Heliyon 6 (2020) e05350

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Case report

Economic evaluation and comparison of migration paths for the smart grid using two case studies

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ARTICLE INFO

Keywords:
Economics
Electrical engineering
Energy
Systems engineering
Environmental economics
Environmental engineering
Migration paths
Smart grids
Cost benefit analysis
Extrapolation
Case study

ABSTRACT

Today, European utility companies are facing the conversion of their power grids from a previously centrally controlled supply to a then decentralized supply. These changes are necessary to achieve the climate targets. In order to create a decentralized power grid, the integration of modern information and communication technologies (ICT) and other hardware is necessary. On the one hand, the utilities must know which paths they can take to make their power grid intelligent, but on the other hand it is also crucial to know the costs involved. In this contribution we outline a possible model for technological migration paths with a corresponding economic analysis based on German and European case studies.

1. Introduction

The German government's energy policy demands a transformation from a centralized to a decentralized energy supply. In order for this transformation to be successful, the utilities need to know what a possible migration path to the future of a smart energy grid shall look like. This must be done against the background of technologies to be installed, in which order this can happen and the dependencies, which need to be considered. It is also important for utilities to know the investment costs involved in a particular implementing migration path. The aim of this contribution is to draw up a roadmap to the modern Smart Grid and to make a monetary assessment for this roadmap.

So far, few research contributions have dealt with roadmaps for the Smart Grid. Farhangi (2010) has done research on this topic and has concluded that the change that is necessary for utilities requires a massive transformation. It is necessary to adapt business processes as well as their organization and technologies used (Farhangi, 2010).

In order to be able to calculate this extensive transformation, research was first carried out on the topic of how a systematic stocktaking covering all the areas mentioned by Farhangi can be carried out for the utilities. Because of this research, a maturity model for smart grids was developed, which takes stock of all dimensions affected by such a massive transformation and presents different maturity levels. For this maturity model, metrics were designed to be used for measurement purposes, such as a questionnaire agreed upon with experts and an evaluation using a Rasch algorithm.

However, since it is not sufficient for a utility to know what its maturity is in the individual dimensions, the next step was to use the maturity model as a basis for determining how the development between the maturity levels is possible. For this purpose, the procedure model for the development of migration paths was created.

As a contribution based on this, this contribution is intended to evaluate the individual migration paths in monetary terms as well, in order to provide utilities with a roadmap and an indication of the costs. Therefore, this contribution presents a process model for migration path development, which has been used for the case studies “Green Access” and “Designetz”. The procedure model was evaluated using the two case studies according to Robert K. Yin (2009) [3]. The case study “Green Access” aims at the realization of an intelligent distribution grid automation. The case study “Designetz” is a realization of an intelligent energy system with the use of flexibility options utilizing an energy market. Due to the different paradigms the utilities follow, different technologies have also been used for the migration paths.

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https://doi.org/10.1016/j.heliyon.2020.e05350
Received 21 August 2020; Received in revised form 30 September 2020; Accepted 22 October 2020

Chapter 2 gives a short overview of the developed process model. However, this contribution will not focus on the development of migration paths as such, but on the monetary evaluation of these migration paths.

The aim is to answer the following research questions at the end of the contribution:

RQ1 How much does the introduction of the technologies cost to implement the migration paths?
RQ2 What are the economic differences in the costs of migration paths for case study "Green Access" and "Designetz"?

In order to adequately answer the research questions, Chapter 3 presents the creation and benefits of a reference cost structure - divided into CAPEX and OPEX - and Chapter 4 presents the cost results for case study "Green Access" and "Designetz". A comparison and discussion of the respective results takes place in Chapter 5 and Chapter 6 concludes with a general conclusion.

2. Method of migration paths development

In a first step, a process model for migration path development was created based on a review (Appelrath et al., 2012) (Büchner et al., 2014), and (De Bruin et al., 2005). According to the definition, a migration path describes a fixed route from one development step to the next. In this case, the necessary development steps of the different dimensions and their dependencies are described in order to move from one maturity level to another (Appelrath et al., 2012).

The development of the migration paths was based on a literature research on this topic and the study of the related work. The development of the migration paths was also particularly considered from the perspective of sustainability. In the authors' view, this includes the following three aspects: the dependencies on the dimensions to be considered, the Technology Readiness Level (TRL), and the costs and benefits of the development steps (Flore and Marx Gómez, 2019). On the topic of migration paths as well as the interdependencies of individual dimensions, we have researched the following literature: acatech study (2012) (Appelrath et al., 2012) (Appelrath and Kagermann, 2012), (Appelrath et al., 2011) and others (Pfeffer and Sutton, 1999) (Luhmann, 2012) (Appelrath et al., 2010), and (Winter and Aier, 2020).

Following the aspect of sustainability, only technologies that are promising were used for the individual development steps of the migration paths. This means that technologies were used which show a certain state of maturity, this is expressed by the TRL (Horizon 2020, 2014) (Graerringer et al., 2002) (Tugurlan et al., 2011) (Kirkham and Marinovici, 2013) (Campbell, 2018) (Mankins, 1995) (Mankins, 2009), and (Mankins, 2002).

As the topic "maturity" has already gained in relevance through the TRL, research was conducted on the topic "maturity models" based on this. Research was conducted on both generally valid and domain-specific maturity level models(Mettler, 2011) (Sun et al., 2011) (Marx et al., 2012) (The GridWise Architecture Council, 2011) (Software Engineering Institute & The GridWise Architecture Council, 2012) (Widergren et al., 2010) (Uebernickel et al., 2015) (Becker et al., 2009) (Becker et al., 2010) (Becker et al., 2010) (Poeppelbuss et al., 2011) (Becker et al., 2008) (Fraser et al., 2002) (U.S. Department of Energy, 2014) (Grid-Interop, 2011) (Gresse von Wangenheim et al., 2010) (Hankel et al., 2014) (Steenbergen, 2011) (Antunes et al., 2014) (Mettler and Rohner, 2009) (Mater and Drummond, 2009) (Software Engineering Institute, 2011) (Khan, 2015) (Hogrebe and Nüttgens, 2009) (Biberoglu and Haddad, 2002) (García-Mireles et al., 2012) (Wittstock et al., 2016) (Lahrmann et al., 2011) (Mettler et al., 2010) (De Bruin et al., 2005) (BPM Maturity Model EDEN e.V., 2009) (Rohjans et al., 2011) (Uslar and Masurkewitz, 2015) (Ahlemann et al., 2005), and (Stevens, 2014).

For the aspect of sustainability, the question of costs and benefits of migration paths is essential and is therefore the focus of this contribution. In our literature search on the topic of migration paths, we were only able to find less than ten contributions in the Smart Grids domain. The basis for the topic of maturity models is different: there the literature is very diverse, but not in the domain-specific area of Smart Grid and especially not for the European unbundled electricity market.

In a contribution, Pfeffer and Sutton (1999) presented a large gap in knowledge. In relation to the topic at hand, this expresses the fact that there are evaluation models for maturity that show gaps and problems in companies, but do not show companies how these gaps can be closed (Pfeffer and Sutton, 1999), and (Mettler, 2011). This fact points to a research gap that should be filled by the studies on maturity models and migration paths.

The process model for the development of migration paths shown in Figure 1 was developed specifically for the present case (Flore et al., 2019), and (Flore and Kumm, 2020). The approach comprises ten steps. The creation of scenarios is described in the first four steps. The selection of the dimensions (dimensions are understood here as specific capabilities, process areas and other design objects that structure an area of interest) and their different manifestations are undertaken in steps five and six. The actual migration path development and their analysis takes place in steps seven to ten.

According to the methodology approach, in step one influencing factors are identified in cooperation with experts, which will have a significant influence on the Smart Grid domain development are derived after prioritization and compiled in a key factor catalog (Appelrath et al., 2012), and (Gausemeier et al., 1996). All key factors relevant for the area under consideration and for the period under consideration are compiled in this key factor catalogue (Flore et al., 2019).

Utilizing literature research and in cooperation with experts the maximum values for the key factors are worked out. The maximum value of a key factor is described by the respective extreme value the target year of the analysis period (Appelrath et al., 2012) (Flore et al., 2019), and (Gausemeier et al., 1996).

The individual projections of the key factors are used to form projection bundles. These are then condensed into pre-scenarios in a plausibility analysis. This is necessary because not all projections are consistent with each other. A possible solution here could be plausibility analyses, which are carried out with software support. This analysis serves to condense the data prescenarios (Flore et al., 2019), and (Mayer et al., 2012).

From this prescenarios the final target scenarios are then extracted. A scenario basically describes consistent and conclusive pictures of possible futures for companies. These are based on hypothetical event sequences (Flore et al., 2019).

For a good structuring, dimensions are defined for further consideration, which are to be specifically considered in the further progress. A literature search can be used as a basis for determining the dimensions that are important for consideration. If the migration paths are to be developed for an existing maturity model, it is recommended to use the dimensions of the maturity model for the migration paths as well (Flore et al., 2019) (Software Engineering Institute, 2011) (U.S. Department of Energy, 2014) (Stevens, 2014), and (Uslar et al., 2012).

Dimensions include by Marx et al. (2012) specific skills, process areas and other design objects to structure an area of interest and should be comprehensive and easily distinguishable. In accordance to de Bruin

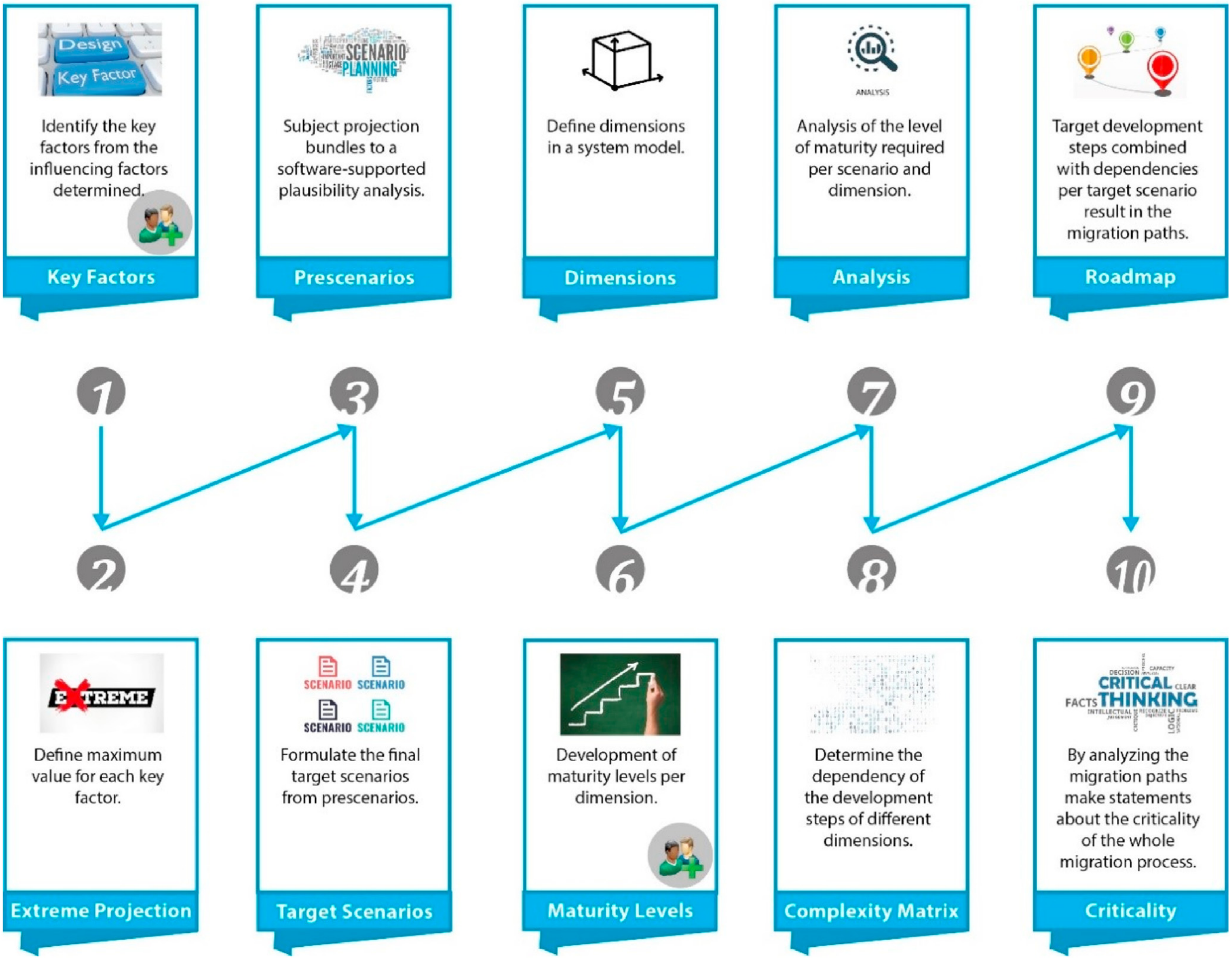

Figure 1. Procedure for developing migration paths (source: own presentation).

et al. (De Bruin et al., 2005), dimensions are characterized by qualitative descriptions or by means of evaluation elements/measurement criteria (practices, objects or activities) (Flore et al., 2019).

For step six, the same applies as for step five: if there is an existing maturity model for which the migration paths are to be developed, then the same maturity levels are taken as in the maturity model. If the migration paths are not to be developed for an existing maturity model and thus no maturity levels already exist, they can be determined on the basis of expert interviews and literature research (Flore et al., 2019), and (Software Engineering Institute, 2011).

Due to the different the target scenarios developed in step four, different levels of maturity are required for each dimension. For each target scenario, is therefore necessary to analyze what level of maturity is required for each dimension in order to achieve the scenario's respective goals (Flore et al., 2019), and (Mayer et al., 2012).

The technologies that are necessary to achieve the next step of development in each dimension are developed and added in step seven. In order to be able to determine the required technologies, expert discussions were held and new use cases defined within the framework of the case studies. These use cases were then mapped using the Smart Grid Architecture Model (SGAM), where all actors, technologies, protocols, etc. were located. This ensured that no components were forgotten. The component layer from the SGAM representation of the use cases was used for step 7. Figure 2 shows an example for a component layer of one of the use cases.

The dimensions were assigned to the three layers of the system level model (European Electricity Grid Initiative and Implementation Plan). These three layers are: closed system layer, ICT infrastructure and the networked system level. In addition, there are also cross-sectional dimensions that relate to technological aspects, which come into play in all three layers. For all dimensions considered, all dependencies are described and all development steps are put in order. The cross-sectional dimensions in particular have influence on many other dimensions and are therefore prerequisites for their further (Appelrath et al., 2012), and (Flore et al., 2019).

This serves as a basis for step eight, in which the dependencies between the development steps of the different dimensions are examined and presented in the form of a complexity matrix. For example, technologies that are controlled via radio or similar should only be used after the required development steps in the dimensions of organizational structure, corporate IT, risk management and standardization of communication protocols have already taken place to protect the company from cyber-

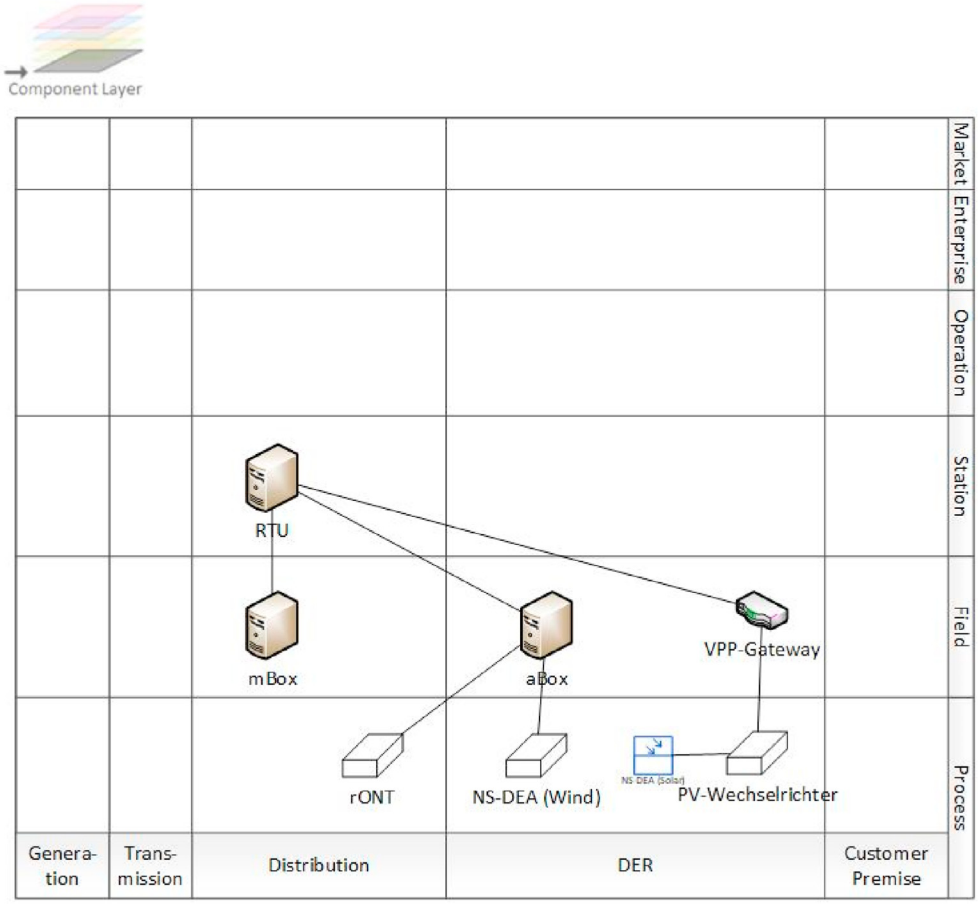

Figure 2. Component Layer for one Use Case of Case Study Green Access. RTU = remote technical unit, mBox = measuring box, rONT = local adjustable intelligent grid transformer, aBox = actuator box, NS-DEA (Wind) = low voltage decentralized generation plant (wind), VPP-Gateway = virtual power plant-gateway, PV-Wechselrichter = photovoltaic inverter.

attacks. Based on the complexity matrix, a form of network was created for each dimension, representing the dependence of one dimension on the others. This is shown as an example for dimension 6 “Grid operation” in Figure 3. Six boxes per dimension are shown in the figure. In 6.0, the start is followed by the five development steps to reach the different maturity levels of the dimension. The other dimensions in the figure are: 2 = Strategy, management and regulation; 3 = Asset management for distributed generation plants; 9 = Grid automation; 10 = General technology; 11 = ICT connectivity and 13 = Forecast management.

This is followed by a quantitative evaluation of the development steps: once at the level of the dimensions and once at the level of the development steps (Flore et al., 2019). Consequently, for each development step, the prerequisites are analyzed. By analyzing in the step seven which development step per dimension per target scenario must be achieved, the total development needs in step nine ultimately become clear. By analyzing the interdependencies of the dimensions and development steps, a continuous further development of the “Smart Grid Readiness” of the utilities should be achieved (Flore et al., 2019).

In step nine, based on the previously analyzed dependencies, flowcharts per dimensions are created, which are then transferred to a complete roadmap (Flore et al., 2019), and (Appelrath et al., 2012). These roadmaps were drawn up for each target scenario and are shown as an example for target scenario 3 for Case Study “Green Access” in Figure 4.

Finally, these migration paths are analyzed to determine whether there are particularly critical developments of individual dimensions that have an influence on the overall migration process (Mayer et al., 2012). This is done by elaborating the critical paths per target scenario (Flore et al., 2019). The critical path is shown in Figure 5.

In principle, this concept for creating migration paths can be applied to both transmission system operators (TSO) and distribution system operators (DSO). Of course, different results would be obtained when working through the ten process steps.

In principle, this concept does not aim to determine individual grids in which a TSO or DSO should invest. The grid area is always viewed as a whole and the interaction between the voltage levels and the technologies to be used is considered. If, for example, a number of local grid stations, wind turbines, ICT etc. is specified which are necessary to achieve the target scenario by a certain point in time, it is useful for the TSO or DSO to decide on the basis of the evaluations of his own grid control center at which points there are critical points in the grid and where the first step should be taken to start replacing the technologies.

3. Method of development of the reference cost structure

The second step included the creation of a reference cost structure, which is to serve as a basis for determining the investment costs for the utility. This reference cost structure was divided into CAPEX (capital expenditure) and OPEX (operation expenditure) as shown in Chapter 3.1 and 3.2.

The determination of reference costs is used for cost forecasting. When you map reference costs, you assume that the costs of comparable

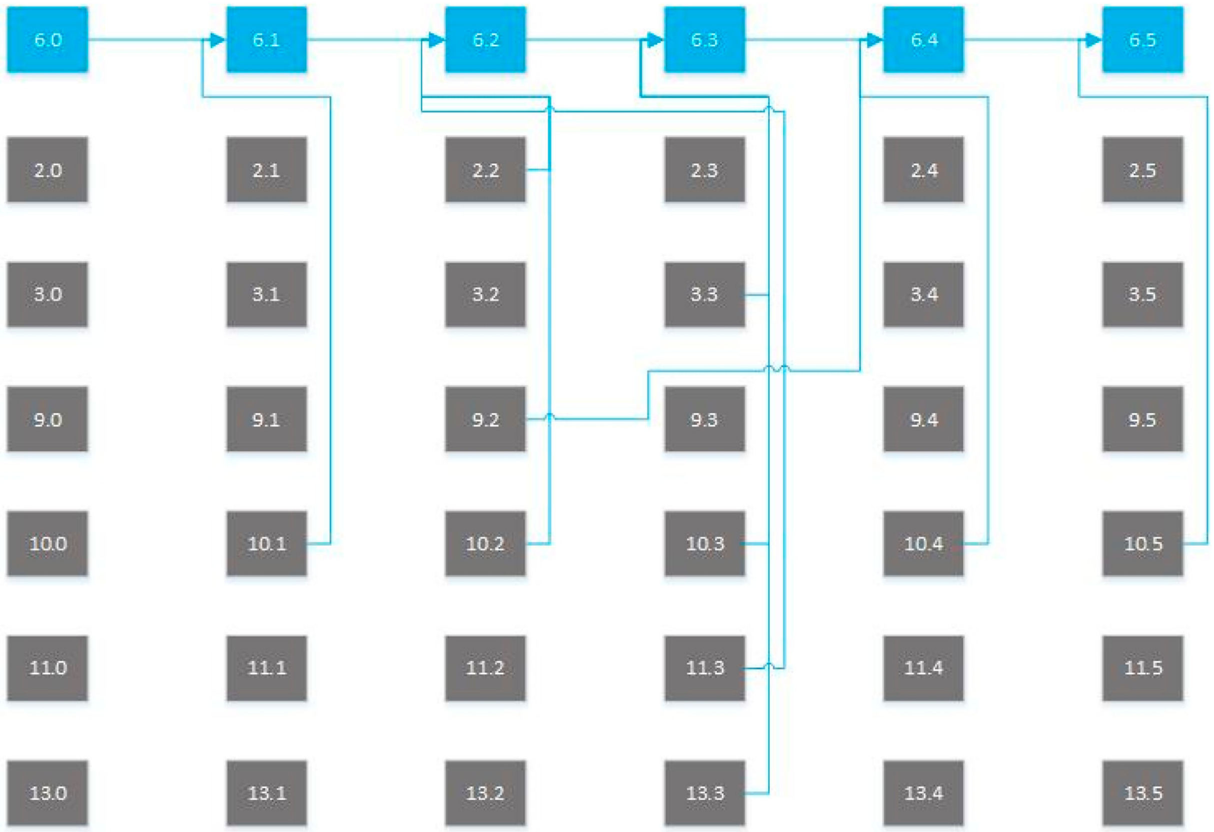

Figure 3. Dependencies of dimension 6. Numbering of the boxes: are the respective dimension and the respective development step, each separated by a dot. Example: 6.1– > Dimension 6 and there the development step 1. Turquoise boxes: are the exemplary considered dimension. Grey boxes: are further dimensions that influence the dimension under consideration. Turquoise arrows: indicate which development step of an influencing dimension influences which development step of the influenced dimension.

sites or cost centers will recur in a comparable manner. The informative value of reference costs depends on the actual comparability of the performed task under consideration and the activity to be performed (Finanzlexikon Online, 2019).

A cost structure indicates the ratio of parts of a cost sum to each other. Cost structures are primarily considered in terms of cost elements (relative proportion of material costs, plant costs, personnel costs, and so on) and cost dependencies (relative proportion of variable costs and fixed costs) (Klodt, 2019).

It is, therefore, the way in which the costs of a cost area or an enterprise are made up during a period from certain parts resulting from decisions, such as direct and overhead costs, fixed and variable costs, number of cost elements, and so on (Wirtschaftslexikon24, 2019).

In the context of this contribution, the cost structure is only subdivided and set up with regard to CAPEX and OPEX. Likewise, for reasons of delimitation, only the costs of dimensions that include technologies will be considered in this contribution.

CAPEX is used to describe capital expenditure on long-term assets, such as machinery, buildings, but also original equipment, spare parts, computer systems, etc. The CAPEX is an important characteristic value of the balance sheet. CAPEX costs increase the balance sheet assets that are depreciated over the long term (Gablers Wirtschaftslexikon, 2018a).

To determine the CAPEX costs for components of the energy domain, a literature search of companies (including the distribution grid study of the BMWi (BMWi is the German ministry of economics and energy) (Büchner et al., 2014)) and surveys of various utilities were carried out. The costs were queried in kEUR and queried per km or per unit.

It must be taken into account that several technologies were demonstrators, which were installed and used in the form for the first time. In these cases, the costs were specified by the respective utility of the case studies.

3.1. CAPEX costs

For CAPEX costs, there was a range of pricing per technology. An average value was always determined for the acquisition value in kEUR. These costs are shown in Table 1 (plus additional references).

3.2. OPEX costs

In contrast to capital expenditure, under which one can almost say long-term fixed assets, operating expenditure refers to the current expenditure for a functioning operational business. OPEX therefore includes the costs of raw materials, operating materials, personnel, leasing, energy etc. They are accounted for in full (Gablers Wirtschaftslexikon, 2018b).

For the calculation of OPEX costs, the specifications of the BMWi's distribution grid study (Büchner et al., 2014) were used. Accordingly, the following assumptions were made:

- Annual flat-rate operating allowances for conventional grid equipment (based on investment volume) for other installations
  - 2 % per year

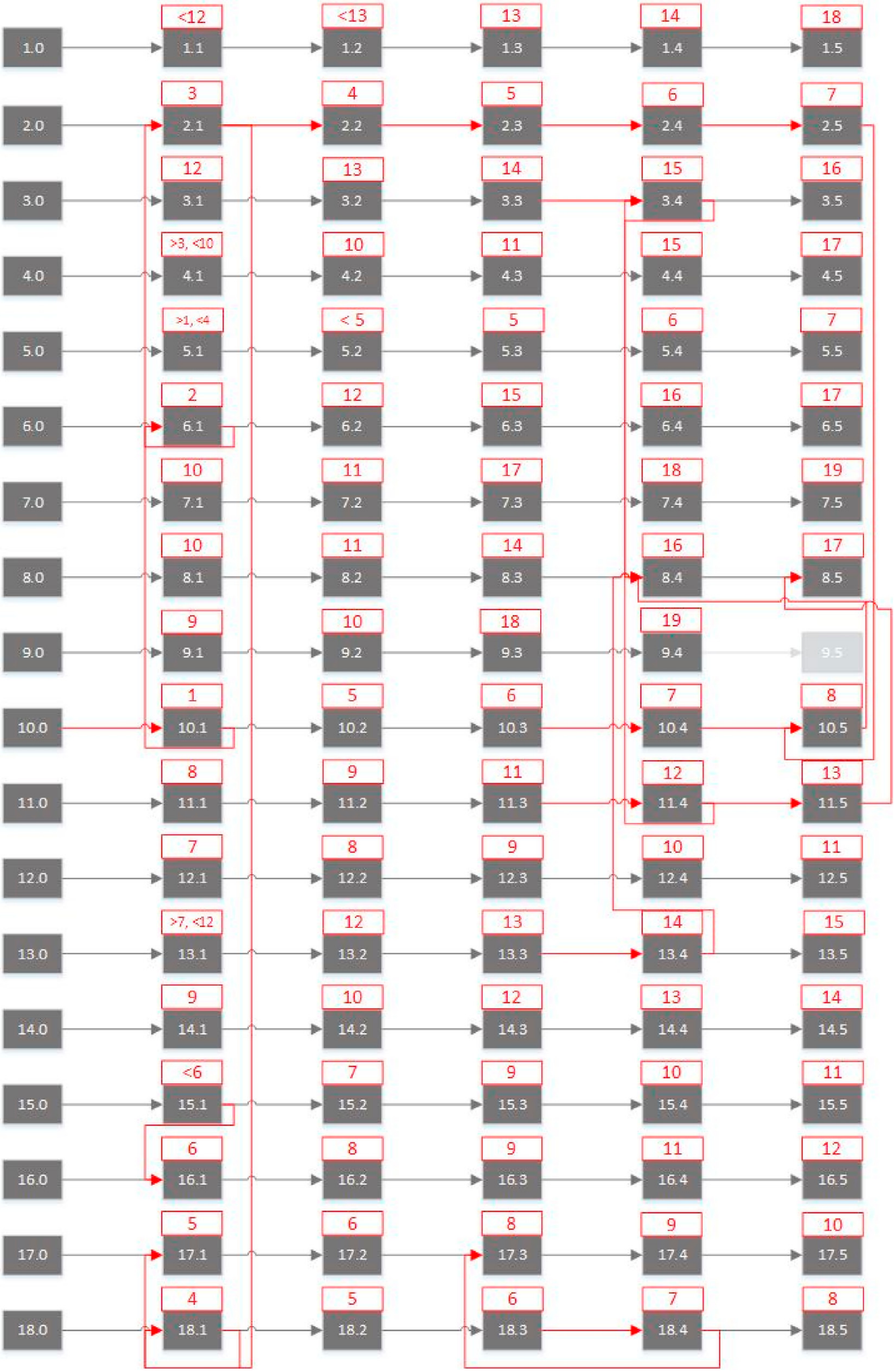

Figure 4. Roadmap for Target Scenario 3. Numbering of the boxes: are the respective dimension and the respective development step, each separated by a dot. Example: 6.1– > Dimension 6 and there the development step 1. Grey boxes: represent the dimensions and the respective development steps. Grey arrows: indicate the normal developmental connections between developmental steps. Red arrows: mark the critical connections between different developmental steps. Red boxes with red numbers: the numbering represents the chronological sequence of the individual development steps for the entire roadmap (starts with number 1 and ends with number 19). Light grey box: a development step that is not necessary in the target scenario according to the target state. Light grey arrow: a connecting arrow to a development step that is not necessary according to the target state in the target scenario.

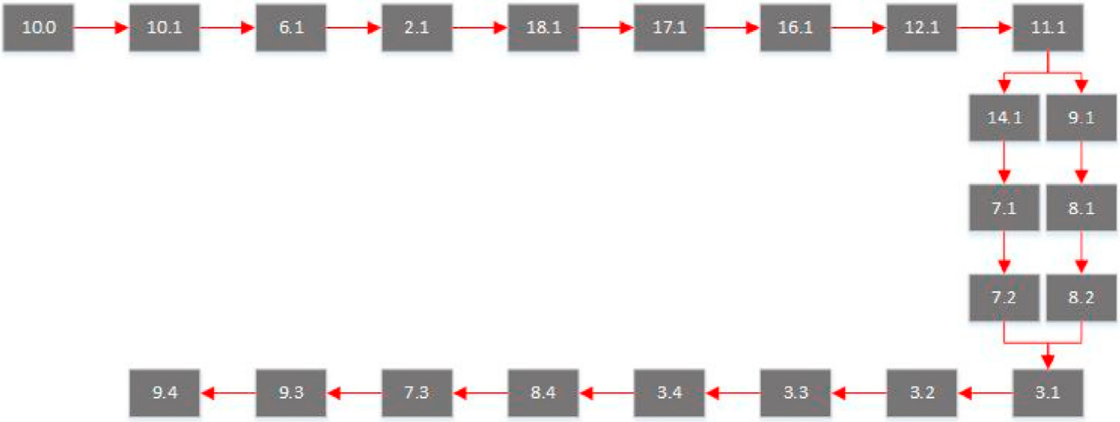

Figure 5. Critical Path for Target Scenario 3. Numbering of the boxes: are the respective dimension and the respective development step, each separated by a dot. Example: 6.1– > Dimension 6 and there the development step 1. Red arrows: clarify the critical path between the individual development steps of the overall roadmap.

- Annual flat-rate operating grants for conventional grid equipment (based on investment volume) for other software
  - 3 % per year
- Specific operating assumptions for ICT per installation
  - 60 EUR per year
- Adjustable local grid transformers per plant (rONT)
  - 600 EUR per year
- Intelligent Measuring System (iMSys) per installation (DENA, 2014)
  - 100 EUR per year

Based on the determined CAPEX and OPEX costs, costs per development step can then be extrapolated. This was done for the two case studies and shown in Chapter 4.

For better comparability, the extrapolation was made for the same model region.

The model region includes

- High voltage: 3 grids; 102 grid nodes; at the nodes are either large-scale consumers or a transformer to medium voltage level
- Medium voltage: 11 grids; 1,342 grid nodes; some nodes have several outgoing feeders; there are subordinate low-voltage grids or connected systems at the nodes
- Low voltage: 31 grids; 884 grid nodes; some nodes represent only one outgoing feeder, housing units, agricultural enterprises, etc. are connected to the nodes

In principle, the model region covers all clusters (urban, semi-urban and rural).

4. Results

Based on the process model, the migration paths for the two case studies were created. For step 5 of the process model to develop the migration paths, dimensions were defined for both case studies ("Green Access" are dimensions 1–18 and "Designetz" dimensions 1–19). For the definition of the dimensions, an individual requirements analysis was carried out for each case study (Flore and Marx Gómez, 2020b). For each dimension five maturity levels were defined in step 6. In step 7, development steps were defined for the five maturity levels, i.e. which technologies can be used to move from one maturity level to the next in each dimension. This can be seen from Tables 2,3,4 and 5 in the first column as follows: "3.1" (this is dimension 3 with development step 1). In order to simplify the procedure, only those dimensions are listed in the tables that contain technologies and have been monetarily evaluated in the context of this contribution.

There are technologies that are used in several dimensions. They were then always considered monetarily in the development step in which they are first used due to the chronological order. In the other development steps, a "0" is noted there.

There are also development steps that do not describe a new use of technologies, but only the interaction of existing technologies or similar. These cases are marked light yellow in the tables.

Cases are marked dark yellow which are not necessary after the target has been reached and therefore do not have to be implemented by the utilities from the point of view of sustainability. Which levels of maturity have to be reached with development steps was also determined in step 7.

Subsequently, the individual development steps of the roadmap were evaluated in monetary terms on the basis of the reference cost structure and extrapolated to the entire roadmap for the two case studies. RQ1 is answered by a cost extrapolation per case study.

The two utilities in the case studies are large distribution companies from Germany, which come from very different regions and therefore have very different requirements. The "Green Access" case study has few urban regions, but many rural and semi-urban regions. In the case of renewable energies, the focus is on wind power plants. The "Designetz" case study has strong urban agglomerations in its area with high load requirements, especially from industry, and few rural or semi-urban regions. In any case, the two utilities are comparable with other utilities, each of which has similar characteristics of the European regulatory framework.

Due to these different framework conditions of the utilities, they pursue different technological approaches. To ensure comparability, the cost extrapolation of the migration paths of the "Green Access" case study and the "Designetz" case study was calculated using the same model region. The calculation procedure for cost extrapolation per case study is shown in Figure 6.

4.1. Results of Case Study "Green Access"

As already described in Chapter 3.2, the cost extrapolation for the migration paths was based on the model region described.

Assumptions have to be made for the extrapolations regarding the size of the components used and the ICT required for this.

Table 1. Overview of capital costs.

Category	Description	Costs [kEUR]
Storages	Large battery storage [4,5 MW]	3600[1]
Storages	District heating and industrial storage [50 MW]	1500[1]
Storage	Industrial and commercial storage [35 kW]	38.5[2]
Storages	House storage tank [100 kW]	160[1]
Storages	Heat storage tank [8 kW]	0.12[3]
Sources	Wind turbine (WT) [3 MW]	4800[4]
Sources	Photovoltaics (PV) [50 kW]	55[1]
Sources	Biomass plant (BMA) [35 kW]	1500[5]
Sources	Combined heat and power unit (CHP) [400 kW]	1600[6]
Sinks	Demand side management [per plant]	50[7]
Sinks	Power to Heat (PtH) system large [2*5 MW]	1500[1]
Sinks	Heat pump [8 kW]	18[1]
Sinks	Power to Gas (PtG) system [6 MW]	12500[8]
Sinks	Electric mobility [11 kW]	2.5[9]
Accessory Components	PtH control system	10[7]
Accessory Components	PtG control system	10[7]
Accessory Components	CHP control system	10[7]
Accessory Components	Small remote control unit (standard)	3[1]
Accessory Components	Software for intelligent flexibility calculation	250[7]
Accessory Components	Sensor [per piece]	0.1[1]
Accessory Components	Meter [per piece]	0.25[7]
Accessory Components	Controller [100 pcs. plus software license]	600[10]
Accessory Components	Energy management system (for large companies >10 million energy costs)	87[11]
Accessory Components	Battery storage control	10[7]
Accessory Components	Grid control system	500[12]
Accessory Components	Smart Grid control system	800[7]
Accessory Components	Generation control room	1000[7]
Accessory Components	Smart station box (software intelligence)	250[7]
Accessory Components	ONS	10[13]
Accessory Components	rONT	13[7]
Accessory Components	gONT	3.5[10]
Accessory Components	Auto-ONS (3 ONS plus ICT)	40[13]
Accessory Components	Intelligent measuring system	0.35[14]
Accessory Components	Process data network (database)	120[7]
Accessory Components	System cockpit	760[7]
Accessory Components	sBox (control box) [complete]	4.7[10]
Accessory Components	aBox (actuator box) [complete]	1.65[10]
Accessory Components	mBox (measuring box) [complete]	0.7[10]
Accessory Components	RTU (Remote Technical Unit)	2[15]
Accessory Components	PV inverter [3–50 kW]	0.03[10]
Accessory Components	PV gateway	0.6[10]
Accessory Components	VPP gateway	0.6[10]
Accessory Components	BPL modem	0.75[16]
Accessory Components	iNES (including aBox (2–3), mBox (5–6), sBox (1), communication setup)	45[16]
Accessory Components	Intelligent safety edge	0.5[10]
Accessory Components	Smart Grid analysis and monitoring platform	1000[10]
Accessory Components	Decision system (database)	120[10]

References of CAPEX costs:

[1] Cost specification of the Transferstelle Bingen (http://www.tsb-energie.de/).

[2] Reference value 1,100 EUR per kW according to https://www.apricum-group.com/wp-content/uploads/2017/03/March-2017-pv-magazin-deutschland-article-Mayr-2.pdf (status: 07.01.2020).

[3] Reference value 15 EUR per kW according to https://www.bves.de/wp-content/uploads/2016/03/FactSheet_thermisch_sensibelWasser.pdf (status: 07.01.2020).

[4] Reference value 1,600 EUR per kW according to https://www.klein-windkraftanlagen.com/basisinfo/wirtschaftlichkeit/beurteilung-der-wirtschaftlichkeit-einer-investition-in-klein-windkraft/(status: 07.01.2020).

[5] Indicative value EUR 5,000 per kW according to www.kesselheld.de/biogasanlage/(status: 21.10.2019).

[6] Indicative value EUR 4,000 per kW according to https://www.energie-experten.org/heizung/blockheizkraftwerk-bhkw/blockheizkraftwerk-kosten.html (status: 07.01.2020).

[7] Cost specification from the "Designetz" case study.

[8] Research Center for Energy Economics, "Short Study Power-to-X," 2017.

[9] Cost specification =https://www.adac.de/rund-ums-fahrzeug/tests/elektromobilitaet/wallboxen/?redirectId=quer.wallboxtestalt (Status: 07.01.2020).

[10] Cost specification from the "Green Access" case study.

[11] Cost specification https://www.eccuro.com/artikel/157-energiemanagement-fuer-einsparungen-steuerermaessigungen (Status: 07.01.2020).

[12] Average: costs range between EUR 20,000 and 2,000,000 depending on the size of the grid to be monitored; BTC cost specification.

[13] Cost specification from the Technische Hochschule Dortmund (http://www.tu-dortmund.de/).

[14] J. Büchner, O. Flörcken, S. Dierkes, L. Verheggen, and M. Uslar, "„ Moderne Verteilernetze für Deutschland "(Verteilernetzstudie) „ Moderne Verteilernetze für Deutschland "(Verteilernetzstudie)," BMWi, no. 44/12, pp. 1–108, 2014.

[15] Mean value: the costs are between 0.2 TEUR and 5 TEUR depending on the equipment; https://www.dpstele.com/insights/2019/06/25/why-price-remote-terminal-unit-rtu-worth-upfront-cost/).

[16] Cost specification from the SPIE (www.spie.de).

- Large battery storage: 4.5 MW
- District heating and industrial storage: 50 MW
- Industrial and commercial storage: 35 kW
- House storage tank: 100 kW
- Heat accumulator: 8 kW
- PV: 50 kW
- WT: 3 MW
- BMA: 300 kW
- CHP: 400 kW
- Electric mobility: 11 kW
- PtG: 4 MW
- PtH: 20 MW

In addition to information on the size, performance and ICT of the technologies, general assumptions must also be made for cost extrapolation:

- In dimension 3, the technologies are not purchased, but only the asset management for them is carried out. Therefore, the costs for this are estimated in dimension 7.
- For simplification, it is assumed that each local exchange station is large enough to have a new transformer installed for an intelligent voltage transformer (i.e. there will be no additional costs for civil engineering, cable laying, etc.).
- Each local substation will be equipped with a rONT.
- Each local substation will be equipped with an intelligent safety edge.
- Each local grid station will be equipped with one MV controller and three LV controllers.
- A PV gateway is installed for each MS-controller and NS-controller.
- One PV inverter is calculated per solar system.
- Equipment of a local grid:
- Distribution grid management system (iNES) (incl. accessories according to Table 1)
- Every system that is already installed or is yet to be installed is equipped with an iMSys and an RTU.

In addition, a further distinction is made with regard to the allocation of costs. Because some of the costs, which result for CAPEX and OPEX, do not pay alone the utility but also investors/companies and/or private customers:

- The costs for large battery storage are borne by the utility.
- The costs for industrial storage are borne by investors/companies.
- Private customers bear the costs for heat and domestic storage.
- The costs for sources are borne by investors/companies or private customers (breakdown for simplification purposes 90%/10%).
- The costs for sinks (except electric mobility) are borne by utilities or investors/companies (breakdown for simplification purposes 50%/50%).
- The costs for electric mobility are borne by utilities, investors/companies or private customers (breakdown for simplification purposes 40%/40%/20%).
- The costs for innovations in the distribution grid such as software or equipment are borne by the utilities.
- The costs for the control of storage, sources and sinks are borne by the utilities (also sensor technology, meters, iMSys etc.)
- Private customers bear the costs for the heat pumps.
- For reasons of simplification, the service life of the devices and systems is not taken into account, but only the one-off purchase is calculated.
- Each technology is only fully charged for the first development step, not for the others.
- As in process step 7 for the development of migration paths, only those dimensions are calculated in monetary terms, which include technologies - namely grid-specific technologies.

Three hints for understanding the cost extrapolation tables (Table 2 and Table 3):

- It has been rounded to the nearest thousand.
- The light yellow fields are development steps that have technologies but no grid-specific ones and are therefore not calculated further here.
- The dark yellow fields are development steps that, according to the determination of the target status for the target scenario, do not have to be achieved. Because of the benefit assumption that only those development steps that are necessary are of benefit, these development steps are omitted and are not included in the calculation.

Cost extrapolation shows that although a large amount of investment (CAPEX) is required for energy system transformation, the utilities only account for just under 30% of this. About 50 % is borne by investors and companies that build large storage facilities, wells and sinks, and about 20 % by private households.

The percentage distribution of OPEX costs is somewhat different: 50 % is borne by the utilities, approx. 40 % by investors and companies and only approx. 10 % by private households.

4.2. Results of Case Study "Designetz"

As already described in Chapter 3.2, the cost extrapolation for the migration paths was based on the model region described.

Assumptions have to be made for the extrapolations regarding the size of the components used and the ICT required for this.

- Large battery storage: 4.5 MW
- per system: 1 battery storage control, 2 counters, 1 measuring system, 25 sensors
- District heating and industrial storage: 50 MW
- per system: 1 counter, 1 measuring system, 25 sensors
- Industrial and commercial storage: 35 kW
- per system: 1 counter, 1 measuring system, 25 sensors
- House storage tank: 100 kW
- per system: 2 m, 1 measuring system, 1 KFWT
- Heat accumulator: 8 kW

Table 2. Cost extrapolation CAPEX for case study “Green Access”.

Development Step	CAPEX total [kEUR]	CAPEX utility [kEUR]	CAPEX investor/company [kEUR]	CAPEX private person [kEUR]
3.1	0			
3.2				
3.3				
3.4	0			
3.5	0			
6.1				
6.2				
6.3	0			
6.4	120	120		
6.5	0			
7.1				
7.2			82.112.764	29.988.002
7.3	124.332.742	12.231.976		
7.4				
7.5				
8.1				
8.2				
8.3	0			
8.4	0			
8.5				
9.1				
9.2	1.000	1.000		
9.3	0			
9.4	0			
9.5				
10.1				
10.2				
10.3	500	500		
10.4	1	1		
10.5	1.000	1.000		
11.1				
11.2				
11.3	27.284.956	27.284.956		
11.4	118.645	118.645		
11.5	15.600	15.600		
12.1				
12.2				
12.3				
12.4				
12.5				
13.1				
13.2				
13.3	4.774.762	4.774.762		
13.4				
13.5				
14.1				
14.2				
14.3	0			
14.4	0			
14.5	0			
Sum	**156.529.326**	**44.428.560**	**82.112.764**	**29.988.002**

- per system: 1 counter, 1 measuring system, 10 sensors
- PV: 50 kW
- per installation: 1 counter, 1 measuring system
- WT: 3 MW
- per system: 1 counter, 1 measuring system, 1 KFWT
- BMA: 300 kW
- 1 counter, 1 measuring system, 1 control unit
- CHP: 400 kW
- 1 m, 1 measuring system, 1 KFWT, 1 KWK controller
- Electric mobility: 11 kW
- 1 counter, 1 measuring system
- PtG: 4 MW
- 1 counter, 2 measuring systems, 20 sensors, 1 PTG control, 1 KFWT
- PtH: 20 MW

Table 3. Cost extrapolation OPEX for case study “Green Access”.

Development Step	OPEX total [kEUR]	OPEX utility [kEUR]	OPEX investor/company [kEUR]	OPEX private person [kEUR]
3.1	0			
3.2				
3.3				
3.4	0			
3.5	0			
6.1				
6.2				
6.3	0			
6.4	4	4		
6.5	0			
7.1				
7.2				
7.3	2.486.655	244.640	1.642.256	599.759
7.4				
7.5				
8.1				
8.2				
8.3	0			
8.4	0			
8.5				
9.1				
9.2	20	20		
9.3	0			
9.4	0			
9.5				
10.1				
10.2				
10.3	10	10		
10.4	0	0		
10.5	30	30		
11.1				
11.2				
11.3	545.699	545.699		
11.4	2.371	2.371		
11.5	720	720		
12.1				
12.2				
12.3				
12.4				
12.5				
13.1				
13.2				
13.3	1.364.218	1.364.218		
13.4				
13.5				
14.1				
14.2				
14.3	0			
14.4	0			
14.5	0			
Sum	**4.399.726**	**2.157.712**	**1.642.256**	**599.759**

- 1 counter, 2 measuring systems, 20 sensors, 1 PTH control, 1 KFWT

In addition to information on the size, performance and ICT of the technologies, general assumptions must also be made for cost extrapolation:

- In dimension 3, the technologies are not purchased, but only the asset management for them is carried out. Therefore, the costs for this are estimated in dimension 7.
- For simplification, it is assumed that each local exchange station is large enough to have a new transformer installed for a rONT (i.e.

there will be no additional costs for civil engineering, cable laying, etc.).
- Each local substation will be equipped with a rONT.

In addition, a further distinction is made with regard to cost allocation. This is because some of the costs incurred for CAPEX and OPEX are not paid by the utilities alone but also by investors/companies and/or private customers:

- The costs for large battery storage are borne by the utility.
- The costs for industrial storage are borne by investors/companies.
- Private customers bear the costs for heat and domestic storage.

Table 4. Cost extrapolation CAPEX for case study "Designetz".

Development Step	CAPEX total [kEUR]	CAPEX utility [kEUR]	CAPEX investor/company [kEUR]	CAPEX private person [kEUR]
3.1	0			
3.2				
3.3				
3.4	0			
3.5				
6.1				
6.2				
6.3	0			
6.4	0			
6.5				
7.1				
7.2				
7.3	71.881.410	1.501.028	63.031.671	7.348.711
7.4	15.254.243	3.213.995	10.066.445	1.973.803
7.5	28.444.668	4.155.969	21.454.449	2.834.250
8.1				
8.2				
8.3	0			
8.4	1.000	1.000		
8.5				
9.1				
9.2	0			
9.3	5.992.853	5.992.853		
9.4	15.600	15.600		
9.5				
10.1				
10.2				
10.3				
10.4				
10.5				
11.1				
11.2	457	457		
11.3				
11.4				
11.5	760	760		
12.1				
12.2				
12.3				
12.4				
12.5				
13.1				
13.2				
13.3	0			
13.4				
13.5				
14.1				
14.2				
14.3				
14.4	4.901.470	4.901.470		
14.5	250	250		
Sum	**126.492.711**	**19.783.382**	**94.552.565**	**12.156.764**

Table 5. Cost extrapolation OPEX for case study "Designetz".

Development Step	OPEX total [kEUR]	OPEX utility [kEUR]	OPEX investor/company [kEUR]	OPEX private person [kEUR]
3.1	0			
3.2				
3.3				
3.4	0			
3.5				
6.1				
6.2				
6.3	0			
6.4	0			
6.5				
7.1				
7.2				
7.3	1.437.628	30.020	1.260.634	146.974
7.4	305.085	64.280	201.329	39.476
7.5	568.893	83.119	429.088	56.686
8.1				
8.2				
8.3	0			
8.4	20	20		
8.5				
9.1				
9.2	0			
9.3	119.857	119.857		
9.4	720	720		
9.5				
10.1				
10.2				
10.3				
10.4				
10.5				
11.1				
11.2	15	15		
11.3				
11.4				
11.5	23	23		
12.1				
12.2				
12.3				
12.4				
12.5				
13.1				
13.2				
13.3	0			
13.4				
13.5				
14.1				
14.2				
14.3				
14.4	1.349.663	1.349.663		
14.5	8	8		
Sum	**3.781.912**	**1.647.725**	**1.891.051**	**243.136**

- The costs for sources are borne by investors/companies or private customers (breakdown for simplification purposes 90%/10%).
- The costs for sinks (except electric mobility) are borne by utility or investors/companies (breakdown for simplification purposes 50%/50%).
- The costs for electric mobility are borne by utilities, investors/companies or private customers (breakdown for simplification purposes 40%/40%/20%).
- The costs for innovations in the distribution grid such as software or equipment are borne by the utility.

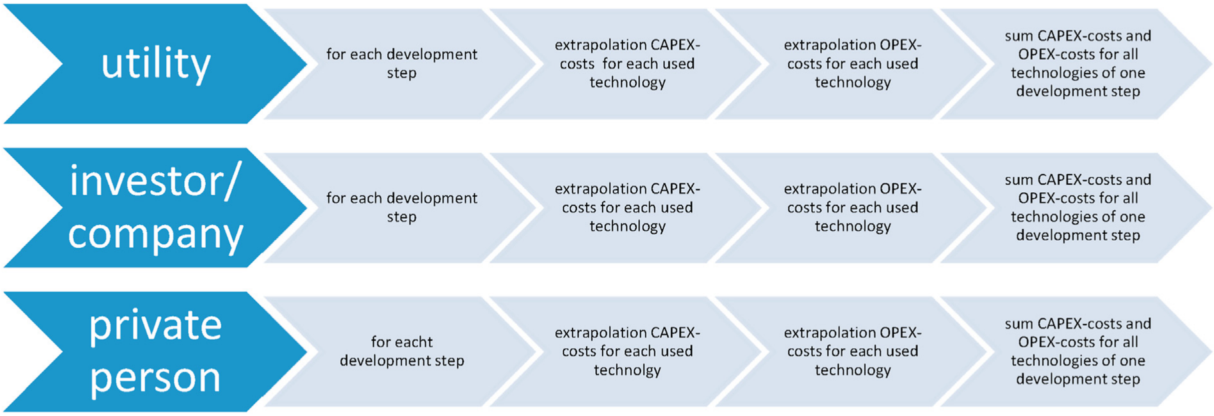

Figure 6. Calculation procedure for cost extrapolation per case study.

- The costs for the control of storage, sources and sinks are borne by the utility (also sensor technology, meters, iMSys etc.)
- For reasons of simplification, the lifetimes of the devices and systems are not taken into account, but only the one-time purchase is calculated.
- Each technology is only completely credited at the first development step, not for the others.
- As in process step 7 when developing the migration paths, only the dimensions that include technologies - namely grid-specific technologies - are calculated in monetary terms.

Three clarifications for understanding the cost extrapolation tables (Table 4 and Table 5):

- It has been rounded to the nearest thousand.
- The light yellow fields are development steps that have technologies but no grid-specific ones and are therefore not calculated further here.
- The dark yellow fields are development steps that, according to the determination of the target status for the target scenario, do not have to be achieved. Because of the benefit assumption that only those

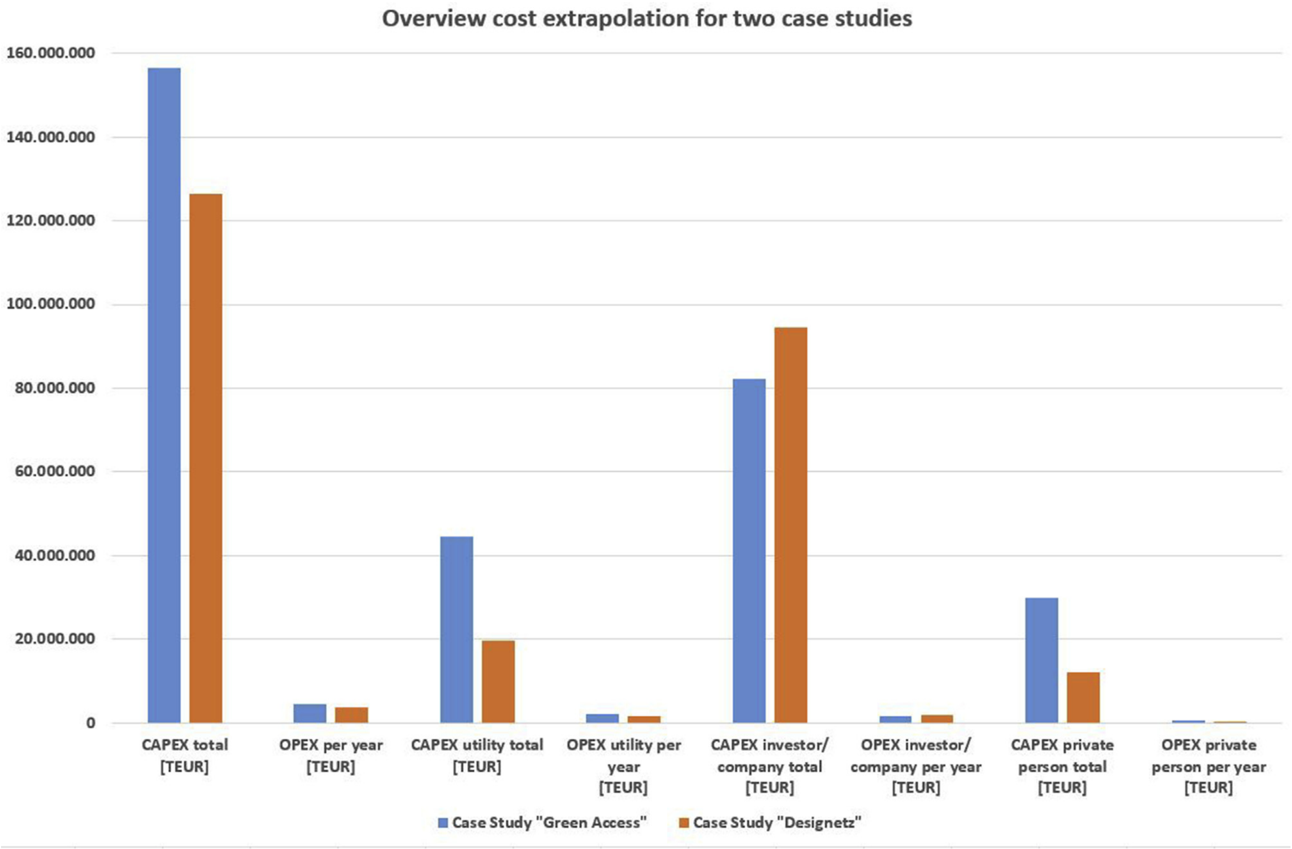

Figure 7. Overview cost extrapolation for two case studies.

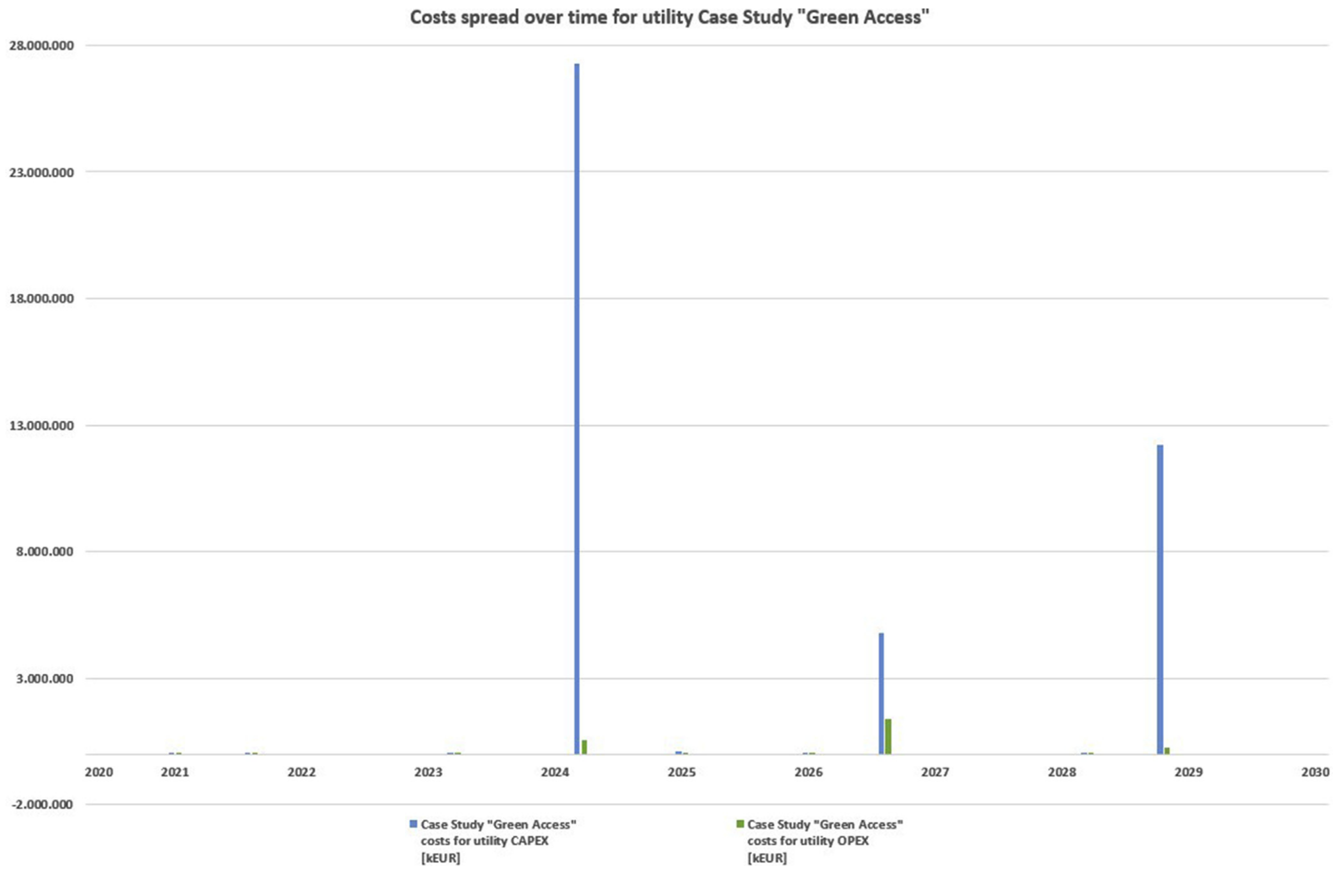

Figure 8. Cost spread over time for utility case study Green Access.

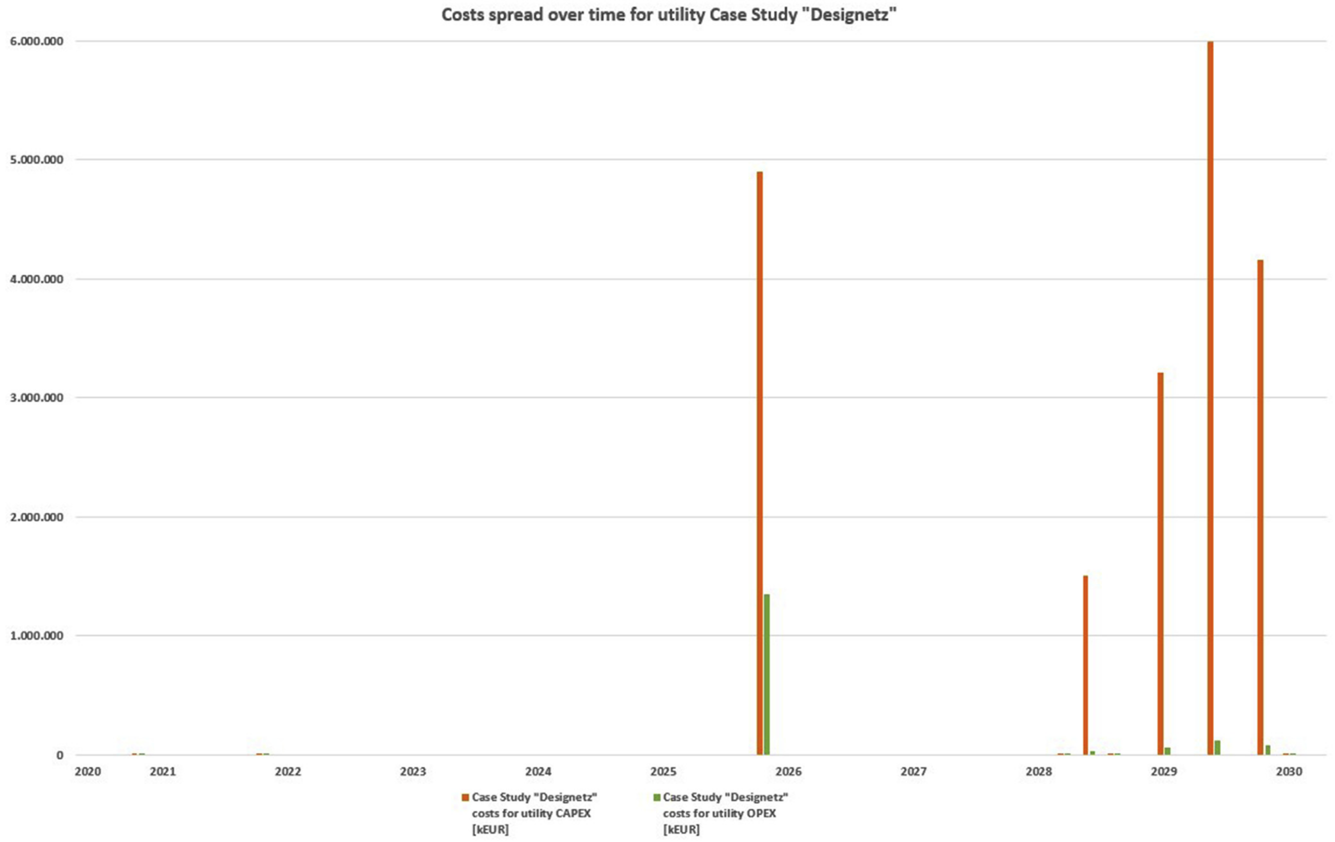

Figure 9. Cost spread over time for utility case study Designetz.

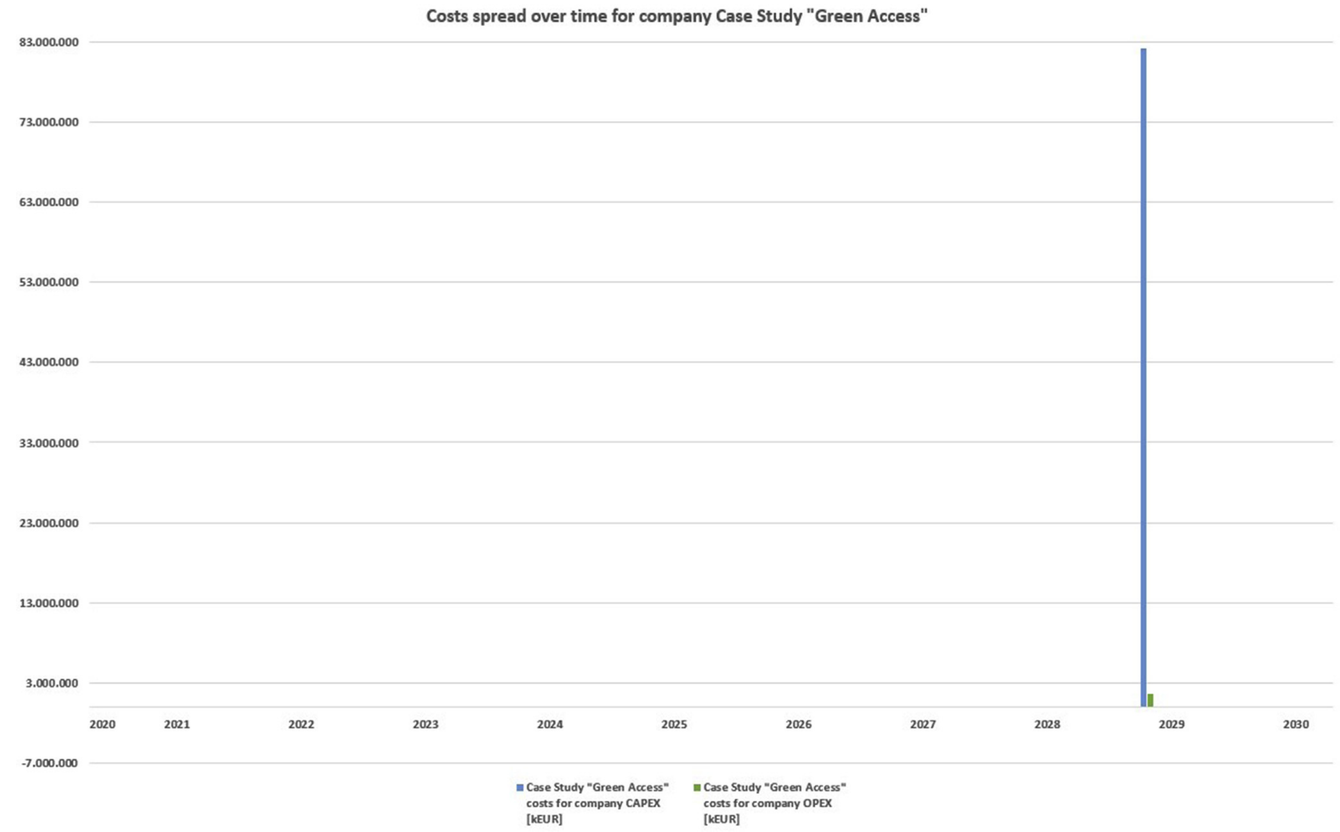

Figure 10. Cost spread over time for company case study Green Access.

development steps that are necessary are of benefit, these development steps are omitted and are not included in the calculation.

Cost extrapolation shows that although a large amount of investment (CAPEX) is required for energy system transformation, only 15 % of this falls to the utilities. Approximately 75 % is borne by investors and companies that build large reservoirs, wells and sinks and approximately 10 % by private households.

The percentage distribution of OPEX costs is slightly different: 45 % are borne by the utilities, approx. 50 % by investors and companies and only approx. 5 % by private households.

5. Comparison and discussion of the results

RQ1 ("How much does the introduction of the technologies cost to implement the migration paths?") was answered with the cost projection in chapter 3.

This means that for the case study "Green Access" the introduction of the technologies would cost a total of kEUR 156,529,326 to implement the migration paths. The operational costs amount to kEUR 4,399,726 per year. For the case study "Designetz" the acquisition costs amount to kEUR 126,492,711 and the operational costs amount to kEUR 3,781,912 per year. In order to answer RQ2 ("What are the economic differences in the costs of migration paths for case study "Green Access" and "Designetz"?"), a comparison of the extrapolation results and an evaluation of these results must be made.

Finally, a comparison of the cost projections (Figure 7) shows that the technology solution of the "Green Access" case study has approximately 20% higher CAPEX costs and 15% higher OPEX costs compared to the technology solution of the "Designetz" case study.

Apart from the fundamentally higher CAPEX and OPEX costs, the percentage distribution of costs to the utility company in the "Green Access" case study is almost 30%, which is twice as high as in the "Designetz" case study. The technology solution of the "Green Access" case study includes many innovative technologies that are installed within the own distribution grid to make the grid particularly intelligent and controllable. However, this means that a large part of the costs must also be borne by the utility, since innovations in the own distribution grid must also be booked to the utilities' account. The technology solution of the case study "Designetz", on the other hand, focuses on more use of flexibilities, which the utilities are supposed to connect by means of new control options, but the acquisition of which is largely borne financially by investors and companies. In conclusion, from a purely monetary point of view, it can be said that the technology solution of the "Designetz" case study is more favorable for a utility to realize the energy turnaround. In principle, however, both expansion options require a lot of new renewable energy capacity. That means a lot of new wind turbines, PV, storage facilities, but also the expansion of electro mobility. Since many of these technologies are to be supported or implemented not only by utilities, but also by investors and companies, as well as by private households, it is important that the right incentives for investment are in place. These incentives can be set by the utilities themselves, but of course they can

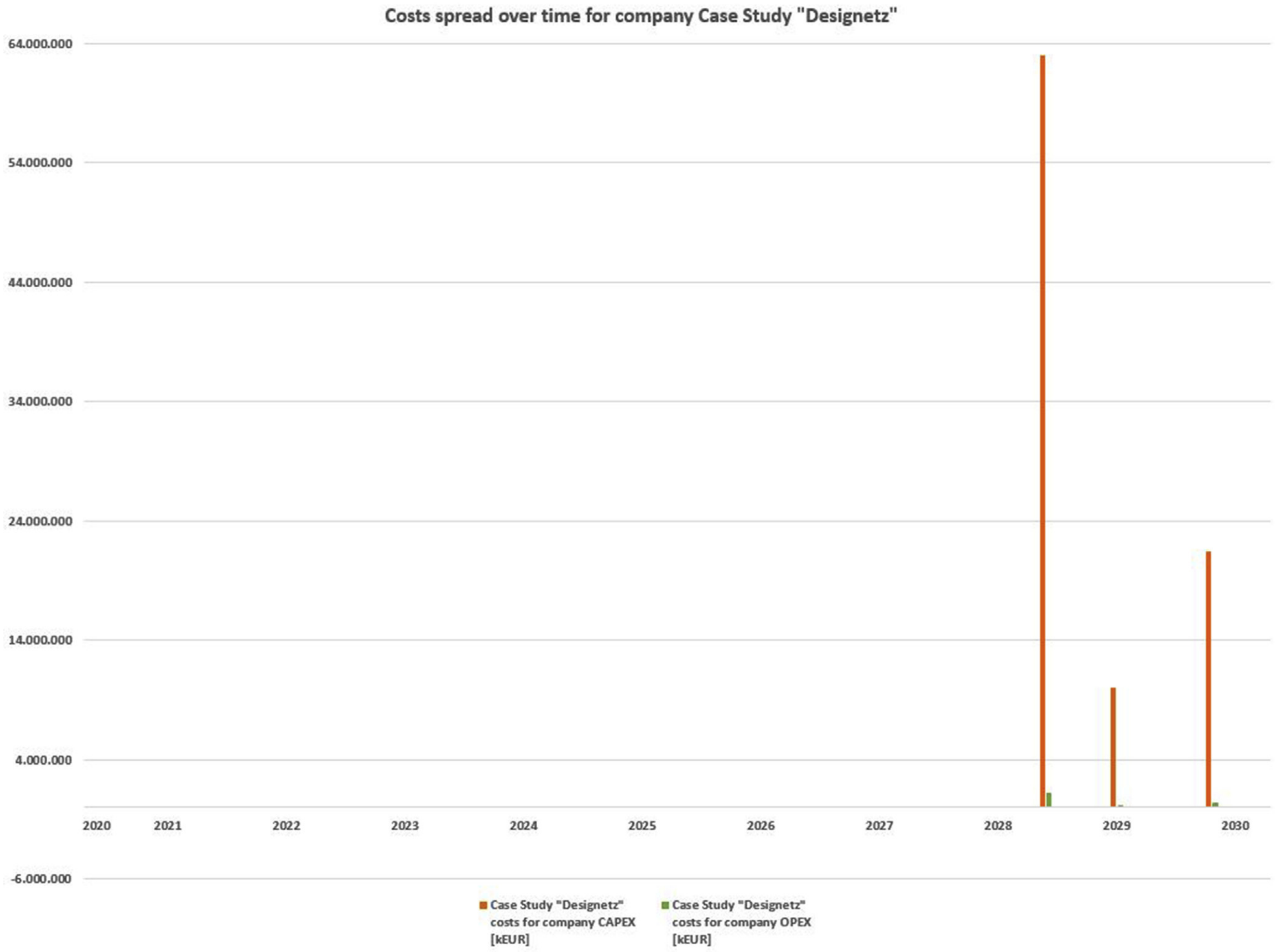

Figure 11. Cost spread over time for company case study Designetz.

also be supported significantly by politics (Flore and Marx Gómez, 2020a).

For the period up to 2030 (target scenario 3), the costs were also presented individually per stakeholder in the order in which they would accrue according to the migration path. This can be seen in Figures 8,9,10,11,12 and 13).

These graphs also show that in the next five to ten years, the various stakeholders will have to incur costs.

Adequate energy policy can have a positive influence on the behavior of the stakeholders in terms of energy system transformation, for example, through allowances, promotional loans, and other benefits.

If a utility chooses an expansion variant to follow the migration paths to a modern Smart Grid, it will opt for the more expensive approach with the Green Access expansion variant according to cost evaluation. The costs also remain largely with the utility. However, this expansion variant offers the advantage that the implementation is largely in the hands of the utility, which means that he has the speed in his own hands. For the utility, this variant also makes it much easier to coordinate the individual development steps with the prevailing dependencies between the dimensions. This is due to the fact that he does the implementation himself and can monitor it. If work steps in a schedule are to be carried out by “third parties” (e.g. investors or private households), the utility lacks control over them and also the necessary stimulus to see whether something is finished and something else can begin. This is very difficult for a project planning, can lead to big problems, friction losses and time delays. Even if the cost point for the utility is higher with this variant, the utility has the decision to bear the costs himself. The utility is not in a position to influence whether investors or private households make investments that are necessary to implement the migration paths. Likewise, the utility is also unable to assess whether the monetary incentives provided by politics are sufficient to motivate investors and private households to make the necessary investments. This shows that the Green Access expansion variant is the more cost-intensive variant, but is easier to plan (Flore and Marx Gómez, 2020a).

If, on the other hand, a utility decides on the Designetz expansion variant, he has chosen the more cost-effective of the two variants. An additional financial advantage of this variant is that a maximum of 1/5 of this investment amount is borne by the utility. The largest part of the investment amount is accounted for by investors and private households. But exactly here is a problem. When implementing such an important

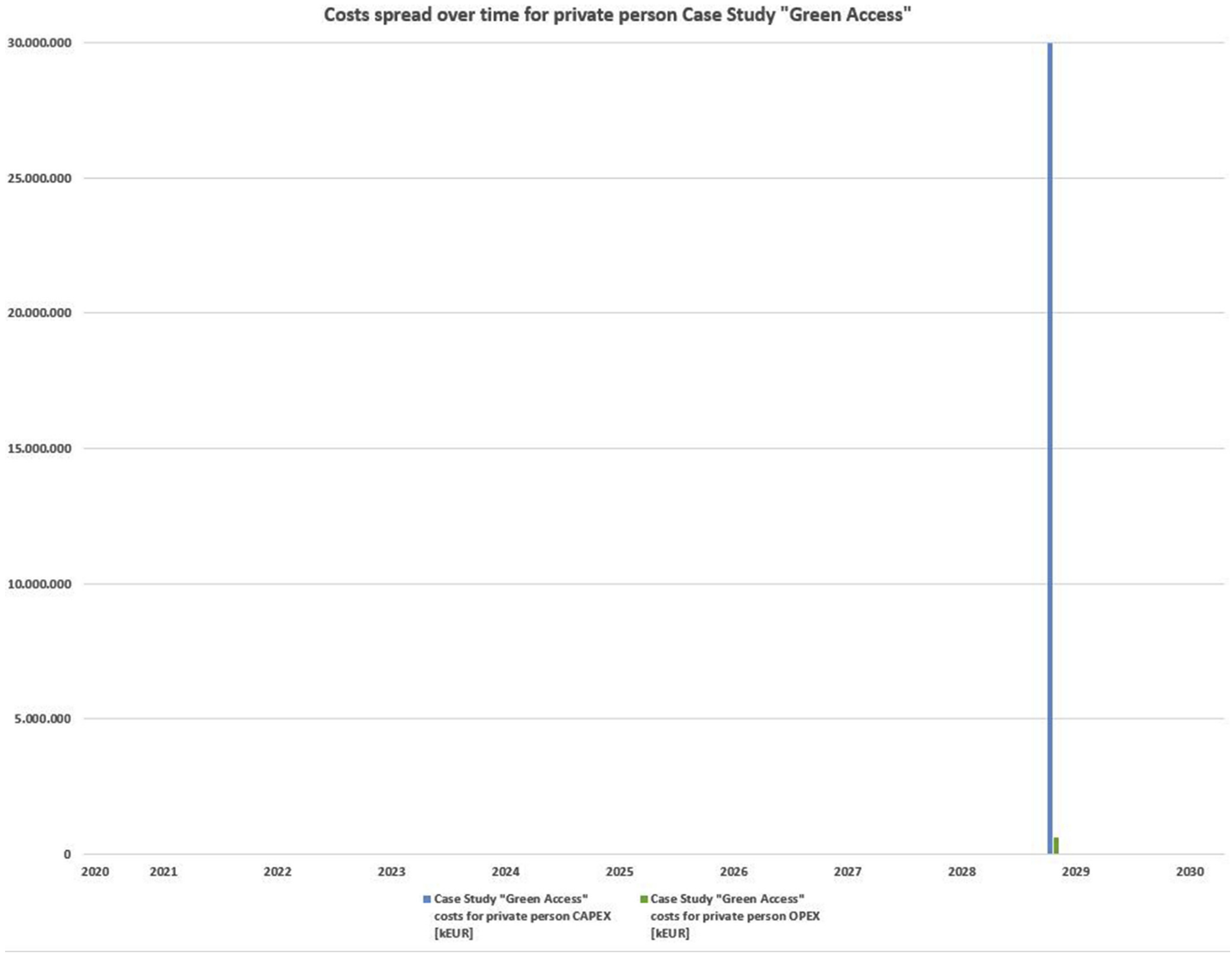

Figure 12. Cost spread over time for private person case study Green Access.

project to achieve the energy turnaround, it is more promising to have not only 20% of a project in your own hands. This is uncertain in planning and therefore very risky. Any development steps in which Flex options must be added are not under the control of a utility. The addition of the Flex options must take place via investors and/or private households. These parties must make this positive decision however first. And the utility cannot influence this decision. This decision contains both financial aspects, and fundamental considerations. For example, the decision of a party whether it is willing to have a new system built on its house, garden, roof, etc. is one of the basic considerations. Of course, politics can positively influence this purchase decision through subsidies, but it is only an influence and not a guarantee for a purchase decision. Thus the development variant Designetz is the substantially more economical variant, but the little plannable variant (Flore and Marx Gómez, 2020a).

As a final comparison to the investment costs of the Green Access and Designetz expansion variants, a grid expansion (instead of a grid modernization) is simulated. For the model region used in the case studies, the TU Dortmund University has carried out a simulation for the necessary grid expansion and calculated the costs of the cable expansion including transformers. For the grid expansion in the model region investment costs of TEUR 81,057,729 would be incurred. These investment costs are considerably lower than those for the Green Access and Designetz expansion variants. The ratio is almost half to the Green Access expansion variant and two thirds to the Designetz expansion variant. One advantage this offers is that the costs are entirely borne by the utility, as are the planning and implementation. If you compare the costs of the utility of the two expansion variants with the cable expansion, the latter is no longer cheaper. On the contrary, the costs are doubled or even quadrupled. There are two additional problems for a pure cable extension:

1. If a utility attempts to achieve the energy turnaround only by expanding the cable grid, he will not enable his grids with innovative and modern ICT to guarantee new services for customers. However, these are indispensable for a utility in the advancing age and the need for smart homes and more.
2. grid expansion is always associated with many problems. The normal earthworks are rather the simple ones. It becomes problematic - especially from a regulatory and legal point of view - to lay new overhead lines for which there is no popularity among the population.

These two points weigh heavily and should not be disregarded when a utility decides how to proceed. A utility should therefore consider all aspects of his decision and choose a solution that is appropriate for him, his location, his region and his customers. It is helpful to design the entire development as a project, appoint an experienced project manager and regularly evaluate the current status. A good way to do this would be to re-apply the maturity model at regular intervals (e.g. every two years) to check in which dimensions an improvement is already to be found and in which dimensions the necessary improvement has not yet occurred.

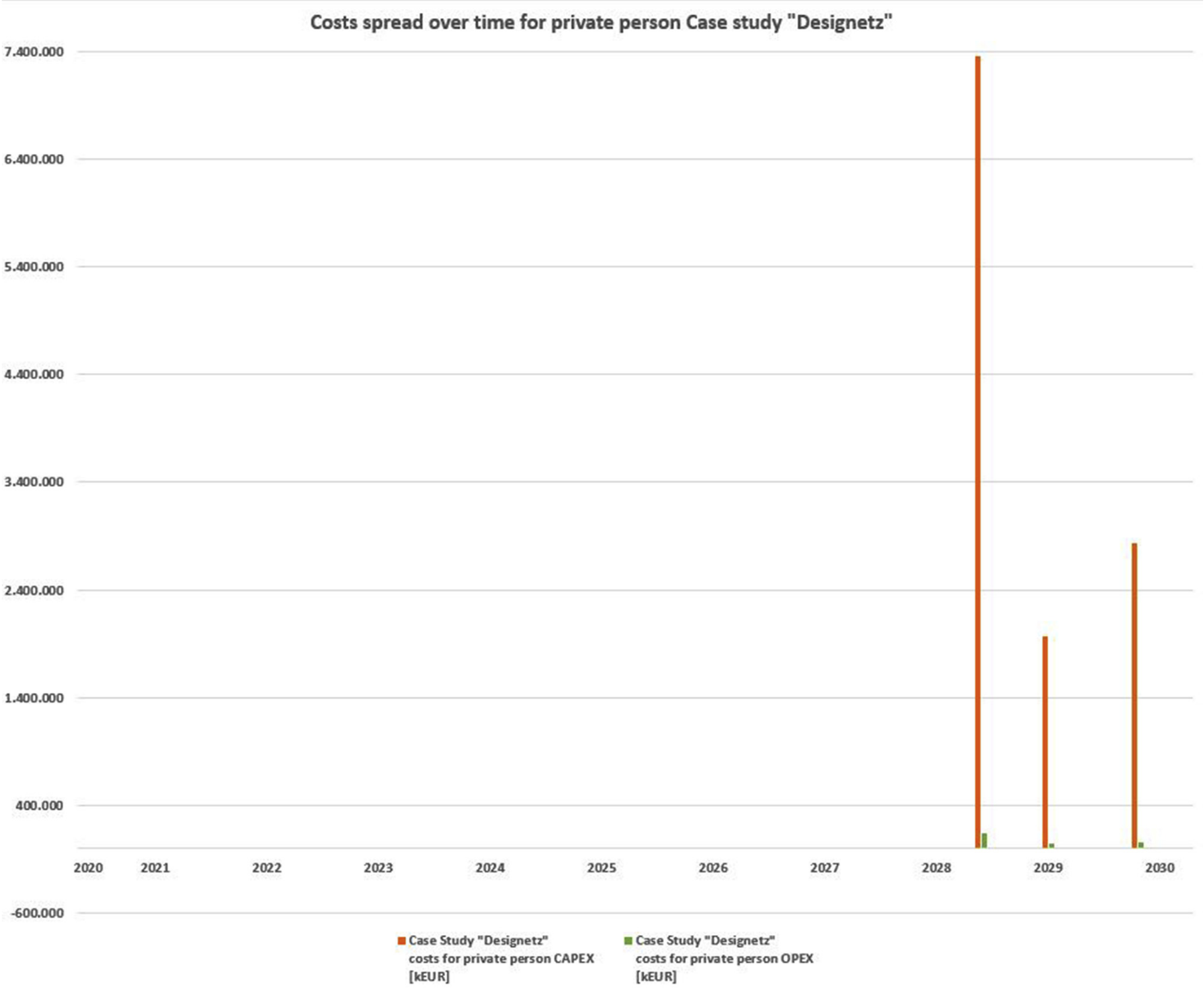

Figure 13. Cost spread over time for private person case study Designetz.

6. Conclusion

In this contribution we outlined the need for utilities to address the upcoming energy change from both a technological and economic perspective. From the point of view of the utilities it is desirable to get a final solution that is technologically the best and, if possible, still the most cost-effective. However, since every utility is different, operates a different grid area and is dependent on different sources and sinks, the one best solution cannot exist. One way to approach this is to look at the economic facts and evaluate different solutions with sensitive factors in advance. In this contribution two different case studies were conducted, presented and the conclusions discussed. The focus was on both European and German utilities, but the scope was based on model topologies and sizes of distribution system operators, so the results are transferable. Future case studies can build on these key economic aspects and reuse the data provided.

Nonetheless, in conclusion, however good a chosen migration path is for a utility and however consistently it is implemented, migration paths in their present form are not meaningful indefinitely. Technologies improve, are replaced by other technologies and a different interaction of technologies may result. This then has to be planned, evaluated and also calculated in monetary terms. The actuality of migration paths should be checked every 2–3 years due to the constantly improving technology.

Declarations

Author contribution statement

Agnetha Flore: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jorge Marx Gomez: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mathias Uslar: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by “Green Access”, which is funded by the German Federal Ministry of Economics and Energy (BMWi) and the German Federal Ministry of Education and Research (BMBF) as part of the research initiative “Sustainable Power Grids”. Further details can be found at http://forschung-stromnetze.info/. The authors, who represent the entire project consortium, are responsible for the content of the article. Members of the consortium: Bergische Universität Wuppertal, BTC AG, DLR Institute for Networked Energy Systems, EWE NETZ GmbH, Fraunhofer Institute for Solar Energy Systems (ISE), OFFIS e. V., PHOENIX CONTACT Energy Automation GmbH, SMA Solar Technology AG, SPIE SAG GmbH. This work was also supported by "Designetz", within the framework of the funding program Showcase Intelligent Energy - Digital Agenda for the Energy Turnaround (SINTEG) of the Federal Ministry of Economics and Energy (funding contract no. 03SIN229).

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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