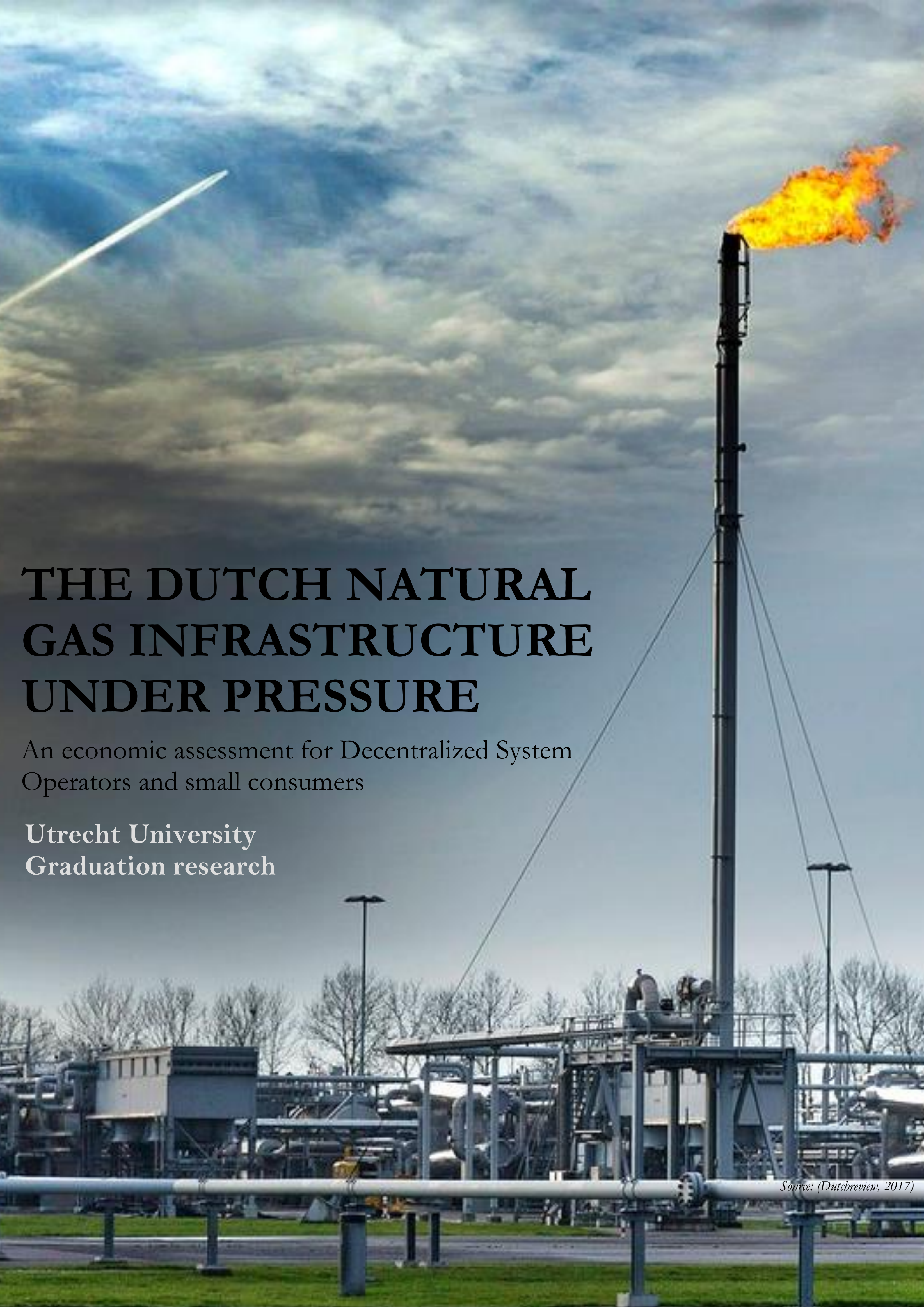

Source: (Dutchreview, 2017)

THE DUTCH NATURAL GAS INFRASTRUCTURE UNDER PRESSURE

An economic assessment for Decentralized System Operators and small consumers

Utrecht University
Graduation research

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ABSTRACT

The Netherlands holds a unique natural gas infrastructure, subdivided in a low- and high-calorific system. Where the low-calorific natural gas is predominantly extracted domestically and is supplying 93% of the built environment. Studies have shown that if decarbonization pathways are taken seriously, low pressure natural gas networks should be mostly abandoned by 2050. However, in recent years significant investments in this natural gas infrastructure have continuously been made, subsequently causing decommissioning of the associated infrastructure in the coming decades. The infrastructure is accountable to Decentralized System Operators (DSOs) which, due to the socialization of the infrastructure, are monitored via a regulatory organization that ascertain comprehensive measures to ensure a DSO will comply its core task: Provide accessibility of a reliable local natural gas infrastructure and transport with respect to efficient costs.

DSOs are unbiased actors and must comply with the accessibility of desired infrastructure. Therefore, this research assesses the economic consequences for DSOs when there is a forced decommissioning of connections within the built environment between the period 2018 and 2050. Results have shown a significant increase for the EI (EI) till 2050 and additional SA (SA) for all DSOs, arising from the natural gas decommissioning.

The EI is divided in four components (decommissioning-, removal-, depreciation- and operational and maintenance costs) and are, due to the socialization, recalculated every five-year to the fixed annual tariff per remaining natural gas connection. From the Regulation Monopoly Model, the best-case results indicate that if zero emissions in 2050 are desired, the EI costs will grow at least with a factor 27 compared to 2018. The SA are estimated via the remaining book value of the infrastructure after 2050, with overall costs varying between 0.5 and 5 billion euros (depending on the type of scenario and strategy that is utilized).

Other findings indicate a strong correlation among EI and SA is seen in relation to the decommissioning of the natural gas infrastructure. When the reduction of connections is increased, an accompanied increase in the EI and SA is evident. Additionally, the current regulation methodology has shown to be an important variable regarding the SA, and causes a mutual relation among both EI and SA. Including additional SA estimated around four billion euro. Concluding that if DSOs will retain the current regulation it cannot endure the future development of EI and SA, since DSOs are obliged to provide a reliable, safe and cost-efficient infrastructure.

Key concepts:
Decommissioning, Natural Gas Infrastructure, Economic Impact, Stranded Assets, Utilities Death Spiral, Regulation Monopoly Model

PREFACE

The graduation research you are currently reading, entitled as 'The Socialized Natural Gas Infrastructure', has been carried out for Utrecht University and Accenture Transmission & Distribution (U&D). I performed this graduate research as part of the Master Program Energy Science for a period of five months (February 2018 till July 2018), combined with an internship at Accenture T&D.

My interest for this research topic has grown in the last two years. During my bachelor thesis I became more aware about the challenges we face regarding the decarbonization, especially within the built environment. A topic that is currently heavily debated within society and politics. In my previous internship at the Ministry of Economic Affairs and Climate policy, I noticed that the current natural gas infrastructure is a complex system which is not simply decommissioned without feeling burdens on several facets. Conducting this graduation research, I made a first attempt to further explain and quantify these consequences from an economic perspective, as lays right in front of you.

I hope you will enjoy reading this research. Feel free contacting me for any additional questions.

Jaap de Keijzer
Amsterdam
July 15th 2018

ACKNOWLEDGEMENT

There are several people that I want to thank for their support and contribution regarding this research. Thanks to them, this study reached my preceding posed expectations. First, I would like to thank my Utrecht University supervisor Robert Harmsen for the discussions we have had and feedback he provided on the delivered products. Secondly, I would like to thank Jip Tombrink and Hidde Ooststroom, my supervisors at Accenture T&D. In special, I would want to show my appreciation to Jip. During our meetings, Jip provided critical feedback and guidance on the further development of my research. Something, which ended up as an instructive added value for me. Finally, I would like to thank the other Accenture T&D employees and interviewees for the meetings and conversations. Each and one of them positively contributed, reaching the level of research as it is now.

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List of abbreviations

ACM	Authority Consumer & Market
BE	Built Environment
CO_2	Carbon dioxide
DG	Distributed Generation
DSO	Distribution System Operator
EE	Energy Efficiency
EI	Economic Impact
G-gas	Groningen gas (= low calorific natural gas)
O&M	Operational & Maintenance
RMM	Regulation Monopoly Model
SA	Stranded Assets
TSO	Transmission System Operator
UDS	Utilities Death Spiral

1. INTRODUCTION

1.1 BACKGROUND

The last decade witnessed significant growth in awareness for greenhouse gas emissions, global warming and fuel scarcity (Messaoudani, Rigas, Binti Hamid, & Che Hassan, 2016). Since 1970 the concentration of greenhouse gases increased from 320 parts per million (ppm) to 445 in 2015 (European Environment Agency, 2015), which implies that the long-term probability of the global average temperature exceeding 1.5 °C above pre-industrial levels is already about 50% (ibid). This, amongst other things, has led to the Paris Agreement that was signed by 195 countries to comply with the long-term climate targets and to prevent our world from catastrophically changes that affect our current living conditions (UNFCCC, 2015).

The Paris Agreement has been translated within the European Union to country specific climate targets and regulations. For the Netherlands the climate goals are set for 49% greenhouse gas emissions reduction in 2030 (Rutte, van Haersma Buma, Pechtold, & Segers, 2017, p. 37) and between 80-95% in 2050 compared to the 1990 levels (SER, 2014). Yet, in 2016 the share of renewable energy generation for the Dutch energy system was 5.9% (CBS, 2017), as a consequence it is perceived that following this path will not result in compliance with the long term climate targets (PBL, 2017). Assessing the Dutch energy system, it is unequivocal that natural gas is the largest energy carrier (ECN, 2017a, p. 7), which is accompanied with a relative high carbon intensity (Khan, Jack, & Stephenson, 2018).

Speirs et al. (2017) state that natural gas is unlikely to be compatible with climate change goals in countries with ambitious climate targets given the carbon dioxide producing during combustion. Substantiated by the Committee on Climate Change (2008) and Steinberg et al. (2017) which entitle that country level emissions abatement scenarios, particularly in regions with high reliance on gas for heating, typically demonstrate a reduced role for natural gas networks in the future. Therefore, it is likely that the current Dutch energy supply must be adjusted from fossil to renewable (ibid). Even though neighbouring countries such as Germany and Belgium are devoting their transition to a renewable energy system by focussing on natural gas for their small connections, utility and electrical powerplants (Wiebes, 2018b). Additionally, the Dutch natural gas infrastructure is split up in two systems, a low calorific[1] (so called G-gas) and high calorific[1] natural gas. The G-gas system extracts predominantly its natural gas from Groningen, while the high calorific natural gas originates mainly from neighbouring countries, the North Sea and small Dutch extraction reservoirs (Correljé, 2011). However, apart from the climate issues, onwards 2012 the extraction of the G-gas from Groningen caused earthquakes and turned in a joint social resistance and hurdles to political decision makers (Berg, 2017). Which, amongst other, has led to a forced reduction of natural gas been laid down in the coalition agreement (Rutte et al., 2017).

The G-gas infrastructure currently supplies 17.4 billion m^3, using 130 thousand kilometer of pipelines (Brouns, 2017), of which the built environment holds the largest share of 93% (ECN, 2017b), corresponding with 7.19 million connections (Netbeheer Nederland, 2018). For the small industry connected to this low-calorific infrastructure, government statements force either a change in their energy carrier or decommission from the low-calorific natural gas infrastructure (Van Hout & Koutstaal, 2015; Wiebes, 2018a). The built environment remains questionable which direction it will take for reducing the natural gas demand. But if the built environment desires zero emissions in 2050, a transformation of roughly 200,000 connections per year is required (Rutte et al., 2017; Stedin, 2018). At this moment, natural gas connections are merely decoupled when the economic lifetime of the infrastructure expires, and therefore the economic relevance still outperforms the intrinsic value of preventing climate change. An accelerated decommissioning of the

[1] Low-calorific (G-gas) refers to natural gas extracted from the gas fields in the province of Groningen. These reservoirs contain approximately 10% nitrogen which causes a lower calorific value (43.5 – 44.4 MJ/m^3) compared to other extraction points (high calorific value natural gas: +/- 45.3 MJ/m^3).

existing connections is inevitable for reaching the climate-targets (Rutte et al., 2017), however this is accompanied with an increasing underused natural gas infrastructure before its economic lifetime has expired (NetbeheerNederland, 2017).

This shift, encouraged by the Dutch government, to decommission the natural gas demand in the built environment will affect the existing natural gas infrastructure. Where more flexibility regarding multiple types of gases that will flow through the grid (Weidenaar, n.d.); increased monitoring of the quality of the grid (ibid) and long-term thinking for minimizing the economic long-term impact of their assets is required. The latter option is currently widely embraced in literature. Van der Vleuten (2018); Caldecott, Harnett, & Cojoianu (n.d.) emphasize it is evident that fossil fuels and infrastructures demonstrate the sector most likely to be affected by stranding assets (SA). SA are defined as the remaining book value of assets substituted before the end of their anticipated economical lifetime and without recovery of any remaining value to achieve 2050 decarbonization targets (IRENA, 2017, p. 14). More specific, emphasis is placed on SA for the natural gas infrastructures. CAT Decarbonisation Series (2017) states that even though natural gas played an important role in modestly improving carbon intensity over the last decade, it is not a viable long-term solution to mitigating climate change. Dodds & McDowall (2013) and Speirs et al. (2017) studied the UK decarbonization pathways, and suggested that from an economic perspective the low-pressure gas pipeline networks should be mostly decommissioned by 2050 or reused by alternative technologies to prevent SA. Furthermore, US-GAO (2014) assessed the SA from a general perspective including process from extraction till distribution. In other words, if the Paris Agreement is taken seriously, new investment in fossil fuel infrastructures should be avoided (IRENA, 2017, p. 6).

Besides SA likewise Economic Impact (EI) could occur which affect both the Distribution System Operators (DSOs) and connected consumers. DSOs are accountable for the Dutch natural gas infrastructures and are attributed to ensure a safe, secure and cost-effective infrastructure (ACM, 2017d). Since most infrastructures cause economies of scale, it could limit the prospects for effective competition, often entitled as monopolies (BIS, 2011, p. 3). A monopoly is obliged to follow the regulation compiled by an impartial party, to ensure an inter-temporal cost growth at some lower rate than an unregulated firm would deliver (Simshauser, 2017). These prerequisites will likely influence the monetary assets over time. The Utilities Death Spiral is a theory that explains how a monopoly that is socialized could be economically affected due to changing behaviors in the market, by focusing on the fixed tariff payed by the connected consumer. To understand the relation among both EI and decommissioning, this theory is put into service. Literature, on this matter, predominantly addresses the electricity market (Costello & Hemphill, 2014; Eid, Reneses Guillén, Frías Marín, & Hakvoort, 2014; Hemphill, R., Costello, n.d.; Simshauser, 2017) and no literature is found pertaining the natural gas infrastructure. However, both electricity- and natural gas possess the same structure regarding regulation and function as monopolist (ACM, 2017a). Therefore, the similarities within the assembled components of the Utilities Death Spiral could introduce a new spectrum for analyzing the natural gas infrastructure.

1.2 PROBLEM DEFINITION

As section 1.1 appoint, it is apparent that decommissioning of the natural gas infrastructure is caused by the overarching climate change dilemma, which subsequently affect both SA and EI for DSOs.

DSOs are responsible for the local natural gas infrastructure and are obligated to provide accessibility of a reliable infrastructure and transport with respect to efficient costs (ACM, 2017d). However, the DSO business model, in which financial viability is based on economies of scale and long-term cost recovery of investments in physical infrastructure, makes utilities reluctant to abandon infrastructure with decades of remaining useful life (Graffy, 2014).

Due to the necessity to reduce the natural gas usage within the built environment, the latter responsibility will affect DSOs and likely the consumers since the natural gas infrastructure is socialized (NetbeheerNederland, 2017). The multitude of renewable substitutes for the existing natural gas infrastructure and the plausible EI, causes that DSOs and other related actors need more insight in suitable development options for the current natural gas infrastructure (Weidenaar, n.d.). Which is substantiated by McCauley (2018) who state that the substantial costs for the unforeseen size of investment needed for the large scale decommissioning of fossil fuel and other undesirable future energy infrastructures is often overlooked.

Therefore, research is required on the magnitude of EI and SA for DSOs when a transformation is deployed for committing to the long-term climate goals. Such transformation is defined as a forced reduction of natural gas connections within the built environment for the low-calorific natural gas infrastructure towards zero in 2050.

1.3 RESEARCH QUESTIONS

Based on the outlined problem, the following research question will be answered:

What are the Economic Impact and Stranded Assets for DSOs when the existing Dutch natural gas infrastructure for the built environment is decommissioned in an early stage of its lifetime?

To answer this research question, the following sub-questions are posed:

- What is decommissioning of the natural gas infrastructure in the built environment?
- What is economic impact and how is it measured?
- What are stranded assets and how is it measured?
- To what extent does the decommissioning of the natural gas infrastructure lead to stranded assets and economic impact for DSOs?

To answer the research question, a quantitative analysis is conducted. This analysis refers to a model that deploys the capital- and operational expenditures when the natural gas infrastructure is decommissioned in an early stage of its economic lifetime, by using its length and age on neighborhood level. Literature and semi structured interviews are utilized to substantiate the model in answering what the economic effects for DSOs are in future decades.

1.4 SOCIAL AND SCIENTIFIC RELEVANCE

The added value for this research is found in the economic evidence that is researched. Since a climate neutral built environment depends on multiple facets (Wijngaart, R., Folkert, R., Middelkoop, 2014), this study will give a first impetus for mapping all of the facets. The social (relevance) facet in this research is appointed to the relation between the socialization and the reduction of existing connections from the natural gas infrastructure, and how this will alter the current monetary assets that is paid annually per connection. In addition, currently there is no shared view of the Dutch decommissioning activities that combines asset information, timelines and costs estimates (EBN, 2017, p. 20). While, each DSO has a view on its own assets (with varying levels of accuracy), but this view is confidential and not widely shared (ibid). Scientifically, this research is based on creating a practical and quantitative understanding for indicating the SA and EI regarding the existing natural gas infrastructure. Both could lead to a benchmark for economic SA regarding the natural gas infrastructure, since these are often named in literature, but quantitatively assessments are limited. In addition, a first perception is provided for implementing the Utilities Death Spiral theory in the natural gas infrastructure.

1.5 RESEARCH OUTLINE

Chapter 2 introduces the theoretical framework and research concepts considering the natural gas infrastructure, including two moderators that are used in the conceptual model. Chapter 3 discusses the methodology, by introducing the model and its operationalization. Then, chapter 4 endows the reader with the results. Finally, chapter 5 describes the discussion and recommendations for follow-up research; the concluding remarks are given in chapter 6.

2. THEORETICAL FRAMEWORK

This chapter provides the theoretical framework for this research by explaining the research concepts 'decommissioning of natural gas infrastructure, SA and EI'. Subsequently two moderators 'Neighborhood strategies and Scenarios' are clarified. Then, the relationships between these concepts and moderators are discussed. Figure 1 illustrates the conceptual framework that is used as foundation for this research.

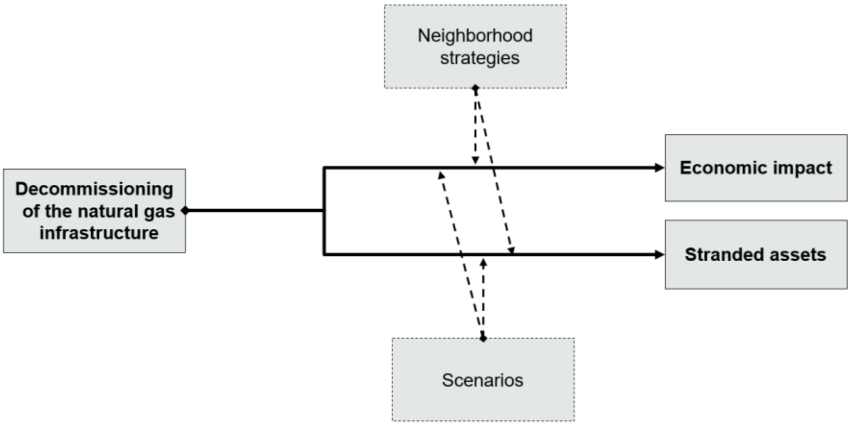

Figure 1: A conceptual framework, explaining the theory and interrelations among the research concepts.

2.1 DECOMMISSIONING FOR ENERGY INFRASTRUCTURES

Due to the relative high carbon intensity for natural gas (Khan et al., 2018), the use of natural gas and associated methane emissions are unlikely to be compatible with climate change goals in countries with ambitious climate targets given the carbon dioxide (CO_2) produced by natural gas combustion (Speirs et al., 2017). Therefore, decommissioning of the natural gas infrastructure is inevitable for reaching zero-emissions in 2050. This induces that small consumers are decommissioned from the natural gas infrastructure more rapidly than the economic lifetime of the initial investment is reached. In addition, studies regarding the United Kingdom decarbonization pathways illustrate that to meet this target the low-pressure gas pipeline network should be mostly decommissioned by 2050 (Dodds & McDowall, 2013).

For this research the following definition is used: Decommissioning is the dismantling, removal and disposal of installations and pipelines (EBN, 2017; UK government, n.d.). Both dismantling and removal are considered, however, disposal is neglected since the focus of this research is on based on the infrastructure and not on its secondary life. The decommissioning is put in relation with the definition of SA and EI for DSOs, where the early dismantling of the existing natural gas infrastructure cause economic SA and the transportation of natural gas has been abandoned. The decommissioning of the natural gas infrastructure is interlined with the reduction of connections over time (see sections 3.2.1 & 3.3).

Within this research, decommissioning implies small consumers relating to the built environment. Small consumers refer to the natural gas connections which use less than 30,000 cubic meter natural gas (m^3) on annual basis. This study used this focus group since it is accountable for 93% of the total low calorific natural gas supply in the Netherlands (ECN, 2017b).

Section 2.2 will grasp this definition for decommissioning, and tries to clarify how the definition of EI is currently affected by decommissioning and which factors influence this process.

2.2 EI IN RELATION TO DECOMMISSIONING

The economic effect of public investment in infrastructure has been at the center of the academic and policy debate for the last two decades (Pereira & Andraz, 2010). Infrastructures generate positive externalities to the private sector, contributing to the well-being of connections and the productivity of firms (ibid). But on the other hand, most infrastructures cause economies of scale and could limit the prospects for effective competition, often titled as monopolies (BIS, 2011, p. 3). Batlle and Ocana (2013) observed different forms of economic regulation, but experience has narrowed this set down to just a few options. What the forms of economic regulation have in common is an objective function intended to guide inter-temporal cost growth at some lower rate than the unregulated firm would deliver (Simshauser, 2017). DSOs are regulated and responsible for the energy infrastructures, and therefore they are restraint to reach desirable profits. To evaluate institutions on their yearly business, and thus the associated EI (EI) for a DSO, multiple regulation models are designed. These models put emphasis on different type of decision variables for calculating business cases. The RPI-X and the regulation monopoly model (RMM) are examples often applied. The RPI-X is implemented for rate of return regulation or institutionalized utilities (Littlechild, 2014), where the RMM is more specific for calculating potential SA (Gomez, 2013).

For the Dutch natural gas infrastructure, a similar method is used by the Authority Consumer and Market (ACM). An organization which regulate all DSOs and the Transportation System Operator (TSO). ACM is responsible for determining the annual tariffs which a DSO can charge the consumer (ACM, 2017c, p. 33). This causes that, due to the socialization of the infrastructure, the yearly income for a DSO is dependent to the number of consumers connected to the infrastructure (ibid). ACM uses a benchmark methodology for assessing the annual, permissible, incomes which increases the yearly performance for DSOs and endeavors to obtain lower fixed costs for the consumers over time.

Figure 2 schematically illustrates the current method, where step 2 and 3 form the core for the 'EI'. Step 1 – standardization: The data from DSOs is standardized to compare it among each other. This is done by calculating the reasonable return, regulatory costs and compiled output, which provide that the costs for all DSOs are levelized among each other and enables the costs calculation for a five-year period (step 2, 3 and 4). Step 2 and 3 calculate the costs for current and future year. Both steps are based on the estimated efficient costs output per DSO, originated from the efficient costs per unit output and optional ORD[2] using the capital- and operational expenses. Step 2 includes an additional factor (tar16 x RV), which refers to the volumetric tariff for that specific year. Evident is the five-year timeframe which is used per regulation period. This implies that for a period of five years, ACM calculate the projected annual capital costs. Within this period, the connected natural gas consumers pay each year the same fixed tariff without any adjustments by DSOs being made. Finally, step 4 calculates the x-factor. A factor that uses the Consumer Price Index (CPI) and historical x-factors, to project the future incomes for DSOs based on unforeseen changes in the market.

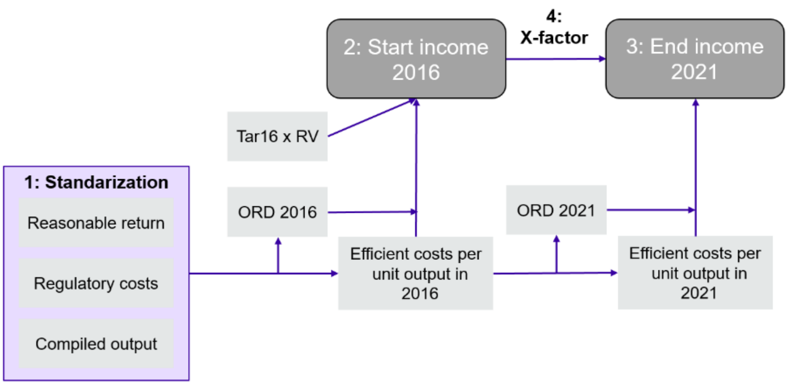

Figure 2: Schematic that indicate the relations of the definitions and how the start- and end income per DSO is calculated for a period of five years, in this case from 2016-2021 (source: ACM, 2017a, p. 43).

[2] ORD: Objective Regional Differences are differences in costs between DSOs which are caused by regional objective factors. In other words, factors which merely impact one or multiple DSOs (ACM, 2017c).

The model explains how ACM assesses per five-year period what the maximum allowed cost income per DSO can. A more quantitative explanation is given in Appendix E: The Regulation Monopoly Model ACM. A DSO is forced to ensure that their own capital- and operational costs will not exceed these maximum incomes. The capital costs are the investments made, divided over the economic lifetime for the natural gas infrastructure (depreciation). Where the operational costs cover both the removal- and other operational & maintenance (O&M) cost elements.

Each DSO uses the income threshold in their business case to calculate the amount of chargeable costs per connected consumer, since a DSO is socialized and therefore all-natural gas consumers pay for the transmission, distribution and connection regarding the infrastructure. These annual fixed costs are divided in three components but are simplified in practice as one fixed cost component (ACM, n.d.):

- Fixed fee: This fee is a fixed price which is paid by the consumer, for e.g. administrative costs;

- Capacity tariff: This tariff is charged for transporting natural gas through the infrastructure. The height of this tariff depends on the capacity which is installed in the building;

- Connection tariff: A DSO has expenses for maintain a natural gas connection. These costs are translated to fixed costs and could differ per DSO, since it depends on the number of connections and length of the associated infrastructure.

The four elements 'Depreciation, Removal, O&M and Fixed tariff per connection' combined shape the definition EI within this research. Additionally, within this research the 'The fixed tariff per connection' is the sum of costs regarding depreciation, removal and O&M. However, the decommissioning of the natural gas infrastructure causes that likewise the income for the fixed tariff per connection will cause changes in the renewed fixed tariff for the remaining natural gas connections. Since when new connections are established or an increased reduction in natural gas connections is seen, this will change the overall asset value for DSOs. When the overall missed assets value exceeds or deteriorates compared the regulatory costs set by ACM this will affect the EI for DSOs.

In other words, four components are further assessed for gaining and understanding regarding the EI. A detailed explanation for these concepts is given in section 2.2.1, where each is defined as key-factor. It should be emphasized that the definition 'EI for DSOs' implies a shift in the fixed tariff per connection. Since the natural gas infrastructure is socialized, and therefore a DSO charges the incurred expenses on the total existing number of natural gas connections.

2.2.1 Utility Death Spiral

To gain a better understanding on relation between EI and regulated monopoly utilities is, the 'Utilities Death Spiral (UDS)' theory is utilized. Costello & Hemphill (2014); Simshauser (2017) define a death spiral as an upward movement along the demand curve, mainly addressing price increases resulting from radically higher utility costs. This feedback-loop for price increase and contracting volumes in the presence of a discontinuity can produce a constructive price cycle (colloquially known as the utilities death spiral).

The UDS theory is deployed since it allows the scope of (energy) infrastructures in relation to regulation to be studied. Additionally, the UDS point out the direct- and indirect key-factors that causes certain price increases due to a shift in the demand curve. Since, this research follows a forced reduction of natural gas connections, it holds the right scope of assessing the key-factors that influence the EI.

Nowadays, a UDS could arise when additional distributed generation (DG) makes the grid more expensive for remaining connections, and in the process makes self-generation further economically attractive (Felder & Athawale, 2014). Since much of the transmission and distribution of fixed costs is recovered via volumetric charges, cost recovery is threatened if there is a major decrease in volume of sales (ibid). Figure 3 illustrate an example for a UDS within the electricity market. Apparent is the influences on the fixed tariff due to direct- and indirect key-factors, each establish their own feedback-loop. If no adjustments within the system are made, it could result in a UDS.

Furthermore, Eid, Reneses Guillén, Frías Marín, & Hakvoort (2014) argue that the utility death spiral is unlikely as this implies an unreasonable inertia from utilities and regulators. To put this in perspective: The example in figure 3 could emerge, however currently the Dutch government has changed their regulation which stated that the consumer could feed their surplus of solar electricity generation back to the electricity grid for relative high fees (PWC, 2016, p. 7).

Hemphill & Costello (n.d.) concluded that it is shown that the occurrence of a death spiral is based on unrealistic conditions about the response of a utility's customer to higher rates, the incentives of and constraints facing regulators regarding pricing and permitting a utility to experience permanent financial distress, and the intense actions of a utility's management to avoid financial disaster. In addition Costello & Hemphill (2014) state five conditions that must hold for UDS:

1] The price elasticity facing a utility must be greater than unity;
2] The price elasticity facing a utility must exceed the ratio [$P_i(P_i$-MC)] where P_i is the average price of energy and MC is marginal cost;
3] Competition has grown where the prospects for a sudden drop in demand can happen because of a disruptive technology;
4] Utilities are unable because or regulators' disapproval, or for other reasons, to offset revenue losses from fewer;
5] Utility management and regulators may face legal or political restrictions in adjusting rate schedules or acting in other ways to avert a spiral.

The UDS theory is solely addressed within the electricity sector, even though the characterizations show similarities with the natural gas sector, such as the regulation for the maximum annual allowable income per DSO is based on changes in their volumetric demand. Therefore, the UDS is applied in this research to assess if there are feedback-loops that cause increased pricing within the existing Dutch natural gas infrastructure. Which, subsequently will shed light on how both EI and decommissioning are inter-linked and influenced by each other (section 2.2.2).

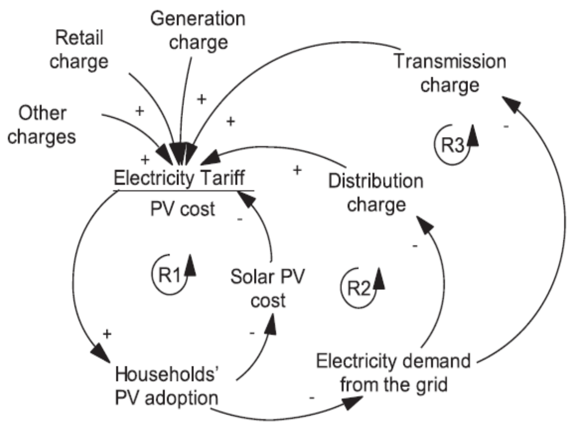

Figure 3: System thinking consideration of the utility death spiral (source: Castaneda, Jimenez, Zapata, Franco, & Dyner, (2017)).

2.2.2 UDS translation from electricity to natural gas

Previous section gave profound literature on the definition and use regarding the UDS. This section translates this theory to the natural gas infrastructure, by implementing the five conditions from Costello & Hemphill (2014). These conditions have shown to be consistent with other literature that explain the UDS, since it used a literature review to assess other UDS implementations. Emphasis is placed on the four key-factors described in section 2.3. The five conditions from Costello & Hemphill (2014) are subsequently generalized in threefold: 1) Change of elasticity, 2) market competition and 3) regulation & utility management. Each condition is assessed:

Change of elasticity

Traditional convex optimization method establish that an optimal price is inversely related to the demand elasticity evaluated at that price, given by the equation (Barthel, 2018):

[0] $$P_i = \frac{MC(p_i)}{1 - \frac{1}{\varepsilon(p_i)}}$$

Where the price elasticity of demand (ε) is defined as the percentile change in quantity demand, divided by the change in price. For a monopoly the ε is set at 1, since the regulator determines how the market price (P_i) changes over time (which are the total costs divided by the number of connected consumers). When the ε is 1, the only variable is the p_i [$MC(p_i)/1\text{-}1/1\cdot(p_i)$]. This causes that a DSO result in a low share of profit, which result in maintaining the cost-efficiency for DSOs.

The conditions state that if ε >1 or ε > [$P_i(P_i\text{-}MC)$], there is a plausible change that a UDS will occur. This could happen when the proportion of average price recovered through a fixed charge is greater than the inverse of the price elasticity. Since we can show that under monopoly pricing the above relationship is an equality, the conclusion reached is that the utility, with a constant allocation of fixed costs, is stable if and only if the price that result from such an allocation is less than the unregulated monopoly level (Hemphill, R., Costello, n.d.).

If more substitutes for utilities occur within the energy market, the demand facing utility becomes more elastic. Which makes a UDS, or at least an unstable equilibrium, more likely. The explanation is that with a more elastic demand curve, for a given price increase the utility will experience higher losses. Examples of these substitutes are given below.

Market competition

If suddenly technologies enter the market and show promising economic outcomes for consumers, it could happen that a sudden drop in demand occurs. Subsequently, utilities will increase the annual fixed tariffs of the connections to recover the lost revenues (shown in the example below). But, the attempt to regain lost profits will aggravate the problem of yet more customers leaving the utility system (Graffy, 2014). Literature often name DG and energy efficiency (EE) as plausible market competition. Examples of both DG and EE are the market availability of hybrid heat pumps and solar water heaters, both have proven to result in a lowering of natural gas demand for connections (Bagarella, Lazzarin, & Noro, 2016; Barthel, 2018; Shang, Li, Wu, Wang, & Shi, 2017). This will cause a lowering in volumetric demand, which again is related to the annual fixed tariff for connections.

Regulators and utility management

While regulators, historically, have protected utilities against severe financial problems, they might confront stakeholders and other entities. This opposition could occur when continuous price increases have reached an inflection point where further increases would trigger a public backflash (Costello & Hemphill, 2014).

The natural gas infrastructure was initially realized with the idea of supplying the built environment for 50-60 years using natural gas, subsequently assuming that nuclear power would become nowadays the dominant and clean energy generator. This caused, amongst other things, that there was not expected a significant decrease in connections over time. The current regulation is set such that each connection of the natural gas infrastructure will relatively pay the same annual fixed tariff. However, due to certain engagements in this methodology the future fixed tariff payments of connected consumers are influenced. Before assessing these influences, first an example is given on how the demand and supply works for a monopoly.

Example: Demand and supply for the natural gas infrastructure

ACM uses its methodology to determine the fixed tariff a DSO could charge the connected consumer. This fixed tariff is based on a detailed calculation form, where the main variables are the total length of infrastructure and the number of connections (volumetric value). Due to the obliged decommissioning of connections, the natural gas volume will significantly decrease over time. Since the regulation state that the fixed tariff will hold for five years, and are calculated beforehand the period, there will occur a drop in volume for this period, which causes a price increase. To illustrate (figure 4): Q_0 decreases to Q_C due to decommissioning of the connections. This causes a change from P_0 to P_C. Resulting in a lost revenue of $(0 \cdot P_0 \cdot D \cdot Q_0 - 0 \cdot P_c \cdot A \cdot Q_C)$, which equals $(P_0 \cdot P_C \cdot A \cdot C)$.

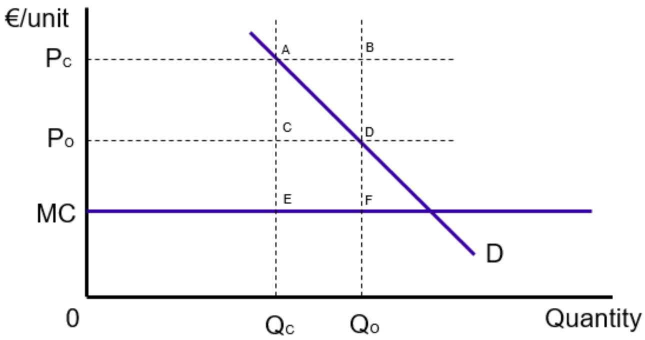

Figure 4: Schematic of the relation among quantity and price/unit for the NGI. The figure is merely used for illustration purposes (source: own interpretation).

The avoided costs are $(Q_c \cdot E \cdot F \cdot Q_0)$. The lost savings exceed the avoided costs and thus the fixed tariff for the connection is raised to recover these losses. The fixed tariff for a DSO concerns of four components which are briefly introduced in section 2.3. An elaboration in line with the UDS is given in the following paragraphs, by using literature and combine this with existing conditions.

Key-factor [1]: natural gas infrastructure connection decommissioning

The natural gas infrastructure is socialized which means that a DSO will charge its annual costs to the number of connected consumers. This implies that the connections which use natural gas will relatively pay an equal amount of fixed tariff on annual basis, where once in five years the income difference regarding to the previous period for DSOs is assessed and recalculated. This research focusses on the decommissioning of the connections from the natural gas infrastructure. Since the volumetric value forms the main variable of calculating the costs DSOs may charge per connections (section 2.3), a reduction in volume would cause that the annual costs for a DSO must be divided by less connections compared to previous period. However, less connections do imply less natural gas infrastructure to maintain. The following three key-factors will elaborate this in more depth. Nevertheless, the reduction of connected consumers and the fact that a DSO is socialized causes that the total costs for a DSO will be smeared over the, at that moment, connected consumers.

Key-factor [2]: Removal costs

When a certain share of the natural gas infrastructure is decommissioned it remains unclear what subsequent step is, either leaving it in the ground or remove the intended share. The gas law[3] states that 'a DSO, storage- or LNG company has the duty to operate, maintain and develop its natural gas transport on economic conditions, which cause a safe, efficient and reliable gas transportation that guarantees the transport of gas and environment (BZK, 2016)'. This does not say anything about their duty, when the natural gas infrastructure is decommissioned. In literature Akerboom et al. (2016) mention often the municipality is decisive authority in this process. But that legally there is nothing arranged for the removal of a natural gas infrastructure, even the exception rules do not state any regulation. Merely, that a DSO is obligated to maintain and operationalize its natural gas infrastructure based on economic conditions (as described in

[3] Article 10, section1 (source: Central Government (2016)).

previous paragraph). The municipality of Amsterdam has a regulation, written in the 'working in the public space (WIOR)' which states the regulation for replacing existing infrastructure[4] (Amsterdam, n.d., p. 10).

However, DSOs do charge costs for the physical removal of the gas meter and connection pipelines. But, this is not regulated by ACM and therefore differ per DSO (Akerboom et al., 2016). In practice, natural gas consumers choose often to disconnect and seal the gas meter (ibid), instead of the complete removal. Even though if no removal work is performed, the question is how this will influence a neighborhood when 90% of the connections are disconnected and the remaining 10% pays for both their own part of the infrastructure and associated infrastructure of the 90%, which must be maintained according to the law.

Literature indicate that three plausible actions can be taken: 1) disconnect and seal the gas connection, but no removal of the associated infrastructure; 2) the complete removal of the associated natural gas infrastructure and 3) the use of substitutes for natural gas. Bruijn & Steen (2006); Gigler & Weeda (2018); Ouden et al. (2018); Wijngaart et al. (2014) emphasize that the use of bio-methane and hydrogen hold proficient potential to be as energy carrier in the built environment. Option one and two will entail unforeseen costs for a DSO which are not considered beforehand. The latter option is disregarded in this research since, even though both substitutes show potential, solely pilot projects have been carried out and more knowledge is needed on the technical potential for using the existing infrastructure as a second life. Additionally, this research puts emphasis on the current regulation to gain an apparent understanding on the economic influences for DSOs when the current natural gas infrastructure is decommissioned, retaining the regulation as it is now.

Finally, ACM state in their regulation that they believe that a DSO can recoup the costs that arise from divestment, as long as the costs can be interpreted as efficient (ACM, 2017c, p. 59). To guarantee the complete remuneration for the efficient costs from the divestment, ACM chooses to not void the divestment assets from the standardized asset value (ibid). This way a DSO remains receiving the remuneration for remaining depreciation period, as if no divestment is made. This method is included in calculating the EIs for a DSO (chapter 3).

Key-factor [3]: Depreciation costs

The increased reduction of connections cause that the natural gas infrastructure will be decommissioned. The investments in the natural gas infrastructure are made in historical years, and spread equally in costs of the economic lifetime of the specific infrastructure. This implies that a DSO will recoup their investments after the economic lifetime has been reached. Even though the economic lifetime has expired, the infrastructure has often proven to be in proper condition for further natural gas supply, which in addition would lead to unforeseen savings for a DSO. Rationally, an increased decommissioning would lead to less annual income for a DSO, but also less operational & maintenance. Both literature and interviews (Appendix B) have shown that 'for each DSO the standardized asset value is divided by the remaining depreciation period. Where the annual standardized depreciation costs are abided by the standardized asset value until it is reduced to nil (ACM, 2017e, p. 14)'. This implies that when a share of the natural gas infrastructure is decommissioned, that even though when this share is not used, the depreciation costs continue to be charged by the connected consumers.

This missing monetary value will be charged to the remaining connections after the five-year period and thus, decommissioning leads to an increased fixed tariff for the remaining consumers connected to the natural gas infrastructure.

Key-factor [4]: Operational & Maintenance costs

Finally, the operational & maintenance (O&M) costs for the natural gas infrastructure must be considered. Currently the O&M are annual expenses for the DSO to ensure that the natural gas supply proceeds

[4] Article 24, section 1;2

efficiently, safe and secured. However, if connections will increasingly reduce, the natural gas infrastructure will gradually decommission. This causes that O&M for the associated shares of infrastructure are no longer needed[5]. Section 3.4 illustrate the extent of these costs. But it is concluded that the decommissioning of the natural gas infrastructure causes a beneficial costs reduction for both the DSO and connections, since it leads to less O&M.

2.2.3 Utilities Death Spiral crafted for the Natural Gas Infrastructure

This research focusses on the changes for the built environment, and thus the decommissioning of the associated natural gas infrastructure, which is again related to the policies set by the government. The model (chapter 3) will only include the UDS theory which puts emphasis on the regulation processes. In other words, both elasticity and competition of the natural gas market are neglected. Figure 5 provide all key-factors from section 2.2.2 and translated these to a Dynamic System model, including its behavioral change regarding the natural gas fixed tariff. Since, Castaneda et al. (2017) explains that the fixed tariff for electricity is the starting point for a UDS. Therefore, likewise the fixed tariff for the natural gas infrastructure is used as starting point.

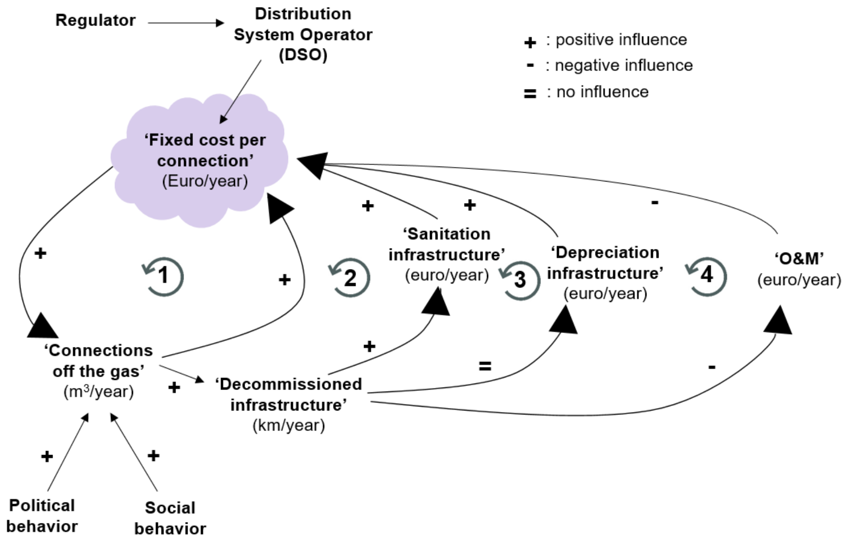

Figure 5: A Dynamic System Model for the natural gas infrastructures, indicating four feedback-loops (source: own interpretation).

Figure 5 indicate that the EI is translated to four main components, which directly influence the fixed annual tariff per connection. Where 'annual' refers to the fixed period stated in the methodology of ACM.

The decommissioning is an event caused by the forced reduction of connections due to both political and social behavior. The political behavior is originated by the current climate targets which state that the built environment must reach zero emissions in 2050. Where the social behavior points to that the mitigation and adaptation to climate change factors will hardly be achieved without public support and engagement (Luís, Vauclair, & Lima, 2018). The reduction of small consumers equals a volumetric decrease, which creates an increase in the fixed tariff per connection (conform the current methodology of ACM). In other words, decommissioning of small consumers equals an increase in the fixed tariff. Subsequently, decommissioning of the natural gas infrastructure causes three price changes to occur: O&M (-), Removal (+) and Depreciation (+). Eventually, the potentially costs increases risk both to utilities themselves and to

[5] Side note: if DG or EE will occur, this means that the costs for O&M must still be covered by the DSO. Which implies that these costs remain constant. However, this research assumes decommissioning of the connections, and therefore a reduction of O&M costs.

society, which depends upon the availability of safe, secure, accessible, and abundant energy (Graffy, 2014, p. 2). Finally, it should be emphasized that this UDS is based on a forced regulation set by the government.

2.3 SA IN RELATION TO DECOMMISSIONING

In this section the definition for SA is discussed and defined for further use in this research. As the origin of decommissioning is derived from the urge of combating climate change, subsequently decommissioning within infrastructures causes SA. Therefore, how stranded monopoly assets are dealt with is of vital importance to social welfare but is a complex area of economics for three reasons: 1) There is no empirical evidence on how to treat SA or regulated monopoly utilities, and efficiency arguments compete with fairness arguments (Martin, 2001; Simshauser, 2017); 2) Amounts at stake are invariably massive (Baumol, W.J., Sidak, 1995) and 3) Remedies are a zero-sum game (Wen, S., Tschirhart, 1997). When recovered from consumers, remedies damage the benefits that emanate from the cause of SA, in other words new competitors and technologies (ibid). However, how SA are subsequently treated is of vital importance to consumers, the market and the financial stability of the utility (Simshauser, 2017).

The concept SA has attracted significant interest over the past five years as the financial community has faced increasing socio-political pressure to calculate its exposure to environment-related risk (Covington & Thamotheram, 2014). According to IEA (2013, p. 98) SA are the investments which have already been made but which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return as a results of changes in the market and regulatory environment brought about by climate policy. Simshauser (2017) finds that SA arise when the sunk costs from prior investments will not be recovered because future revenues (via prices, volumes or both) are expected to be significantly lower than assumed when the commitment was made due to materially changed circumstances. While, Caldecott et al. (n.d.) defines SA as assets that have suffered from unanticipated or premature write-down, devaluations, or conversion to liabilities. Lastly, OECD/IEA & IRENA (2017, p. 106) define SA as the capital investment in fossil fuel infrastructure which ends up failing to be recovered over the operating lifetime of the assets because of reduced demand or reduced prices resulting from climate policy.

Each definition puts an accent on a different factor. IEA (2013, p.98); OECD/IEA & IRENA (2017, p. 106) emphasize mainly the economic lifetime as main variable, where Simshauser (2017) tries to put focus on prices and volumes of energy. Subsequently Caldecott et al. (n.d.) hold a more general definition. For this research, the given definitions are combined to ensure that the link among DSO, infrastructure and SA recurs in the definition. Therefore, SA are defined as the remaining book value of assets substituted before the end of their anticipated economical lifetime and without recovery of any remaining value to achieve 2050 decarbonization targets. This definition emphasizes that assets become SA because of the requirement to reduce fossil fuel use to achieve a deeply decarbonized energy system by mid-century (IRENA, 2017, p. 14).

2.4 NEIGHBORHOOD STRATEGIES

As figure 1 illustrates, the component 'neighborhood strategies' could influence the relation among EI and SA regarding decommissioning. This section elaborates what is meant by neighborhood strategies and how this could influence the variables.

The ministry of Economic Affairs and Climate Policy and Internal Affairs, in collaboration with other parties, have initiated the green deal 'natural gas free neighbourhoods' (Rijksoverheid, 2017). A deal which assigned 29 municipalities to gain insight in pilot projects for an off-the-gas transformation of specific neighbourhoods (ibid). These areas were primarily chosen due to a natural moment for the removal or renovation of the natural gas infrastructure. Additionally, the coalition agreement from October 2017 states their vision to create a sustainable built environment in 2050 (Rutte et al., 2017, p. 32). Both the neighbourhood approach and envisioned climate goals set by the government cause that this research will use a neighbourhood approach to indicate the role of natural gas decommissioning for the built environment.

Additionally, in general, often there is spoken of competitive strategy when a company can outperform rivals only if it can establish a difference that it can preserve. It must deliver greater value to customers or create comparable value at a lower cost, or do both (Mazzucato, 2002). This research puts focus on DSOs that are accountable for the Dutch natural gas infrastructure and secure a monopoly position. Hence, a DSO is regulated, what implies that annually the monetary begin income is fixed and benchmarked based on historical performances, to ensure that the natural gas infrastructure is maintained cost-efficiently over time.

For this research the latter term strategy, is combined with the term neighbourhood and, is defined as an action that is looking towards the future, and simultaneously withhold the associated costs for a DSO.

The combining of neighbourhoods and strategy will result in multiple strategies which assess the age and length per neighbourhood and try to find plans on how the forced decommissioning would be most cost-efficient.

2.5 SCENARIOS

Scenario planning can be a useful tool in strategic management. In a rapidly changing environment it can avoid the pitfalls of more traditional methods (Goodwin, P., Wright, 2002). Moreover, it provides a means of addressing uncertainty without resource to the use of subjective probabilities, which can suffer from serious cognitive biases (ibid). The original intention to develop scenarios is to have a better understanding of the impact of uncertainty on decision-making, and to show more potential decision-making in different scenarios (Fei & Shuang-Qing, 2012, p. 6). This research incorporates the diffusion of innovation theory to gain a better insight on how the reduction process regarding natural gas connections could evolve towards 2050. This theory seeks to explain how, why, and at what rate new ideas and technology spread through cultures (Rogers, 1995). Defining this for the scenarios, the formula is used to provide an understanding on the rate of adoption for a certain technology, in this case the decommissioning of natural gas. This rate of adoption is defined as the relative speed at which participants adopt an innovation (Rogers, 1995).

To put this in perspective. Climate targets have been set for the long term, without any profound intermediate objectives for the periods 2030 and 2040 regarding the built environment. To understand the mutual relations between the concepts of decommissioning, EI and SA, multiple scenarios concerning the reduction of natural gas connections are introduced, including the neighborhood strategies. A scenario will gain insight on how the reduction rate of natural gas connections (and thus the infrastructure) will economically influence a DSO in the coming decades.

3. METHODS

This chapter introduces the model which is used to assess the EI and SA for the early decommissioning of the existing natural gas infrastructure for small consumers in the built environment. This section consists of 5 sections. Section 3.1 introduces the framework of the model. Followed by section 3.2 till 3.4, where each input component is highlighted by describing the operationalization and the origin of the data. Finally, section 3.5 indicate how all components are coherent to each other. As mentioned, this research is merely focused on the decommissioning of the natural gas infrastructure and therefore substitutes for natural gas are neglected.

3.1 MODEL FRAMEWORK

In the theoretical framework, the model is initially introduced using concepts originated from scientific literature and interview with experts working closely with the natural gas infrastructure. This section translates the literature into a framework used for finding the EI and SA for the DSOs on a national scale, specifically for the built environment. The three components at the top of **Figure *6*** represent the input data of the model. The added value of this model is to calculate annually, till 2050, what the EI and SA are in quantitative values for certain scenarios and strategies. A revised 'regulated monopoly model' is constructed to simulate on a yearly basis what the potential costs impact is towards 2050. This model is derived from Simshauser (2017) and Gomez (2013) in combination with the current methodology[6] of ACM. Albeit this model uses a generalized approach, neglecting price elasticities and focusing on existing data from DSOs. It does give a comprehensive insight in the overall relations within the regulated monopoly infrastructure, including a quantitative indication of the associated EIs and SA.

In addition, the framework is adjusted by including neighbourhood strategies and scenarios. Since emphasis is put on the natural gas infrastructure and not primarily on how the future reduction of the connections could look like. The scenarios are not based on scientific substantiated literature, but used to address the changing behaviour for the EI and SA over time.

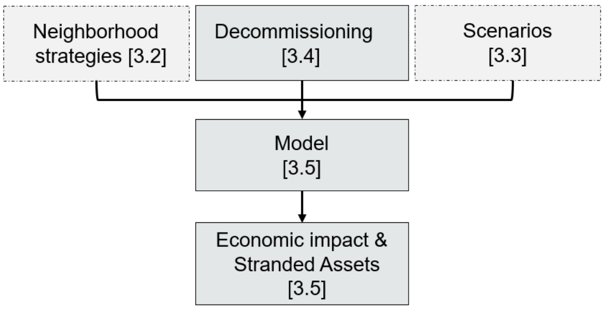

Figure 6: Model framework for assessing the EI and SA, due to decommissioning of the Dutch natural gas infrastructure.

The research scope is limited to small consumers on a national scale. However, the model allows to modify the input and scale. Which means that apart from small consumers the model allows to include large utility and other sectors for performing calculations varying from local-, regional- and national scale.

In 2017 in total 7,188,172 connections are connected to the natural gas infrastructure (Brouns, 2017, p. 19), which holds 130,329 km length for all DSOs combined (Netbeheer Nederland, 2018). Each unit of the natural gas infrastructure has its individual length and age. Based on a usability factor (section 3.2.1), length of the NG pipeline and associated connections, the average length of the natural gas infrastructure per neighbourhood (or connection) is calculated. The scarce availability of data for the length, location and age

[6] The framework for this model is based on the model from the regulatory organisation ACM, which uses assessment models for calculating the yearly allowed incomes for DSOs (ACM, 2017c).

of the natural gas infrastructure on neighborhood level, caused that assumptions had to be made (section 3.2).

3.2 Neighbourhood strategies

The Netherlands has about 13,200 neighbourhoods (ACM, 2017b), each having its own characterization such as building types and year of construction. This input component will assess the average length and age of the natural gas infrastructure in combination with the number of connections per neighbourhood. The results forms three strategies on a national level. Each strategy is based on ranges and the share of age classifications that occur the most within the assessed sample of neighbourhoods. Each strategy is calculated over time, which means that the rate of decommissioning per classification type will evolve over time.

> **Practical example**: If a neighbourhood contains 100 connections, and 10 kilometer of natural gas infrastructure must be decommissioned over time. It matters which age of the infrastructure is decommissioned first. Economically, it is preferable to decommission the oldest share of the infrastructure first. However, in real-life this is not always the case due to unforeseen influences (e.g. building characteristics, social-, political influences, and more).

The strategies are assembled using four data sources. First, the study Wijngaart et al. (2014) is used, which classified the 13,200 neighbourhoods in 15 generalized categories. This generalization is done via a survey among building owners, using open source data, and their own energy transition model. The characterizations per neighbourhood indicate the age, type, size and number of the buildings. Then, for each general neighbourhood type five samples are used to gain one overall generalization of the neighbourhoods within the Netherlands.

These samples are assessed in a method called Geographical Information System (GIS), which allows a user to perform quantitative analysis including the geographical location of an object. Since the study Wijngaart et al. (2014) cannot be translated to GIS, data from the Basic Addresses Registration (BAG[7]) is used. Manually, the chosen neighbourhoods are searched for within GIS.

Added to these samples, are the length and age of the opensource data from Stedin. This data provides the length of the existing natural gas infrastructure between high pressure (8 bar) and low pressure (300 mbar). The age is classified in 'to be replaced/older than 45 years', 'older than 30 years' and 'younger than 30 years'. Even though DSOs adjudicate more detailed information regarding the age, location and type of the natural gas infrastructure, it has shown to be confidential and not widely shared. In this research the opensource data from Stedin is supplemented with data from literature. Since each classification covers multiple years (e.g. younger than 30 years covers 30 years) the model used linear ageing: When a pipeline is 'younger than 30' and covers 100 km, each year this size will diminish by $1/30^{th}$ compared to previous year until it reaches zero. An assumption is made that no new natural gas infrastructure for small consumers is initialized, and that the length is equally divided over 30 years (formula 1).

[1] $$L_{t,x,total} = L_{t,x} - \left(L_{t,x} \cdot \frac{1}{y_x}\right) + \left(L_{t,x+1} \cdot \frac{1}{y_{x+1}}\right) \ \forall \ x_{1-3}$$

Non- negativity constraint $L_{t,x} \geq 0 \ \forall \ t$

Balance constraint $\sum_{t=2018}^{32} \sum_{x=1}^{4} L_{t,x} = D_t$

Where:

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[7] BAG: A semi-governmental cadaster which is responsible for recording all the addresses and buildings within the Netherlands ("BAG," n.d.).

$L_{t,x,total}$ =	Total remaining length per year t for classification x in kilometer (km)
$L_{t,x}$ =	Length per year t for classification x in kilometer (km)
y_x =	Range of years per classification x. y_{x+1} refers to the younger classifications x2-4 (years)
x =	Type of classification, in total four classifications are used. x_1 = older than 45 years, x_2 = between 31-44 years, x_3 = between 16 and 30 and x_4 = younger than 15 years (-)
D_t =	Total length natural gas infrastructure available for the Dutch built environment (km)

The non-negativity constraint is used to ensure that the model does not allow the infrastructure to become negative over time. Since the model uses multiple classifications with a certain length, the decommissioning over time will cause that at some point the length within that specific classification reached zero. The model will than shift to the remaining length in the other classifications. The balance constraint is incorporated to maintain that over the whole-time frame, the sum of the decommissioned infrastructure equals the total length of existing natural gas infrastructure in the start year 2018. Section 3.2.1 will introduce a Usability Factor (UF), in addition to the balance constraint. Eventually, each year a share of natural gas infrastructure length is assumed to be replaced naturally (section 3.3) since it attained its economical end of life. Finally, the sum Dt indicate that the total natural gas infrastructure length for all DSOs combined must equal the natural replacement and forced decommissioning for the natural gas infrastructure between 2018 and 2050.

Combining both the data of the neighbourhoods, age and location in GIS, the length and share of age per neighbourhood (or connection) is calculated. However, this merely indicate the current (2018) share of age per connections per unit of length. The strategies express what the share (%) reduction per classification will be over time. In other words, these values demonstrate what shares for infrastructure decommissioning of the remaining classifications is used if the non-negativity constraint for a certain classification applies. Figure 7 provide three strategies 'old, average, young'. The vertical axis of these strategies implies the change of share in natural gas infrastructure reduction when a classification (e.g. 44-31 years) has reached zero in year x (e.g. year 2034). Since, it depends on the model, it is not known which year this occurs. Each added layer on the vertical axis thus illustrate the new percentages used for decommissioning of the natural gas infrastructure when one classification reached zero. As figure 7 indicate, if a classification reaches zero, automatically the missed percentage from this classification is added to the oldest classification (<45). The data is based on data analyses, interviews with experts working at DSOs and literature research.

<45 | 44-31 | 30-16 | >15

Strategy: **Old** $\downarrow [time] \begin{bmatrix} 0.57 & 0.17 & 0.16 & 0.10 \\ 0.67 & 0.17 & 0.16 & 0.00 \\ 0.83 & 0.17 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}$

Strategy: **Average** $\downarrow [time] \begin{bmatrix} 0.09 & 0.71 & 0.10 & 0.10 \\ 0.19 & 0.71 & 0.10 & 0.00 \\ 0.29 & 0.71 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}$

Strategy: **Young** $\downarrow [time] \begin{bmatrix} 0.15 & 0.17 & 0.59 & 0.10 \\ 0.25 & 0.17 & 0.59 & 0.00 \\ 0.84 & 0.17 & 0.00 & 0.00 \\ 1.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}$

Figure 7: Neighborhood strategies: Used to assess how connections, on neighborhood level, will decommission their natural gas infrastructure over time.

Appendix C.1. provide a further elaboration for the strategies. The column 'younger than 15 years' is based on existing data from CBS (ACM, 2018b). Which gives an overview of the newly built connections within the built environment from the last 15 years. This historically data is multiplied by the length per connection and incorporated as length (km) within the classification 'younger than 30 years' (formula 2). The remaing three age classifications are based on the assessment of the opensource data from Stedin (appendix C.1.).

[2] $$L_{t,x4} = \left((\sum_{t=2004}^{13} H_t) \cdot L_c \right)$$

Where:

$L_{t,x4} =$ Length (km) of the natural gas infrastructure for classification 'younger than 15 years'

$H_t =$ Number of newly built connections in year t

$L_c =$ Length of natural gas infrastructure per connection taken from the calculation of the model, formula 3 (km/connection)

For each strategy, the yearly reduction will be conform the shares given in figure 7. If the length for a classification reached zero, the remaining classifications will cover the percentile share from that classification. In this process, emphasis is placed on reducing the oldest natural gas infrastructure first. This could conflict with how it is done in reality, since this process depends on multiple factors such as consumer behavior, the choice of neighborhood, structural aspects of the buildings, local regulation, et cetera. Additionally, the length of NGI per connection (L_C) is simplified by dividing the total length of natural gas infrastructure by the number of connections. This is done to ensure that the whole infrastructure is included in assessing the EI and SA. Even though, the length of natural gas infrastructure per connection on neighborhood level differ significantly (Appendix C.2.).

3.2.1 Usability Factor (UF): Transportation, Distribution and Connection pipelines

The natural gas infrastructures consist of three types of pipelines: distribution, transportation and connection pipelines. The transportation pipelines distribute the largest pressure (8 bar) and connect different utilities (mainly buildings, utility and industry). The data that is used does not specifically indicate the type of pipeline. However, the study Brouns (2017) gives for each DSO operating within the Netherlands the length of pipeline classified per type. This distinctions in pipelines is relevant since the reduction of connections is not 1:1 per length of the infrastructure. The connection and distribution pipelines are laid out within a neighbourhood, while the transportation pipelines are overarching and connect multiple neighbourhood or other utilities (Figure 8). Therefore, it is not reasonable to assume that if one connection hold, e.g., 10 metres of pipeline, the entire length will be decommissioned. Table 1 gives an overview for the ratios among the distribution, transportation and connection pipelines, where the share ratio is the length of distribution- and connection pipelines summed and divided by the transportation length. However, additional data regarding the natural gas infrastructure length per connection is found in establishing the neighbourhood's strategies (appendix C.2.).

Table 1: Usability Factor (UF): Distinction of natural gas infrastructure for the three largest DSOs (in terms of length and connections), including the Netherlands (source: Brouns, 2017).

Length infrastructure translated to a Usability Factor (UF)					
Type of pipeline / DSO	**Enexis**	**Liander**	**Stedin**	**The Netherlands**	**LT_economic**
Transportation (km)	8,830	7,224	3,899	22,685	55
Distribution (km)	37,359	34,038	19,610	101,982	55
Connection (km)	1,975	1,820.24	1,404.29	5,662	45
Usability factor (%)	78%	80%	81%	79%	54.6 (average)

This leads to a ratio factor of 79% for the decommissioning of the natural gas infrastructure. This share, further defined as Usability Factor (UF), is used as default in the model. From the model, it will be indicated what the remaining length of the natural gas infrastructure would be after 2050. Since, eventually there is merely infrastructure without any connections, while the investments have not been recouped, resulting in SA. Formula 3 and 4 indicate how this ratio is used within the model. Since calculating the SA, together with the EI, is leading in this research, the UF is supplementary placed in a sensitivity analysis to see the differences in the quantitative outcomes (Appendix A). Additionally, it remains unknown what the exact share of decommissioning of the transportation pipelines is, due to factors such as reduction rate, location, et cetera. The L_{TP}, L_{DP} and L_{CP} relate to the transmission-, distribution- and connection infrastructure. Formula 3 and 4 indicate how the usability factor is established:

[3] $$L_c = \left(\frac{D_t}{C_{2018}}\right) \cdot UF$$

[4] $$UF = 1 - \left(\frac{L_{TP}}{L_{DP}+L_{CP}}\right)$$

Where:

$C_{2018} =$ Total number of natural gas connections in year t = 2018 = 7,188,172 (number)

$UF =$ Usability Factor that indicate the reduction of natural gas infrastructure over time (%)

$L_{TP} =$ Length per type of natural gas infrastructure (km)

$L_{DP} =$ Length per Distribution infrastructure (km)

$L_{CP} =$ Length per Connection infrastructure (km)

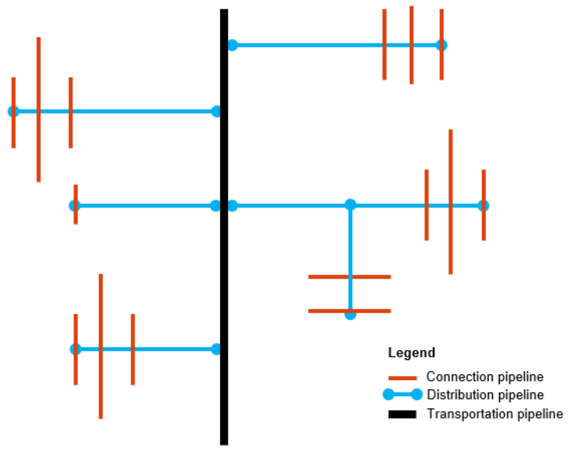


Figure 8: Schematic overview for the type of pipelines used by DSOs to distribute the demanded natural gas (source: own interpretation).

3.3 SCENARIO'S

The added value of this research is to find the underlying relations and potential EI and SA implementing certain scenario's and strategies. The scenarios are based on the climate targets for 2050 set by the Dutch government. Therefore, it is known what the current- and desired situation (2050) is. 'Desired' refers to the situation where the built environment has reached zero-emissions in 2050 (EC, 2011; Naber, Schepers, Schuurbiers, & Rooijers, 2016; Wijngaart, R., Folkert, R., Middelkoop, 2014). This target is translated to connections equivalents. In other words, to reach zero-emissions in 2050, all connections must be decommissioned from the natural gas. This research merely focusses on the infrastructure in combination with connections decommissioning from the natural gas, including the ratio of decommissioned infrastructure per connections (section 3.2.1). The structure per scenario is demonstrated:

[1] A **Business as Usual (BAU)** scenario is set such that policy has excluded all the policies and measures adopted or to be adopted after the starting point of the projection (Fei & Shuang-Qing, 2012). This will specify the number of connections that will be decommissioned from natural gas, when the infrastructure is at the end of its economic lifetime. The outcome is used as a benchmark for investigating the gap to reach

a zero-emission built environment in 2050. Table 2 gives the used parameters and origin of the data. Formula 5 is used to assess the natural replacements of the connections, where the length of natural gas infrastructure that is replaced remains annually equal:

[5] $$C_{BAU,t} = \left(\left(\frac{1}{LT_{ECO}-LT_{x1}}\right) \cdot \left(L_{x1,2018} \cdot S_{x1,2018}\right)\right) \cdot L_c$$

Where:

$C_{BAU,t} =$ Annual connection reduction (number of disconnections/year)

$LT_{ECO} =$ Economic lifetime per connection (years, default = 55 years)

$LT_{x1} =$ Minimum lifetime for classification x_1 (years, default = 45 years)

$L_{x1,2018} =$ Length of infrastructure for classification 'older than 45 years' in year t = 2018 (km_{2018})

$S_{x1,2018} =$ Percentile share of natural gas infrastructure reduction in year t = 2018 (%, default = 8% of the total length: 130,329 kilometer)

The economic lifetime per connection is set at 54.6 years (Table 1). This age is based on the regulatory economic lifetime which is given by ACM (2017), and re-evaluated by taken the total length and associated lifetime per type of infrastructure (e.g. the 'connection' pipelines hold a certain length, but has an economic lifetime of 45 years instead of 55 for both transport- and distributions pipelines). The assumption is made that after 55 years, the natural gas infrastructure will not be used anymore.

[2] The **Paris Agreement (PA)** scenario is set as a linear pathway of connection reduction from the natural gas infrastructure towards a zero-emission built environment for 2050. As mentioned in the introduction, a yearly reduction of approximately 200,000 connections is required. The following formula is used:

[6] $$C_{PA,t} = C_{2018} - \left(\frac{C_{2018}}{(t_{End}-t_{Start})}\right) \cdot t_t$$

Where:

$C_{PA,t} =$ Annual connection reduction (number of disconnections/year)

$t_{End} =$ End year scenario (default = 2050)

$t_{Begin} =$ Start year scenario (default = 2018)

$t_t =$ Time in year t (years)

Since this formula is linear, the annual reduction for this scenario equals 7,188,172 connections divided by 32 years (2050-2018), which equals 224,620 and equates a 3.1% annual decrease compared with the current number of connections. To illustrate, between 2012 and 2016 the total use of natural gas reduced by 10.7%. However, this was due to the energy intensity, the population effect caused a growth of respectively 3.9%. While the average share of persons per building dropped from 2.3 to 2.2 in 20 years' time (CLO, 2014; WLO, n.d.). In other words, on national scale there is currently no reduction (nor stabilization) of the amount of connections using natural gas (CBS, 2018b).

[3] The **Hybrid** scenario is built to illustrate the zero-emission built environment, using another pathway between 2018 and 2050. Since, the pathway is not known, this scenario uses the diffusion of innovations theory. This theory explains how adopters of a technology or innovation are influenced and react (Xiong, Payne, & Kinsella, 2016). In general, the adopters are divided in three categories: Early stage; intermediate stage and late stage (ibid), where the critical mass is always found in the intermediate stage. Figure 9 illustrates all scenarios.

The following formula is used:

[7] $$C_{Hybrid,t} = \left(\frac{C_{2018}}{1+e^{-k\cdot(t_t-t_0)}}\right)$$

Where:

$C_{Hybrid,t} =$ Annual connection reduction (number of disconnections/year)

$k =$ The steepness of the curve (default = 0.30, source: Franceschinis et al. (2017))

$t_0 =$ Time for year midpoint (default = year 2032)

The steepness factor is set at 0.30. This factor is taken from the study Franceschinis et al. (2017) which conducted a study on the adaptation of renewable heat systems, using a probability factor of 0.31 for the early adopters of renewable heating systems. This is more or less contrary to the natural gas infrastructure decommissioning. Additionally, the midpoint for 2032 is used since recently the reduction of natural gas connections has started phasing out, presuming that till 2050 half of this time frame is required for reaching half of the reduction.

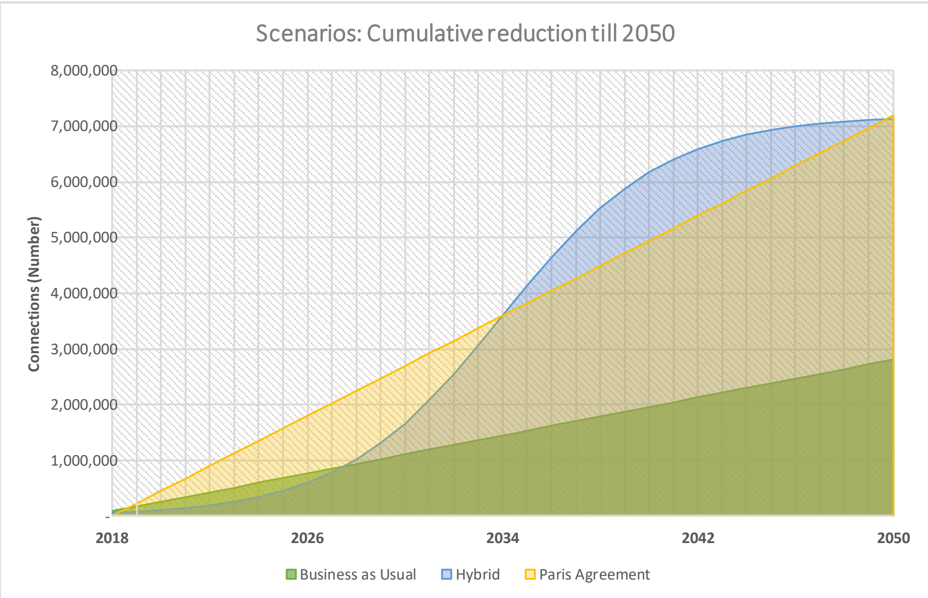


Figure 9: Illustration of the small consumer reduction per scenario, from 2018 until 2050 (source: own illustration).

3.4 DECOMMISSIONING

To calculate the EI and SA affiliated to a certain neighbourhood strategy (section 3.2) and scenario (section 3.3), monetary data input is required. Chapter 2 provided the underlying relations among the four key-factors, using the UDS. These will be quantified in the model between the period 2018 and 2050. The implementation of the UDS regarding the natural gas infrastructure was purely based on literature. In addition, to refine this theory, semi-structured interviews with experts working closely on the natural gas infrastructure at DSOs are conducted to substantiate the findings via literature (Appendix B).

This section elaborates the additional steps required for executing the analysis and processing the model to reach the eventual results. Where the assumption is made that both current regulation applies and an increased decommissioning of connections is set in motion till 2050.

The 'decommissioning' component (figure 6) uses these results to compile the model and therefore calculating the costs regarding the EI (fixed tariff per connection, removal, depreciation and operational & maintenance) and SA of the natural gas infrastructure. Table 2 demonstrates an overview of all input values, including the origin of the source.

3.4.1 Fixed tariff per connection

The cost per connection can be divided in three fixed price elements (fixed tariff, capacity tariff and connection tariff). Since, these costs do not mutually change much, this research uses one fixed tariff. Once per five years, ACM determines what the maximum income per DSO can be. Based on these maximums, a DSO calculate what they can charge per connection. Thus, for a period of five years a natural gas connection annually pays one fixed tariff[8]. The following formulas are used to simulate the costs for the small consumers, including the UDS:

[8] $$P_{t,2018} = \sum_{i=1}^{3}\left(\frac{BI_{t,i}}{C_{t,i}}\right)$$

[9] $$P_{t+1} = \left(\frac{(C_t - C_{t+1}) \cdot P_t}{C_{t+1}}\right) + P_t \quad \forall_{t=2018}^{33} t$$

[10] $$C_{t+1} = (C_t - S_{t+1}) \quad \forall_{t=2018}^{33} t$$

[11] $$P_{fixed_{t,z_x}} = P_{t+1} \text{ for } z_x = 1\ldots7$$

Where:

$P_{t(2018)} =$ The fixed tariff per connection, taken from the three largest DSOs i: Stedin, Liander, Enexis. Start year is 2018 (euro/connection)

$BI_{t,i} =$ Total Begin Income per DSO i, taken from the three largest DSOs are used: Stedin, Liander, Enexis. Start year is 2018 (euros/year)

$C_{t,i} =$ Number of total remaining connection for DSO i. Taken from the largest three DSOs: Stedin, Liander, Enexis. Start year is 2018 (number of connections/year)

$P_{t+1} =$ The fixed tariff per connection on annual basis. Where t+1 refers to the subsequent year t (euro/connection)

$C_t =$ The number of remaining connections in year t (number of connections/year)

$C_{t+1} =$ The number of remaining connections in year t+1 (number of connections/year)

$S_{t+1} =$ Number of connection reduction for year t+1 and scenario S (number of connections/year)

$P_{fixed_{t,z}} =$ The fixed tariff per connection for period z. Where one period is fixed for five years. Length of the fixed regulation period {z_1=t0..4; z_2=t5..9; z_3=t10..14; z_4=t15..19; z_5=t20..24; z_6=t25..29; z_7=t30..34}. Where t0 equals 2018. And in total seven periods are used till 2050 (t33 = 2050) (euro/period/connection)

$\forall_{t=2018}^{33} t =$ t is depended for the period 2018 till 2050

Formula 8 and 9 indicate a linear increase costs per connection over time. It must be emphasized, that the model starts with a fixed tariff per connection in 2018 using literature from Stedin, Liander and Enexis. The consecutive years the P_t is set as the P_{t+1} from previous year. Since the prices per connection are calculated for the period between 2018 and 2050, the dependency symbol (∀) is used. Additionally, the z is introduced to ensure that the fixed price per tariff remains constant per five-year period (formula 12). The time periods

[8] This varies depending on the type of consumer that is connected, large consumers a higher fixed tariff. However, this research uses merely the capacity tariff for small consumers: "G4/G6 SJV 500-4,000 m³".

for the z value are shown in the description of the formulas. Additionally, the Begin Incomes (BI) are extracted from ACM (2017c).

The data used in the model is based on the prices for 2018. Future price indications are set for periods of five years including the assumption that no alternations in the x-factor nor Consumer Price Index (CPI) will occur. Therefore, both the increase and decrease of the annual fixed tariff per connection merely depends on the required expenses of the DSO in relation to the maximum costs income set by the regulator. See appendix E for a more comprehensive explanation on this fixed tariff per connection used by the regulator ACM.

3.4.2 Costs for Removal

Section 2.3.1 describes that the removal costs for the natural gas infrastructure remain unclear when a connection is decommissioned. Therefore, the model will calculate two options: (1) Costs for disconnecting and seal the gas connection and (2) complete removal of both the gas connection and associated pipelines. As described in section 3.2.1 there is a usability factor for the natural gas infrastructure. For both the distribution- and connection pipelines, the assumption is made that 100% will be used, and thus costs will be fully charged. The costs for removal are shown in Table 2. In the model, the 'early' removal costs will be charged in the same year of decommissioning, where a cost learning curve is applied to count for the future efficiency of costs for removal (Blok, K., Nieuwlaar, 2017, p. 224). Formula 12-16 illustrate the compiled costs onwards 2050, in the model the option is made for merely calculating the quantitative effect for option 1 or 2:

[12] $$P_{sanitation_{t,x}} = \left(I_{t,x} \cdot ST_{t,x} \cdot PS_t^b \cdot CR\right) + \left(S_{t+1} \cdot PD_t^b\right)$$

[13] $$I_{t,x} = (S_{t+1} \cdot L_c) - I_{BAU_t}$$

[14] $$b = \frac{\log(learning\ rate)}{\log(2)}$$

[15] $$P_{sanitation_t} = \frac{\sum_{x=1}^{4} P_{sanitation_{t,x}}}{C_{t+1}} \quad \forall_{t=2018}^{32} t$$

[16] $$P_{sanitation,t,z_x} = P_{sanitation_t} \text{ for } z_x = 1\ldots7$$

Where:

$P_{sanitation_{t,x}}$ = Removal costs for classification x and year t (euro · classification/year)

$I_{t,x}$ = Decommissioned natural gas infrastructure I for classification x and year t (km· classification/year)

I_{BAU_t} = Decommissioned natural gas infrastructure due to natural replacement of the connection (km· classification/year)

$ST_{t,x}$ = Share of infrastructure decommissioning I per classification x in year t (%)

PS_t = Costs for removal of the natural gas infrastructure in year t (euro/km · year)

PD_t = Costs for disconnecting the natural gas boiler in year t (euro/connection · year)

b = Learning curve (%), default = 1.5% (average number based on interviews, Appendix B)

CR = Cost reduction due collaboration of removal (%)

$P_{sanitation_t}$ = Removal costs in year t for classifications x1-4 per connection (euro/year/connection)

$P_{sanitation,t,z_x} =$ The fixed tariff per connection for period z. Where one period is fixed for five years. Length of the fixed regulation period {z_1=t0..4; z_2=t5..9; z_3=t10..14; z_4=t15..19; z_5=t20..24; z_6=t25..29; z_7=t30..34}. Where t0 equals 2018. And in total seven periods are used till 2050 (t33 = 2050) (euro/period/connection)

The CR is a percentile factor which can be alternated if the removal of the natural gas infrastructure goes simultaneously with the removal of another infrastructure, which will reduce the costs. As default 100% is used, which means that solely the natural gas infrastructure is removed. Additionally,

3.4.3 Costs for depreciation

Depreciation is the process which indicate what the future payments for a DSO would have been when the natural gas infrastructure had not been decommissioned in an early stage of its economic lifetime. The data used is given in Table 2, including the sources. The following formulas are used for calculating the size of depreciation until 2050.

[17] $$P_{\alpha_{t,x}} = \left(\frac{I_{t,x} \cdot ST_{t,x} \cdot P_I}{LT_{ECO}}\right) \cdot (LT_{ECO} - LT_{a,x})$$

[18] $$LT_{a,x} = LT_{\max,x} - LT_{min,x}$$

[19] $$P_{\alpha_t} = \frac{\sum_{x=1}^{4} P_{\alpha_{t,x}}}{C_{t+1}} \qquad \forall_{t=2018}^{32} t$$

[20] $$P_{\alpha_{t,z_x}} = P_{\alpha_t} \text{ for } z_x = 1 \ldots 7$$

Where:

$P_{\alpha_{t,x}} =$ Depreciation costs for classification x in year t (euro · classification/year)

$P_I =$ Investment costs natural gas infrastructure (euro/km)

$LT_{a,x} =$ Average lifetime per classification (years)

$LT_{max,x} =$ Maximum lifetime per classification x (years)

$LT_{min,x} =$ Minimum lifetime per classification x (years)

$P_{\alpha_t} =$ Depreciation costs in year t for classifications x1-4 per connection (euro/year/connection)

$P_{\alpha_{t,z_x}} =$ The fixed tariff per connection for period z. Where one period is fixed for five years. Length of the fixed regulation period {z_1=t0..4; z_2=t5..9; z_3=t10..14; z_4=t15..19; z_5=t20..24; z_6=t25..29; z_7=t30..34}. Where t0 equals 2018. And in total seven periods are used till 2050 (t33 = 2050) (euro/period/connection)

The costs are calculated per age classification; therefore, the LT $_a$ is used to find the average costs that is depreciated per classification (since the model uses a linear aging assumption).

3.4.4 Costs for Operational & Maintenance (O&M)

The O&M costs will reduce over time, due to the lower share of existing natural gas infrastructure. The following formula explains how O&M is included in the total costs, where the 2.5% is the default percentile for the share of O&M per invested length of natural gas infrastructure.

[21] $$P_{O\&M_{t,x}} = (I_{t,x} \cdot P_I \cdot 2.5\%) \cdot (1 + b)$$

[22] $$P_{O\&M_t} = \frac{\sum_{x=1}^{4} P_{O\&M_{t,x}}}{C_{t+1}} \qquad \forall_{t=2018}^{32} t$$

[23] $$P_{O\&M_{t,z_x}} = P_{O\&M_t} \text{ for } z_x = 1 \ldots 7$$

Where:

$P_{O\&M_{t,x}} =$ Operational & maintenance costs in year t for classification x (euro · classification/year)

$P_{O\&M_t} =$ Operational & maintenance costs in year t for all classifications (euro/year/connection)

$P_{O\&M_{t,z_x}} =$ The fixed tariff per connection for period z. Where one period is fixed for five years. Length of the fixed regulation period $\{z_1$=t0..4; z_2=t5..9; z_3=t10..14; z_4=t15..19; z_5=t20..24; z_6=t25..29; z_7=t30..34$\}$. Where t0 equals 2018. And in total seven periods are used till 2050 (t33 = 2050) (euro/period/connection)

As mentioned in the text, Table 2 summarizes all input values that are used in the model, including the origin of the data.

Table 2: Costs parameters for assessing the extent of economic SA (sources: given in the table).

Input parameter	Description input parameter (unit)	Value
Transportation pipeline	Investment costs [€/m]	286[4]
	Removal costs [€/m]	137[2]
	Depreciation costs [€/m/year]	5[5]
	Economical lifetime [years]	55[1]
Distribution pipeline	Investment costs [€/m]	286[4]
	Removal costs [€/m]	137[2]
	Depreciation costs [€/year]	5[5]
	Economic lifetime [years]	55[1]
Connection pipeline	Investment costs [€/m]	286[4]
	Removal costs [€/m]	50[2]
	Depreciation costs [€/year]	45[1]
	Economical lifetime [years]	55[1]
Fixed tariff per connection	Connection tariff_{2018} [€/connection]	137[6]
Operational & Maintenance	Operational & maintenance (O&M) costs (%/invested natural gas infrastructure/year)	2.5
Learning rate	Share of annual costs improvement for both removal and O&M (%/year)	1.45[5]
Disconnection	Costs for disconnecting the NG (€/connection)	639[5]

[1] ACM (2017d, p. 48) provide the regulated economic lifetime per type of natural gas infrastructure. The model uses the average age of the three natural gas infrastructures combined, including the mutual share of length, which equals 54.6.

[2] The study Van den Wijngaart, Van Polen, & Van Bemmel (2017, p. 21) state that for the VESTA-mais model a factor of 50% of the investment costs are used for calculating the associated removal costs. Since working hours cause the highest share of the cost component (Speirs et al., 2018).

[3] The study Van den Wijngaart, Van Polen, & Van Bemmel (2017, p. 21) indicate a 2.5% O&M per unit length of the capital investment of the natural gas infrastructure.

[4] Check appendix C.3 for the calculation of the value.

[5] This number relate to the investment costs divided by the economic lifetime of the natural gas infrastructure. For each year a meter pipeline is decommissioned earlier than its economic lifetime, the value increased by 5 €/m.

[6] The fixed tariff per connection is set at €137 euro in 2018. This is the average price in 2018 pays by connections using a G4 SJV <4,000 m^3. Appendix C.2 provides a more comprehensive explanation on this matter.

3.5 MODEL & OUTPUT

Sections 3.2 – 3.4 indicated the origin of the data and how this data is formulated for running the model. The model itself is a static calculation process, where the user can adjust both scenarios and strategies.

Ultimately the four key-factors combined form the EI (formula 24 and 25). The SA (formula 26) are the resulting monetary assets from the remaining natural gas infrastructure after 2050. The residual infrastructure regarding the SA is calculated by dividing this by range of years for classification x, subsequently multiplied by the remaining years and the investment costs from the initial investment year.

The EI is given in euro/period/connection. However, to understand to total extent of asset value which is reimbursed by all DSOs for the natural gas connections, additionally the sum of annual costs is given. These assets are the EI_{total} multiplied by the number of consumers and illustrated per period (formula 25).

[24] $$EI_{total} = P_{Fixed_{t,z_x}} + P_{O\&M_{t,z_x}} + P_{sanitation_{t,z_x}} + P_{\alpha_{t,z_x}}$$

[25] $$EI_{total_{cumulative}} = (P_{fixed_t} + P_{O\&M_t} + P_{sanitation_t} + P_{\alpha_t}) \cdot C_t$$

[26] $$SA_{total} = \left(\frac{L_{x(2050)}}{y_x}\right) \cdot (LT_{ECO} - LT_{real}) \cdot P_I$$

Where:

$EI_{total} =$	Total Economic Impact between 2018 and 2050 (euro/period/connection)
$EI_{total_{cumulative}} =$	The annual sum of Economic Impact between 2018 and 2050 (euro/year)
$SA_{total} =$	Total Stranded Assets after 2050 (euros)
$L_{x(2050)} =$	Remaining natural gas infrastructure after 2050 for classification >45 (km)

4. RESULTS

This chapter first highlights the quantitative results from the model and other notable outcomes regarding the EI. Complementary, it provides the results for the SA and relations among decommissioning. The results are primarily shown in time frames of five years.

4.1 BUSINESS AS USUAL (BAU)

Before assessing the results concerning the main question, the results regarding the BAU natural gas infrastructure are shaped. The model used a BAU scenario to illustrate the differences with the hybrid and PA scenario, when the natural gas infrastructure is reduced via natural replacement. The results indicate that an annual reduction of approximately 85,000 connections will occur. This reduction is predominantly caused by the linear ageing regarding the annual reduction of the natural gas infrastructure[9]. In 2050, approximately 2.8 million connections are decommissioned from the natural gas infrastructure. Compared to the 7.2 million existing connections, merely 39% of the connections will be decommissioned.

Coherent with the 2.8 million connections, there is a reduction of 40,200 km. This length is based on the linear ageing used in this model. This means that the share of total length (km) for the classification 'older than 45' years is divided by the difference in years between the economic lifetime (default = 55 years) and minimum age of this classification (46 years). In real-life it is noticed that often the natural gas infrastructure is in adequate condition for extending the natural gas supply by multiple years (ACM, 2017e; NetbeheerNederland, 2017). Nevertheless, for this research 55 years is used as default. Figure 10 illustrate both the reduction of connections and natural gas infrastructure till 2050.

Furthermore, there are no significant costs regarding EI and SA accountable to the DSOs nor natural gas infrastructure connections, since all the components are already included within the real-life business cases. The total fixed tariff per connection increases by a factor 1.9 between 2018 and 2050, which is the effect of the connection reduction and the assumption that no newly built connections will use natural gas. The strategies are neglected in the BAU scenario, since the reduction of connections uses the natural replacement (end of economic lifetime). Additionally, the

Finally, the results are shown for the Dutch natural gas infrastructure commissioned for the built environment. Even though the Dutch natural gas infrastructure is divided in regions, and each DSO is responsible for one region, from a mathematical perspective it is possible to perform the assessment both individually and collectively. Because the ratio between the length and number of connections remains respectively the same (e.g. $\frac{80}{4} = \frac{200}{10}$).

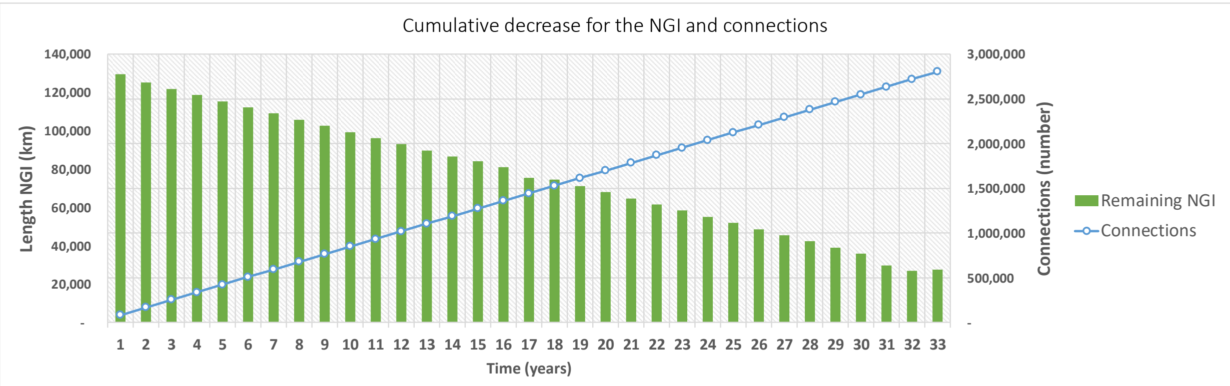


Figure 10: The cumulative decrease for both the natural gas infrastructure and number of connections. Scenario: BAU.

[9] This research used an economic lifetime of 54.6 years. Therefore, if the economic lifetime is in- or decreased it will influence the annual number of reduced connections, since the BAU depends on the natural replacement.

4.2 Economic Impact (EI)

The EI is divided in four components. First, the fixed tariff per connection due to decommissioning of the connections is given, subsequently removal and depreciation are addressed and finally the results for the operational & maintenance costs are given. Additionally, several general findings are described and the link with the UDS is made to illustrate what the EI is in terms of total costs when these costs were plainly stacked over time.

4.2.1 Fixed tariff for connection (connection decommissioning)

The UDS evidently illustrate (section 2.3) that due to the decommissioning of connections, the EI for a DSO can be reimbursed on the remaining connections of the natural gas infrastructure. To understand the extent of this component, the tariff increase is shown (table 3), including the total costs between 2018 and 2050 which again are distributed over the existing connections (table 4).

For the fixed tariff per connection it is visible that there occurs a strong price increase. Table 3 illustrate the results, differing in scenario. The strategies are neglected since the reduction of connections solely depends on the type of scenario, and the strategy places emphasis on the classification of the natural gas infrastructure reduction.

Table 3: Fixed tariff per connection due to connection decommissioning

Fixed tariff per connection (€/connection)						
Scenario	2018	2025	2030	2040	2050	Factor*
BAU	€ 173	€ 187	€ 197	€ 220	€ 249	1.4
Hybrid	€ 137	€ 142	€ 158	€ 561	€ 8,651	63.2
PA	€ 137	€ 176	€ 219	€ 416	€ 2,295	16.8

*Factor illustrates the price ratio between 2018 and 2050.

The PA scenario causes the largest impact for the fixed tariff of the connection until 2030, which is taken over in the latter 10-20 years by the hybrid scenario. This takeover arrives from the large surplus of connections which are disconnected between the period of 2028 and 2040 compared to the PA, approximately 2.5 million connections. This causes a large fixed tariff increase per connection onwards 2035 (a factor 3.7 between the hybrid and PA). This acceleration in the hybrid scenario originate from the steepness of the slope (Chapter 3.3, formula 7). When the steepness is increased even further (e.g. 0.3 to 0.32), an even further cost increase occurs (**Figure *11***). **Table *3*** conclude that for reaching a zero-emission built environment, the last consumers connected to the natural gas infrastructure will pay at least 16.8 times more compared to the current fixed tariff. Appendix D: illustrates on a yearly level what the increase in fixed tariff per connection would be, including the number of connections that are still connected in that year.

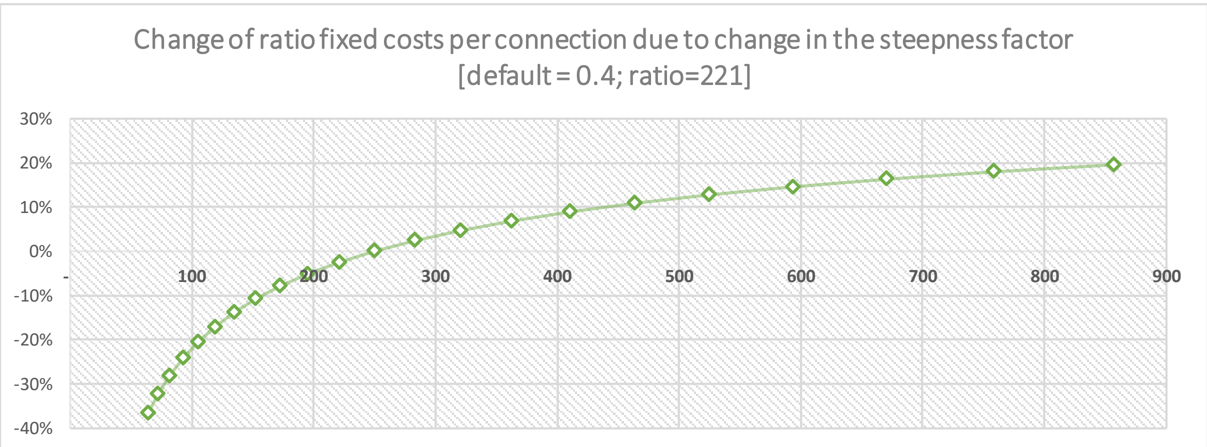


Figure 11: Impact on the fixed tariff per connection when the steepness factor is in- or decreased for the (Scenario: Hybrid, Strategy: Old).

In addition, the increased 'fixed tariff per connection' originates from the annual missed monetary value of the DSO due to the reduction of connections. **Table *4*** indicate these costs without making the translation to the costs per connection. Figure 12 represent these total costs for the PA – old situation. Noticeable are the mutual differences of total costs for the hybrid scenarios. It states that the 'young and old' strategy is more cost efficient compared to the 'Average' strategy. This difference arises from the percentages used per strategy. The total length of young infrastructure is relative low compared to the other infrastructures, after this classification reaches 0, it automatically shifts to the classification >45 years. The average classification starts with the largest share of length (>58,000 km in 2018). Therefore, it takes longer before the strategy will shift to the older classification. This mutual difference causes that in 2050 the cumulative costs for the average strategy are higher. To clarify, even though the costs in 2050 per connection remain the same, it is envisioned to reach the smallest total costs. Since ultimately the costs must be paid.

Table 4: The sum of the annual costs due to decommissioning of connections divided per timeframe.

Fixed tariff per connection (million €)							Cumulative costs*
Scenario	Strategy	2018	2025	2030	2040	2050	Total (billion €)
Hybrid	Old	€ -	€ 62	€ 685	€ 739	€ -	€ 12.1
	Average	€ -	€ 79	€ 882	€ 1,507	€ -	€ 19.0
	Young	€ -	€ 113	€ 1,258	€ 743	€ -	€ 14.9
PA	Old	€ 91	€ 398	€ 494	€ 371	€ -	€ 14.9
	Average	€ 90	€ 513	€ 637	€ 756	€ -	€ 17.6
	Young	€ 90	€ 731	€ 908	€ 373	€ -	€ 18.7

*The cumulative costs illustrate the total costs till 2050 which are reimbursed by the DSO to the fixed tariff per connection.

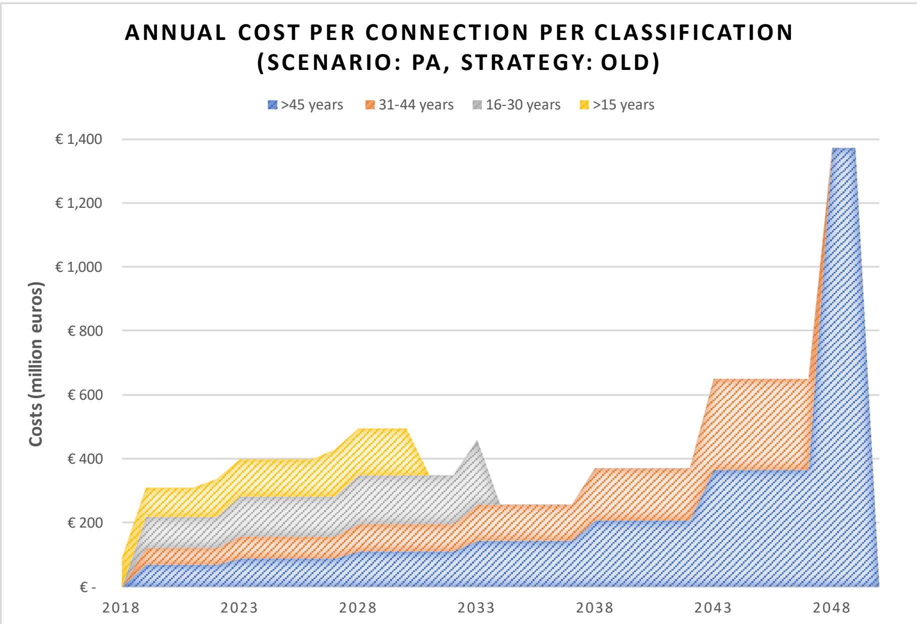


Figure 12: The sum of annual missed asset value for DSOs divided per classification.

The costs shown in figure 12 are caused by the price per connection in year x multiplied with the remaining economic lifetime of the natural gas infrastructure which is decommissioned. It appears that the >45 classification does not illustrate the largest reduction for the length of natural gas infrastructure. This is due to that the classification 16-30 years contains the largest share in length, and therefore a lower percentage does still cover a larger length. In total 14.9 billion euro is distributed over the remaining of connected consumers until 2050 (scenario PA; Strategy Old). Mainly the latter decade illustrates the highest costs, which is asserted by the increased fixed tariff per period, even though the number of connections it already reduced to 2.25 million.

4.2.2 Costs for Removal

The UDS stated that the reduction of connection causes a forced increase in removal costs, where two options are possible: First, both disconnection and removal of the infrastructure. This implies that the remaining connection will both pay these costs for the connection that have left the natural gas infrastructure. Second, merely the disconnection of the natural gas infrastructure. Again, the costs will be charged by the remaining connections, but the removal costs for the natural gas infrastructure are neglected due to inconclusive regulation. **Table *5*** and **Table *6*** provide the results for both options.

Table 5: Removal costs (both disconnection and removal) due to the natural gas infrastructure decommissioning

Removal costs (€/connection)							
Scenario	Strategy	2018	2025	2030	2040	2050	Factor*
Hybrid	Old	€ -	€ 30	€ 79	€ 685	€ 2,236	2236
	Average	€ -	€ 30	€ 92	€ 758	€ 2,236	2236
	Young	€ -	€ 30	€ 95	€ 684	€ 2,241	2241
PA	Old	€ -	€ 122	€ 143	€ 208	€ 1,247	1247
	Average	€ -	€ 146	€ 170	€ 218	€ 1,246	1246
	Young	€ -	€ 150	€ 175	€ 205	€ 1,253	1253

*Factor illustrates the price ratio between 2018 and 2050.

Table 6: Removal costs (merely disconnection) due to the decommissioning

Removal costs (€/connection)							
Scenario	Strategy	2018	2025	2030	2040	2050	Factor
Hybrid	Old	€ -	€ 6	€ 16	€ 142	€ 465	465
	Average	€ -	€ 6	€ 16	€ 140	€ 465	465
	Young	€ -	€ 6	€ 19	€ 137	€ 466	466
PA	Old	€ -	€ 25	€ 29	€ 43	€ 260	260
	Average	€ -	€ 24	€ 28	€ 43	€ 259	259
	Young	€ -	€ 31	€ 36	€ 43	€ 260	260

It is evident that the removal of the natural gas infrastructure is a cost intensive procedure for the overall price increase per connection. And that it would be beneficial for a DSO (and the small consumers) to maintain the natural gas infrastructure even if it has no further use. This implies that the decommissioned infrastructure would be left in the ground. As mentioned in the method section, the RMM does allow to change the Cost Ratio. It has been found that when a certain soil is excavated, multiple actors are incentivized (or forced) to alternate or remove their existing infrastructure, since this leads to shared removal or realization costs. This is interesting for the natural gas infrastructure, because the overall removal costs account for 26% of the total increase of the costs for connections over time (**Figure *19***) and after decommissioning the connections do require an alternative heat supply. New proposals on this matter could lead to future lower costs for both DSO and the associated connections. ETI et al. (2017, p. 28) calculated a cost reduction due to shared excavation of € 100/meter for the district heating network. And Hunt, Nash, & Rogers (2014) indicate the closeness of underground infrastructures, which show that the natural gas infrastructure could share its excavation with water or (tele)communication infrastructure.

When the model uses a discount of € 100/meter the results show that the overall cost for removal will decrease from 26% to 11% for the fixed tariff per connection, and the costs in 2050 end up at € 620 instead of €1250 (Table 5) for scenario PA; strategy Old.

Table *7* and Table 8 represent the total costs for a certain time frame and cumulative costs onwards 2050. Where the difference is made between merely disconnecting the natural gas infrastructure or disconnecting and removal. The difference among the options is a factor 4-5. The costs for disconnected are already significant (€ 639, Table 2) which is about 4 á 5 years of the current (2018) fixed tariff per connection. Due to the continuous increase for the fixed tariff per connection, there could arise a tipping point where a connection is more beneficial in disconnecting their natural gas infrastructure from a costs perspective.

Table 7: Sum of the annual costs for removal (including both disconnection and replacement costs)

Removal costs (million €)							Cumulative costs
Scenario	Strategy	2018	2025	2030	2040	2050	Total (billion €)
Hybrid	Old	€ -	€ 85	€ 793	€ 403	€ -	€ 11.5
	Average	€ -	€ 108	€ 1,005	€ 403	€ -	€ 14.0
	Young	€ -	€ 114	€ 1,058	€ 407	€ -	€ 12.9
PA	Old	€ 493	€ 445	€ 414	€ 272	€ -	€ 11.3
	Average	€ 608	€ 549	€ 510	€ 262	€ -	€ 12.9
	Young	€ 634	€ 572	€ 532	€ 264	€ -	€ 12.9

Table 8: **Sum of the annual costs for removal (including solely disconnection costs)**

Removal costs (million €)							Cumulative costs
Scenario	Strategy	2018	2025	2030	2040	2050	Total (billion €)
Hybrid	Young	€ -	€ 19	€ 181	€ 96	€ -	€ 2.6
	Average	€ -	€ 18	€ 172	€ 96	€ -	€ 2.6
	Young	€ -	€ 26	€ 244	€ 97	€ -	€ 3.0
PA	Old	€ 113	€ 102	€ 94	€ 65	€ -	€ 2.6
	Average	€ 107	€ 97	€ 90	€ 65	€ -	€ 2.5
	Young	€ 151	€ 137	€ 127	€ 65	€ -	€ 3.1

Furthermore, both tables indicate a lowering in removal costs over time. This decline is dually explained: first the model uses a learning curve for the annual costs that are made by the DSO; second, for the hybrid scenario the costs are shown in a bell curve since the reduction rate of the connections is done via the steepness factor originated from the diffusion of innovation theory. Furthermore, the cumulative costs between the PA and hybrid scenario are relative similar.

Then, ***Figure 13*** and ***Figure 14*** illustrate that the classification 'older than 45 years' is the dominant factor for the annual costs increase. This is caused by two factors: 1) both figures illustrate the 'old' strategy, when the average or young strategy is chosen the natural gas infrastructure '> 45' is merely dominant after 2040 and 2). All strategies assume that if a certain length for a classification is zero, the percentile share reduction in the next year is added to the 'older than 45 years' classification. In the year 2049 the costs do considerably drop to zero in 2050. This is explained by that in the latest year (2050) no connections are using natural gas, hence zero associated depreciation costs can be reimbursed by the DSO as EI.

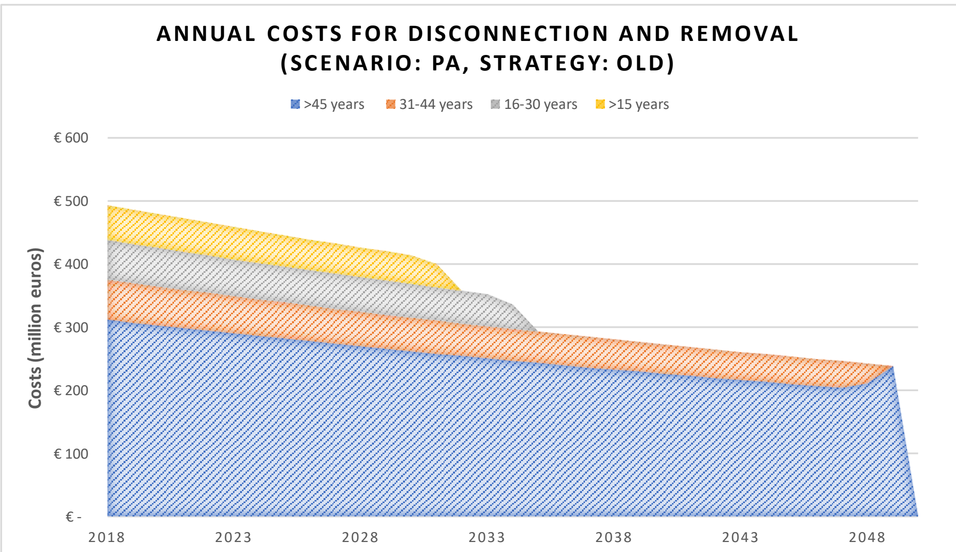


Figure 13: The sum of annual missed asset value for removal (include both disconnection and removal).

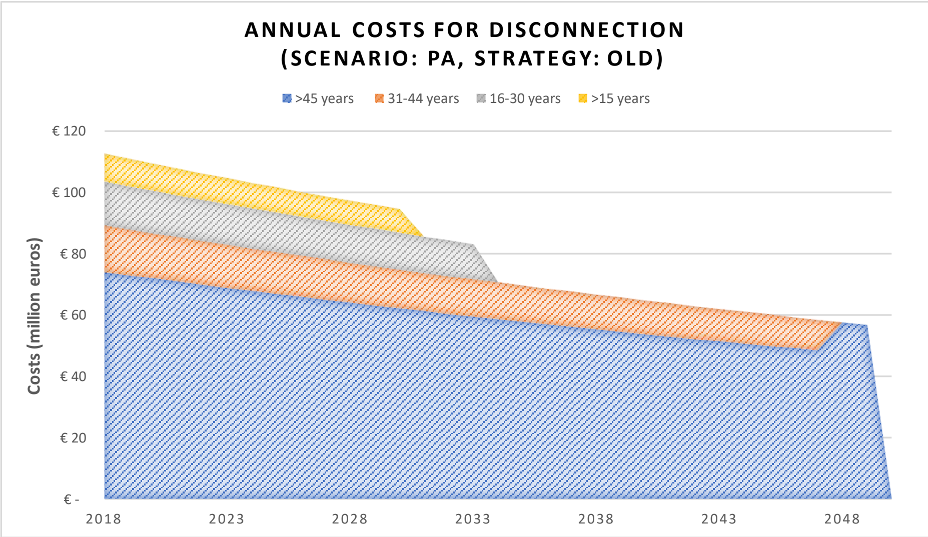


Figure 14: The sum of annual missed asset value for removal (merely disconnection).

In addition, publicity has raised regarding the costs related to the disconnection of the natural gas infrastructure. In May 2018 a natural gas consumer pursued a case in which the person demanded the disconnection costs of 605 euro to be remitted (Ernste, 2018). Ultimately, the energy arbitration commission stated that factually these costs (and interventions) are not necessarily needed (Ernste, 2018; Wiebes, 2018c). And thus, the natural gas consumer won this case.

Currently a DSO charges the consumer for the removal of the energy meter and a small piece of the natural gas infrastructure. Where the energy arbitration commission stated that simply sealing and plugging the existing natural gas pipeline in the connection is enough (ibid). Finally, the DSO responded that preserving the connection is dangerous, however the energy arbitration commission did not any evidence for this. The conclusion is that for this specific consumer, the natural gas connection is merely sealed and plugged, which costs about € 100.

This conclusion substantiates the fact that the remaining connections of the natural gas infrastructure will be affected by the increased reduction of connections. However, the model additionally calculated the EI when the connections that decommission from the NGI is charged by approximately €100. Results show a cost reduction is the fixed tariff per connection between 3 – 5 euros in 2030 and 50 and 90 euros in 2050. The overall share of removal for the fixed tariff per connection, as illustrated in Figure 198, is merely affected by 0.3%.

Based on the results and practical example, it would be beneficial to develop a guideline for both the municipality and DSO to better understand and record the requirements for removal in the current and future situation.

4.2.3 Costs for Depreciation

The costs for depreciation are the fictive expenses of infrastructure investment in year zero, which will be paid back on annual basis using the economic lifetime as main variable. The result indicates what the extent of costs is when sections of the natural gas infrastructure will not directly be recouped due to decommissioning of connections, which triggers the increase of the fixed tariff.

In general, the depreciation costs do not indicate any significant mutual differences. In total the costs per connection increase on average € 40 until 2030, growing to a maximum of € 250-300 in the period afterwards (**Table 9**).

Table 9: Depreciation costs translated to the fixed annual tariff due to the use of natural gas. Costs are given in euro per connection.

Depreciation costs (€/connection)						
Scenario	Strategy	2018	2025	2030	2040	2050
Hybrid	Old	€ -	€ -	€ 19	€ 161	€ 135
	Average	€ -	€ -	€ 25	€ 284	€ 91
	Young	€ -	€ -	€ 35	€ 249	€ 136
PA	Old	€ -	€ 29	€ 39	€ 35	€ 215
	Average	€ -	€ 37	€ 51	€ 65	€ 144
	Young	€ -	€ 52	€ 72	€ 31	€ 216

The main difference in costs for the strategies within the hybrid scenario is, again, explained by the different percentile changes per strategy. The classification 31-44 years holds the largest length, and the average strategy causes a relative high percentile decrease for this classification. The focus on the middle age classification (between 31-44 years), causes a relative high cost peak around 2030, including a high flattening compared to the other strategies after this period.

Table *10* illustrates that the total cumulative costs do not exceed the 6 billion euros. Compared to other components, the depreciation fluctuates between 6-10% of the total fixed tariff onwards 2050 (Figure 19).

Table 10: Sum of annual costs for depreciation. All scenarios and strategies are given. 'Cumulative costs' is the sum of costs from 2018 until 2050 (given in billion euros).

Depreciation costs (million €)							Cumulative costs
Scenario	Strategy	2018	2025	2030	2040	2050	Total (billion €)
Hybrid	Old	€ -	€ 32	€ 325	€ 99	€ -	€ 3.8
	Average	€ -	€ 42	€ 419	€ 202	€ -	€ 5.8
	Young	€ -	€ 60	€ 598	€ 99	€ -	€ 5.6
PA	Old	€ 50	€ 170	€ 170	€ 67	€ -	€ 3.6
	Average	€ 49	€ 219	€ 219	€ 136	€ -	€ 4.7
	Young	€ 49	€ 312	€ 312	€ 67	€ -	€ 5.5

Figure 15 indicate the annual depreciation costs. The costs for the classification >15 are high even though the old strategy is chosen. This is due to the remaining economic lifetime, since the depreciation of the natural gas infrastructure within >15 is multiplied with at least 40 years (55 years – 15 years).

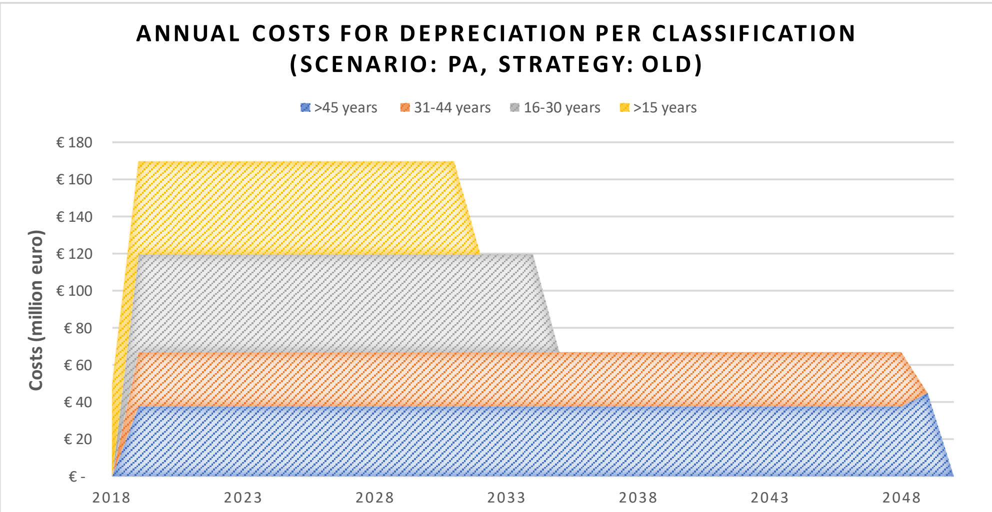


Figure 15: Annual costs for Depreciation. Scenario: PA, Strategy: Old.

DSOs encourage the lowering of the economic lifetime to reduce the potential SA (NetbeheerNederland, 2017). Appendix A gives additional results when the economic lifetime and UF are varied as input parameter.

However, this is beyond the scope of this research, but does lead to interesting outcomes for a follow-up research.

Furthermore, a DSO will be more beneficial by an early (between 2020-2040) decommissioning of connections and an early decrease of natural gas infrastructure for the classification which holds the largest length (30-16 years) and is relatively young. The large decrease of natural gas infrastructure that originates from the described classification is accompanied with the highest costs for depreciation costs. In other words, the hybrid scenario causes lower residual costs, thus a lower EI increase, in the last period and both strategies young and average cause relative lower residual costs.

4.2.4 Costs for Operational & Maintenance

The operational & maintenance generates a plain lowering of the fixed tariff per connection over time, since less natural gas infrastructure accompanies less O&M costs for a DSO.

Table 11: O&M costs translated to the fixed annual tariff due to the use of natural gas. Costs are given in euro per connection.

Operational & Maintenance costs (€/connection)						
Scenario	Strategy	2018	2025	2030	2040	2050
Hybrid	Old	€ -	€ -	€ -2	€ -22	€ -20
	Average	€ -	€ -	€ -2	€ -22	€ -20
	Young	€ -	€ -	€ -2	€ -26	€ -20
PA	Old	€ -	€ -3	€ -4	€ -6	€ -31
	Average	€ -	€ -3	€ -4	€ -5	€ -31
	Young	€ -	€ -4	€ -5	€ -6	€ -32

Table *11* show the reduction of costs per connected consumer until 2050. Over time an increase is seen, with a maximum of €32 per connected consumer. The negative monetary values promote a positive influence on the overall fixed tariff per connection. Per scenario the costs remain about the same, because the O&M costs are not reliable on the average reduction of natural gas infrastructure per classification but merely the share of natural gas infrastructure reduction counts.

Figure *19* state that the O&M costs are negligible since it accounts for <1% per time frame. It could be discussed that the percentage (default = 2.5%) should be higher. The O&M costs is a share for the investment costs per unit length, which implies a linear growth of decline when the input variable is in- or decreased. However, even if the default is changed to 10% (randomly chosen). The total share of costs for the fixed tariff is solely 3-7%.

Table 12: Sum of annual costs for O&M. All scenarios and strategies are given. 'Cumulative costs' is the sum of costs from 2018 until 2050 (given in billion euros).

Operational & Maintenance costs (million €)							Cumulative costs
Scenario	Strategy	2018	2025	2030	2040	2050	Total (billion €)
Hybrid	Old	€ -	€ 3.1	€ 29.0	€ 15.4	€ -	€ 0.4
	Average	€ -	€ 3.0	€ 27.6	€ 15.3	€ -	€ 0.4
	Young	€ -	€ 4.2	€ 39.1	€ 15.5	€ -	€ 0.5
PA	Old	€ 1.4	€ 16.3	€ 15.1	€ 10.4	€ -	€ 0.4
	Average	€ 1.4	€ 15.5	€ 14.4	€ 10.4	€ -	€ 0.4
	Young	€ 1.4	€ 21.9	€ 20.4	€ 10.5	€ -	€ 0.5

For all scenarios the sum of total costs lays between 0.4 – 0.5 billion euros, of which the hybrid scenarios carry the highest costs (**Table *12***). Closing, figure 16 indicate the share of costs distributed per classification, where the highest costs reduction is seen in the oldest classification. This can be explained in trifold: 1) This classification has a forced share of connection reduction, 2) the <45 classification hold the natural replacement share per year and 3) the figure illustrates the old strategy.

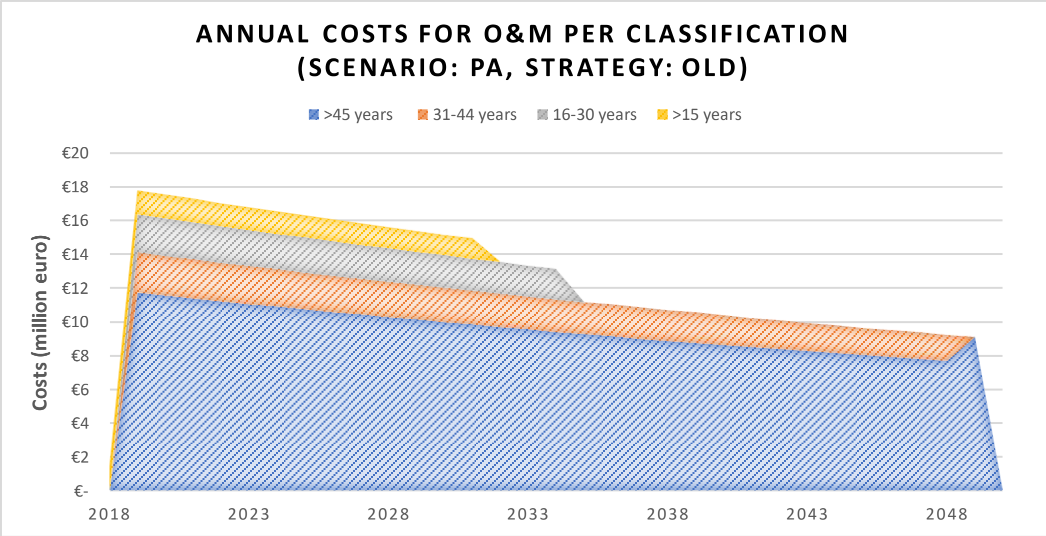


Figure 16: Annual costs for O&M. Scenario: PA, Strategy: Old.

Supplementary, section 4.2.5 offer the results regarding the total EI slash fixed tariff per connection.

4.2.5 EI: total fixed tariff per connection

The four key-factors combined form the total fixed tariff per connection (Table 13). Complementary, some findings are elaborated below this table.

Table 13: The total fixed tariff per connection by summon the four key-factors.

Scenario & strategies		EI: Fixed tariff per connection - Total (€/connection)						
Scenario	Strategy	2018	2025	2030	2040	2050	Factor	Costs*
BAU	Old	€ 137	€ 184	€ 194	€ 220	€ 257	1.9	€ -
	Average	€ 137	€ 184	€ 194	€ 220	€ 257	1.9	€ -
	Young	€ 137	€ 184	€ 194	€ 220	€ 257	1.9	€ -
Hybrid	Old	€ 137	€ 174	€ 258	€ 1,411	€ 11,089	81.0	€ 27
	Average	€ 137	€ 174	€ 276	€ 1,606	€ 11,044	80.6	€ 39
	Young	€ 137	€ 174	€ 289	€ 1,493	€ 11,094	81.0	€ 33
PA	Old	€ 137	€ 329	€ 402	€ 662	€ 3,774	27.6	€ 30
	Average	€ 137	€ 360	€ 441	€ 702	€ 3,703	27.0	€ 36
	Young	€ 137	€ 380	€ 467	€ 654	€ 3,781	27.6	€ 38

*The cumulative costs illustrate the total costs till 2050 which are reimbursed by the DSO to the fixed tariff per connection.

Combining the four input components, one overall fixed tariff per connection is given. Figure 17 provide the costs per key-factor and what this will mean for the overall costs in the year 2030 and 2050, using the dynamic system model from the Utilities Death Spiral. Appendix D provide the EI per year for the period 2018 till 2050 for all scenarios and strategies.

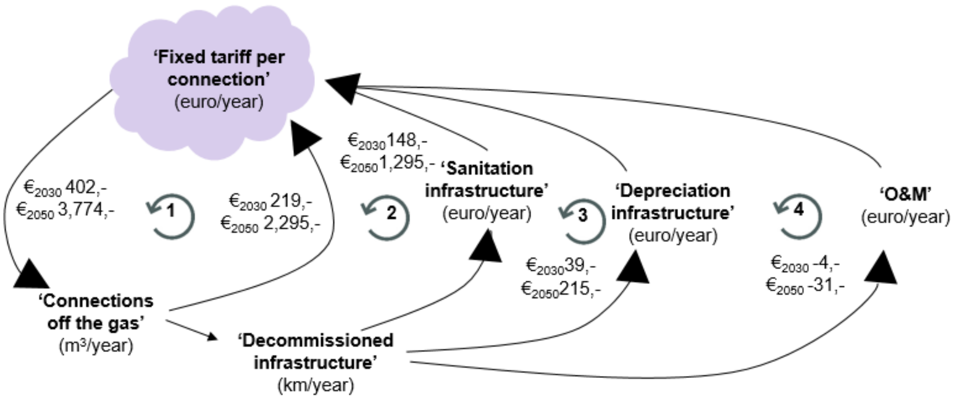


Figure 17: Scenario PA, Strategy Old. Results for the EI on the fixed tariff per connection in the year 2030 and 2050 (source: own interpretation).

A point which could impact the DSOs are the cumulative costs within the period 2018 – 2050 compared to the fixed tariff per connection. Since the current regulation states a fixed period of five years for altering the fixed tariff per connection. This could influence the residual costs after 2050 (SA). Because if in the year 2047-2050 a relative high reduction of connections occurs; the costs cannot be charged on the remaining connections in the period after since there are no connections left. Therefore, it can be said that there is a relation between the EI and SA in relation to decommissioning, assuming a continuation of the current regulation.

Then, the overall costs effects lay closer to the use of the natural gas infrastructure, in terms of volume, than the economic lifetime of the natural gas infrastructure. In other words, if the number of natural gas connections remains stable, the linear depreciation of the fixed tariff per connection will remain about the same (factor 1.9). However, preserving the current regulation methodology and reaching the desired zero emissions in 2050 for the built environment, the depreciation costs will increase the fixed tariff significantly and lead to disproportionate costs for both the DSO and remaining connections.

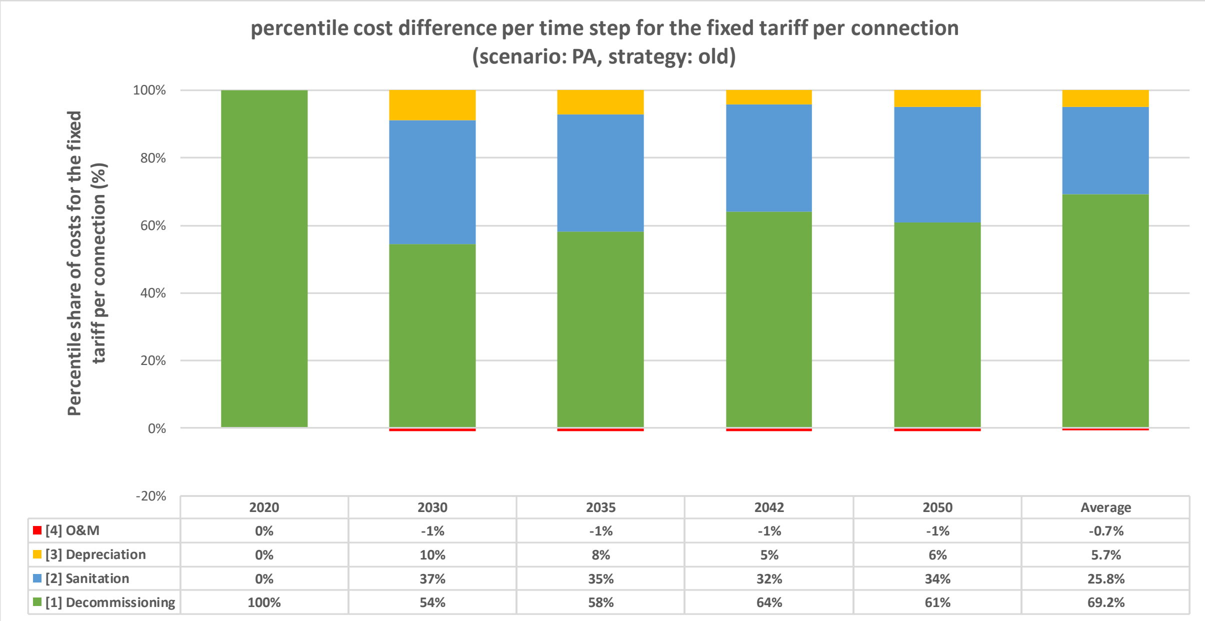
Finally, as mentioned in section 3 (Table 2) the costs for the removal of the natural gas connection at the connection is about 4 times the annual fixed tariff paid by a connection in 2018 (€ 505/€ 136 = 3.7). However, onwards 2032[10] the new period of fixed tariff will exceed these costs in all scenarios. Which could cause an incentive for connections to decommission from the natural gas infrastructure.

And increased fixed tariff per connection could enable other discussions. The current market situation shows a strong correlation between the amount of income and managing your living. Connections having a low income, generally show more difficulty to manage their monthly expenses. For example, connections having a monthly income of € 1,200 gross per month (40% of the population in 2012) or between € 1,200 – € 1,800 per month, have expressed financial difficulties for manage their expenses on monthly level (Madern & Van der Schors, 2012). An increase of several euros could cause financial stress (ibid). In relation to the results, the increase of the fixed tariff per connections of natural gas is relative low compared to other sustainable solutions such as insulation or installing an electric air-source heat pump. Nevertheless, in the long run the fixed tariff for using natural gas evolve rapidly and will mainly affect the population with a low income. Since these natural gas consumers cannot afford any other alternatives to decommission from the natural gas infrastructure.

Assessing all four key-factors till 2050 (figure 18 and 19), it is evident that the direct reduction of connections, in combination with the removal of the natural gas infrastructure, causes the highest costs to increase for the fixed tariff per connection. Furthermore, the costs for O&M are nihil compared to the costs for removal and decommissioning. Depreciation becomes more dominant after 2020, but remains relative

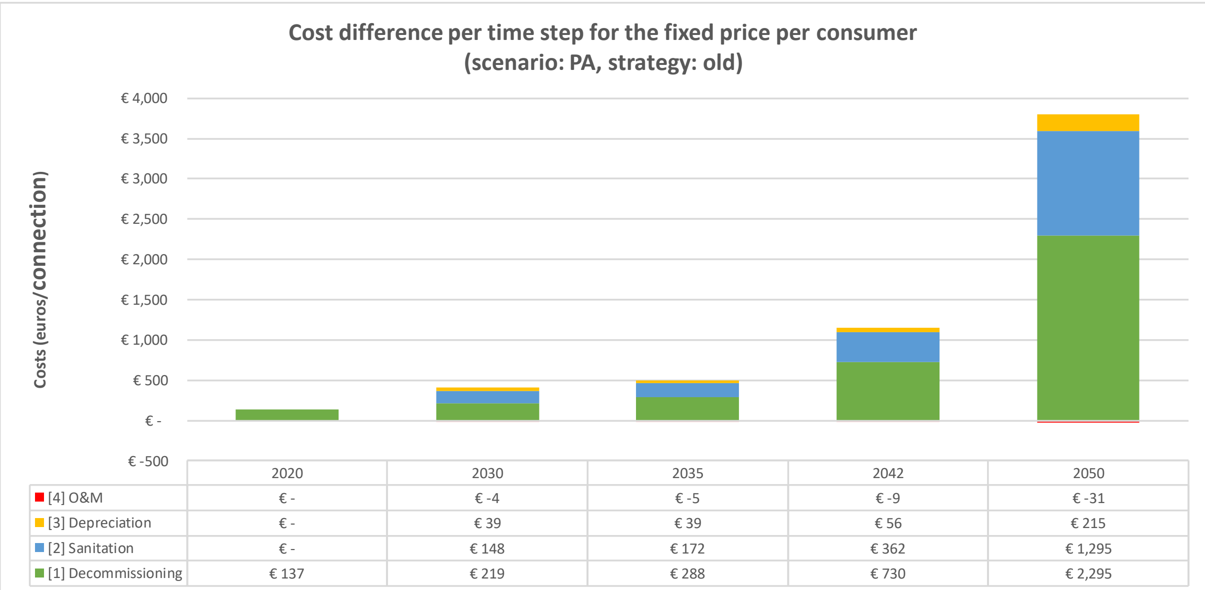
[10] Scenario: Paris Agreement; Strategy: Old.

low compared to removal and decommissioning. Both figures show the PA scenario and Strategy Old. However, choosing another scenario or strategy does result in similar results with variations which do not exceed a 10% in- or decrease.



	2020	2030	2035	2042	2050	Average
[4] O&M	0%	-1%	-1%	-1%	-1%	-0.7%
[3] Depreciation	0%	10%	8%	5%	6%	5.7%
[2] Sanitation	0%	37%	35%	32%	34%	25.8%
[1] Decommissioning	100%	54%	58%	64%	61%	69.2%

Figure 18: Division of costs components over time in mutual percentages (scenario: PA, Strategy: Old).



	2020	2030	2035	2042	2050
[4] O&M	€ -	€ -4	€ -5	€ -9	€ -31
[3] Depreciation	€ -	€ 39	€ 39	€ 56	€ 215
[2] Sanitation	€ -	€ 148	€ 172	€ 362	€ 1,295
[1] Decommissioning	€ 137	€ 219	€ 288	€ 730	€ 2,295

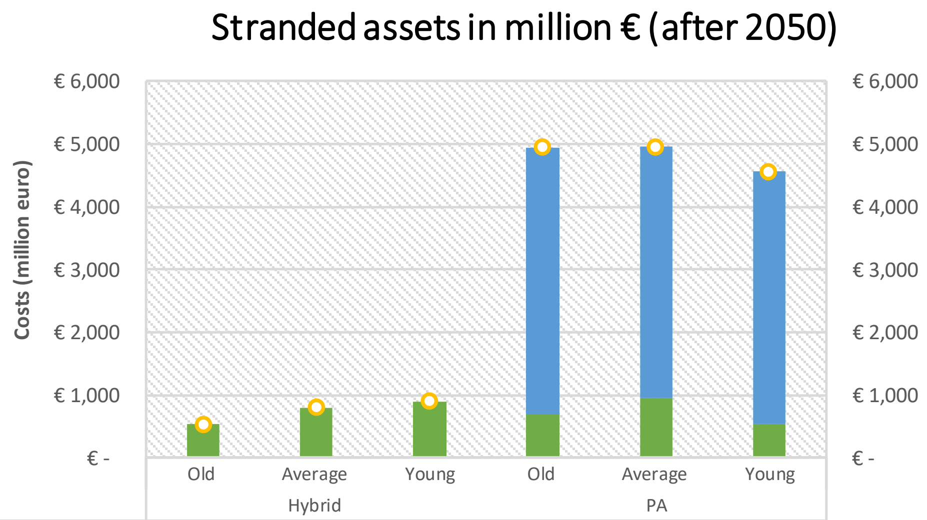
Figure 19: Division of costs components over time in numbers (scenario PA, Strategy: Old).

4.3 STRANDED ASSETS (SA)

As defined, SA are the remaining book value of assets substituted before the end of their anticipated economic lifetime without recovery of any remaining value to achieve 2050 decarbonization targets. DSOs often call this principle the 'baksteen', the non-covered costs (NetbeheerNederland, 2017). The SA are divided in two costs components. Firstly, the SA originate from the remaining natural gas infrastructure in the soil, which still has economic value. Secondly, the missed value in the latter period (regarding the regulation of ACM) cannot be recouped by the remaining connections since after this period there will be zero connections left. The sum of both indicate the total SA.

Section 4.2 has shown that for the hybrid scenario no SA occur in the latter period of the regulation. This is due to that the number of reduction for natural replaced connections exceed the number of needed connections that must be decommissioned in the hybrid scenario (for the BAU a linear replacement of 85,000 connections is set, where the hybrid scenario requires a reduction between 20,000 – 49,000 in the years 2047-2050). The PA scenario requires an annual reduction of 224,000 connections, which mean that the remaining costs in the latter period cannot be recouped.

Figure 20 illustrate the sum of the remaining monetary value after 2050 which cannot be recouped, including the SA for the PA due to missed value in the latter period of regulation.



	Old (Hybrid)	Average (Hybrid)	Young (Hybrid)	Old (PA)	Average (PA)	Young (PA)
Remaining assets due to the regulation	€ -	€ -	€ -	€ 4,248	€ 3,990	€ 4,014
Remaining NGI	€ 536	€ 803	€ 899	€ 702	€ 964	€ 551
Total	€ 536	€ 803	€ 899	€ 4,950	€ 4,954	€ 4,565

Figure 20: Stranded Assets per scenario and strategy after 2050 divided in UF and regulation.

According to the results, the SA results in significant costs compared to the remaining natural gas infrastructure in the soil, caused by the regulation methodology. About 85% of the total SA for the PA (per strategy) is due to the remaining regulation costs. Assessing the SA due to the remaining natural gas infrastructure (caused by the UF), there is small difference in results. Both the old and average strategy for the hybrid scenario are lower compared to the PA, but the young strategy vice versa causes higher overall SA for the hybrid scenario. This difference is due to the percentile set-up of the strategy, the young strategy first puts emphasis on the young natural gas infrastructure while the other two strategies place the accent on the older natural gas infrastructure. The younger natural gas infrastructure does increase in age over time, and therefore it is economically beneficial to focus on the neighborhoods with a higher percentile share in age. In other words, the type of neighborhoods decommissioning has influence on the extent of SA. For the PA this increase is not seen, because the linear ageing in this scenario causes that the length for the younger classification has reached zero in an earlier stage.

Figure 21 gives an overview on how the standardized asset value is decreasing over time[11]. The figure indicates that compared to the current assets, the SA represent 28% of the total assets. Even though this is about a quarter of the total assets, still 4.95 billion euro needs to be recouped without any consumers being connected to the natural gas infrastructure.

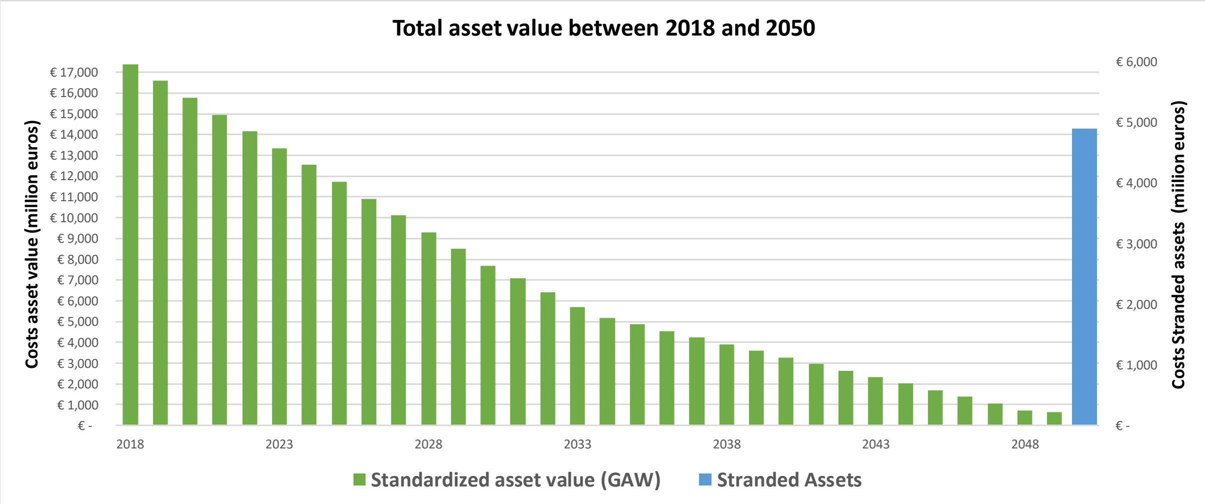


Figure 21: The total value of assets which is operational between 2018 and 2050. Including the remaining value after 2050 (costs are in million euros; Scenario: PA, Strategy: Old).

It is apparent that both the UF and economic lifetime of the natural gas infrastructure influence the quantitative outcome of the results. For the usability factor of the natural gas infrastructure, no substantiated data has been found of what the exact share will be in future decades. Therefore, it remains obscure what the exact share of usable pipeline would be for the existing small consumers within the Netherlands. Multiple sources state different percentages, such as van Melle, Menkveld, Oude Lohuis, de Smidt, & Terlouw (2015) which give a UF of 60% or the interviews that mentioned that the transportation pipelines are remained to connect the overarching infrastructure. The economic lifetime of the natural gas infrastructure is currently heavily debated by DSOs, since the reduced role of natural gas is mentioned in relation to the earthquakes in Groningen.

However, beforehand both input parameters have not been incorporated as moderator in this research. To preserve the consistency of the research, but at the same time deliver an unbiased and complete research, additional sensitivity analyses have been carried out in Appendix A. The general remarks are mentioned below in bullet-points:

- Varying the economic lifetime of the natural gas infrastructure induces a four billion difference in asset value between the default 55 years and the increments 50 and 60 years, for the UF the difference is about one billion (varying UF between 60% and 90%). For the EI the changes in fixed tariff per connection, due to a changing economic lifetime, lay between € 6 – 8 for 2030 and € 80 – 150 for 2050 (UF=79%).

- The increase of UF causes lower SA. This process seems rational, since the volume of the SA depends primarily on the share of the natural gas infrastructure which is maintained in the soil. The maximum discrepancy is € 55 (Scenario: PA; Strategy: old).

[11] The assumption was made that that no new NGI is built onwards 2018. This will cause merely a reduction of standardized asset value over time.

4.4 EI AND SA IN RELATION TO THE UDS

The question remains if the UDS will truly occur on the long run, since as Eid, Reneses Guillén, Frías Marín, & Hakvoort (2014) stated that this implies an unreasonable inertia from both utilities and regulators. Interviews (Appendix B) emphasize that both ACM and several DSOs are concerned about the plausible impact on the fixed annual tariff for the remaining connected consumers. Nevertheless, Simhauser (2017) state that regulatory approval at the time of investment commitment does not form a basis for full recovery because as (Maloney & Sauer, 1998; Navarro, 1996) and many others highlight, regulators have neither the resources, nor responsibility, to create and guarantee investment plans. Regulators review plans and hear arguments of interested parties. Regulators cannot be expected to match the expertise and resources of utilities, nor come close to second-guessing what constitutes a prudent investment program (Douglas et al., 2009).

Nevertheless, the development of EI and SA have demonstrated that current policy, used by DSOs, cannot endure in the future. With a continuation of their current policy, it can be expected that their costs will increase significantly.

5. DISCUSSION

The discussion chapter provide a trifold of information. First, the contribution of established knowledge is outlined. Subsequently the limitations are given and finally the necessity for further research is clarified.

5.1 CONTRIBUTIONS OF ESTABLISHED KNOWLEDGE

This research focused on the EI and SA for DSOs, and results clearly state that if the current regulation will retain, the future for both the DSOs and connections (read: small consumers) will foresee considerably costs increases. These results are of importance since currently the focus is put on 'sustainable' alternatives, while ignoring the existing assets the society is using and paying for. Subsequently, among DSOs and the regulator a debate has started on how the society will be 'deprived' by this transformation, of which these results give a substantiated impression.

With respect to the adjusted RMM that is applied in this research, at this moment there is no shared view on the decommissioning activities which combines asset information, timelines and costs estimates (EBN, 2017). The RMM in this research can serve as a first impetus towards a comprehensive model that maintains the confidentiality of the natural gas infrastructure data while allowing the database to still serve it purpose. Since, the model enables the option to generalize the natural gas infrastructure data without commercially sharing sensitive data, simultaneously being opensource and adjustable to all users.

Internationally, countries could take advantage using the results to gain new insight on how their infrastructure could be impacted if the necessity for reducing a fossil fuel based energy carrier is inevitable. Even though the results from this study are specifically for the Netherlands, with some adjustments other countries or regions can be assessed. Likewise, on a national level these results provide an embedded substantiation on a possible future for DSOs and connection small consumers.

For this research the UDS theory is used to assess the development of the existing natural gas infrastructure. This theory demonstrated new insights in the four components used to quantify the EI and SA, retaining the current regulation process. Additionally, this theory accommodates science with a new perspective on how a monopoly oriented organization is affected by an enforced alteration regarding the shift from fossil to renewable. While this research solely used one component from the five which were identified within literature (section 2.3.1), it could provide enlarged potential for future research to indicate the potential effects for organizations (monopolized, private, et cetera) regarding the shift from fossil to renewable.

5.2 RESEARCH LIMITATIONS

However, despite the added value of this research there have been identified five limitations which could influence the results, especially regarding the future outcomes. The first notable research limitation is the natural gas infrastructure data used for this research. The outcomes are a combination of economic parameters and the characteristics for the natural gas infrastructure. These characteristics are the length, age and location of the natural gas infrastructure. Data for the length and age of the natural gas infrastructure is solely found in a generalized form. Example: 20,000 km of the natural gas infrastructure has an age between 16-30 years. This denotes that within this age range, large variations in length per specific age could occur (e.g. 15,000 of the 20,000 km has an age of 18 years). Subsequently influencing the overall EI and SA. However, the results have proven to be consistent with the limited data that has been found in grey literature and interviews conducted with experts relating to the natural gas infrastructure (Appendix B). The study NetbeheerNederland (2017), the DSO branch organization, and interviews estimated SA about five billion euros, which is in line with the PA scenario of this research.

Secondly, this research assumes that the infrastructure which is decommissioned neglect the possibility for (renewable) substitutes to evolve by giving the existing infrastructure a second life. Literature and interviews (Appendix B) have shown a solid substantiation that bio-methane and hydrogen could play a significant role in the future energy supply of the built environment, and more important the second life of the natural gas infrastructure (Dodds & McDowall, 2013; Haeseldonckx & D'haeseleer, 2007; Kreijkes, 2014; Speirs et al., 2018). Additionally, both substitutes have proved to be utilized as energy supply within the built environment, if some minor adjustments will be carried out regarding the existing natural gas infrastructure. Numbers indicate reduction about 50% of the total costs regarding SA and EI are mentioned in literature, inter alia Speirs et al. (2017), and validated by the model used in this research.

Thirdly, the research presumes that the current methodology is used until 2050. However, since the beginning of the socialized natural gas infrastructures, multiple adjustments have been incorporated in the regulation methodology. Which the new regulation 'called Progress Energy Transition (Dutch: Voortgang Energy Transitie)' as latest example (VNG, 2018). At this moment the natural gas infrastructure is uncertain in its future, and it is likely that the methodology will not maintain without any adjustments. This can be substantiated by section 4.4, where Eid, Reneses Guillén, Frías Marín, & Hakvoort (2014) stated that to let a Utilities Death Spiral to take place, this implies an unreasonable inertia from both utilities and regulators.

Fourthly, this research solely assessed the cost-effectiveness approach, neglecting both safety and reliability. The question raises if the conclusions of this research still stands if safety and reliability are included. For this reason, it would be interesting to investigate the alternations on the results when safety and a reliable energy supply are included, where this model used a usability factor to indicate the reduction rate. The study Brouns (2017) assessed these topics in future replacement needs, neglecting a forced reduction process of the natural gas use. Combining this knowledge within this research could lead to an enhanced model which provide the core values of a DSO to be quantitatively calculated.

Lastly, as pointed out frequently. The energy transition is a complex transformation, which brings along a broad set of influencers. This research focused on the economic influence, neglecting the social-, environmental-, demographic, perception of other actors, et cetera. Focusing, or consider, these other factors by altering the scope of the research could provide more realistic results.

5.3 FURTHER RESEARCH

There are four areas which require future research or follow up. First, both science and business require novel research on substitutes for the infrastructure which is currently utilized for natural gas. The adjusted RMM applied for this research allows to incorporate these substitutes. This will gain proficient insight for the renewable substitutes regarding the existing infrastructure translated to EI and SA for DSOs.

Secondly, the outcomes and conclusions from the model provide further research with the notion for finding alternations that suppress or gain new perceptions regarding the current regulation which is used. Focus should be placed on the depreciation regarding the age of the natural gas infrastructure and uncertainty of the UF (Appendix A.). Additionally, literature has indicated other regulation methodology which are applied for monopolized infrastructures. Even though, this presumably demands a new RMM. It could result in suppressing the EI and SA over time, and thus investigating these results quantitatively would be beneficial for future decision making.

Thirdly, it would be recommended to further asses the UDS in relation to infrastructures. The theory indicated a clear relation among climate change and (policy) regulation and how the future for infrastructures will be presumably affected. The UDS could provide a renewed understanding on the relevant relations within such systems and can be utilized such that it could be internationally applied.

Finally, another way of looking at decommissioning is to translate decommissioning in a business opportunity. Whilst, the results have shown that decommissioning is accompanied with enlarged costs, a study by McCauley (2018) investigated how decommissioning project could lead to new opportunities. This study showed that most interviewees mentioned 'job creation', 'investing in local communities' and 'technological renewal'. Research on this matter to suppress the overall decommissioning costs could lead to new insights and economic savings, since the forced decommissioning of natural gas connections seems inevitable.

6. CONCLUSIONS

A Regulation Monopoly Model is used to answer the EI and SA regarding the existing natural gas infrastructure for Dutch DSOs, when a forced reduction of small consumers for the Built Environment is initialized to reach zero emissions in 2050.

What are the Economic Impact and Stranded Assets for DSOs when the existing Dutch natural gas infrastructure for the built environment is decommissioned in an early stage of its lifetime?

For answering this question, two moderators are inserted: Scenarios and Strategies. The three scenarios (BAU, Hybrid, PA) illustrate the annual reduction rate of natural gas connections towards 2050. While the strategies (Old, Average, Young) determine what share of natural gas infrastructure per classification (e.g. <45 year) is annually decommissioned, based on the reduction rate of connections. Combining the moderators, the results use the BAU outcomes to compare the overall EI and SA for the remaining two scenarios and three strategies. The results in this study have found the following conclusions regarding the research question:

The BAU scenario indicate that without forced influences the EI will increase by a factor 1.9 till 2050. Additionally, in 2050 about 4.4 million connections are still using natural gas, and mere 40,200 kilometer of the natural gas infrastructure is decommissioned.

Assessing the hybrid and PA scenario, it is evident that for the EI it is preferable that the PA scenario is deployed. This lead to a factor 3 lowering of EI in 2050 compared to the hybrid scenario, if the current methodology is preserved. Nevertheless, compared to the BAU scenario, the EI will raise at least by a factor 27 (PA scenario) if a zero-emission built environment is desired. Other results drawn from the model indicate that the SA are more cost-efficient if the hybrid scenario will arise for reaching a zero-emission built environment. Nevertheless, this is contradictory to the EI and raises the question whether to focus on suppressing the EI (fixed tariff per natural gas connection) or the plausible SA after 2050. Noteworthy for this conclusion is that the PA solely leads to higher SA after 2050 compared to the hybrid scenario because of the remaining costs due to the current regulation purposes. If these would not occur, the overall costs result in the same order of magnitude. Subsequently this leads to the conclusion that maintaining the current regulation methodology till 2050 cause a mutual relation among EI and SA. This relation, accompanied by decommissioning, does result in significant SA when the PA is deployed.

The strategies do not preserve mutual differences which considerable influence the results, and variate in a range of multiple millions for the SA and solely about 150 euro regarding the EI in 2050. To put this in perspective, changes among the scenarios cause differences between 1-5 billion-euro in 2050. Thus, from a cost perspective, DSOs should closely monitor the annual reduction rate till 2050.

Overall, a DSO will be most beneficial by an early (between 2020-2040) decommissioning of natural gas connections and an early decrease of natural gas infrastructure for the classification that hold the largest length and is relatively young. In other words, the hybrid scenario causes lower residual costs, thus a lower SA, in the last period and both strategies young and average cause lower residual costs compared to the old strategy.

Summarized, the compiled hypotheses for EI and SA regarding decommissioning can be answered. A strong correlation among EI and SA is seen in relation to the decommissioning of the natural gas infrastructure. When the reduction of connections is increased, an accompanied increase in the EI and SA is evident. Regarding the moderators, it would be most cost-efficient for a DSO if the reduction of connections follows a hybrid scenario pathway, which lead to lower SA but higher EI. Finally, compared to 2018, cost-efficiently the EI increases by a factor 27 and ancillary SA of 4.5 billion euro (PA scenario) or a factor 81 regarding the EI and 0.5 billion euro for SA (Hybrid scenario). Concluding that if DSOs will retain the current regulation it cannot endure the future development of EI and SA, since they are obliged to provide a reliable, safe and cost-efficient infrastructure.

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APPENDIX A: VARIABILITY IN THE UF AND ECONOMIC LIFETIME

In the result section is has been found that some input variables do influence the eventual results significantly. However, an analysis of these parameters within the result section does not fit the scope of the research. Therefore, to preserve the consistency of this research, these outcomes are further assessed in this appendix to provide the reader an overarching view on how the potential conclusions and recommendations drawn from the results will affect the EI and SA for DSOs. The economic lifetime of the natural gas infrastructure and the usability factor (UF) are the parameters which will be assessed, and thus added as additional moderators in the conceptual framework. Within the following Appendices, the term 'Natural Gas Infrastructure' is abbreviated as NGI.

The sensitivities are done using the 'what if' tool within Microsoft excel. This tool gives an overview of the results, when one variable is changed within the model. Since this research already used the neighborhood strategies and scenarios as moderator, basically another moderator is added.

A1. EI: USABILITY FACTOR AND ECONOMIC LIFETIME

As the research is divided in EI and SA. Table 15 illustrates the variety of fixed tariff per connection for the years 2030 and 2050, when the UF and economic lifetime are changed. The following evident outcomes are seen: Additionally, Figure 22 and Figure 23 indicate the mutual differences for UF=79% and the year 2030 and 2050.

- The changing costs are solely allocated to the changing left-over depreciation costs;
- Lowering the economic lifetime of the existing NGI cause a lowering in the fixed tariff per connection. This is explained by two factors: the annual depreciation is calculated by dividing the economic lifetime by 1 and multiplying this with the associated length and remaining age of the infrastructure. When the economic lifetime decreases, a higher annual cost per unit length is used. However, the remaining age of the NGI will decrease when the economic lifetime decreases. This factor outperforms the annual depreciation factor. Thus, overall the depreciation costs result lower. Since the sum of left-over depreciation is reimbursed on the remaining connections, a lowering in fixed tariff per connection occurs.
- The UF illustrates an increase in fixed tariff per connection, with a maximal discrepancy of € 55 (Scenario PA; Strategy Old).
- The maximal discrepancy for the economic lifetime is about € 80 for the hybrid scenario, and € 150 for the PA (UF=79%, year=2050).
- The maximal discrepancy for the economic lifetime is about € 6 for the hybrid scenario, and € 14 for the PA (UF=79%, year=2030).

Table 14: Overview of the SA differing in Usability factor and Economic lifetime for the years 2030 and 2050.

Economic impact - Usability factor and Economic lifetime for 2030 & 2050																					
Scenario [years]	Strategy	UF=79%	UF=79%	UF=60%	UF=60%	UF=65%	UF=65%	UF=70%	UF=70%	UF=75%	UF=75%	UF=80%	UF=80%	UF=85%	UF=85%	UF=90%	UF=90%
-	-	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Hybrid [55 years]	Old	€ 258	€ 11,089	€ 231	€ 10,861	€ 238	€ 10,915	€ 245	€ 10,974	€ 252	€ 11,037	€ 259	€ 11,104	€ 267	€ 11,037	€ 274	€ 11,245
	Average	€ 276	€ 11,044	€ 243	€ 10,927	€ 252	€ 10,896	€ 261	€ 10,947	€ 269	€ 11,000	€ 278	€ 11,056	€ 287	€ 11,000	€ 296	€ 11,173
	Young	€ 289	€ 11,094	€ 251	€ 10,870	€ 261	€ 10,925	€ 272	€ 10,983	€ 282	€ 11,044	€ 292	€ 11,108	€ 302	€ 11,044	€ 312	€ 11,240
PA [55 years]	Old	€ 402	€ 3,774	€ 354	€ 3,452	€ 366	€ 3,535	€ 379	€ 3,620	€ 392	€ 3,706	€ 405	€ 3,793	€ 418	€ 3,706	€ 432	€ 3,968
	Average	€ 441	€ 3,703	€ 381	€ 3,478	€ 397	€ 3,561	€ 412	€ 3,644	€ 428	€ 3,644	€ 444	€ 3,718	€ 460	€ 3,644	€ 475	€ 3,867
	Young	€ 467	€ 3,781	€ 399	€ 3,471	€ 417	€ 3,553	€ 435	€ 3,634	€ 453	€ 3,716	€ 471	€ 3,798	€ 489	€ 3,716	€ 507	€ 3,896
Hybrid [50 years]	Old	€ 252	€ 11,001	€ 228	€ 10,825	€ 235	€ 10,866	€ 241	€ 10,911	€ 247	€ 10,960	€ 254	€ 11,012	€ 260	€ 10,960	€ 267	€ 11,125
	Average	€ 272	€ 10,953	€ 241	€ 10,894	€ 249	€ 10,844	€ 257	€ 10,881	€ 265	€ 10,920	€ 273	€ 10,962	€ 282	€ 10,920	€ 290	€ 11,052
	Young	€ 283	€ 11,005	€ 248	€ 10,833	€ 257	€ 10,874	€ 266	€ 10,919	€ 276	€ 10,966	€ 285	€ 11,016	€ 294	€ 10,966	€ 303	€ 11,121
PA [50 years]	Old	€ 391	€ 3,634	€ 347	€ 3,368	€ 359	€ 3,437	€ 370	€ 3,507	€ 382	€ 3,578	€ 394	€ 3,650	€ 406	€ 3,578	€ 418	€ 3,794
	Average	€ 431	€ 3,558	€ 375	€ 3,393	€ 390	€ 3,462	€ 405	€ 3,531	€ 419	€ 3,512	€ 434	€ 3,571	€ 449	€ 3,512	€ 464	€ 3,690
	Young	€ 454	€ 3,639	€ 391	€ 3,385	€ 408	€ 3,452	€ 424	€ 3,519	€ 441	€ 3,586	€ 458	€ 3,654	€ 474	€ 3,586	€ 491	€ 3,721
Hybrid [60 years]	Old	€ 263	€ 11,182	€ 234	€ 10,899	€ 242	€ 10,968	€ 249	€ 11,041	€ 257	€ 11,118	€ 265	€ 11,199	€ 273	€ 11,118	€ 281	€ 11,371
	Average	€ 281	€ 11,141	€ 246	€ 10,960	€ 255	€ 10,951	€ 265	€ 11,017	€ 274	€ 11,085	€ 283	€ 11,156	€ 292	€ 11,085	€ 302	€ 11,303
	Young	€ 296	€ 11,188	€ 255	€ 10,910	€ 266	€ 10,979	€ 277	€ 11,051	€ 288	€ 11,127	€ 299	€ 11,205	€ 309	€ 11,127	€ 320	€ 11,366
PA [60 years]	Old	€ 414	€ 3,921	€ 361	€ 3,540	€ 375	€ 3,639	€ 388	€ 3,739	€ 403	€ 3,841	€ 417	€ 3,944	€ 431	€ 3,841	€ 446	€ 4,151
	Average	€ 450	€ 3,856	€ 387	€ 3,567	€ 404	€ 3,665	€ 421	€ 3,763	€ 437	€ 3,786	€ 454	€ 3,875	€ 471	€ 3,786	€ 488	€ 4,055
	Young	€ 481	€ 3,929	€ 408	€ 3,563	€ 427	€ 3,660	€ 447	€ 3,756	€ 466	€ 3,853	€ 485	€ 3,950	€ 505	€ 3,853	€ 524	€ 4,083

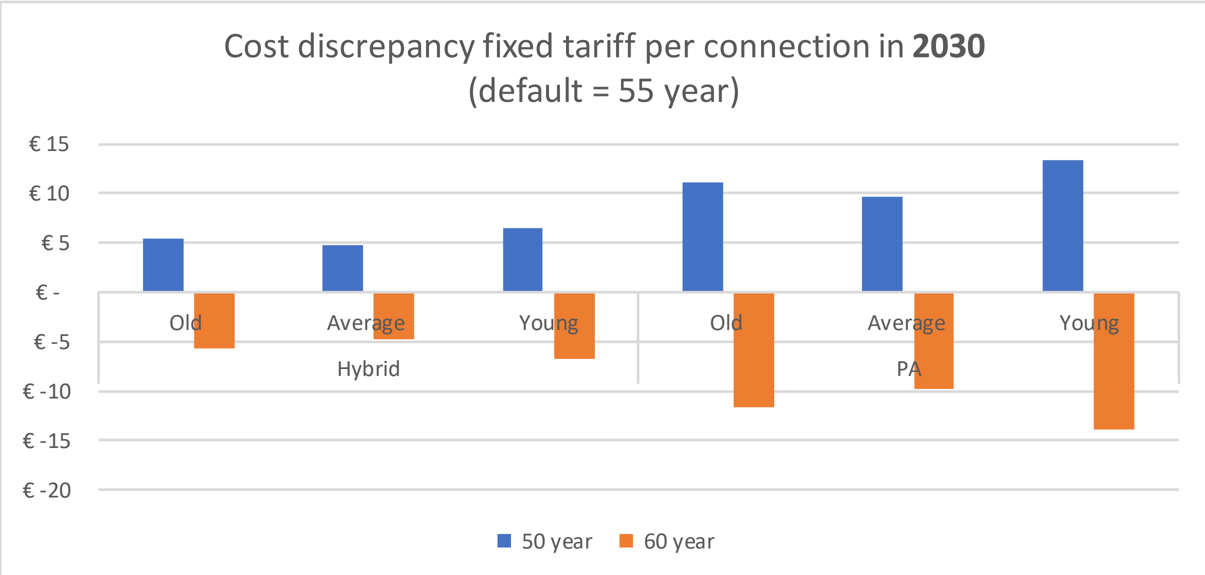

Figure 22: Cost discrepancy among each scenario and strategy for UF=79% and year 2030. Data in Figure is derived from table 15.

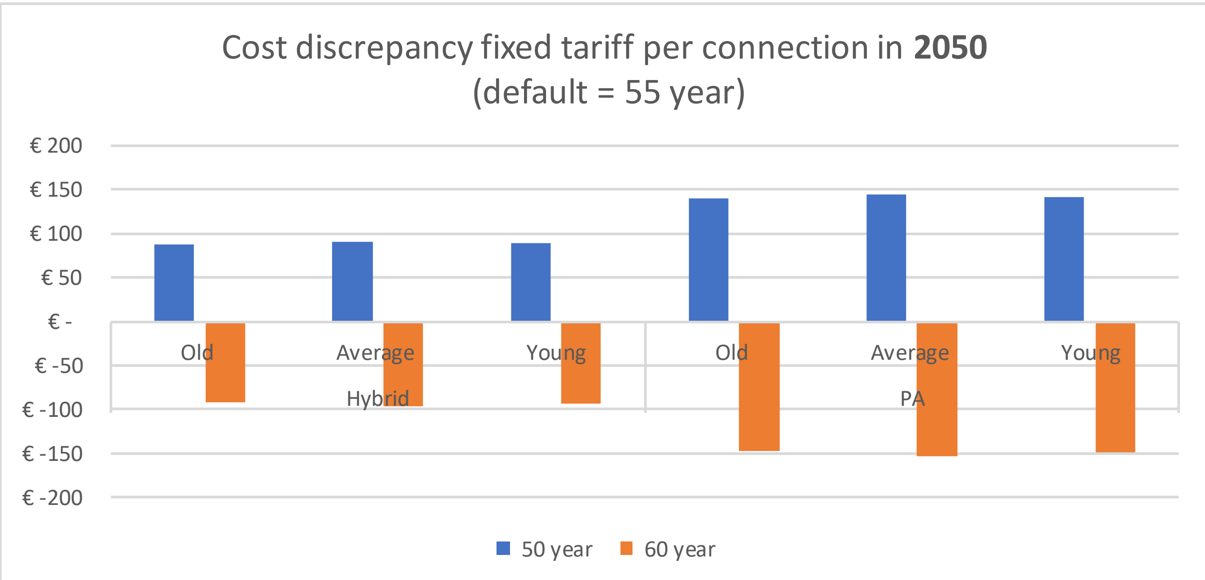

Figure 23: Cost discrepancy among each scenario and strategy for UF=79% and year 2050. Data in Figure is derived from table 15.

A2. SA: Usability factor and Economic lifetime

The economic lifetime determines the annual share of reimbursement for the DSOs. When this lifetime is increased (for example: to 60 years), the depreciation will be lower and thus less income for a DSO is requested, this could potentially lead to higher SA since in 2050 no connections can use natural gas. Vice versa, a decrease in lifetime could work the other way around. Understanding these processes for the different neighborhood strategies and scenarios, the following tables and figures are taken from the model. The results that are given, vary in economic lifetime between 50 and 60 years.

Subsequently, as mentioned multiple times within this research, the UF represent the share of NGI which is decommissioned. Or inversed, the UF indicate what share of NGI will remain to maintain the infrastructure for supplying conform the DSOs obligations (a continuous supply of safe, secure, and cost-efficient natural gas). The exact share of the UF in the coming decades remains obscure, since it depends on a large variety of indicators (such as type of neighborhood, decision making on local level, et cetera). Therefore, a range between 60% till 95% is assessed (default = 79%), using increments of 5%.

Table 15: SA differing in economic lifetime and UF per scenario and strategy (neglecting the SA due to regulation).

Stranded assets (million euros) - Usability factor									
Scenario [years]	Strategy	UF=79%	UF=60%	UF=65%	UF=70%	UF=75%	UF=80%	UF=85%	UF=90%
Hybrid [55 years]	Old	€ 536	€ 1,381	€ 1,220	€ 1,000	€ 778	€ 720	€ 494	€ 567
	Average	€ 803	€ 1,235	€ 1,152	€ 1,042	€ 927	€ 776	€ 579	€ 663
	Young	€ 899	€ 1,477	€ 1,255	€ 1,197	€ 973	€ 916	€ 858	€ 632
PA [55 years]	Old	€ 702	€ 1,421	€ 1,231	€ 1,178	€ 962	€ 718	€ 603	€ 349
	Average	€ 964	€ 1,499	€ 1,148	€ 1,000	€ 836	€ 659	€ 767	€ 578
	Young	€ 551	€ 1,368	€ 1,307	€ 1,059	€ 996	€ 933	€ 501	€ 430
Hybrid [50 years]	Old	€ 326	€ 604	€ 542	€ 480	€ 410	€ 345	€ 279	€ 211
	Average	€ 342	€ 555	€ 539	€ 522	€ 470	€ 322	€ 255	€ 281
	Young	€ 356	€ 606	€ 565	€ 524	€ 392	€ 364	€ 336	€ 220
PA [50 years]	Old	€ 344	€ 612	€ 551	€ 489	€ 426	€ 362	€ 298	€ 198
	Average	€ 384	€ 557	€ 541	€ 524	€ 475	€ 364	€ 316	€ 260
	Young	€ 410	€ 598	€ 556	€ 514	€ 420	€ 423	€ 339	€ 310
Hybrid [60 years]	Old	€ 1,109	€ 2,046	€ 1,728	€ 1,648	€ 1,469	€ 1,135	€ 798	€ 457
	Average	€ 1,005	€ 2,114	€ 1,592	€ 1,627	€ 1,339	€ 978	€ 1,070	€ 610
	Young	€ 942	€ 1,674	€ 1,587	€ 1,407	€ 1,312	€ 1,218	€ 874	€ 779
PA [60 years]	Old	€ 1,130	€ 1,865	€ 1,980	€ 1,667	€ 1,268	€ 1,155	€ 1,069	€ 703
	Average	€ 1,098	€ 2,122	€ 1,892	€ 1,641	€ 1,369	€ 1,077	€ 764	€ 430
	Young	€ 1,167	€ 1,879	€ 1,778	€ 1,676	€ 1,301	€ 1,197	€ 551	€ 435

Table 15: SA differing in economic lifetime and UF per scenario and strategy (neglecting the SA due to regulation). gives an overview of all SA which arose by changing both the UF and economic lifetime, including the two moderators 'scenario' and 'strategy'. Figure 24 translated these quantitative results in a bar graph for merely the PA scenario. Evident is the mutual deviation between the economic lifetimes compared to the UF. The economic lifetime cause about a factor 2 in overall SA, where the UF show differences of a factor 1. Figure 25 gives the entire table 14 in a bar diagram. This is caused by that the model calculate the annual income per unit length of NGI by dividing the investment costs by the economic lifetime and subsequently multiplying this with its specific age. Extending the economic lifetime, means a higher numerator and thus the annual depreciation decreases. This causes more NGI to be remained after 2050 and therefore results in higher SA. Formula A explains this, where $C_{Remaining}$ are the costs per meter per year recovered by the DSO.

[A] $$\boldsymbol{C_{Remaining}} = \frac{\frac{€}{m}}{\boldsymbol{LT_{eco}}} \cdot \boldsymbol{LT_{spec}} \rightarrow [a] = \frac{250\left(\frac{€}{m}\right)}{55(LT_{eco})} \cdot 30 = 136 \left(\frac{\frac{€}{m}}{year}\right) \boldsymbol{or}\ [b] = \frac{250\left(\frac{€}{m}\right)}{60\ (LT_{eco})} \cdot 30 = 125 \left(\frac{\frac{€}{m}}{year}\right)$$

This also works the other way around when the Economic lifetime would decrease, it automatically causes higher beneficial costs for the DSO and thus a reduction in SA compared to the default of.

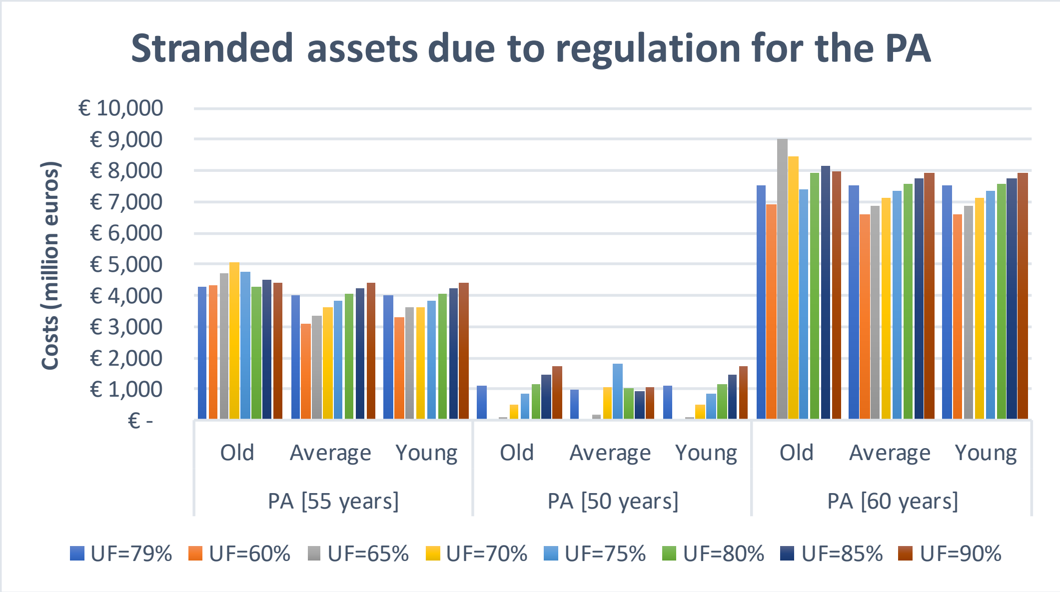

Figure 24: SA illustrated per UF and eco-LT and for each scenario. Costs are given in million euros.

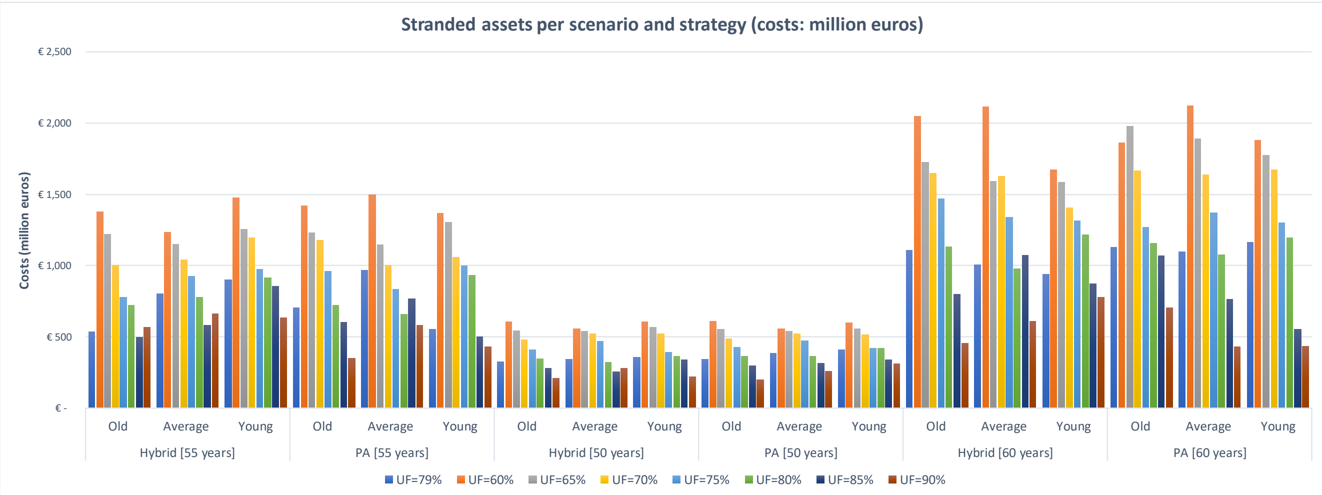

Figure 25: SA per scenario and strategy, varying from UF and economic lifetime (costs: in million euros).

Furthermore, the results indicate that an increase in the UF causes lower SA. This decrease in SA seems rational since the volume of the SA depends primarily on the share of NGI which is left in the ground. Among the strategies minor differences are seen. The most outstanding is that for the UF=60% the share of the remaining NGI in 'Hybrid; Young' and 'PA; Average' is significant larger compared to the other results.

In

Table ***16*****: SA for the PA due to the missed value in the latter period of the regulation.** and Figure 26 the SA due to the regulation are shown. Evident is that a lower economic lifetime equals lower SA over time, where the UF=60% even leads to zero additional SA. For the default in this research (55 years and UF=79%) the SA for regulation will cause about 4 billion euros. Which is doubled when the economic lifetime is increased to 60 years, and halved when decreased by 5 years. In other words, the SA due to the missed value in the latter period of the regulation (2047-2050) will decrease significantly when the economic lifetime is decreased by 5 years. This is explained by the reduced depreciation period, since a DSO will recoup a relative higher annual share of costs when the economic lifetime is decreased. This causes that in the latter period less monetary value needs to be reimbursed.

Additionally, from Figure 26 it is apparent that mutual changes in UF is seen for the old strategy and economic lifetime of 50 and 60 years. Where the other results show a linear growth in SA when the UF increases. The mutual differences occur due to that the changing UF causes that the linear ageing requires less years to decommission to reach zero compared to others. The formula for calculating all costs is based on four components: Length, costs, age and UF. A changing UF influences the reduction of length for a certain age. Therefore, it could occur that more length is decommissioned in the latter period. Closing, the model could result in no SA for the PA in the latter period of regulation. This is happening when solely 60% of the NGI will be decommissioned, resulting in zero SA due to that less length per connection is decommissioned over time and due the lower economical lifetime, all costs are charged.

Table 16: SA for the PA due to the missed value in the latter period of the regulation.

Stranded assets (million euros) - regulation									
Scenario [years]	Strategy	UF=79%	UF=60%	UF=65%	UF=70%	UF=75%	UF=80%	UF=85%	UF=90%
PA [55 years]	Old	€ 4,248	€ 4,314	€ 4,704	€ 5,055	€ 4,733	€ 4,290	€ 4,494	€ 4,416
	Average	€ 3,990	€ 3,092	€ 3,365	€ 3,608	€ 3,828	€ 4,028	€ 4,213	€ 4,385
	Young	€ 4,014	€ 3,298	€ 3,589	€ 3,628	€ 3,850	€ 4,053	€ 4,213	€ 4,385
PA [50 years]	Old	€ 955	€ 1,718	€ 1,885	€ 2,038	€ 1,547	€ 970	€ 1,045	€ 862
	Average	€ 699	€ 462	€ 526	€ 589	€ 651	€ 711	€ 771	€ 830
	Young	€ 724	€ 662	€ 744	€ 610	€ 674	€ 737	€ 771	€ 830
PA [60 years]	Old	€ 8,453	€ 7,603	€ 8,275	€ 8,876	€ 8,784	€ 8,531	€ 8,897	€ 8,958
	Average	€ 8,198	€ 6,462	€ 7,000	€ 7,472	€ 7,893	€ 8,271	€ 8,614	€ 8,929
	Young	€ 8,221	€ 6,670	€ 7,226	€ 7,491	€ 7,914	€ 8,294	€ 8,614	€ 8,929

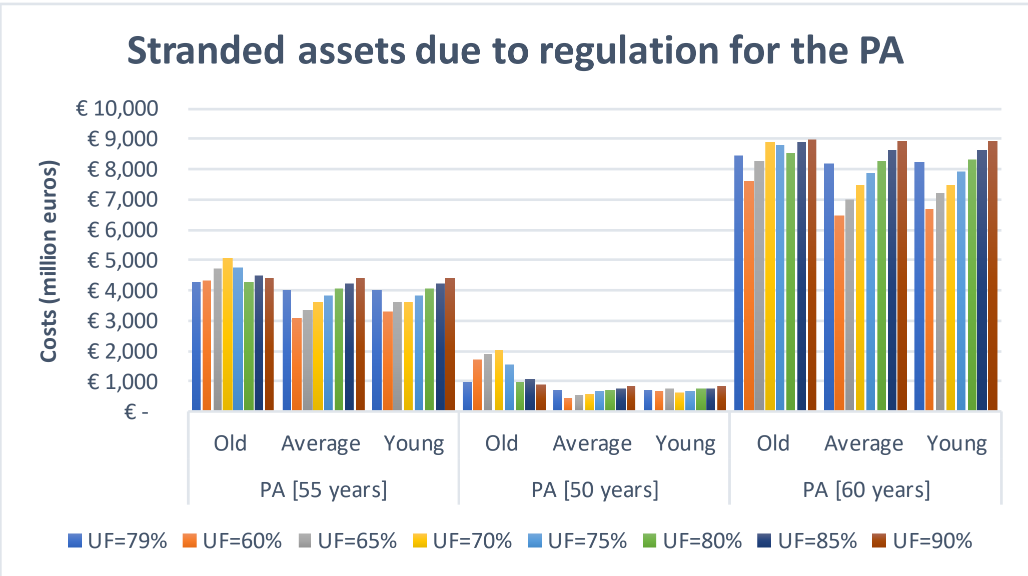

Figure 26: Results from the SA due to the regulation in the PA, differing in economic lifetime and UF.

Below the SA for both regulation and UF are merged in one table. Both **Table *17*** and Figure 27 substantiate the findings which are described in the previous paragraphs.

Table 17: SA for all scenarios including both the SA for regulation and the Usability Factor.

Stranded assets (million euros) - **Usability factor & Regulation**									
Scenario [years]	Strategy	UF=79%	UF=60%	UF=65%	UF=70%	UF=75%	UF=80%	UF=85%	UF=90%
Hybrid [55 years]	Old	€ 536	€ 1,381	€ 1,220	€ 1,000	€ 778	€ 720	€ 494	€ 567
	Average	€ 803	€ 1,235	€ 1,152	€ 1,042	€ 927	€ 776	€ 579	€ 663
	Young	€ 899	€ 1,477	€ 1,255	€ 1,197	€ 973	€ 916	€ 858	€ 632
PA [55 years]	Old	€ 4,950	€ 5,735	€ 5,935	€ 6,234	€ 5,695	€ 5,008	€ 5,097	€ 4,766
	Average	€ 964	€ 4,592	€ 4,513	€ 4,608	€ 4,664	€ 4,687	€ 4,980	€ 4,963
	Young	€ 551	€ 4,666	€ 4,896	€ 4,687	€ 4,846	€ 4,986	€ 4,714	€ 4,815
Hybrid [50 years]	Old	€ 326	€ 604	€ 542	€ 480	€ 410	€ 345	€ 279	€ 211
	Average	€ 342	€ 555	€ 539	€ 522	€ 470	€ 322	€ 255	€ 281
	Young	€ 356	€ 606	€ 565	€ 524	€ 392	€ 364	€ 336	€ 220
PA [50 years]	Old	€ 1,298	€ 2,331	€ 2,436	€ 2,527	€ 1,973	€ 1,332	€ 1,343	€ 1,060
	Average	€ 1,083	€ 1,019	€ 1,067	€ 1,113	€ 1,126	€ 1,076	€ 1,087	€ 1,090
	Young	€ 1,134	€ 1,260	€ 1,300	€ 1,123	€ 1,094	€ 1,160	€ 1,110	€ 1,140
Hybrid [60 years]	Old	€ 1,109	€ 2,046	€ 1,728	€ 1,648	€ 1,469	€ 1,135	€ 798	€ 457
	Average	€ 1,005	€ 2,114	€ 1,592	€ 1,627	€ 1,339	€ 978	€ 1,070	€ 610
	Young	€ 942	€ 1,674	€ 1,587	€ 1,407	€ 1,312	€ 1,218	€ 874	€ 779
PA [60 years]	Old	€ 10,319	€ 9,583	€ 9,942	€ 10,144	€ 9,939	€ 9,600	€ 9,599	€ 8,958
	Average	€ 10,321	€ 8,354	€ 8,641	€ 8,842	€ 8,970	€ 9,035	€ 9,044	€ 8,929
	Young	€ 10,100	€ 8,448	€ 8,903	€ 8,792	€ 9,110	€ 8,845	€ 9,050	€ 8,929

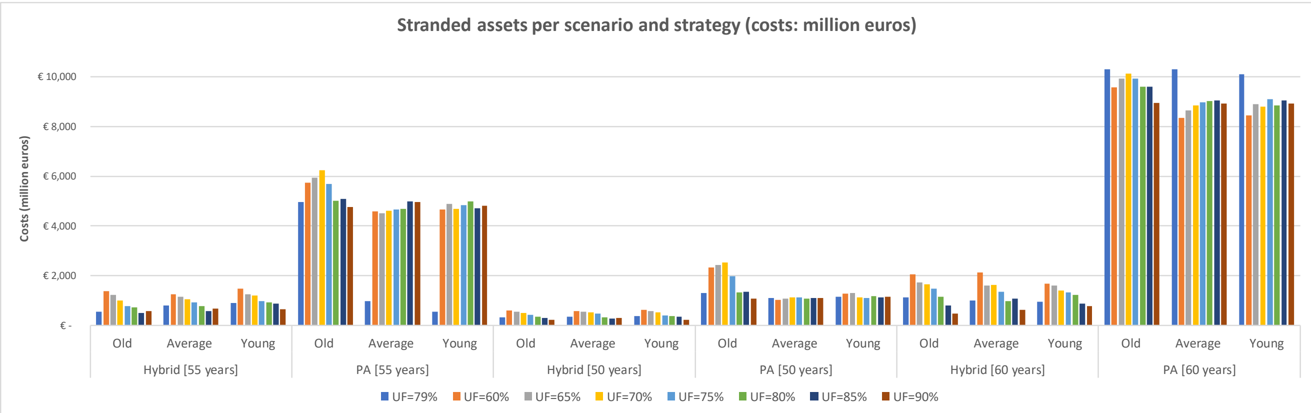

Figure 27: SA including both the SA regarding the UF and regulation, differing in UF percentage and economic lifetime.

Lowering the economic lifetime means a higher depreciation. As an example, shown in formula [A]. For the oldest classification this will mean that the annual income for DSO is reduced by x years and thus, higher annual costs are reimbursed on the remaining natural gas consumer.

APPENDIX B: SEMI-STRUCTURED INTERVIEWS

The emphasis of this research is quantitative. However, to disentangle the data input and associated results, in total 14 semi-structures interviews have been carried out with personnel working (in)directly at a decentralized- or transmission system operator. Table 18 provide an overview of all interviewees, using simplification of the contact details to maintain privacy and confidentially.

Table 18: List of interviewees working at a grid operator (in)directly.

Interview	Company/organization	Date
1	Enexis	May 2018
2	Enexis	April 2018
3	Enexis	April 2018
4	Stedin	May 2018
5	Stedin	May 2018
6	Alliander	May 2018
7	Quintel	April 2018
8	Accenture – Gasunie	June 2018
9	Accenture – Gasunie	March 2018
10	Accenture – ACM	May 2018
11	Accenture – Enexis	Feb-Jun 2018
12	Accenture – Enexis	Feb-Jun 2018
13	Accenture – Alliander	April 2018
14	Accenture – Alliander	May 2018

Below, multiple bullet-point are given which are mention-worthy for this research:

- EI and SA are known within our organization (DSO). Especially the rate of impact on our existing assets is an increasing rate of discussion in the last couple of years.

- Our organization (DSO) did not realized until 4 years ago that internally the number of colleagues would growth by a factor 4. At this moment calculating and meeting with clients regarding the NGI became a daily task.

- SA (in Dutch called 'baksteen') is estimated around 5 billion euro after 2050 for all DSOs combined. This is for all consumers that are connected to the Groningen-gas infrastructure.

- The missed value for our organization due to forced reduction of connections is recharged by the remaining consumers. An example: the lawsuit between a DSO and small consumer regarding the costs for disconnecting from the NGI was won by the consumer. But what most people do not know, is that these costs will be charged on the remaining consumers. Not the DSO itself, since a DSO is socialized.

- Each DSO is focusing on substitutes for the natural gas to maintain the existing infrastructure. The substitutes which are most likely to be used are bio-methane and hydrogen. Both can be used for small consumers in the built environment. The study conducted by CE Delft indicate the future potential and is used by most DSOs as estimation for future processes. Mainly emphasis is placed on bio-methane, covering about 50% of the future natural gas demand for the built environment.

- There should arise alternations in the current regulation by ACM. Since both DSOs and consumers will be impaired significantly.

- Regarding removal of the NGI, it can be done multiple ways. Since on local level it often remains unclear what actions must be taken when a consumer does not make use of the natural gas, two options are possible: First, the associated NGI can be removed and the natural gas unit is sealed and removed from the connection. Or the natural gas unit is merely sealed and disconnected from, maintaining the associated NGI.

- You should understand that the research question you focus on is one piece of the entire puzzle. In practice, there are a wide variety of variables which influence the eventual decision making to get off the gas.

- If there will arise a forced reduction of natural gas connections for the built environment, first the DSOs will feel the burden since they are responsible for the 'low' pressure infrastructure (8-16 bar). For the TSO

– For Gasunie it would be wise to follow the developments. But ultimately Gasunie oversees the high-pressure infrastructure and merely needs to maintain the infrastructure, in other words. Gasunie will the last party in the entire supply chain which feel the 'economic' impact.

- From a technical perspective it is recommended to make a clear distinction on the type of natural gas used in the research. The difference in low- and high-calorific natural gas is based on the percentile share of nitrogen, and if indicated via the Wobbe Index.

- It would be interesting to gain more knowledge, when there is a forced reduction of natural gas connections, on what the impact will be on the existing infrastructure in terms of maintaining pressure. If suddenly entire neighborhoods will be decommissioned, it still requires an overarching infrastructure to connect the neighborhoods which lay multiple kilometers from each other.

- The cost-efficiency for the investment costs are seen over time, mainly due to the current regulation which is put in place. I think reductions in costs between 1-3% could occur annually. However, this depends on multiple factors. E.g. if new materials are used, or we change part of our region with another DSO, unforeseen costs could occur which could raise the costs.

- Bio-methane is mentioned as solution. But this would make balancing the infrastructure more difficult. Bio-methane is often inserted on the relative low-pressure pipelines. However, momentarily the grid is balanced from top-down. Due to the input of bio-methane on the low-pressure grid, it is not possible (during e.g. summer period when the demand is low) to distribute the inserted bio-methane to the higher-pressure infrastructure. This is due the values which are placed between the pressure pipelines and solely allow the gas to go one direction.

- It would be interesting if you could insert in the model what the differences will be in SA for DSOs when alternations occur in the current regulation. E.g. I would be interested to see what happens when part of the future costs will be reimbursed by the government. In other words, the government would control an increased 'fictive' number of connections to suppress the fixed tariff per consumer. These costs by the government could be spread over the entire nation.

APPENDIX C: DATA VALIDATION

This appendix is written for both strategies, the usability factor (UF) and the associated economic values. Part C.1 will illustrate which type of neighborhoods are used and how the specific percentiles are found. Subsequently part C.2 will indicate the sensitivity of the length of NGI per neighborhood, which is originated from part the assessment of the strategies. Finally, C.3 provide an overview of all economic input values and, if needed, a sensitivity on the data.

C.1. NEIGHBORHOOD STRATEGIES

As described in chapter 3.2, for the length and age of the natural gas infrastructure an ongoing linear ageing process is used. Where for the classification 'younger than 15 years' the data is taken from CBS (2018). In total 75 neighborhoods are analyzed based on the generalization method of Wijngaart, R., Folkert, R., Middelkoop (2014). Table X illustrate the name of the neighborhood, the associated municipality and the share of age classifications. As mentioned, the classification 'younger than 30' year is adjusted by subtract the length of NGI for the newly built connection in the past 15 years.

nr.	To be replaced	Older than 30 years	Younger than 30 years	younger than 15 years	Total	To be replaced	Older than 30 years	Younger than 30 years	younger than 15 years	Total	Neighbourhood	Municipality	Length/ house	Strategy	Type neighborhood
	km	km	km	km	km	%	%	%	%	%	-	-	m/hh	-	
1	0.0	26.1	1.5	0	**27.66**	0%	94%	6%	0%	**100%**	Lunetten-Zuid	Utrecht	7.43	Average	1
2	0.0	9.8	3.7	0	**13.49**	0%	73%	27%	0%	**100%**	Lunetten-Noord	Utrecht	4.71	Average	1
3	0.3	2.8	11.1	0	**14.31**	2%	20%	78%	0%	**100%**	Nieuw Hoograven-zuid	Utrecht	9.00	young	1
4	0.6	0.5	5.0	0	**6.08**	10%	9%	82%	0%	**100%**	Oud Hoograven-zuid	Utrecht	5.96	young	1
5	0.7	1.1	4.9	0	**6.68**	10%	16%	74%	0%	**100%**	Nieuw Hoograven-Noord	Utrecht	5.61	young	1
6	0.0	2.0	6.1	0	**8.15**	0%	25%	75%	0%	**100%**	Oud Hoograven-Noord	Utrecht	5.95	young	2
7	0.1	1.1	2.6	0	**3.73**	1%	28%	70%	0%	**100%**	Bokkenbuurt	Utrecht	8.29	young	2
8	1.0	0.6	8.3	0	**9.83**	10%	6%	84%	0%	**100%**	Tolsteeg en Rotsoord	Utrecht	4.25	young	2
9	0.7	3.8	3.2	0	**7.78**	10%	49%	41%	0%	**100%**	Vondellaan	Beverwijk	13.77	Average	2
10	1.7	6.7	1.3	0	**9.70**	18%	69%	13%	0%	**100%**	Ronde Boogaard	Beverwijk	8.33	Average	2
11	17.8	6.3	8.5	0	**32.64**	54%	19%	26%	0%	**100%**	Nieuwe Westen	Rotterdam	3.36	old	3
12	5.6	1.3	22.2	0	**29.12**	19%	5%	76%	0%	**100%**	Oude Noorden	Rotterdam	3.20	young	3
13	8.1	3.4	9.1	0	**20.55**	39%	16%	44%	0%	**100%**	Mideelland	Rotterdam	3.11	young	3
14	7.5	2.5	4.6	0	**14.69**	51%	17%	31%	0%	**100%**	Oude Westen	Rotterdam	2.92	old	3
15	4.4	2.2	5.5	0	**12.06**	37%	18%	45%	0%	**100%**	Cool	Rotterdam	3.48	young	3
16	4.3	6.4	9.7	0	**20.42**	21%	32%	48%	0%	**100%**	Stadsdriehoek	Rotterdam	2.08	young	4
17	5.0	5.8	1.8	0	**12.59**	40%	46%	14%	0%	**100%**	Rubroek	Rotterdam	2.64	Average	4
18	4.8	4.3	3.5	0	**12.54**	38%	35%	28%	0%	**100%**	Oud Crooswijk	Rotterdam	3.05	old	4
19	12.4	2.3	10.2	0	**24.90**	50%	9%	41%	0%	**100%**	Kralingen West	Rotterdam	2.78	old	4
20	-	9.1	9.7	0	**18.81**	0%	48%	52%	0%	**100%**	Drevenbuurt	Vlaardingen	13.93	Average	4
21	-	8.5	6.0	0	**14.50**	0%	59%	41%	0%	**100%**	Hoevenbuurt	Vlaardingen	10.62	Average	5
22	-	5.8	1.3	0	**7.04**	0%	82%	18%	0%	**100%**	Kuidenbuurt	Vlaardingen	9.03	Average	5
23	-	0.4	7.1	0	**7.48**	0%	5%	95%	0%	**100%**	Vaart Noord	Vlaardingen	9.65	young	5
24	-	1.2	3.6	0	**4.82**	0%	25%	75%	0%	**100%**	Loper Noord	Vlaardingen	9.27	young	5
25	-	5.1	0.9	0	**6.01**	0%	85%	15%	0%	**100%**	Loper Zuid	Vlaardingen	7.80	Average	5
26	0.2	2.8	1.7	0	**4.74**	5%	60%	36%	0%	**100%**	Vogelbuurt Noord	Vlaardingen	3.78	Average	6
27	0.0	3.3	2.6	0	**5.87**	1%	55%	44%	0%	**100%**	Vaart Zuid	Vlaardingen	2.34	Average	6
28	1.5	4.0	2.2	0	**7.69**	19%	52%	29%	0%	**100%**	Statenbuurt	Vlaardingen	6.75	Average	6
29	1.0	2.1	3.8	0	**7.03**	15%	30%	55%	0%	**100%**	Vogelbuurt Zuid	Vlaardingen	4.95	young	6
30	-	35.1	1.8	0	**36.96**	0%	95%	5%	0%	**100%**	Buytenwegh	Zoetermeer	7.73	Average	6
31	-	35.1	1.8	0	**36.88**	0%	95%	5%	0%	**100%**	De leyens	Zoetermeer	8.89	Average	7
32	-	8.8	3.0	0	**11.80**	0%	74%	26%	0%	**100%**	Noordhove-West	Zoetermeer	8.31	Average	7
33	-	3.3	17.3	0	**20.60**	0%	16%	84%	0%	**100%**	Noordhove-Oost	Zoetermeer	9.79	young	7
34	-	29.8	1.6	0	**31.37**	0%	95%	5%	0%	**100%**	Seghwaert-Noord-Oost	Zoetermeer	7.89	Average	7
35	-	26.5	0.4	0	**26.84**	0%	99%	1%	0%	**100%**	Seghwaert-Zuid-West	Zoetermeer	3.37	Average	7
36	0.0	12.1	3.9	0	**16.09**	0%	75%	24%	0%	**100%**	Palenstein	Zoetermeer	5.63	Average	8
37	-	7.8	2.9	0	**10.74**	0%	73%	27%	0%	**100%**	Stadscentrum	Zoetermeer	4.43	Average	8
38	-	16.3	6.6	0	**22.94**	0%	71%	29%	0%	**100%**	Dorp	Zoetermeer	9.32	Average	8
39	-	18.0	2.0	0	**20.10**	0%	90%	10%	0%	**100%**	Driemanspolder	Zoetermeer	6.00	Average	8
40	-	11.8	1.2	0	**13.06**	0%	91%	9%	0%	**100%**	Meerzicht-Oost	Zoetermeer	4.22	Average	8
41	-	27.7	1.9	0	**29.63**	0%	94%	6%	0%	**100%**	Meerzicht-West	Zoetermeer	7.13	Average	9
42	-	7.5	0.0	0	**7.50**	0%	100%	0%	0%	**100%**	Vogelbuurt-Oost	Delft	10.95	Average	9
43	-	5.6	0.1	0	**5.65**	0%	99%	1%	0%	**100%**	Boerderijbuurt	Delft	9.42	Average	9
44	-	5.3	0.0	0	**5.31**	0%	99%	1%	0%	**100%**	Dierenbuurt	Delft	12.22	Average	9
45	-	3.4	0.2	0	**3.56**	0%	95%	5%	0%	**100%**	Aziëbuurt	Delft	3.06	Average	9
46	-	3.7	4.9	0	**8.55**	0%	43%	57%	0%	**100%**	Afrikabuurt-West	Delft	11.03	Average	10
47	-	0.7	5.2	0	**5.87**	0%	11%	89%	0%	**100%**	Afrikabuurt-Oost	Delft	6.02	young	10
48	-	5.1	0.5	0	**5.60**	0%	91%	9%	0%	**100%**	Latijns Amerikabuurt	Delft	6.59	Average	10
49	-	4.1	1.4	0	**5.54**	0%	74%	26%	0%	**100%**	Verzetstrijderbuurt	Delft	4.06	Average	10
50	3.2	0.2	3.2	0	**6.69**	48%	4%	48%	0%	**100%**	Vrijheidsbuurt	Delft	8.47	old	10
51	4.1	1.1	0.2	0	**5.36**	76%	20%	4%	0%	**100%**	Pijperring	Delft	15.54	old	11
52	11.5	2.1	2.3	0	**15.95**	72%	13%	14%	0%	**100%**	Buitenhof-Noord	Delft	3.52	old	11
53	4.0	1.9	1.2	0	**7.15**	56%	27%	17%	0%	**100%**	Roland Holstbuurt	Delft	2.30	old	11
54	4.3	1.7	4.1	0	**10.07**	43%	17%	40%	0%	**100%**	Multatulibuurt	Delft	4.26	old	11
55	18.2	4.4	14.3	0	**36.92**	49%	12%	39%	0%	**100%**	Centrum	Delft	18.88	old	11
56	18.3	4.4	14.3	0	**37.02**	50%	12%	39%	0%	**100%**	Olofsbuurt	Delft	4.68	old	12
57	20.8	5.1	8.2	0	**34.09**	61%	15%	24%	0%	**100%**	Oud-Rijswijk	Rijswijk	4.87	old	12
58	7.8	2.1	3.9	0	**13.77**	56%	15%	29%	0%	**100%**	De plaatsen	Amersfoort	3.61	old	12
59	11.4	4.6	3.2	0	**19.18**	60%	24%	17%	0%	**100%**	Queekhoven	Amersfoort	9.05	old	12
60	-	9.4	1.8	0	**11.14**	0%	84%	16%	0%	**100%**	Hoge Hoven	Amersfoort	13.58	Average	12

61	-	7.7	2.2	0	**9.87**	0%	78%	22%	0%	**100%**	Stadskwartier	Amersfoort	8.55	Average	13
62	0.0	7.5	4.3	0	**11.76**	0%	64%	36%	0%	**100%**	Lage Hoven	Amersfoort	10.65	Average	13
63	0.0	8.1	3.1	0	**11.15**	0%	72%	28%	0%	**100%**	Waterkwartier	Amersfoort	9.33	Average	13
64	3.0	10.4	4.5	0	**17.94**	17%	58%	25%	0%	**100%**	Klaarwater	Soest	10.74	Average	13
65	-	8.9	10.8	0	**19.71**	0%	45%	55%	0%	**100%**	Smitsveen	Soest	8.88	Average	13
66	5.0	6.2	13.2	0	**24.35**	21%	25%	54%	0%	**100%**	De zoom	Soest	9.86	young	14
67	6.1	8.3	15.8	0	**30.20**	20%	28%	52%	0%	**100%**	Soest Zuid	Soest	14.49	young	14
68	5.3	1.0	0.5	0	**6.86**	77%	15%	8%	0%	**100%**	Neksloot	Heemskerk	11.53	old	14
69	1.2	4.6	0.1	0	**6.01**	21%	77%	2%	0%	**100%**	De Maer	Heemskerk	12.15	Average	14
70	3.6	2.4	1.2	0	**7.18**	50%	33%	17%	0%	**100%**	Breedweer	Heemskerk	6.19	old	14
71	-	9.1	0.6	0	**9.72**	0%	94%	6%	0%	**100%**	De die	Heemskerk	13.23	Average	15
72	0.1	8.3	1.0	0	**9.43**	1%	88%	11%	0%	**100%**	Slotherenbuurt	Heemskerk	9.87	Average	15
73	4.6	1.5	1.7	0	**7.69**	60%	19%	22%	0%	**100%**	Oud-Rijswijk	Heemskerk	1.10	old	15
74	6.4	2.2	3.8	0	**12.34**	52%	18%	31%	0%	**100%**	Beijnesbuurt	Heemskerk	9.56	old	15
75	0.4	7.9	11.6	0	**19.95**	2%	40%	58%	0%	**100%**	Halfweg	Haarlemmerliede	19.18	young	15

Figure 28: Overview of the 75 samples which form the foundation for the three scenarios, using the opensource data from Stedin.

Table 19: Classification per neighbourhood type used for the distribution of the neighbourhood strategies.

Type of neighbourhood	Area	Year of construction
1	Oude binnensteden	<1900
2	1e ringen, hoogstedelijk	1900-1945
3	wederopbouw, hoogstedelijk	1945-1965
4	Wederopbouw, matig stedelijk	1945-1965
5	Wederopbouw, suburbaan	1945-1965
6	Bloemkoolwijk, hoogstedelijk, wonen	1965-1990
7	Bloemkoolwijk, hoogstedelijk, wonen & utiliteit	1965-1990
8	Bloemkoolwijk, matig stedelijk	1965-1990
9	Bloemkoolwijk, suburban	1965-1990
10	Kantorenpark	Different
11	Recente nieuwbouw, hoogstedelijk en matig stedelijk	1990-2010
12	Recente nieuwbbouw, suburbaan en niet stedelijk	1990-2010
13	Dorpskernen	<1945
14	Niet-stedelijk gebied	<1990
15	Overig	Different

all these values are put in a boxplot (figure 29, 30 and 31), where the mutual ranges are seen. The question remains what the tipping point among each strategy is. For each neighborhood it is investigated whether the larges percentile share of a classification reaches 0.4 (=40%). If so, that specific neighborhood falls within a strategy. Manually it is checked if this causes any defects between neighborhoods, which it doesn't.

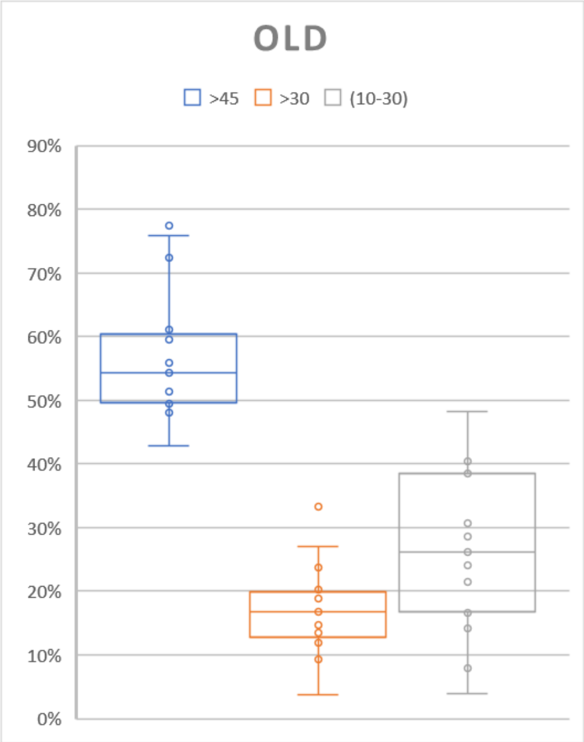

Figure 30: Strategy young boxplot illustration.

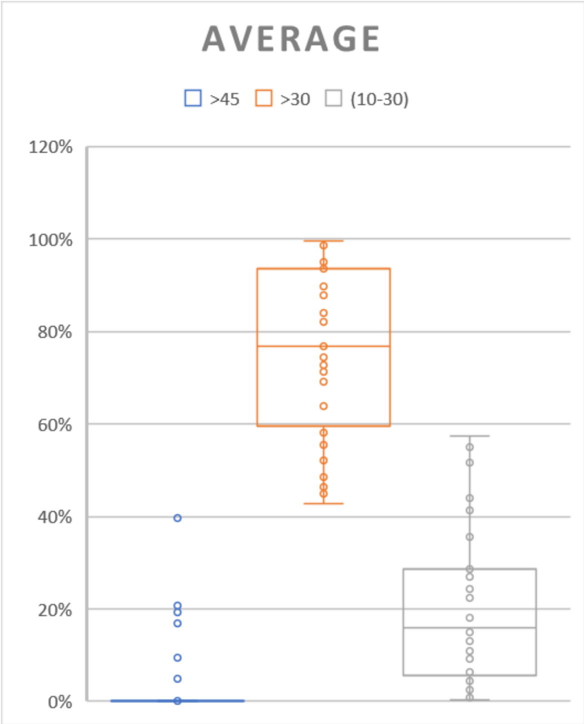

Figure 29: Strategy average boxplot illustration

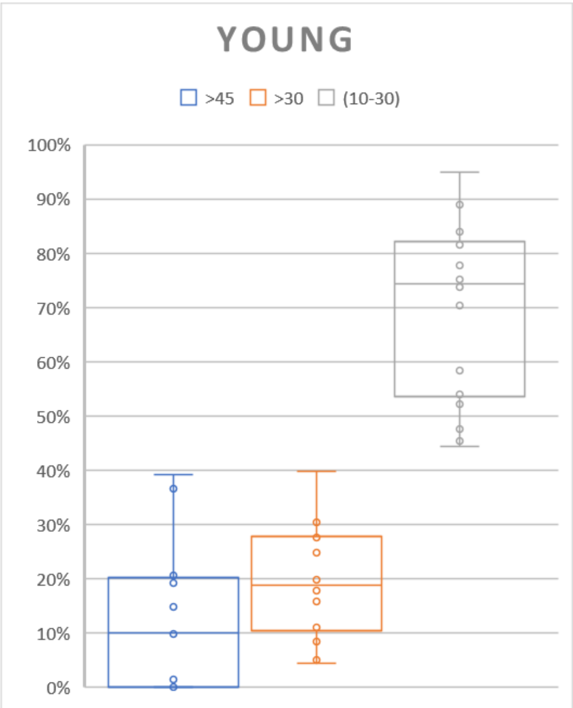

Figure 31: Strategy young boxplot illustration.

Noticeable is that for the average scenario, the share of 'to be replaced' is relative low compared to the other strategies.

C.2. LENGTH PER CONNECTIONS (L_C)

Shown in figure 33, the assessment per neighborhood gave an indication of the average length of NGI per connection. This length is significant for calculating the overall SA for all DSOs combined. Therefore, the figure below gives a boxplot to see what the average length per neighborhood level is. Because the generalization of neighborhood types is used from the study Wijngaart, R., Folkert, R., Middelkoop (2014), it directly include the different type of connections. Thus, the NGI length in an average where it does not matter whether there is an abundance of apartments or single-family connections.

The average NGI per connections for all 75 neighborhoods combined is estimated at 7.6 meter per connections, the first quartile is set at 4.2, second at 7.7 and finally the third quartile having the range of 9.7 meter per connection. The research uses a length per connections of 14.8 meter, which is the total NGI length divided by the number of connections including the usability UF. The 14.8 meter corresponds with the parameter used in the study van Melle, Menkveld, Oude Lohuis, de Smidt, & Terlouw (2015, p. 87) which use 15 meter per connection. The main reason for the lower length per connections is due to the type of neighborhoods which are assessed. Most of the generalized neighborhood types are located in urban areas and coincide with a higher connection density, which automatically decreases the length of NGI.

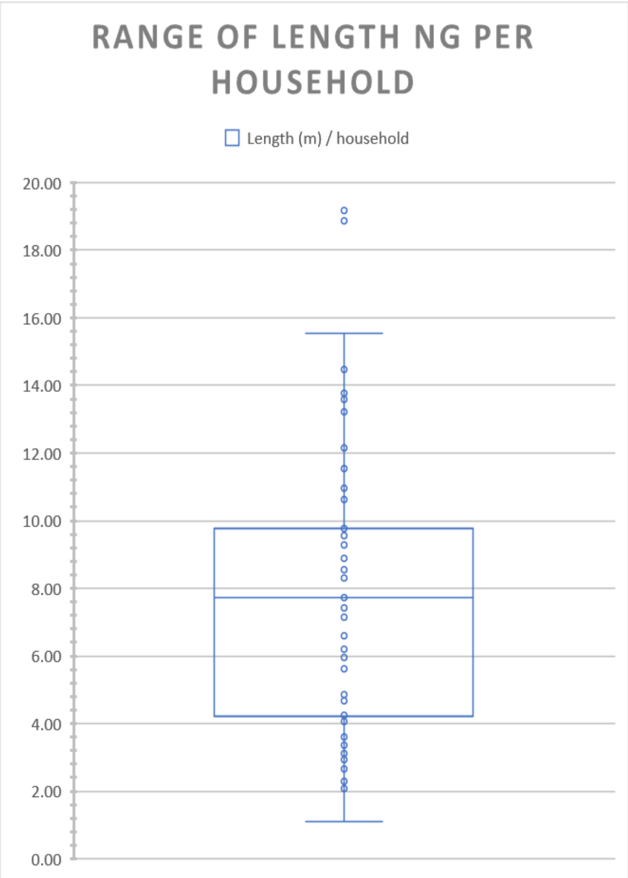

Figure 322: Boxplot which indicate the average length differences per neighborhood.

C.3. ECONOMIC INPUT VALUES

The economic input provides the main variables and indicate the extent of the overall costs. To understand the size of the costs components, and which values are used, this section describes the origin of both the investment costs, total costs for consumers$_{2018}$ and the costs for disconnecting from the NGI. Starting with the investment costs.

C.3.1. Investment costs

The investment costs are based on the Standardized Asset Values[12] per DSO from the period 2004 and 2016, to calculate the costs for 2017-2021. This document, initialized by ACM, provide on annual basis what the number of invested costs were for both transportation-, distribution- and connection pipelines. For the three largest DSOs[13] (Stedin, Enexis and Liander) the investments costs are analyzed and divided by the length of natural gas (km) that was realized in that same year.

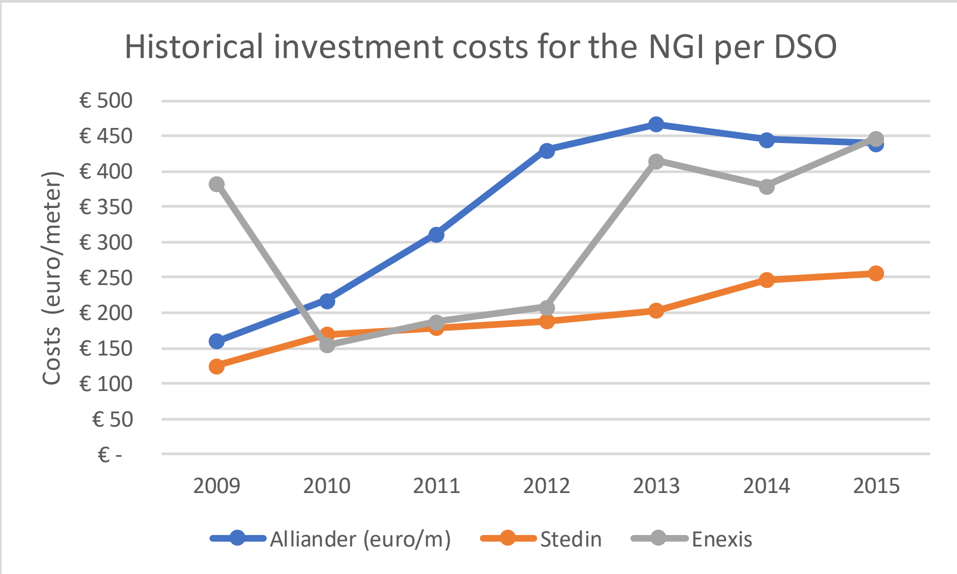

Figure 33: The investment costs per year for Liander, Enexis and Stedin (source: footnote 11 & the annual reports from all three DSOs from 2009 until 2015).

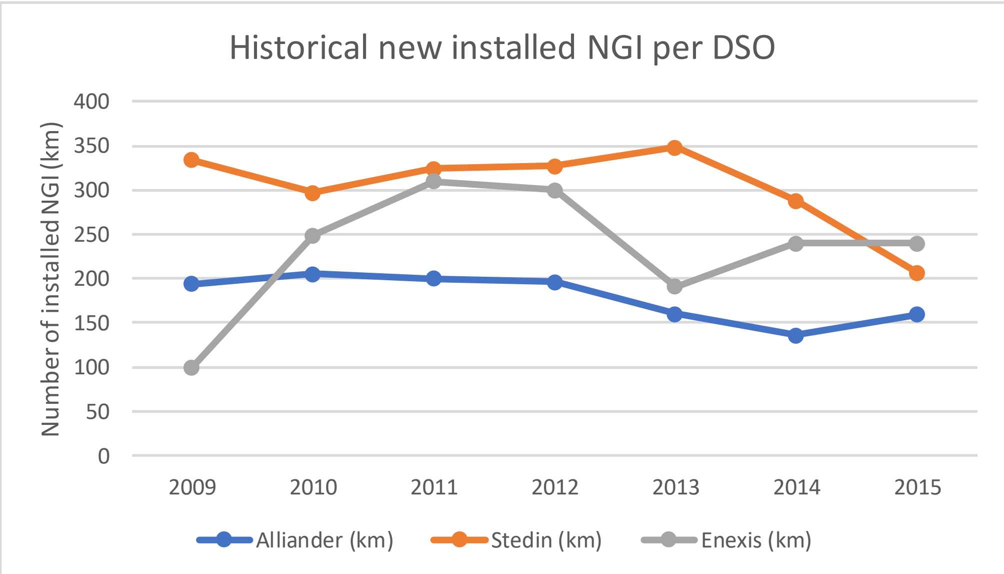

Figure 34: The new installed length of NGI per year for Liander, Enexis and Stedin (source: the annual reports from all three DSOs from 2009 until 2015).

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[12] https://www.acm.nl/nl/publicaties/publicatie/16355/GAW-sheet-bij-x-factorbesluiten-RNBs-gas-2017-2021

[13] The three DSOs combined hold 88% of the total number of connection connections to the NGI.

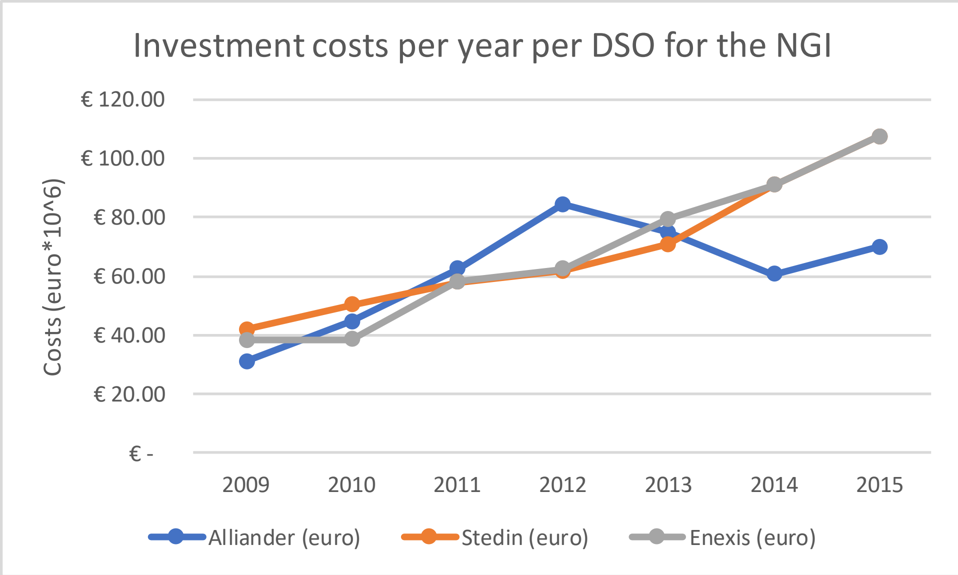

Figure 35: The total costs per DSO per year for the investment of NGI (source: footnote 11).

Both the total invested costs per meter and the total newly installed NGI are presented (Figure 34 and Figure 35). By dividing both results an estimate of historical costs per meter is given in Figure 33.

C.3.2. Fixed tariff per consumer$_{2018}$

The model runs the fixed tariff per consumer until 2050. For 2018 the fixed tariff is set by using existing grey literature. The prices for each DSO are set per year, based on their extent of NGI and number of connections. **Table *20*** illustrate for 2018 the numbers that were used per DSO. Appendix C4 further explains the type of connections mentioned in **Table *22*** and where the fixed price per DSO originates from.

Table 20: Information per DSO which show the fixed price for small-, medium- and utility consumers in 2017, including the associated length, connections and demand (sources: ACM, 2018; Alliander, 2016; Enexis, 2017; Netbeheer Nederland, 2018; Stedin Groep, 2017).

Type of DSO	Small consumer	Medium consumer	Utility	Length	Connections	Demand
-	G4/G6 SJV 500-4,000	G4/G6 SJV > 4,000	G10	km	number	m3*10^6/year
Enexis B.V.	€ 166.94	€ 254.52	€ 433.61	44,734	2,083,467	6,075
Liander	€ 175.99	€ 277.89	€ 471.68	35,303	2,256,085	6,349
Stedin B.V.	€ 168.82	€ 261.53	€ 452.93	23,464	1,958,462	4,453
Endinet				7,418	401,659	
Enduris	€ 168.41	€ 258.36	€ 449.01	4,793	190,626	469
Cogas infra & beheer B.V.	€ 165.14	€ 251.81	€ 446.05	4,389	140,165	
N.V. Rendo	€ 221.90	€ 328.33	€ 552.96	3,492	104,062	
Westland Infra	€ 146.22	€ 217.23	€ 350.69	1,039	53,646	
Average or total	**€ 173.35**	**€ 264.24**	**€ 450.99**	**124,632**	**7,188,172**	**17,346**

For this research the average fixed price per consumer is used (173.35 €, including VAT). Mainly because based on the data and the regulation method from ACM the values do not differ more than 5% per period (neglecting Rendo and Westland infra, which both merely present 3.6% of the total length and 2.2% of the number of connections). This Which makes it reasonable to take the average of all DSOs combined.

C.3.3 Disconnection costs

The disconnection costs are included in the costs for removal, since in this process there are two options: 1) merely disconnect and seal he natural gas unit or 2) disconnect and remove the associated NGI. For disconnecting the natural gas within the connections, again the costs which are charged by Liander, Enexis and Stedin[14] are used. All costs are originated from 2017.

Table 21: Costs per DSO (2017) for disconnecting the existing natural gas unit per connections (source: footnote 14).

DSO	**Costs per disconnection**
-	**€/connection**
Liander	687
Enexis	597
Stedin	632
Total (average)	639

C.4. SUBSTANTIATION OF 'SMALL CONSUMERS'

The term connection is a general definition used by all DSOs. A distinction is made between small consumers and large consumers. This research puts focus on the small consumers. To understand what is meant by this and how the Dutch natural gas infrastructure is divided by the type of small consumers, this appendix is written. The three largest DSOs within the Netherlands are Stedin, Enexis and Liander, combined they cover about 88% of all connections.

A connection is called a small consumer when it uses a connection smaller than G40 and uses less than 30,000 m^3 natural gas on a yearly basis. Within the definition of small consumers, there are five options G4, G6, G10, G16 and G25. Within these connection types, there can be chosen what the annual amount of natural gas supply is. Table X gives an overview of all G types including the associated natural gas demand.

Table 22: Overview of the natural gas connection types, including the maximum allowed annual consumption in cubic meter.

Natural gas meter type	**Annual consumption (m^3)**
G4	0 – 4,000
G6	0 – 10,000
G10	10,000 – 15,000
G16	15,000 – 30,000
G25 or larger	>30,000

This research uses merely the fixed cost per connection regarding the type: 'G4/G6 SJV <4,000', where SJV is the abbreviation for Standard Annual Consumption (Dutch: Standaard Jaar Verbruik). The main reason that this connection type is chosen is that this connection represents approximately 95% of all the small consumer connections. To illustrate, the data from both Liander and Enexis is shown below for the year 2018. For this reason, the model uses the fixed tariff for small consumers (G4/G6 SJV <4,000), which is set at €137 in 2018, for calculating the overall change in costs.

[14] Liander: (Liander, n.d.)
Enexis: (Enexis, n.d.)
Stedin: (Stedin, n.d.)

Table 23: Data for small consumers for the year 2018 (source:

Liander: Small consumers			
Type of connection	Demand (m3/yr)	connections	Share (%)
G4	500-4,000	2,522,071	96.17%
	>4,000	63,826	2.43%
G6	500-4,000	24,332	0.93%
	>4,000	12,234	0.47%
G8	~10,000	-	0.00%
G10	10,000-15,000	-	0.00%
G16	15,000-30,000	-	0.00%
G25	>30,000	-	100%
		2,622,463	

Table 24: Data for small consumers for the year 2018 (source:

Enexis: Small consumers					
Type of connection	Demand (m3/yr)	connections	Share (%)	Demand (m3)	Share (%)
G4	500-4,000	2,219,464	94.83%	3.90E+09	94.23%
	>4,000	57,203	2.44%		0.00%
G6	500-4,000	43,512	1.86%	1.83E+08	4.41%
	>4,000	13,679	0.58%		0.00%
G8	~10,000		0.00%		0.00%
G10	10,000-15,000	588	0.03%	4.14E+06	0.10%
G16	15,000-30,000	5,442	0.23%	4.46E+07	1.08%
G25	>30,000	624	0.03%	7.42E+06	0.18%
		2,340,512	**100.00%**	**4.14E+09**	**100.00%**

APPENDIX D: OVERALL FIXED TARIFF PER CONNECTION

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	7,129,498
2020	€ 137	€ -	€ -	€ -	€ 137	7,109,196
2021	€ 137	€ -	€ -	€ -	€ 137	7,081,974
2022	€ 142	€ 31	€ -	€ -	€ 174	7,045,556
2023	€ 142	€ 31	€ -	€ -	€ 174	6,996,988
2024	€ 142	€ 31	€ -	€ -	€ 174	6,932,480
2025	€ 142	€ 31	€ -	€ -	€ 174	6,847,267
2026	€ 142	€ 31	€ -	€ -	€ 174	6,735,509
2027	€ 158	€ 82	€ 19	€ -2	€ 258	6,590,312
2028	€ 158	€ 82	€ 19	€ -2	€ 258	6,403,965
2029	€ 158	€ 82	€ 19	€ -2	€ 258	6,168,522
2030	€ 158	€ 82	€ 19	€ -2	€ 258	5,876,866
2031	€ 158	€ 82	€ 19	€ -2	€ 258	5,524,288
2032	€ 232	€ 301	€ 108	€ -9	€ 632	5,110,427
2033	€ 232	€ 301	€ 108	€ -9	€ 632	4,641,089
2034	€ 232	€ 301	€ 108	€ -9	€ 632	4,129,192
2035	€ 232	€ 301	€ 108	€ -9	€ 632	3,594,086
2036	€ 232	€ 301	€ 108	€ -9	€ 632	3,058,980
2037	€ 561	€ 711	€ 161	€ -22	€ 1,411	2,547,083
2038	€ 561	€ 711	€ 161	€ -22	€ 1,411	2,077,745
2039	€ 561	€ 711	€ 161	€ -22	€ 1,411	1,663,884
2040	€ 561	€ 711	€ 161	€ -22	€ 1,411	1,311,306
2041	€ 561	€ 711	€ 161	€ -22	€ 1,411	1,019,650
2042	€ 2,037	€ 1,414	€ 237	€ -37	€ 3,651	784,207
2043	€ 2,037	€ 1,414	€ 237	€ -37	€ 3,651	597,860
2044	€ 2,037	€ 1,414	€ 237	€ -37	€ 3,651	452,663
2045	€ 2,037	€ 1,414	€ 237	€ -37	€ 3,651	340,905
2046	€ 2,037	€ 1,414	€ 237	€ -37	€ 3,651	255,692
2047	€ 8,651	€ 2,323	€ 135	€ -20	€ 11,089	191,184
2048	€ 8,651	€ 2,323	€ 135	€ -20	€ 11,089	142,616
2049	€ 8,651	€ 2,323	€ 135	€ -20	€ 11,089	106,198
2050	€ 8,651	€ 2,323	€ 135	€ -20	€ 11,089	8,674

Figure 36: Results of the fixed tariff per connection over time (Scenario: Hybrid; Strategy: Old)

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	7,129,498
2020	€ 137	€ -	€ -	€ -	€ 137	7,109,196
2021	€ 137	€ -	€ -	€ -	€ 137	7,081,974
2022	€ 142	€ 31	€ -	€ -	€ 174	7,045,556
2023	€ 142	€ 31	€ -	€ -	€ 174	6,996,988
2024	€ 142	€ 31	€ -	€ -	€ 174	6,932,480
2025	€ 142	€ 31	€ -	€ -	€ 174	6,847,267
2026	€ 142	€ 31	€ -	€ -	€ 174	6,735,509
2027	€ 158	€ 95	€ 25	€ -2	€ 276	6,590,312
2028	€ 158	€ 95	€ 25	€ -2	€ 276	6,403,965
2029	€ 158	€ 95	€ 25	€ -2	€ 276	6,168,522
2030	€ 158	€ 95	€ 25	€ -2	€ 276	5,876,866
2031	€ 158	€ 95	€ 25	€ -2	€ 276	5,524,288
2032	€ 232	€ 370	€ 139	€ -9	€ 732	5,110,427
2033	€ 232	€ 370	€ 139	€ -9	€ 732	4,641,089
2034	€ 232	€ 370	€ 139	€ -9	€ 732	4,129,192
2035	€ 232	€ 370	€ 139	€ -9	€ 732	3,594,086
2036	€ 232	€ 370	€ 139	€ -9	€ 732	3,058,980
2037	€ 561	€ 784	€ 284	€ -22	€ 1,606	2,547,083
2038	€ 561	€ 784	€ 284	€ -22	€ 1,606	2,077,745
2039	€ 561	€ 784	€ 284	€ -22	€ 1,606	1,663,884
2040	€ 561	€ 784	€ 284	€ -22	€ 1,606	1,311,306
2041	€ 561	€ 784	€ 284	€ -22	€ 1,606	1,019,650
2042	€ 2,037	€ 1,413	€ 373	€ -37	€ 3,785	784,207
2043	€ 2,037	€ 1,413	€ 373	€ -37	€ 3,785	597,860
2044	€ 2,037	€ 1,413	€ 373	€ -37	€ 3,785	452,663
2045	€ 2,037	€ 1,413	€ 373	€ -37	€ 3,785	340,905
2046	€ 2,037	€ 1,413	€ 373	€ -37	€ 3,785	255,692
2047	€ 8,651	€ 2,322	€ 91	€ -20	€ 11,044	191,184
2048	€ 8,651	€ 2,322	€ 91	€ -20	€ 11,044	142,616
2049	€ 8,651	€ 2,322	€ 91	€ -20	€ 11,044	106,198
2050	€ 8,651	€ 2,322	€ 91	€ -20	€ 11,044	8,674

Figure 37: Results of the fixed tariff per connection over time (Scenario: Hybrid; Strategy: Average)

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	7,129,498
2020	€ 137	€ -	€ -	€ -	€ 137	7,109,196
2021	€ 137	€ -	€ -	€ -	€ 137	7,081,974
2022	€ 142	€ 31	€ -	€ -	€ 174	7,045,556
2023	€ 142	€ 31	€ -	€ -	€ 174	6,996,988
2024	€ 142	€ 31	€ -	€ -	€ 174	6,932,480
2025	€ 142	€ 31	€ -	€ -	€ 174	6,847,267
2026	€ 142	€ 31	€ -	€ -	€ 174	6,735,509
2027	€ 158	€ 99	€ 35	€ -2	€ 289	6,590,312
2028	€ 158	€ 99	€ 35	€ -2	€ 289	6,403,965
2029	€ 158	€ 99	€ 35	€ -2	€ 289	6,168,522
2030	€ 158	€ 99	€ 35	€ -2	€ 289	5,876,866
2031	€ 158	€ 99	€ 35	€ -2	€ 289	5,524,288
2032	€ 232	€ 387	€ 199	€ -13	€ 805	5,110,427
2033	€ 232	€ 387	€ 199	€ -13	€ 805	4,641,089
2034	€ 232	€ 387	€ 199	€ -13	€ 805	4,129,192
2035	€ 232	€ 387	€ 199	€ -13	€ 805	3,594,086
2036	€ 232	€ 387	€ 199	€ -13	€ 805	3,058,980
2037	€ 561	€ 709	€ 249	€ -26	€ 1,493	2,547,083
2038	€ 561	€ 709	€ 249	€ -26	€ 1,493	2,077,745
2039	€ 561	€ 709	€ 249	€ -26	€ 1,493	1,663,884
2040	€ 561	€ 709	€ 249	€ -26	€ 1,493	1,311,306
2041	€ 561	€ 709	€ 249	€ -26	€ 1,493	1,019,650
2042	€ 2,037	€ 1,423	€ 239	€ -38	€ 3,661	784,207
2043	€ 2,037	€ 1,423	€ 239	€ -38	€ 3,661	597,860
2044	€ 2,037	€ 1,423	€ 239	€ -38	€ 3,661	452,663
2045	€ 2,037	€ 1,423	€ 239	€ -38	€ 3,661	340,905
2046	€ 2,037	€ 1,423	€ 239	€ -38	€ 3,661	255,692
2047	€ 8,651	€ 2,327	€ 136	€ -20	€ 11,094	191,184
2048	€ 8,651	€ 2,327	€ 136	€ -20	€ 11,094	142,616
2049	€ 8,651	€ 2,327	€ 136	€ -20	€ 11,094	106,198
2050	€ 8,651	€ 2,327	€ 136	€ -20	€ 11,094	8,674

Figure 38: Results of the fixed tariff per connection over time (Scenario: Hybrid; Strategy: Young)

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	6,963,542
2020	€ 137	€ -	€ -	€ -	€ 137	6,738,911
2021	€ 137	€ -	€ -	€ -	€ 137	6,514,281
2022	€ 176	€ 127	€ 29	€ -3	€ 329	6,289,651
2023	€ 176	€ 127	€ 29	€ -3	€ 329	6,065,020
2024	€ 176	€ 127	€ 29	€ -3	€ 329	5,840,390
2025	€ 176	€ 127	€ 29	€ -3	€ 329	5,615,759
2026	€ 176	€ 127	€ 29	€ -3	€ 329	5,391,129
2027	€ 219	€ 148	€ 39	€ -4	€ 402	5,166,499
2028	€ 219	€ 148	€ 39	€ -4	€ 402	4,941,868
2029	€ 219	€ 148	€ 39	€ -4	€ 402	4,717,238
2030	€ 219	€ 148	€ 39	€ -4	€ 402	4,492,608
2031	€ 219	€ 148	€ 39	€ -4	€ 402	4,267,977
2032	€ 288	€ 172	€ 39	€ -5	€ 494	4,043,347
2033	€ 288	€ 172	€ 39	€ -5	€ 494	3,818,716
2034	€ 288	€ 172	€ 39	€ -5	€ 494	3,594,086
2035	€ 288	€ 172	€ 39	€ -5	€ 494	3,369,456
2036	€ 288	€ 172	€ 39	€ -5	€ 494	3,144,825
2037	€ 416	€ 216	€ 35	€ -6	€ 662	2,920,195
2038	€ 416	€ 216	€ 35	€ -6	€ 662	2,695,565
2039	€ 416	€ 216	€ 35	€ -6	€ 662	2,470,934
2040	€ 416	€ 216	€ 35	€ -6	€ 662	2,246,304
2041	€ 416	€ 216	€ 35	€ -6	€ 662	2,021,673
2042	€ 730	€ 362	€ 56	€ -9	€ 1,139	1,797,043
2043	€ 730	€ 362	€ 56	€ -9	€ 1,139	1,572,413
2044	€ 730	€ 362	€ 56	€ -9	€ 1,139	1,347,782
2045	€ 730	€ 362	€ 56	€ -9	€ 1,139	1,123,152
2046	€ 730	€ 362	€ 56	€ -9	€ 1,139	898,522
2047	€ 2,295	€ 1,295	€ 215	€ -31	€ 3,774	673,891
2048	€ 2,295	€ 1,295	€ 215	€ -31	€ 3,774	449,261
2049	€ 2,295	€ 1,295	€ 215	€ -31	€ 3,774	224,630
2050	€ 2,295	€ 1,295	€ 215	€ -31	€ 3,774	-

Figure 39: Results of the fixed tariff per connection over time (Scenario: PA; Strategy: Old)

Year	A: Real costs consumer (5 year period) (euro/hh)		B: Sanitation cost translated to cost consumer (eur/hh)		C: Depreciation costs translated to cost consumer (eur/hh)		D: Reduced O&M costs decomissioning (eur/hh)		T: Total yearly cost increase (eur/hh)		Numbers of consumers (-)
2018	€	137	€	-	€	-	€	-	€	137	7,188,172
2019	€	137	€	-	€	-	€	-	€	137	6,963,542
2020	€	137	€	-	€	-	€	-	€	137	6,738,911
2021	€	137	€	-	€	-	€	-	€	137	6,514,281
2022	€	176	€	150	€	37	€	-3	€	360	6,289,651
2023	€	176	€	150	€	37	€	-3	€	360	6,065,020
2024	€	176	€	150	€	37	€	-3	€	360	5,840,390
2025	€	176	€	150	€	37	€	-3	€	360	5,615,759
2026	€	176	€	150	€	37	€	-3	€	360	5,391,129
2027	€	219	€	175	€	51	€	-4	€	441	5,166,499
2028	€	219	€	175	€	51	€	-4	€	441	4,941,868
2029	€	219	€	175	€	51	€	-4	€	441	4,717,238
2030	€	219	€	175	€	51	€	-4	€	441	4,492,608
2031	€	219	€	175	€	51	€	-4	€	441	4,267,977
2032	€	288	€	209	€	55	€	-4	€	547	4,043,347
2033	€	288	€	209	€	55	€	-4	€	547	3,818,716
2034	€	288	€	209	€	55	€	-4	€	547	3,594,086
2035	€	288	€	209	€	55	€	-4	€	547	3,369,456
2036	€	288	€	209	€	55	€	-4	€	547	3,144,825
2037	€	416	€	226	€	65	€	-5	€	702	2,920,195
2038	€	416	€	226	€	65	€	-5	€	702	2,695,565
2039	€	416	€	226	€	65	€	-5	€	702	2,470,934
2040	€	416	€	226	€	65	€	-5	€	702	2,246,304
2041	€	416	€	226	€	65	€	-5	€	702	2,021,673
2042	€	730	€	362	€	56	€	-9	€	1,139	1,797,043
2043	€	730	€	362	€	56	€	-9	€	1,139	1,572,413
2044	€	730	€	362	€	56	€	-9	€	1,139	1,347,782
2045	€	730	€	362	€	56	€	-9	€	1,139	1,123,152
2046	€	730	€	362	€	56	€	-9	€	1,139	898,522
2047	€	2,295	€	1,294	€	144	€	-31	€	3,703	673,891
2048	€	2,295	€	1,294	€	144	€	-31	€	3,703	449,261
2049	€	2,295	€	1,294	€	144	€	-31	€	3,703	224,630
2050	€	2,295	€	1,294	€	144	€	-31	€	3,703	-

Figure 40: Results of the fixed tariff per connection over time (Scenario: PA; Strategy: Average)

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	6,963,542
2020	€ 137	€ -	€ -	€ -	€ 137	6,738,911
2021	€ 137	€ -	€ -	€ -	€ 137	6,514,281
2022	€ 176	€ 156	€ 52	€ -4	€ 380	6,289,651
2023	€ 176	€ 156	€ 52	€ -4	€ 380	6,065,020
2024	€ 176	€ 156	€ 52	€ -4	€ 380	5,840,390
2025	€ 176	€ 156	€ 52	€ -4	€ 380	5,615,759
2026	€ 176	€ 156	€ 52	€ -4	€ 380	5,391,129
2027	€ 219	€ 182	€ 72	€ -5	€ 467	5,166,499
2028	€ 219	€ 182	€ 72	€ -5	€ 467	4,941,868
2029	€ 219	€ 182	€ 72	€ -5	€ 467	4,717,238
2030	€ 219	€ 182	€ 72	€ -5	€ 467	4,492,608
2031	€ 219	€ 182	€ 72	€ -5	€ 467	4,267,977
2032	€ 288	€ 176	€ 83	€ -6	€ 541	4,043,347
2033	€ 288	€ 176	€ 83	€ -6	€ 541	3,818,716
2034	€ 288	€ 176	€ 83	€ -6	€ 541	3,594,086
2035	€ 288	€ 176	€ 83	€ -6	€ 541	3,369,456
2036	€ 288	€ 176	€ 83	€ -6	€ 541	3,144,825
2037	€ 416	€ 212	€ 31	€ -6	€ 654	2,920,195
2038	€ 416	€ 212	€ 31	€ -6	€ 654	2,695,565
2039	€ 416	€ 212	€ 31	€ -6	€ 654	2,470,934
2040	€ 416	€ 212	€ 31	€ -6	€ 654	2,246,304
2041	€ 416	€ 212	€ 31	€ -6	€ 654	2,021,673
2042	€ 730	€ 364	€ 56	€ -9	€ 1,141	1,797,043
2043	€ 730	€ 364	€ 56	€ -9	€ 1,141	1,572,413
2044	€ 730	€ 364	€ 56	€ -9	€ 1,141	1,347,782
2045	€ 730	€ 364	€ 56	€ -9	€ 1,141	1,123,152
2046	€ 730	€ 364	€ 56	€ -9	€ 1,141	898,522
2047	€ 2,295	€ 1,301	€ 216	€ -32	€ 3,781	673,891
2048	€ 2,295	€ 1,301	€ 216	€ -32	€ 3,781	449,261
2049	€ 2,295	€ 1,301	€ 216	€ -32	€ 3,781	224,630
2050	€ 2,295	€ 1,301	€ 216	€ -32	€ 3,781	-

Figure 41: Results of the fixed tariff per connection over time (Scenario: PA; Strategy: Young)

Year	A: Real costs consumer (5 year period) (euro/hh)	B: Sanitation cost translated to cost consumer (eur/hh)	C: Depreciation costs translated to cost consumer (eur/hh)	D: Reduced O&M costs decomissioning (eur/hh)	T: Total yearly cost increase (eur/hh)	Numbers of consumers (-)
2018	€ 137	€ -	€ -	€ -	€ 137	7,188,172
2019	€ 137	€ -	€ -	€ -	€ 137	7,103,111
2020	€ 137	€ -	€ -	€ -	€ 137	7,018,049
2021	€ 137	€ -	€ -	€ -	€ 137	6,932,988
2022	€ 151	€ 33	€ -	€ -	€ 184	6,847,927
2023	€ 151	€ 33	€ -	€ -	€ 184	6,762,865
2024	€ 151	€ 33	€ -	€ -	€ 184	6,677,804
2025	€ 151	€ 33	€ -	€ -	€ 184	6,592,743
2026	€ 151	€ 33	€ -	€ -	€ 184	6,507,681
2027	€ 161	€ 33	€ -	€ -	€ 194	6,422,620
2028	€ 161	€ 33	€ -	€ -	€ 194	6,337,559
2029	€ 161	€ 33	€ -	€ -	€ 194	6,252,497
2030	€ 161	€ 33	€ -	€ -	€ 194	6,167,436
2031	€ 161	€ 33	€ -	€ -	€ 194	6,082,375
2032	€ 173	€ 33	€ -	€ -	€ 206	5,997,313
2033	€ 173	€ 33	€ -	€ -	€ 206	5,912,252
2034	€ 173	€ 33	€ -	€ -	€ 206	5,827,190
2035	€ 173	€ 33	€ -	€ -	€ 206	5,742,129
2036	€ 173	€ 33	€ -	€ -	€ 206	5,657,068
2037	€ 187	€ 33	€ -	€ -	€ 220	5,572,006
2038	€ 187	€ 33	€ -	€ -	€ 220	5,486,945
2039	€ 187	€ 33	€ -	€ -	€ 220	5,401,884
2040	€ 187	€ 33	€ -	€ -	€ 220	5,316,822
2041	€ 187	€ 33	€ -	€ -	€ 220	5,231,761
2042	€ 203	€ 34	€ -	€ -	€ 237	5,146,700
2043	€ 203	€ 34	€ -	€ -	€ 237	5,061,638
2044	€ 203	€ 34	€ -	€ -	€ 237	4,976,577
2045	€ 203	€ 34	€ -	€ -	€ 237	4,891,516
2046	€ 203	€ 34	€ -	€ -	€ 237	4,806,454
2047	€ 223	€ 35	€ -	€ -	€ 257	4,721,393
2048	€ 223	€ 35	€ -	€ -	€ 257	4,636,332
2049	€ 223	€ 35	€ -	€ -	€ 257	4,551,270
2050	€ 223	€ 35	€ -	€ -	€ 257	4,381,148

Figure 42: Results of the fixed tariff per connection over time (Scenario: BAU; Strategy: All three)

APPENDIX E: THE REGULATION MONOPOLY MODEL ACM

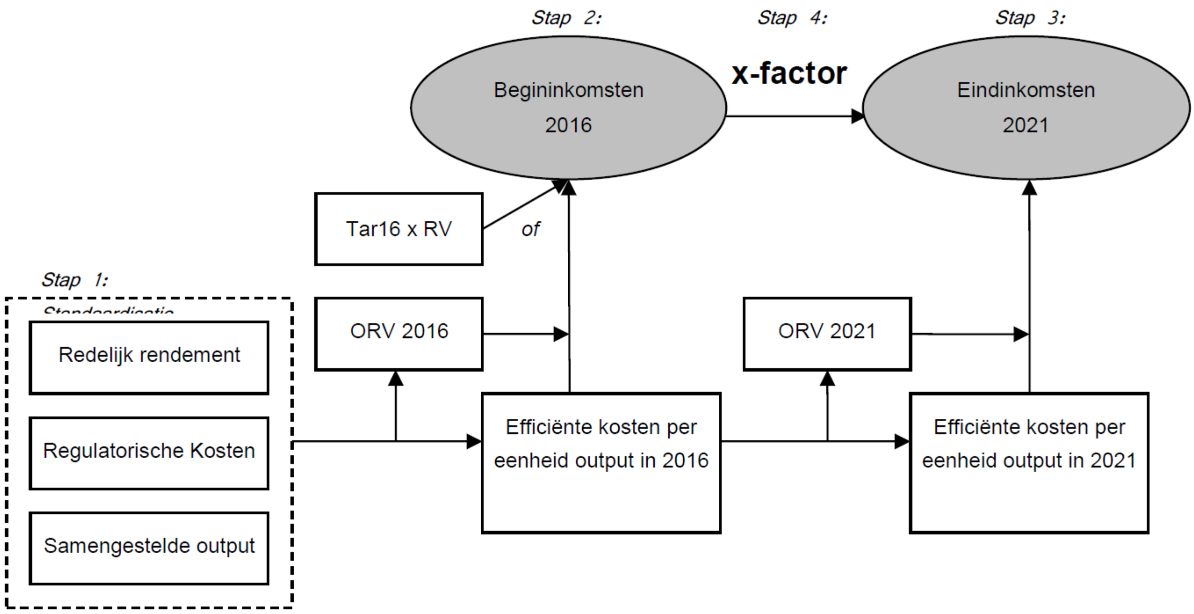

Figure 43: Overview of the method used by ACM for assessing the annual incomes per DSO for a period of five years (source: ACM, 2017b, p. 40).

Via Figure 43 each step is mathematically explained in the sections below. The six period is used as example, which refers to the year 2013 – 2016. The formulas are in accordance to ACM (2013). This appendix is merely used to give a better understanding on how the current methodology by ACM is mathematically assembled to determine the begin income for DSOs and the allowed fixed tariff per connection. The formulas used for the model in this research are shown in chapter 3 – methodology.

STEP1 STANDARDIZATION OF DETERMINE PARAMETERS

Reasonable return

To calculate the reasonable return per DSO, the WACC is used. This formula is often used in businesses for calculating their average weighted assets in a specific year. Both formulas are used for each DSO. Using the WACC a first step is set in standardizing the costs among DSOs.

$$WACC_{x1-3}^{actual} = \frac{1 + WACC_{x1-3}^{nominal}}{1 + CPI_{x1-3}} - 1$$

$$WACC^{nominal} = g \cdot k_{VV} + \left((1-g) \cdot \frac{k_{EV}}{1-T} \right)$$

Where:

$g = Gearing: share\ of\ borrowed\ capital\ in\ total\ of\ own\ and\ borrowed\ assets$

$k_{VV} = Average\ costs\ of\ capital\ (kostenvoet)\ for\ borrowed\ assets$

$k_{EV} = Average\ costs\ of\ capital\ (kostenvoet)\ for\ own\ assets$

$T = Expected\ tariff\ for\ corporate\ tax\ (percentiles)$

$$WACC_{x1-3}^{actual} = The\ actual\ weighted\ average\ costs\ of\ capital\ for\ taxes\ between\ year\ x\ to\ x3\ (\%)$$

$$CPI_{x1-3} = Expected\ consumer\ pirce\ index\ for\ year\ x1-3$$

$$WACC_{x1-3}^{Nominal} = The\ nominal\ weighted\ average\ costs\ of\ capital\ for\ taxes\ between\ year\ x\ to\ x3\ (\%)$$

Regulatory costs

Knowing the weighted average costs per DSO, the regulatory costs are calculated by looking at the height of net investments, depreciation, benefits from divestments, operational costs and small 'other' costs which must be considered. The Consumer Price Index (CPI) is used for translating both the WACC and costs to future years in that particular period.

$$KK_{i,t}^{W} = VK_{i,t}^{W} + AK_{i,t} - OO_{i,t}^{KAP} - OD_{i,t}$$

$$TK_{i,t}^{k,W} = OK_{i,t} + KK_{i,t}^{W} + EAV_{i,t}$$

$$VK_{i,t}^{W} = WACC_{relevant\ period}^{actual} \cdot GAW_{i,t}$$

$$GAW_{i,t} = \sum\nolimits_{l=2004}^{t} \left(GAW_{i,t,l} \cdot \left(1 + CPI_{i,t}\right)\right)$$

$$CPI_{t,w} = \prod_{l=t+1}^{W} (1 + CPI_l) - 1$$

$$AK_{i,t} = \sum\nolimits_{l=2004}^{t} \left(AK_{i,t,l} \cdot \left(1 + CPI_{i,t}\right)\right)$$

$$OK_{i,t} = OK_{i,t}^{bruto} - OO_{i,t}^{operational} - FDD_{i,t}$$

Where:

$$KK_{i,t}^{W} = the\ netto\ capital\ cost\ using\ the\ WACC - level\ W\ from\ DSO\ i\ in\ year\ t$$

$$KK_{i,t}^{W} = assets\ costs\ by\ using\ WACC - level\ W\ from\ DSO\ i\ in\ year\ t$$

$$AK_{i,t} = Depreciation\ from\ DSO\ i\ in\ year\ t$$

$$OO_{i,t}^{KAP} = Other\ benefits\ from\ DSO\ i\ in\ year\ t\ which\ will\ be\ eliminated\ with\ the\ capitalcosts$$

$$OD_{i,t} = Benefits\ from\ divestments\ from\ DSO\ i\ in\ year\ t$$

$$TK_{i,t}^{k,W} = total\ costs\ by\ using\ WACC - level\ w\ from\ DSO\ i\ in\ year\ t\ for\ actitvity\ k$$

$$OK_{i,t} = netto\ operational\ costs\ for\ DSO\ i\ in\ year\ t$$

$$EAV_{i,t} = Received\ onetime\ connection\ fee\ for\ the\ connection\ of\ NG\ from\ DSO\ i\ in\ year\ t$$

$$GAW_{i,t} = standardized\ assetvalue\ for\ DSO\ i\ in\ ultimo\ year\ t$$

$$GAW_{i,t,l} = Asset\ value\ above, which\ refers\ to\ the\ investments\ in\ year\ l$$

$$CPI_{l,t} = Consumer\ price\ index\ between\ year\ l\ and\ year\ t$$

$$CPI_l = Consumer\ price\ index\ for\ year\ l$$

$$AK_{i,t,l} = standardized\ depreciation\ for\ DSO\ i\ in\ year\ t\ for\ investments\ from\ year\ l\ and\ pricelevel\ l$$

$$OK_{i,t}^{bruto} = Gross\ operational\ costs\ from\ DSO\ i\ in\ year\ t$$

$$OO_{i,t}^{operational} = Other\ benefits\ from\ DSO\ i\ in\ year\ t\ which\ will\ be\ eliminated\ with\ the\ operational\ costs$$

$$FDD_{i,t} = flatrate\ value\ for\ the\ doubtful\ receivables\ of\ small\ consumers\ for\ DSO\ i, year\ t$$

Compiled output

Knowing both the reasonable return and regulatory costs for a DSO, the numbers are combined with the volumes calculated per DSO in a certain year. The Weighting factor and tariff price per element is introduced to find what share in costs for each element. E.g. the price for the capacity tariff (j) for DSO i, in year t is multiplied with the volume of that same DSO and element in that same year (this case 2013). The volume of 2013 is estimated by taken the average volume of the period before. Same goes for the price per element, using the correction factor.

$$SO_{i,t}^{excl\ NV} = \sum_{j} \left(wf_j \cdot v_{i,j,t} \right)$$

$$wf_j = \frac{\sum_i (p_{i,j,x=1}^{-NC} \cdot v_{i,j,x=1})}{\sum_i v_{i,j,x=1}}$$

$$v_{i,j,x=1} = \frac{v_{i,j,x=-2} + v_{i,j,x=-1} + v_{i,j,x=0}}{3}$$

$$P_{i,j,x=1}^{-NC} = \frac{\sum_j \left(p_{i,j,x=1} \cdot rv_{i,j}^{x-1,0,1} \right) - corr_{i,x=1}}{\sum_j \left(P_{i,j,x=1} \cdot rv_{i,j}^{x-1,0,1} \right)} \cdot p_{i,j,x=1}$$

$$\forall j = transportservice\ exclusive\ fixed\ tariff\ small\ consumers$$

$$P_{i,j,t}^{-NC} = p_{i,j,t}$$

$$\forall j = Fixed\ tariff\ small\ consumers\ and\ connection\ fees$$

$$BF = \frac{\sum_i GTK_{i,x=1}^{AD,WACCNG5R}}{\sum_i BI_{i,x=1}^{AD}} \cdot \frac{\sum_i BI_{i,x=1}^{TD}}{\sum_i GTK_{i,2013}^{TD,WACCNG5R}}$$

$$\forall j = connection\ service$$

$$wf_j = BF \cdot wf_j$$

Where:

$$SO_{i,t}^{excl\ NV} = Performance\ DSO\ i\ in\ year\ t\ measures\ in\ compiled\ output,$$

$$wf_j = Weighting\ factor\ for\ tariff\ element\ i$$

$$v_{i,j,t} = volumes\ for\ tariff\ element\ j\ for\ DSO\ i\ in\ year\ t.$$

$$j = fixed\ tariff\ for\ small\ consumers$$

$$P_{i,j,t}^{-NC} = tariffs\ for\ tariff\ element\ j\ for\ DSO\ i\ in\ year\ t = 1, corrected\ for\ the\ subsequent\ calculation\ which\ is\ not\ related\ to\ the\ costs\ in\ x = 1.$$

$rv_{i,h}^{x=1-3} = Compiled\ calculation\ volume\ for\ tariff\ element\ h\ for\ DSO\ i\ in\ period\ x1-3.$

$$Corr_{I,x=1} = costs\ for\ the\ tariffs\ for\ DSO\ i\ that\ are\ corrected\ in\ year\ x = 1\ but\ which\ are\ not\ related\ to\ the\ costs\ before\ x1.$$

$P_{i,j,t} = Tariffs\ for\ tariff\ element\ j\ for\ DSO\ i\ in\ year\ t$

$BF = balance\ factor\ for\ both\ under\ and\ upper\ weight$

$to\ neutralize\ the\ natural\ gas\ connection\ service\ in\ the\ compilded\ output$

$$GTK_i^{k,w} = The\ average\ total\ costs\ for\ activity\ k, calculated\ with\ the\ WACC\ level\ W, for\ DSO\ i\ in\ x1$$

$BI_{i,x=1}^{k} = Begin\ income\ for\ DSO\ i\ in\ year\ x = 1\ for\ activity\ k$

STEP 2: DETERMINING THE BEGIN INCOME

The Begin Income (BI) can be determined by three input values as illustrated in figure 43, at the beginning of this Appendix. Before these input values can be used to calculate the BI, several basic formulas are set.

General formulas for determining the begin income

$$TV_I = BI_{i,x=1}^{wett.form} - EK_{i,x=1}^{WACCNG4R}$$

$$AT = \sum_i BI_{i,x=1}^{wett.form.} - SK_{x=1}$$

$$SK_{x=1} = \sum_i EK_{i,x=1}^{WACCNG4R} + BLM_{x=2}^{excl.DD} + DD_{x=1} - BLM_{x=1} + IKNV_{x=1}$$

$$BLM_t^{excl.DD} = BLM_t - DD_{x=1}$$

$$DD_{x=1} = \frac{\sum_{t=x-2}^{x=2} DD_t \cdot (1 + CPI_{t,x=1}}{3}$$

$$BI_{i,x=1}^{wett.form.} = \sum_J p_{i,j,x=1}^{-NC} \cdot v_{i,j,x=1}$$

$$BI_{i,x=1} = BI_{i,x=1}^{wett.form}$$

Where:

$TV_i = implementation\ condition\ to\ check\ if\ the\ BI\ for\ DSO\ i\ hold.$

$BI_{i,x=1}^{wett.form} = BI\ for\ DSO\ i\ in\ year_{x=1} using\ the\ statutory\ regulation$

$$EK_{i,x=1}^{WACCNG4R} = Efficient\ costs_{x=1} of\ DSO\ i, calculated\ as\ ek_{x=1}^{W,excl\ ORV}, and\ previous\ regulation\ period.$$

$AT = test\ to\ check\ the\ costs\ calculated\ for\ period_{N=1}, based\ on\ previous\ period.$

$SK_{x=1} = total\ efficient\ costs\ per\ sector\ based\ on\ WACC\ previous\ period.$

Objective regional differences

The ORV illustrate the unforeseen costs or local taxes for a DSO within a certain year. As example, each DSO holds its own region. However, it could occur than for a certain region other local taxes must be paid. To maintain the equality within the regulation methodology, two formulas are used to assess the ORVs and check whether the alternations seem valid or not.

$$ORV_{i,x=1}^{W} = LH_{i,x=1}^{W}$$

$$LH_{i,x=1}^{W} = \frac{\sum_{t=-2}^{x=2}(LH_{i,t}^{W} \cdot (1 + CPI_{t,x=1})}{3}$$

Where:

$$ORV_{i,x=1}^{W} = estimation\ of\ costs\ for\ ORV\ using\ WACC\ level\ w\ for\ DSO\ i\ in\ year_{x=1}$$

$$LH_{i,t}^{W} = Local\ taxes\ for\ using\ WACC\ level\ w\ for\ DSO\ i\ in\ yer\ t$$

Efficient costs per unit output

The efficient costs per unit output is linked to the first year of a period. Reaching the output, the PV is incorporated to indicate the changes in future years (applying the CPI and WACC). Overall, the efficient costs per DSO is calculated by multiplying the extent of the compiled per DSO and additionally sum up the ORV (if present).

$$GK_{t}^{W} = TK_{t}^{W} + BLM_{t} - ORV_{t}^{W} + IKNV_{t}^{exclEHD} + IKNV_{t}^{EHD}$$

$$IMNV^{TV} = \frac{\frac{NVV_{TV}^{NV}}{NVV^{NV}} \cdot IKNV_{x=1}^{excl.EHD}}{\sum_{i,j} wf_{i,j,x=1}^{increasedNV} \cdot v_{i,j,x=1}}$$

$$IKNV_{x=1}^{EHD} = IMNV^{TV} \cdot \sum_{i,j}\left(wf_{i,j,x=1}^{verhoogdNV} \cdot v_{i,j,x=1}\right)$$

$$PV_{t} = \left\{1 - \frac{(\frac{TK_{t}^{TD,WACC} \cdot \left(1 + CPI_{t,x=1}\right)}{SO_{t}^{PV}}}{\frac{TK_{t-1}^{TD,WACC} \cdot (1 - CPI_{t-1,x=1}}{SP_{t-1}^{PV}}}\right\} for\ t = \{2010,2011,2012\}$$

(the PV_t is merely show for regulation period 5, but it is intended to include all previous periods).

$$PV = \sqrt[7]{\prod_{t=-4}^{x=0}(1 + PV_{t})} - 1$$

$$GK_{t}^{W,x=1} = ((GK_{t}^{W} - BLM_{t}) \cdot (1 - PV)^{x=1-t} + BLM_{t}) \cdot (1 + CPI_{t,x=1})$$

$$EK_{x=1}^{W,exclORV} = \frac{\sum_{x-2}^{x=0} GK_{t}^{w,x=1}}{3} - BLM_{x=2}^{exclDD}$$

$$ek_{x=1}^{W,excl\ ORV} = \frac{EK_{x=1}^{W,exclORV}}{\sum_{i} SO_{i,x=1}}$$

$$SO_{i,x=1} = \sum_{j}(wf_{j}^{verhoogdNV} \cdot v_{i,j,x=1}$$

Where:

$GK_t^W = normalized\ costs\ for\ the\ efficient\ cost\ level\ by\ use\ of\ WACC\ w\ in\ year\ t.$

$TK_t^{TD,WACCforPV} = total\ costs\ for\ transport\ service\ in\ year\ t, by\ using\ wacc\ w$

$PV_t = The\ annual\ productivity\ alternation\ between\ year\ t\ and\ year\ t-1$

$SO_{i,t} = Compiled\ output\ for\ DSO\ i\ in\ year\ t, including\ grid\ losses$

$SO_t^{PV} = Compiled\ output\ for\ calculating\ the\ PV\ in\ year\ t, merely\ for\ transport\ sercives.$

$PV = Expected\ productivitychanges\ for\ regulation\ period\ X.$

$GK_t^{W,x=1}$
$= Normalized\ costs\ for\ efficient\ costlevel\ in\ year\ t, expressed\ in\ WACC\ for\ year_{x=1}$

STEP 3: DETERMINING THE END INCOME

For the end income, again the ORV and PV are included. This is done for each DSO in the latest year of the specific period. The results of the end income are based on the sum-product of the estimated efficient costs per unit output regarding the latest year. This is done per service and the compiled output for the latest year of each individual DSO per service. Additionally, the ORV is added.

$$ORV_{i,x=4}^{WACCG5R} = ORV_{i,x=4}^{WACCG5R} \cdot (1 + CPI_{x=2\dots4})^3$$

$$EK_{x=4}^{WACCG5R,excl.ORV} = \left(EK_{x=3}^{WACCG5R,excl.ORV} + BLM_{x=2}^{exclDD} - BLM_{x=4}^{exclDD}\right) \cdot (1 - PV)^3$$

$$SO_{i,x=4} = SO_{i,x=1}$$

$$ek_{x=4}^{WACCG5R,excl.ORV} = \frac{EK_{x=4}^{WACCG5R,excl.ORV}}{\sum_i SO_{i,2016}}$$

$$EI_{i,2016} = EK_{i,2016}^{WACCG5R} = ek_{x=4}^{WACCG5R,excl.ORV} \cdot SO_{i,x=4} + ORV_{i,x=4}^{WACCG5R}$$

Where:

$EI_{i,x=4} = total\ income\ for\ DSO\ i, yeart\ x4, which\ is\ reached\ due\ the\ use\ of\ the\ x - factor$

$EK_{i,x=4}^{WACCG5R} = Efficient\ costs\ x4\ of\ DSO\ i, using\ the\ WACC\ from\ previous\ period$

STEP 4: DETERMINING THE X-FACTOR

The x-factor is merely the sum of the consumer price indexes from the years 2013 until 2016, minus the end income divided by the begin income to the power of 1/3, for reaching a factor that can be deployed on an annual basis. Both BI and EI are explained in previous steps, but for finding the end income in the latter year of the period (e.g. 2016) simply the sum of CPI from 2013-2016 are added and multiplied with the x factor (to the power of three for each additional year) and multiplied with the begin income (2013).

$$EI_{i,x4} = (1 + CPI_{x=1\dots.4}) \cdot (1 - x_i)^3 \cdot BI_{i,x=1}$$

$$x_i = (1 + CPI_{x=1\dots4}) - \left(\frac{EI_{i,x=4}}{BI_{i,x=1}}\right)^{\frac{1}{3}}$$

Where:

$x_i = the\ x\ factor\ for\ DSO\ i, rounded\ down\ with\ two\ decimals$

ADDITIONAL FORMULA

This formula indicates that the volume (m^3) of 2013 is equals the volume of year 2014, 2015 and 2016.

$$rv_{i,j,x=2\ldots4} = v_{i,j,x=1}$$