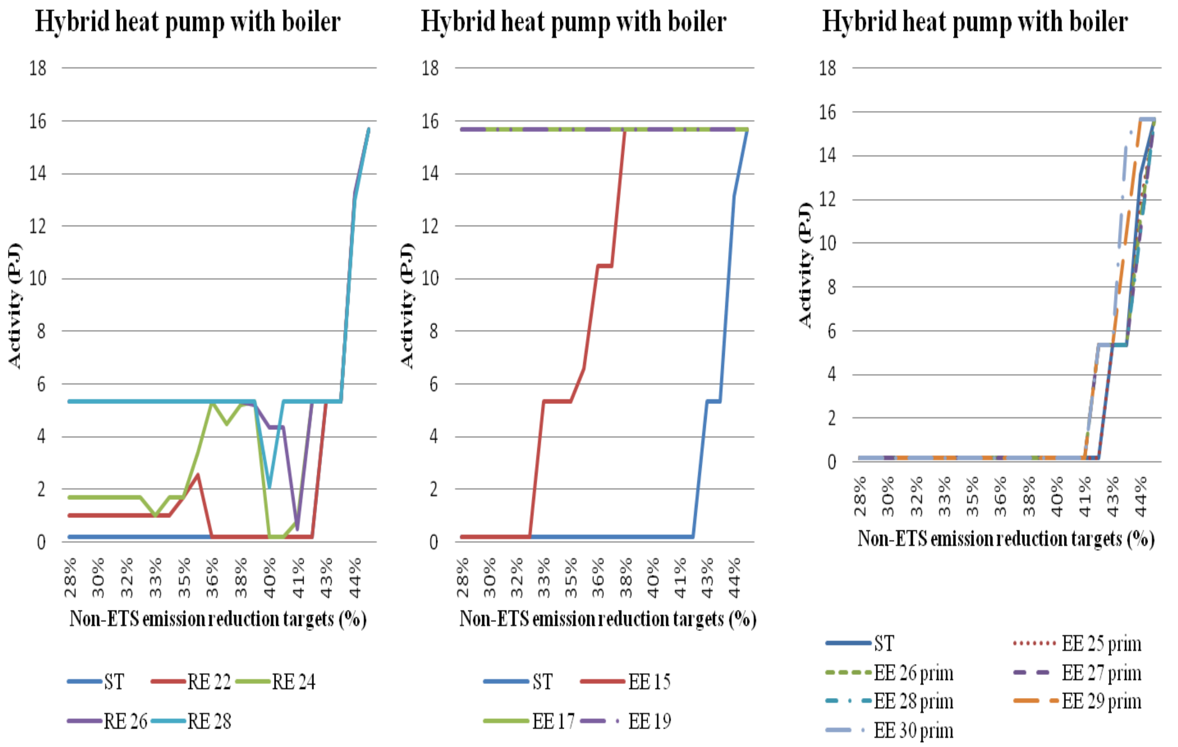


Figure 31: Hybrid heat pump with boiler activity development over the non-ETS emission reduction targets for the RE, EE, EE prim scenarios (from left to right respectively)

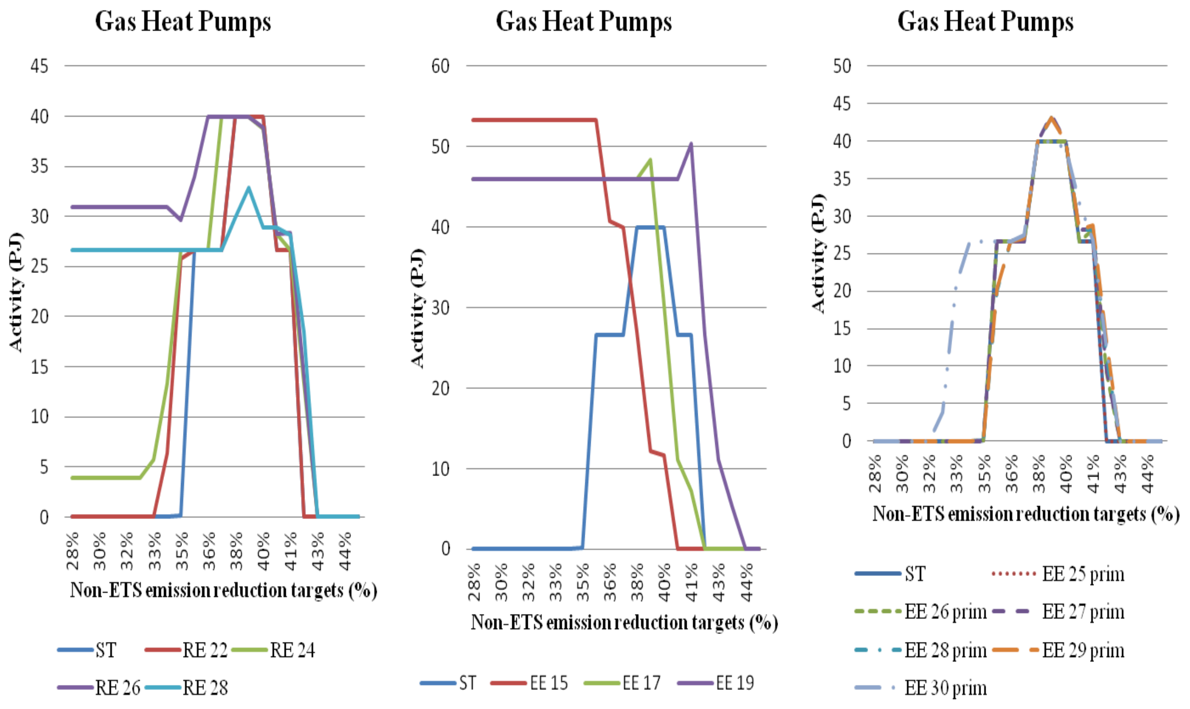


Figure 32: Gas heat pump activity development over the non-ETS emission reduction targets for the RE, EE, EE prim scenarios (from left to right respectively)

E. Cost effectiveness estimation of technologies

Under this section the graphs of the cost development of the assessed technologies under the different scenarios are presented.

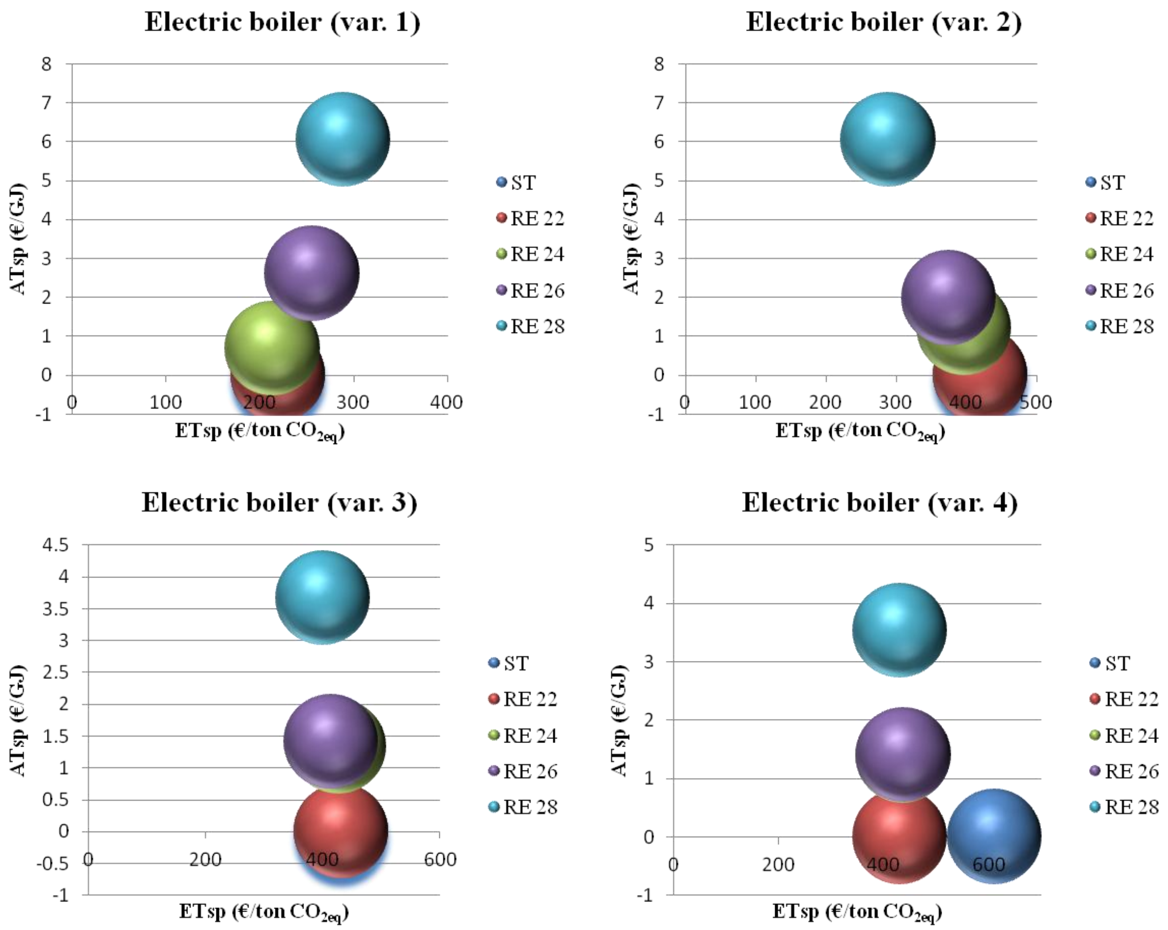


Figure 33: Electric boiler (all variants) cost development under RE scenarios as compared to the ST scenario

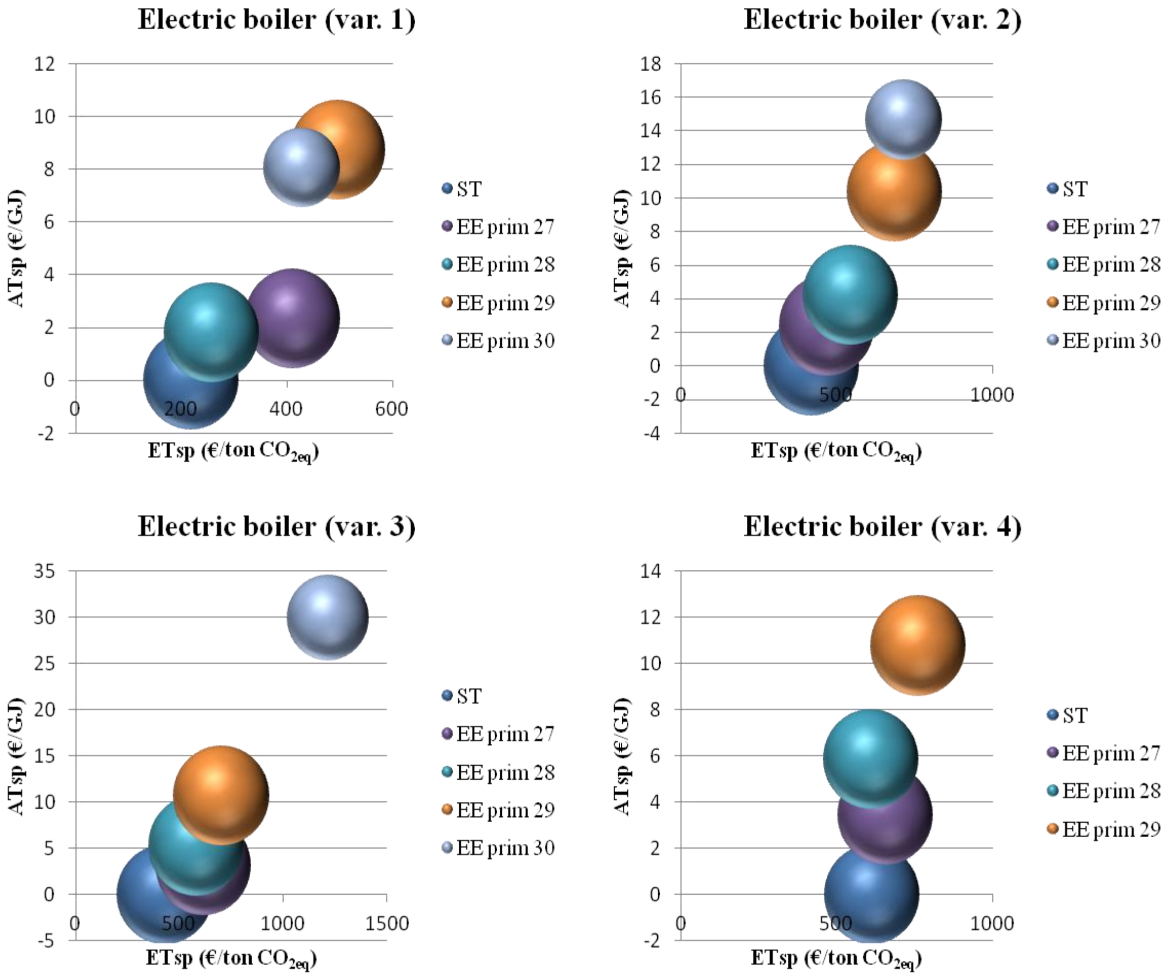


Figure 34: Electric boiler (all variants) cost development under EE prim scenarios as compared to the ST scenario [variant 4 is not part of the solution in EE prim 30%]

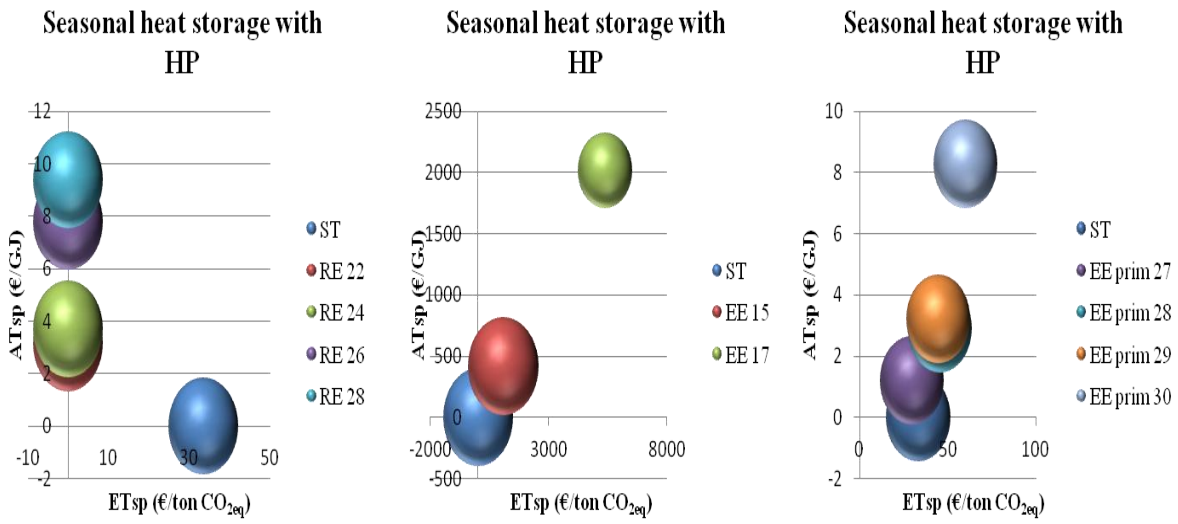


Figure 35: Seasonal heat storage with H.P. cost development under RE, EE, and EE prim scenarios (from left to right respectively) as compared to the ST scenario [the option is not part of the solution for EE 19%]

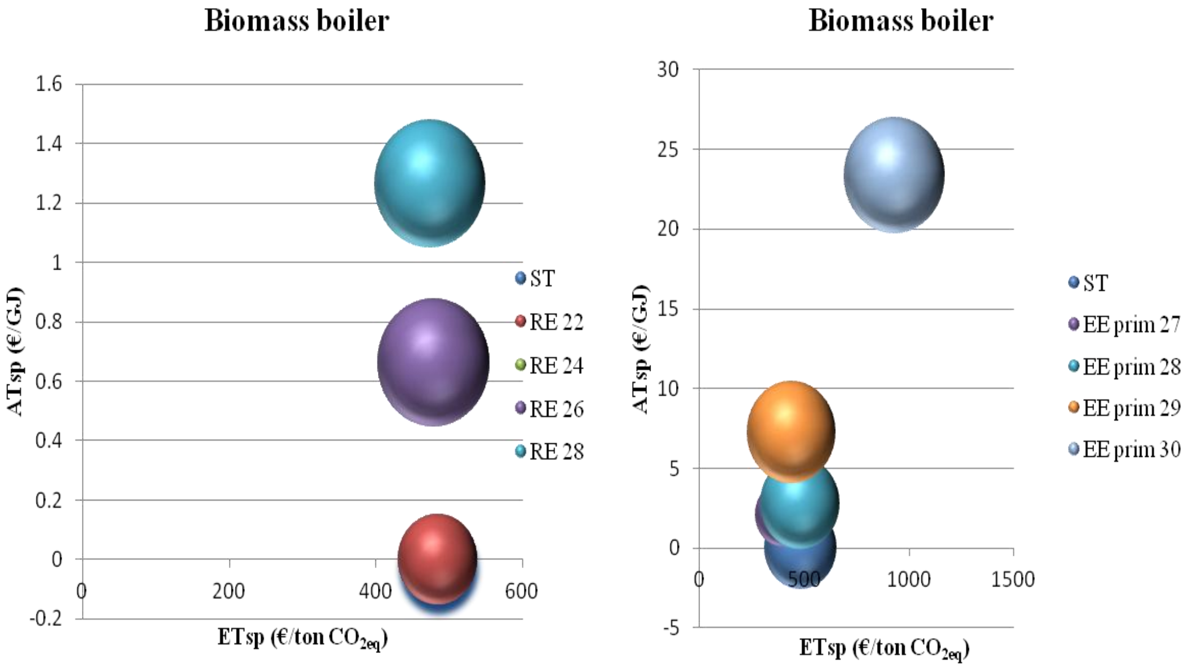


Figure 36: Biomass boiler cost development under RE and EE prim scenarios (from left to right respectively) as compared to the ST scenario

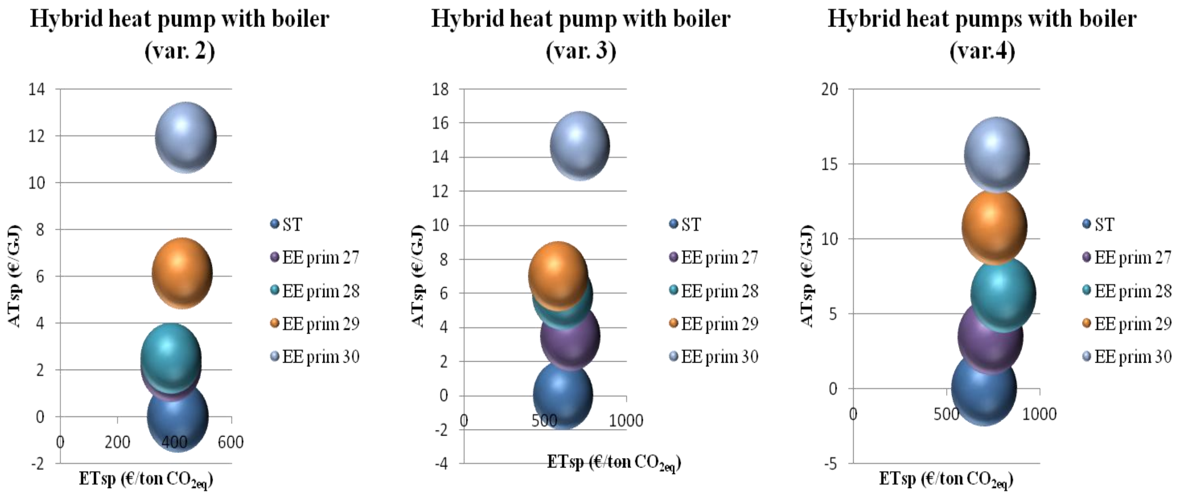


Figure 37: Hybrid heat pump with boiler (all variants) cost development under EE prim scenarios as compared to the ST scenario

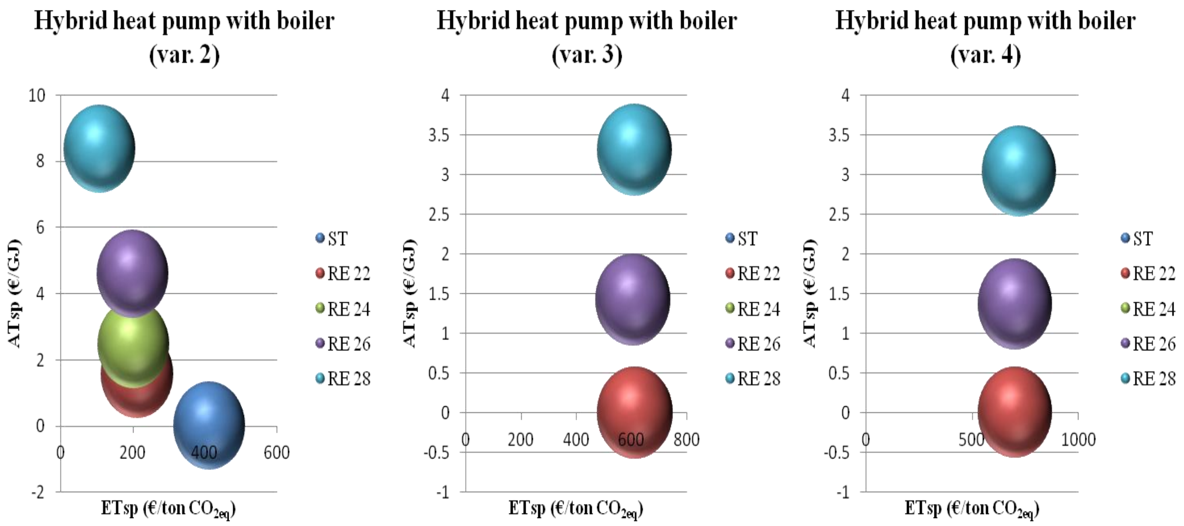


Figure 38: Hybrid heat pump with boiler (all variants) cost development under RE scenarios as compared to the ST scenario

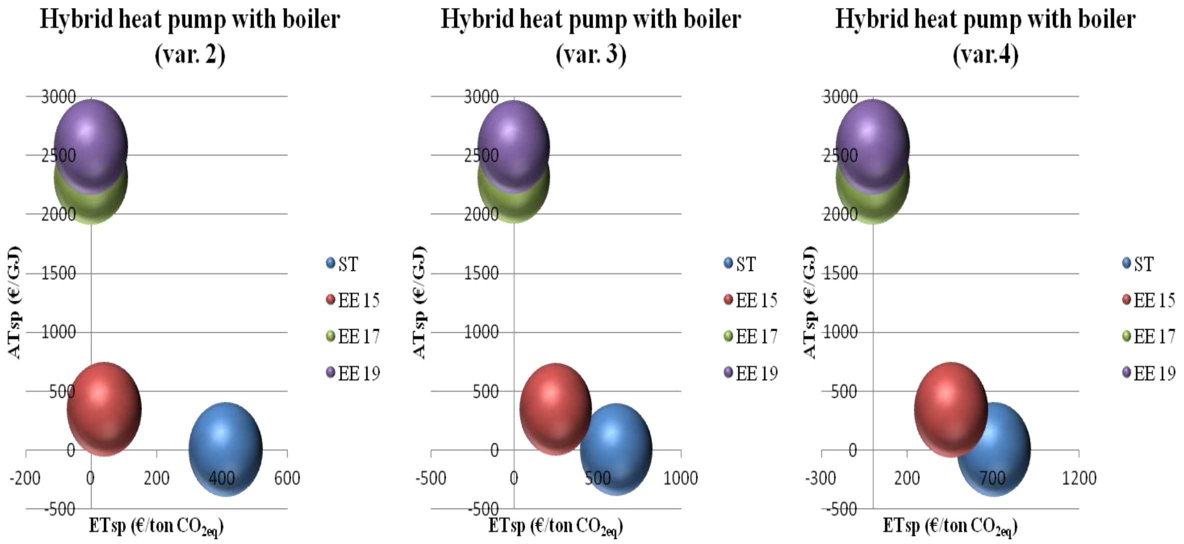


Figure 39: Hybrid heat pump with boiler (all variants) cost development under EE scenarios as compared to the ST scenario

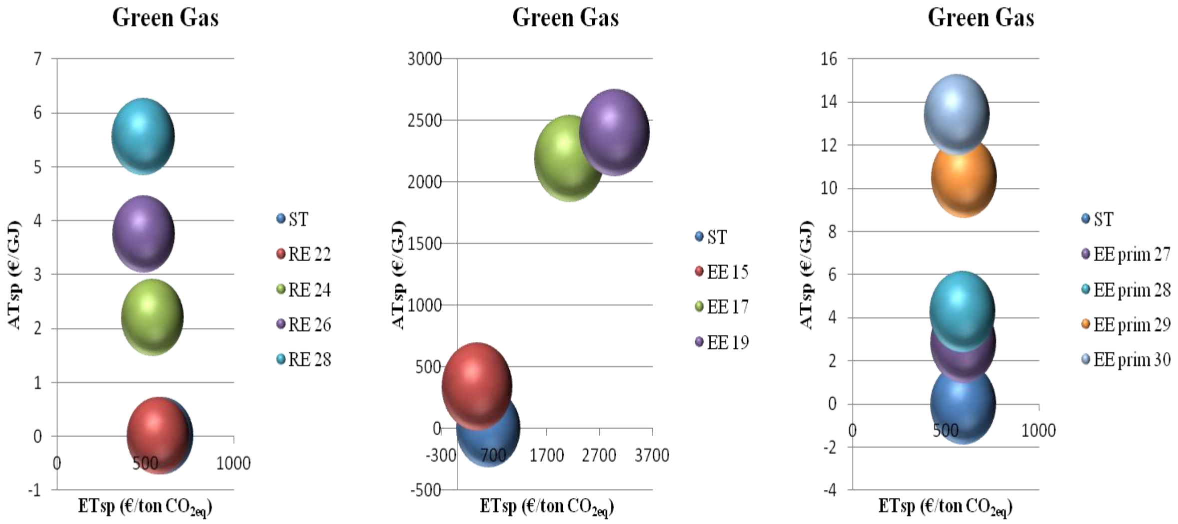


Figure 40: Green gas cost development under RE, EE, and EE prim scenarios (from left to right respectively) as compared to the ST scenario

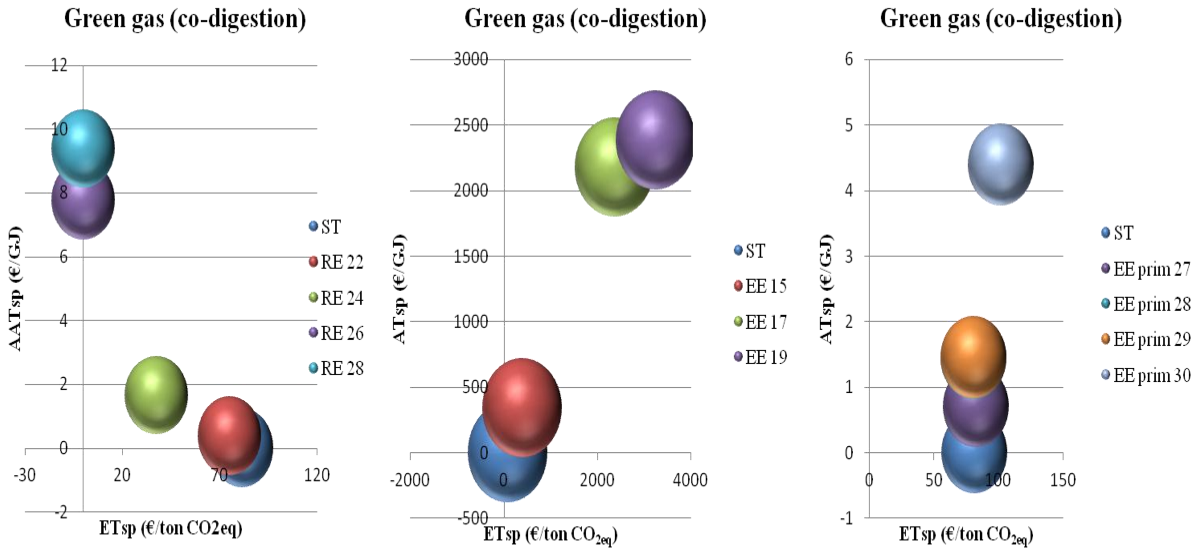


Figure 41: Green gas (co-digestion) cost development under RE, EE, and EE prim scenarios (from left to right respectively) as compared to the ST scenario

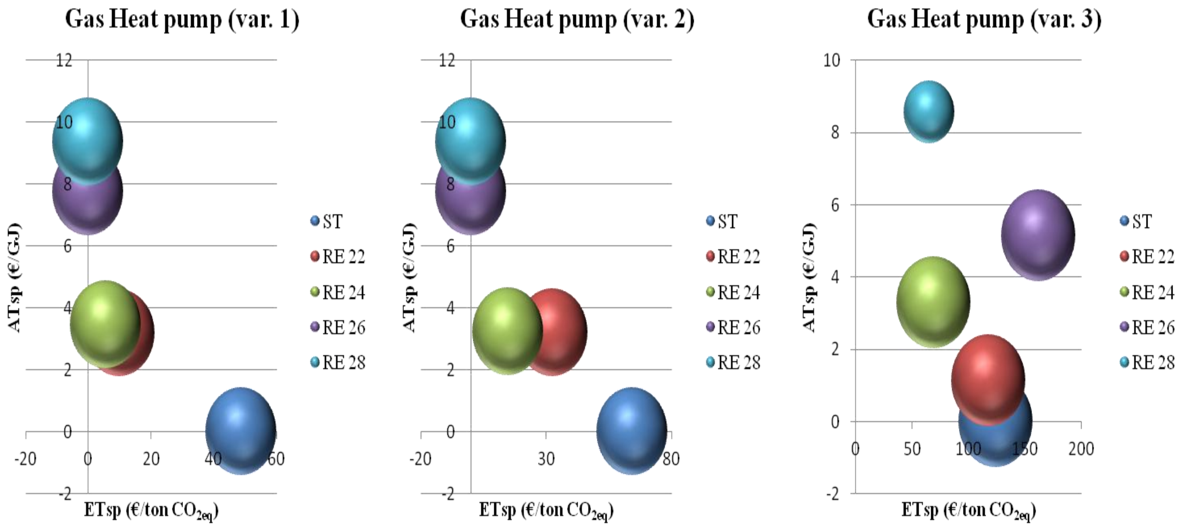


Figure 42: Gas heat pump (all variants) cost development under RE scenarios as compared to the ST scenario

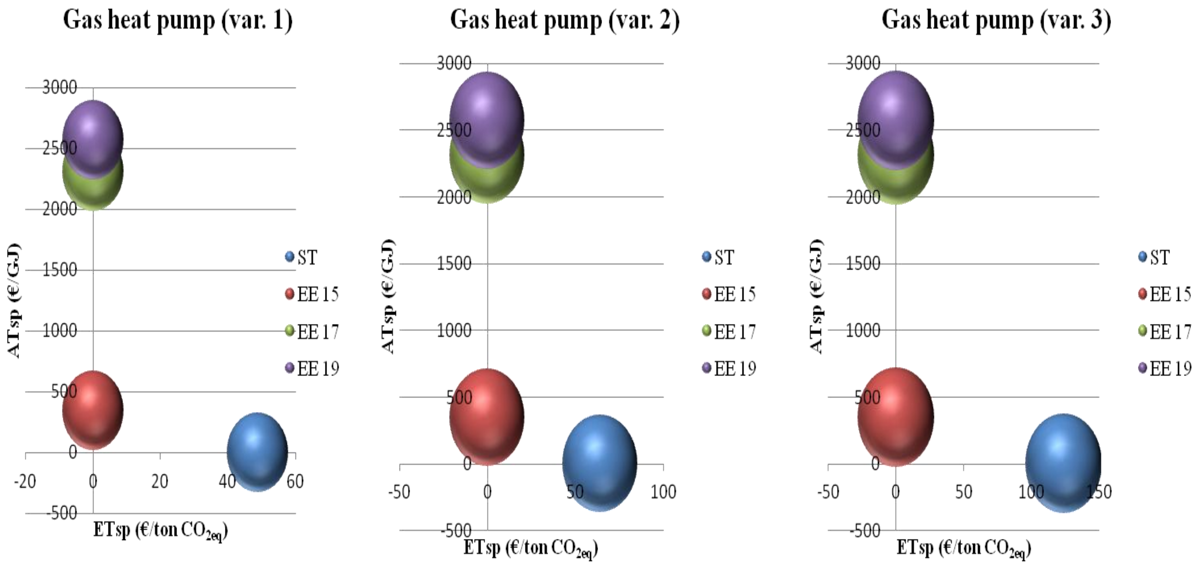
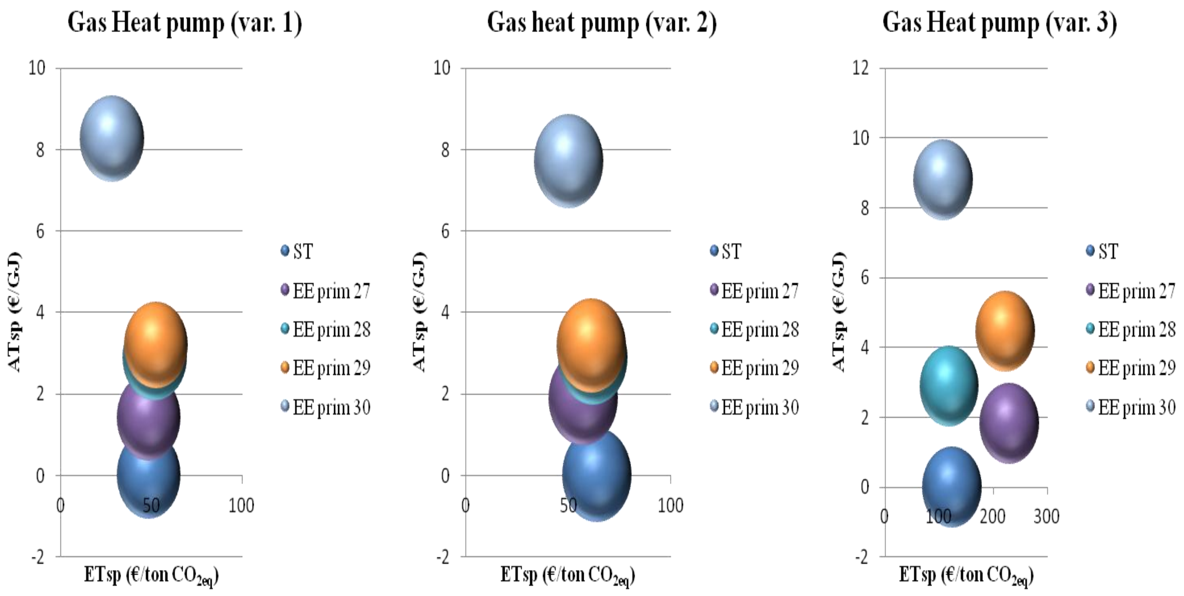


Figure 43: Gas heat pump (all variants) cost development under EE scenarios as compared to the ST scenario

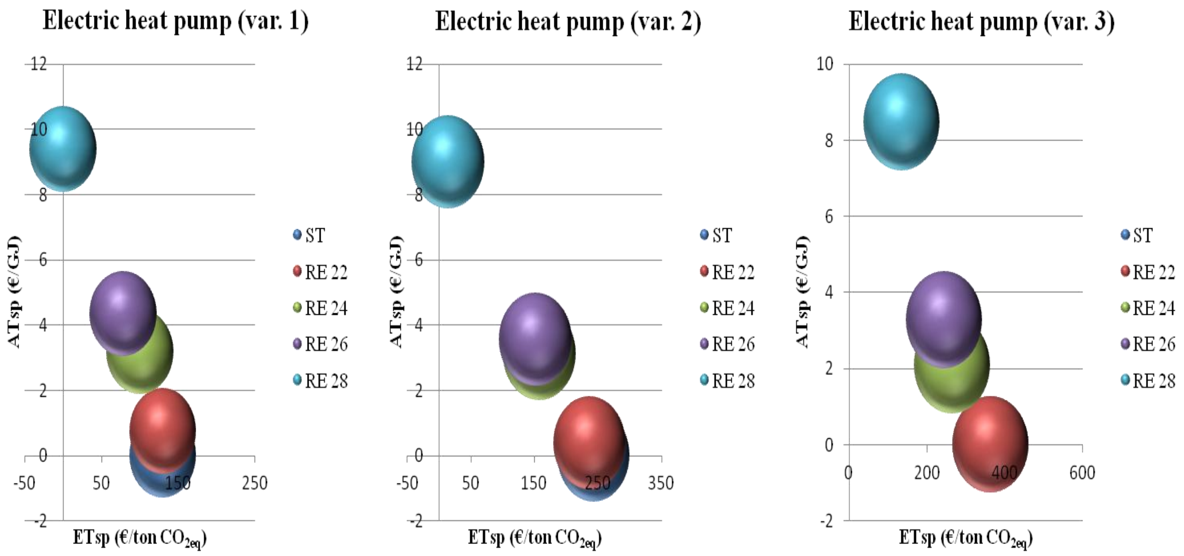


Gas Heat pump (var. 1)

Gas heat pump (var. 2)

Gas Heat pump (var. 3)

Figure 44: Gas heat pump (all variants) cost development under EE prim scenarios as compared to the ST scenario



Electric heat pump (var. 1)

Electric heat pump (var. 2)

Electric heat pump (var. 3)

Figure 45: Electric heat pump (all variants) cost development under RE scenarios as compared to the ST scenario

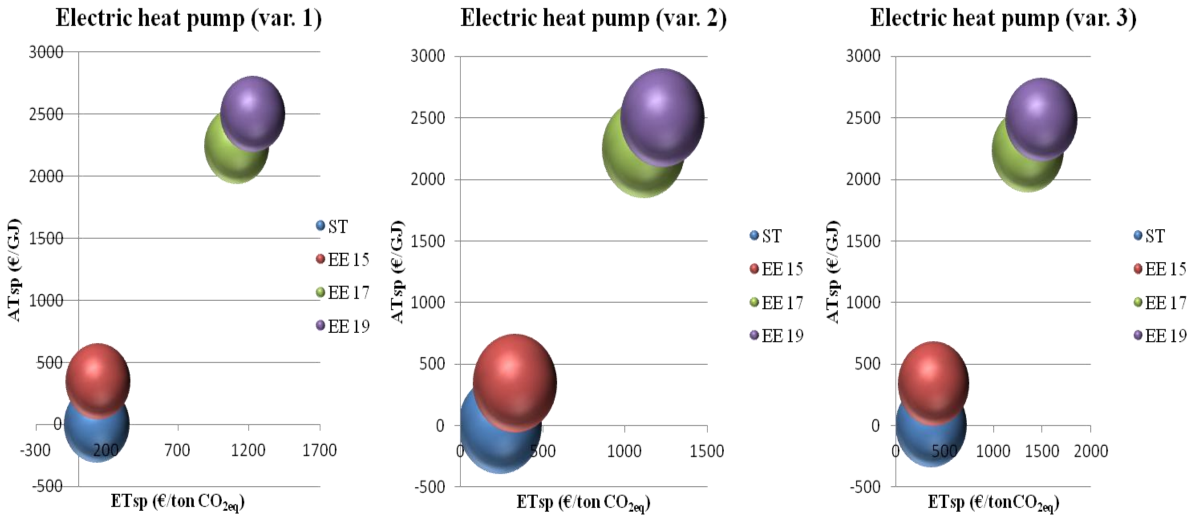


Figure 46: Electric heat pump (all variants) cost development under EE scenarios as compared to the ST scenario

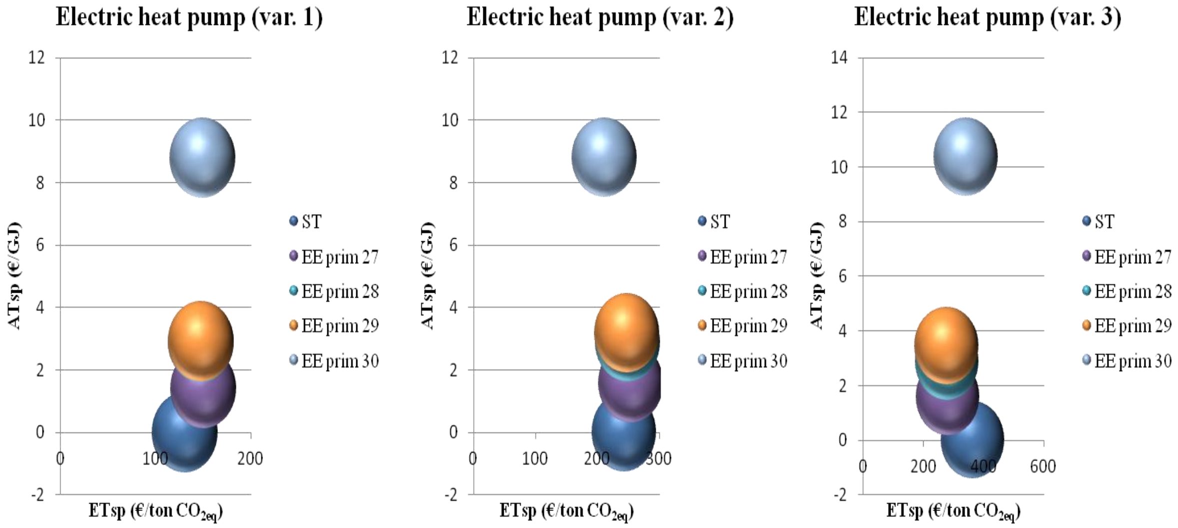


Figure 47: Electric heat pump (all variants) cost development under EE prim scenarios as compared to the ST scenario