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Research article

Development and comparison of migration paths for smart grids using two case studies

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ABSTRACT

Due to the energy turnaround in German politics, it is necessary to integrate more and more wind and solar energy into the existing energy system. In particular, power generation is changing from a previously centralized to a decentralized structure, which also has consequences for requirements for safe, reliable and efficient grid operation. Generation and utilization characteristics will become more dynamic and flexible in the future. Increased demand for the measurement, control and automation of voltage and electricity will require the further development of grid infrastructure, the expansion of storage capacity and the introduction of information and communication technology (ICT)-based energy management (Appelrath et al., 2012). Utilities therefore need to know what migration paths into the future of a smart energy grid could look like. And this against the background of which technologies have to be installed, in which order this can happen and which dependencies have to be considered. The aim is to create roadmaps to the modern Smart Grid for two case studies. Within the framework of the Green Access project (Projekt Green Access, 2019), and (Flore & Kumm, 2020), a maturity model and, based on this, migration paths were developed for this purpose, which describe a path from one development stage to the next. It describes the necessary development steps that have to be implemented in the context of migration paths. These migration paths have been developed for a specially designed maturity model and describe the technologies used to move from one maturity level to the next. Finally, there will be a comparison of the developed migration paths of the two case studies.

1. Introduction

In order to achieve the climate targets set by the German government in Germany, considerable adjustments in the energy supply by transmission system operators (TSO) and distribution system operators (DSO) are necessary. The energy from power plants and nuclear power, which has so far been predominantly used, must give way to the use of sustainable energy from renewable sources. This conversion of energy sources also requires an adjustment in the control of the energy grids as well as the entire grid infrastructure: this must be expanded from a previously centrally controlled to a then decentralized grid infrastructure (Appelrath et al., 2012) and (Appelrath et al., 2010).

The changed, rather decentralized energy system is characterized by high generation volatility and new consumers (e.g. electric mobility). Furthermore, if the climate protection goals are to be consistently achieved, the coupling of sectors (essentially transport and heat with electricity) will also gain in importance. This will create completely new challenges for grid operation, which are to be met by increased measurement, control and automation of the power flow. The distribution grid is to be expanded through innovative information and communication technologies (ICT) and thus become an intelligent smart grid.

To this end, more and more research and development (R&D) projects are being initiated to investigate innovative technologies that will make it possible to integrate more electricity from renewable energy sources into the distribution grid.

In this paper, roadmaps to a modern and intelligent energy grid is presented to the utilities on the basis of a procedure model for the development of migration paths. The procedure model is evaluated in two case studies in chapter 3 and 4 according to Robert K. Yin (2009) (Hollweck, 2016). After the process model has been presented in general, the individual development steps are shown on the basis of the two case studies and are compared in chapter 5. Finally, in chapter 6, a conclusion is drawn (Mehmann et al., 2015).

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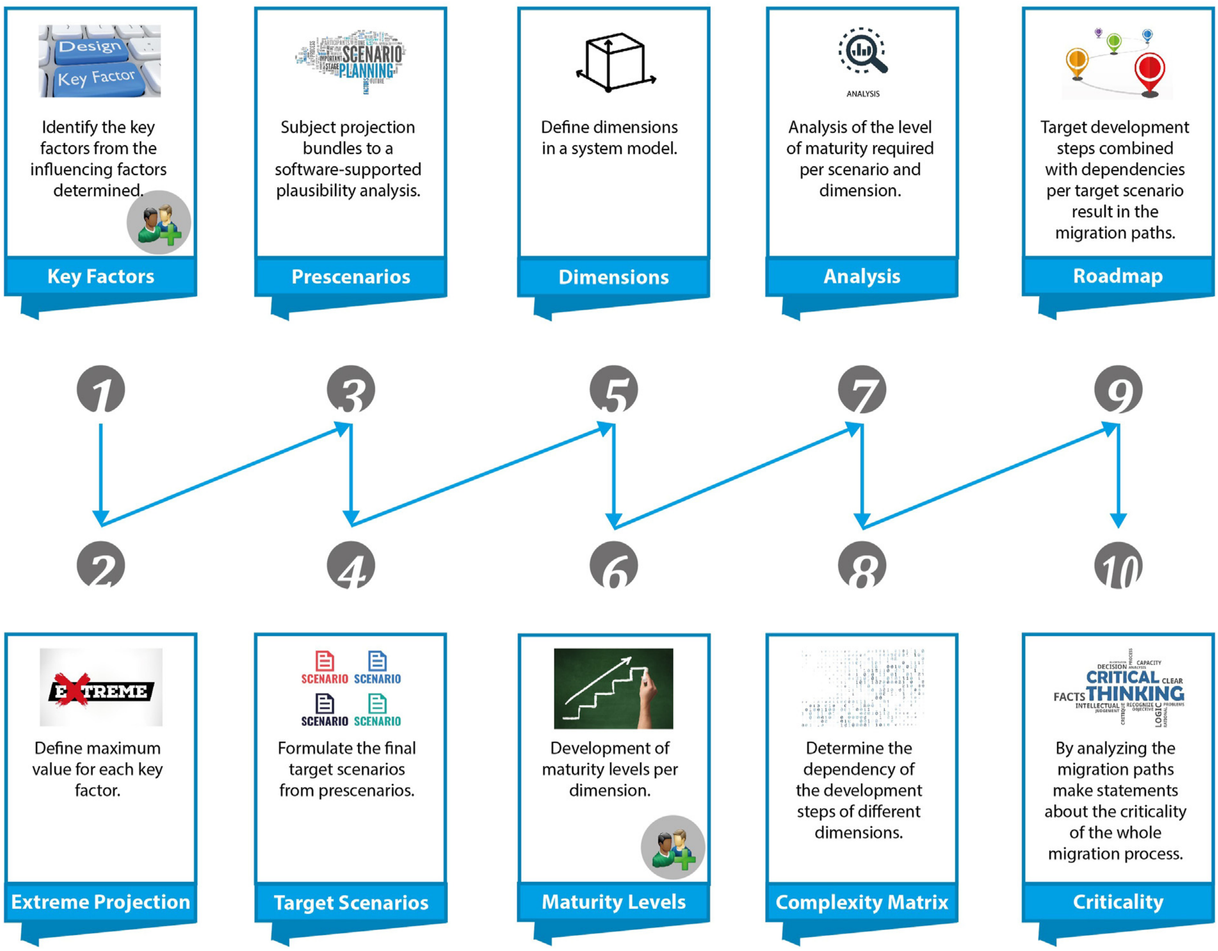


Figure 1. Procedure for developing migration paths (source: own presentation).

Table 1. Target scenarios 1–3.

Topic	Scenario 1	Scenario 2	Scenario 3
Technology option	technically realistic	technically realistic	technically optimistic
EE scenario	EEG 2014	2*EEG 2014	2*EEG 2014
PV expansion	17GW/44%	34GW/88%	34GW/88%
WTG expansion	17.7GW/45%	35.4GW/90%	35.4GW/90%
Heat pumps	8%	8%	15%
CHP	5.2%	5.2%	5.2%
Electric vehicles	1%	1%	17%
Stationary storage tanks	5.3%	5.3%	12.5%

2. Migration paths for smart grids

2.1. Definition

Migration paths are used to describe a (defined) path from one development step to the next. In the present case, the developmental steps that must be completed in order to move from one level of maturity to another are meant (Appelrath et al., 2012). Maturity levels describe a state, the development steps the changes (in this case the use of technologies) necessary to achieve a desired state (e.g. from maturity level 3 to maturity level 4).

2.2. Related works

In order to be able to develop the migration paths, a literature research on this topic was first conducted.

From a sustainability perspective, it is important to take this into account when developing migration routes. In our view, this includes three aspects: the dependencies on the dimensions to be considered, the Technology Readiness Level (TRL), and the costs and benefits of development steps (Flore and Marx Gómez, 2019), and (Flore and Marx Gómez, 2020a, b).

The acatech study (2012) was an important basis for the development of the migration paths as well as the consideration of the interdependencies of individual dimensions (Appelrath et al., 2012), (Appelrath, 2012), (Appelrath et al., 2011) and others (Pfeffer and Sutton, 1999), (Luhmann, 2012), (Appelrath et al., 2010), and (Winter & Aier, n.d.).

The aim was to develop sustainable migration paths. This means that only technologies that have already been sufficiently developed and tested should be used. To be able to assess this, the Technology Readiness Level (TRL) was considered (Horizon, 2020, 2014), (Graerringer et al., 2002), (Tugurlan et al., 2011), (Kirkham and Marinovici, 2013), (Campbell, 2018), (Mankins, 1995), (Mankins, 2009), and (Mankins, 2002).

A literature search for "maturity models" was also conducted (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., 2010a), (Becker et al., 2010b), (Poeppelbuss et al., 2011), (Becker et al., 2008),

Table 2. dimensions project green access.

No.	Dimension
1	General information about the organization
2	Strategy, management and regulation
3	Asset management for distributed generation plants
4	Value chain
5	Plant, change and configuration management
6	Grid operation
7	Grid components
8	Grid control systems
9	Grid automation
10	General technology
11	ICT connectivity
12	Data management
13	Forecasting systems
14	Plant communication and control modules
15	Information exchange and communication
16	Event and reaction; continuity of operation
17	Threat and vulnerability management
18	Risk management

Table 3. Target state per target scenario.

No. of Dimension	Scenario 1/Target State	Scenario 2/Target State	Scenario 3/Target State
1	3	4	5
2	3	4	5
3	3	4	5
4	3	4	5
5	3	4	5
6	3	4	5
7	3	4	5
8	4	5	5
9	2	3	4
10	3	4	5
11	3	4	5
12	3	4	5
13	3	4	5
14	3	4	5
15	4	5	5
16	3	4	5
17	3	4	5
18	3	4	5

(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).

Under the aspect of sustainability, a cost and benefit analysis of the migration paths to be developed is essential. However, this will be carried out in a separate contribution. The result of the literature research was that there is little literature on the topic of migration paths, but a lot on the topic of maturity models. However, there are only a few domain-specific maturity models for the Smart Grid and, in particular, none for the European unbundled electricity market.

In their contribution, Pfeffer and Sutton (1999) point to a blatant knowledge gap. This is due to the fact that there is a large number of maturity models in the literature that point to gaps and problems in the organization, but do not offer a solution as to how or by what means they can be closed and resolved (Pfeffer and Sutton, 1999). Mettler (2011) strengthens this statement in his studies on “Maturity Assessment Models” (Mettler, 2011).

This contribution should help to close the research gap that has been identified.

2.3. Process model for the development of migration paths for utilities

For the development of the migration paths a methodical procedure was chosen, which is shown in Figure 1. This procedure contains ten process steps and adapts the approach of the German Acatech study “Future Energy Grid” (Appelrath et al., 2012).

In total, the approach comprises ten steps. The first four steps relate to the creation of the scenario, steps five and six to the design of the dimensions to be considered (dimensions are understood here as specific capabilities, process areas and other design objects that structure an area of interest). Steps seven to ten are concerned with the analysis of dimensions and the development of actual migration paths (Flore & Kumm, 2020).

In cooperation with experts of the energy domain, first of all influencing factors are identified, which are essential for the development of the energy domain for the next years. The identified influencing factors are then prioritized and key factors are derived from them, which are documented in a key factor catalog (Appelrath et al., 2012) and (Gausemeier et al., 1996). Accordingly, the key factors catalog contains all key factors for the energy domain for the period under consideration.

Maximum values for the key factors are worked out in cooperation with experts. The extreme value describes the maximum value of a key factor in the target year of the analysis period (Appelrath et al., 2012) and (Gausemeier et al., 1996).

After projections have been made for each key factor, these are then bundled into a projection package. This projection package is then subjected to a plausibility analysis, since not all individual projections are compatible with each other. This process can be supported by software that helps to develop pre-scenarios from the projection package (Mayer et al., 2012).

The pre-scenarios form the basis for the target scenarios to be derived from them. A scenario describes thereby consistent and meaningful pictures of possible future prospects for enterprises and represents hypothetical event sequences.

In a next step, dimensions are identified that are to be considered in the scenarios. To identify the dimensions, a literature search can be performed. However, if the migration paths are to be developed for a specific maturity model - as in the present case - it is appropriate to use the dimensions of the maturity model (Software Engineering Institute, 2011), (U.S. Department of Energy, 2014), (Stevens, 2014) and (Uslar et al., 2012).

Dimensions describe specific capabilities, process areas and other design objects to structure an area of interest (Marx et al., 2012). The dimensions are specified by evaluation elements and/or measurement criteria (practices, objects or activities). Instead, this can also be done by a qualitative description (De Bruin et al., 2005).

Then, five maturity levels are developed for each dimension in cooperation with experts. If there is a maturity model for which the migration paths are to be developed, the maturity levels of the maturity model are adopted (Software Engineering Institute, 2011).

The different target scenarios place different demands on the maturity levels of the dimensions. Therefore, it is analyzed which degree of maturity must be achieved per dimension in order to realize the respective target scenario (Mayer et al., 2012).

The next step is to determine which technologies need to be used to reach the next level of maturity. This process is carried out for each

Dimension	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	(x)	x				x		x										
2		(x)				x				x								
3		x	(x)				x	x			x	x	x	x	x	x	x	x
4		x	x	(x)						x				x				
5		x			(x)					x								
6		x	x			(x)			x	x	x		x					
7		x			x		(x)	x	x		x	x		x	x	x	x	x
8		x	x					(x)	x	x	x	x	x		x	x	x	x
9		x				x	x		(x)	x	x	x			x	x	x	x
10		x				x				(x)								
11		x							x	x	(x)	x			x	x	x	x
12		x								x		(x)				x	x	x
13		x								x	x	x	(x)		x	x	x	x
14		x							x		x	x		(x)	x	x	x	x
15		x													(x)		x	x
16		x													x	(x)	x	x
17		x															(x)	x
18		x																(x)

Figure 2. Complexity Matrix of Green Access. * The (x) in Figure 2 means: If only dimensions are considered, the influence of a dimension on itself must be disregarded; at the layer of the developmental steps, the influence of a dimension on itself must necessarily be considered.

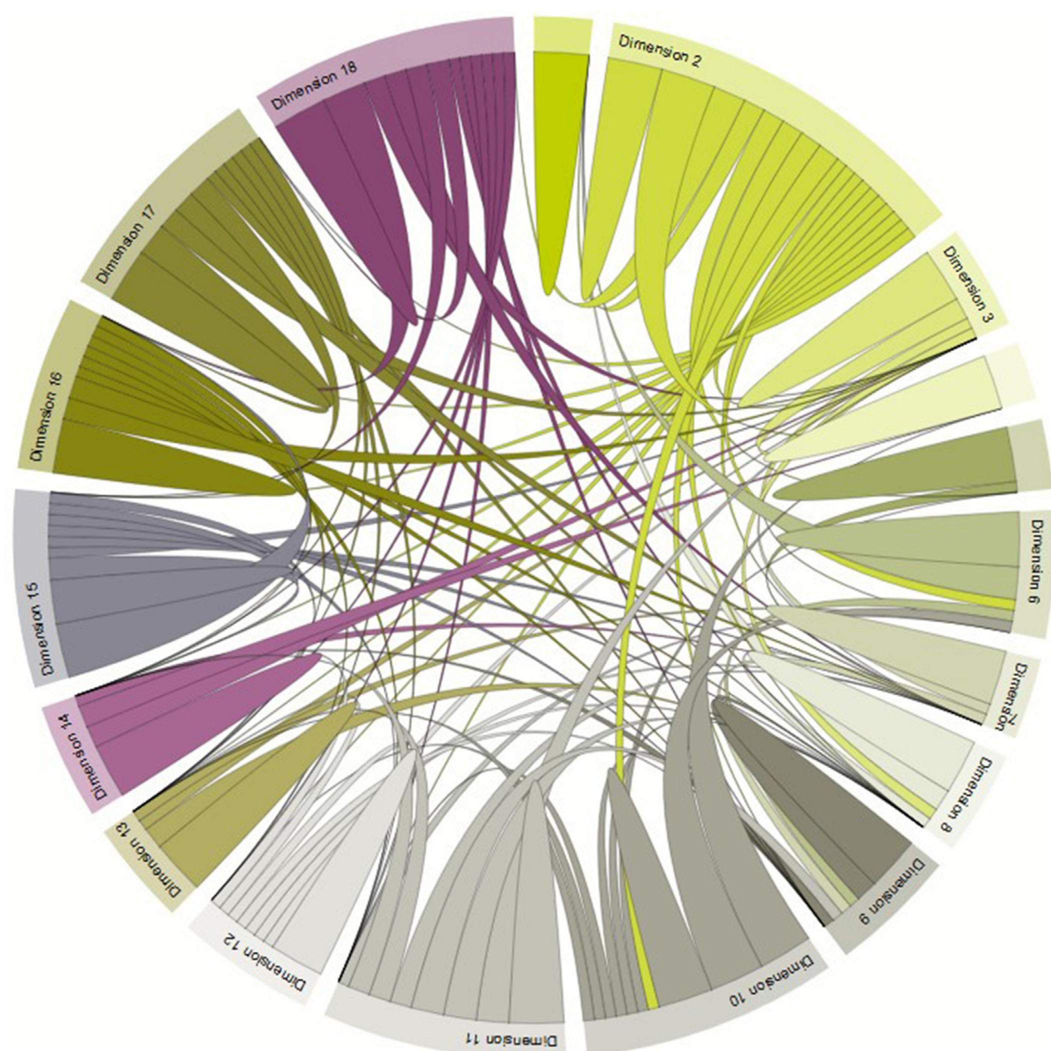


Figure 3. Presentation of the influences on the layer of the dimensions.

Algorithm result for c(s) for the development steps of Green Access				
1.1: 1,94	**1.2:** 1,88	**1.3:** 1,75	**1.4:** 1,50	**1.5:** 1,00
2.1: 5,82	**2.2:** 5,43	**2.3:** 4,00	**2.4:** 4,00	**2.5:** 3,02
3.1: 2,5	**3.2:** 3,01	**3.3:** 4,02	**3.4:** 3,28	**3.5:** 1,50
4.1: 1,94	**4.2:** 1,88	**4.3:** 1,75	**4.4:** 1,50	**4.5:** 1,00
5.1: 3,00	**5.2:** 1,88	**5.3:** 1,75	**5.4:** 1,50	**5.5:** 1,00
6.1: 4,41	**6.2:** 2,69	**6.3:** 1,88	**6.4:** 1,75	**6.5:** 1,50
7.1: 2,13	**7.2:** 2,25	**7.3:** 2,63	**7.4:** 1,50	**7.5:** 1,00
8.1: 2,75	**8.2:** 3,50	**8.3:** 2,53	**8.4:** 3,06	**8.5:** 1,50
9.1: 3,38	**9.2:** 4,28	**9.3:** 1,75	**9.4:** 1,50	**9.5:** 1,00
10.1: 3,95	**10.2:** 4,62	**10.3:** 3,88	**10.4:** 3,77	**10.5:** 3,53
11.1: 5,48	**11.2:** 4,41	**11.3:** 5,57	**11.4:** 4,32	**11.5:** 2,50
12.1: 5,18	**12.2:** 1,88	**12.3:** 1,75	**12.4:** 1,50	**12.5:** 1,00
13.1: 3,07	**13.2:** 4,13	**13.3:** 3,89	**13.4:** 3,03	**13.5:** 1,00
14.1: 4,25	**14.2:** 3,38	**14.3:** 2,13	**14.4:** 2,25	**14.5:** 1,00
15.1: 4,20	**15.2:** 3,51	**15.3:** 3,52	**15.4:** 5,03	**15.5:** 1,50
16.1: 4,53	**16.2:** 2,70	**16.3:** 3,39	**16.4:** 1,50	**16.5:** 1,00
17.1: 4,44	**17.2:** 3,63	**17.3:** 4,01	**17.4:** 1,50	**17.5:** 1,00
18.1: 3,94	**18.2:** 3,38	**18.3:** 2,75	**18.4:** 3,50	**18.5:** 1,00

Figure 4. Algorithm results of green access.

dimension and maturity level. The results are then used to check the dependencies between the individual dimensions and levels of maturity. For example, the prerequisites for the development of the organizational structure, corporate IT, risk management and the standardization of communication protocols would have to be determined before certain technologies that can be controlled via radio or similar can be used to protect against cyber-attacks. Based on the analysis of the dependencies, a sequence can be defined in which the various developments should take place. This then represents the roadmap (Appelrath et al., 2012).

The previously analyzed dependencies are then quantitatively examined and evaluated at the level of dimensions and individual development steps.

The findings from the analysis of the dependencies are then presented in a complexity matrix. This is used to create a roadmap for each target scenario (Mayer et al., 2012).

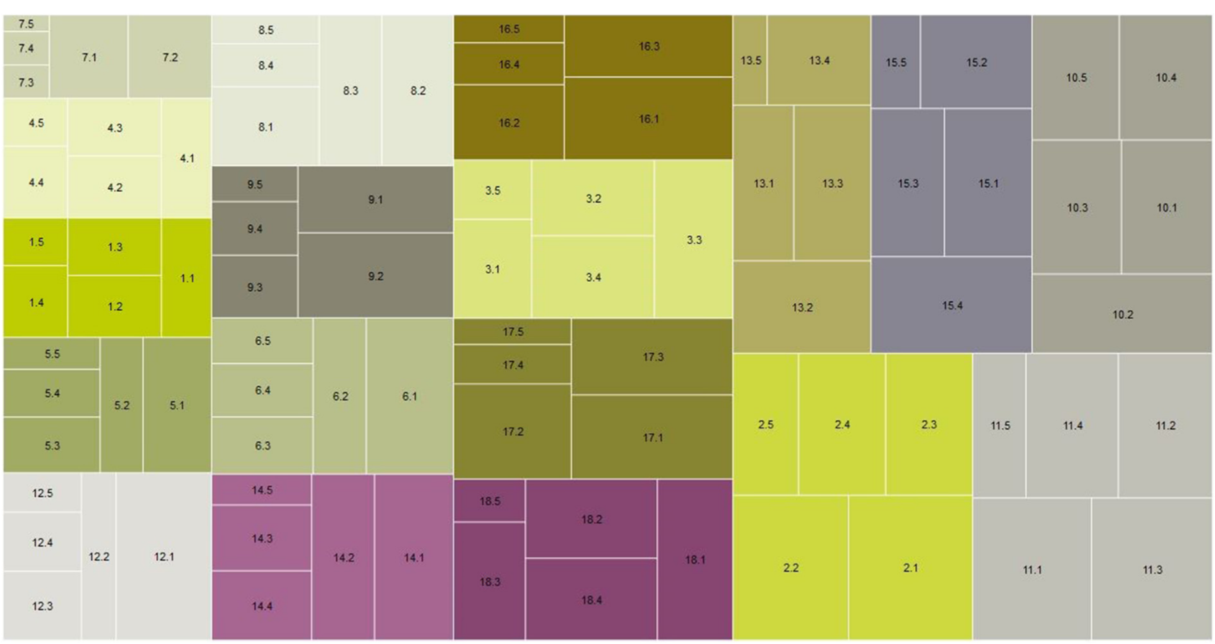


Figure 5. Presentation of the influences at the layer of the development steps.

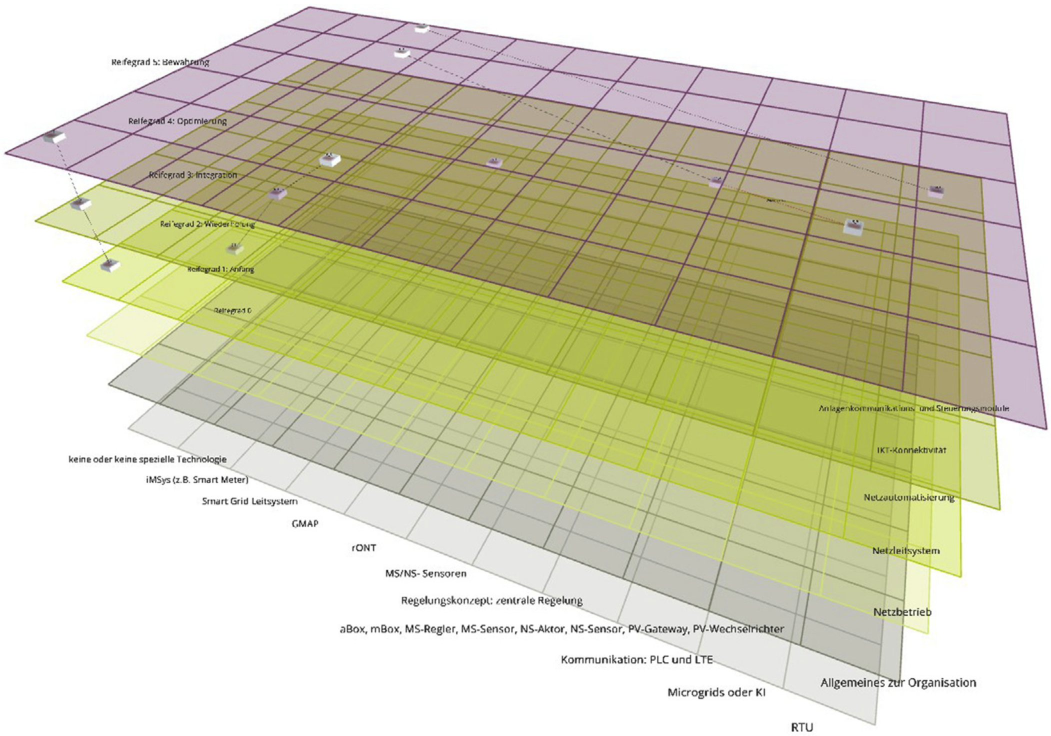


Figure 6. Roadmap Green Access (source: own presentation).

Finally, the roadmaps created are analyzed to identify particularly time-critical development steps in individual dimensions (Mayer et al., 2012). Furthermore, the critical path of each roadmap is determined.

2.4. Description of the two case studies

The case study "Green Access" is a research and development project, which was carried out in the years 2015–2019 and aimed at the realization of an intelligent distribution grid automation in the sense of a plug & automat principle for the creation of a sustainable, stable and reliable distribution grid. An essential feature of the project was the joint consideration of the low and medium voltage levels.

The ecological objective was to integrate large amounts of renewable energy sources into the distribution grid efficiently and without loss of grid stability or security of supply. The economic goal was to show what contribution smart grid components can make to the cost-efficient operation of the grids and thus to the restructuring of the utilities. The technical objective of the project was to guarantee voltage maintenance in accordance with DIN EN 50160 despite highly utilized grids. This was to be achieved by incorporating grid-compatible inverters. In addition, control concepts were to be tested for reliability and stability.

Case study "Designetz" is a research and development project that was carried out in the years 2017–2020. It aims to bring future utility in line with the goals of energy system transformation, which will require significant investments in grid and storage capacities. Central links for a future intelligent energy system are information and communication technologies and an interaction between the smart grids and the energy markets. Concepts are examined for mutual complementation and their further development for mass production. Individual solutions are to be integrated into an efficient, stable and thus sustainable overall system. The possibilities of market and grid are to be used in combination to limit the necessary grid expansion at distribution grid level to an economically optimal level.

3. Case study Green Access

3.1. Step 1: Key Factors

In preparation for the development of the scenarios, a literature search was carried out in a first step in cooperation with all project partners (*[1] Future scenarios of Fraunhofer ISE from the Green Access project.).

The following points were identified as key factors here - also by specifying the project assignment:

- Development of Renewable Energies
- Load development
- Information and communication technologies (ICT)

In general, the following key factors can also be mentioned:

- Standardization
- Political environment

3.2. Step 2: Extreme Projection

Based on the literature research, the maximum values for the three key factors "Renewable Energy Development", "Load Development" and "ICT" were worked out.

Development of Renewable Energies

→ Key question: What is the penetration rate of the individual plants in the distribution grid?
Possible projections:

- EEG 2014: low plant expansion; based on target figures of the EEG amendment 2014, in 2025 expansion of PV plant capacity of 50.1 GW

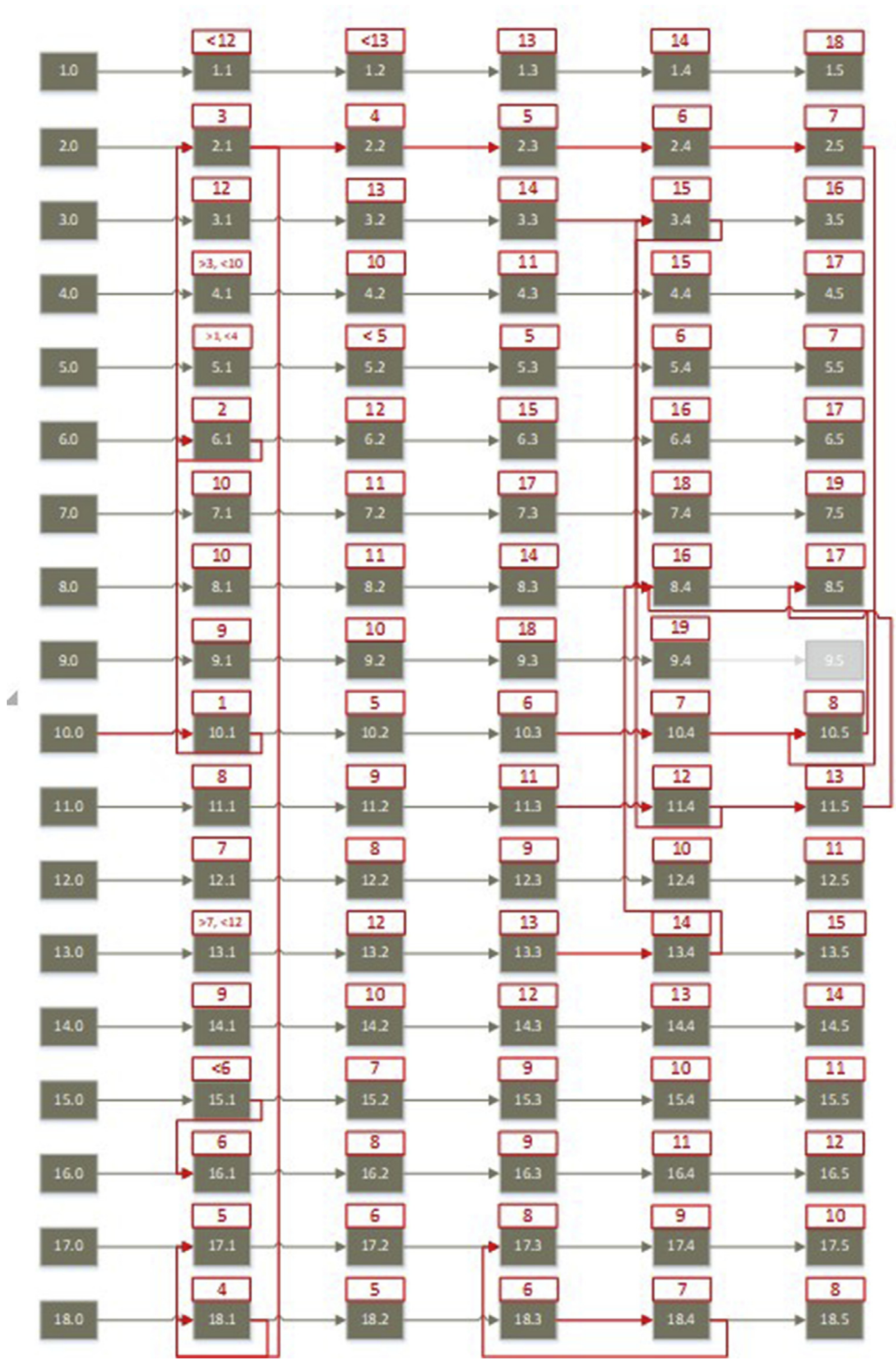


Figure 7. Roadmap target scenario 3 (source: own presentation).

and of onshore wind energy plant capacity of 50.6 GW; for 2030 nationwide expansion of 56 GW and 56.7 GW for PV and wind energy plants

- Median: average value of the plant capacity of all analyzed studies; in 2025, expansion of PV plant capacity of 55.4 GW and onshore wind energy plant capacity of 52.2 GW; for 2030, expansion of 61.9 GW and 57.4 GW for PV and wind energy plants throughout Germany
- Federal states: optimistic assessment of the development of renewable energies; in 2025 an expansion of PV plant capacity of 81.0 GW and onshore wind power plant capacity of 66.3 GW; in 2030 nationwide expansion of 102.4 GW and 80.2 GW for PV and wind power plants

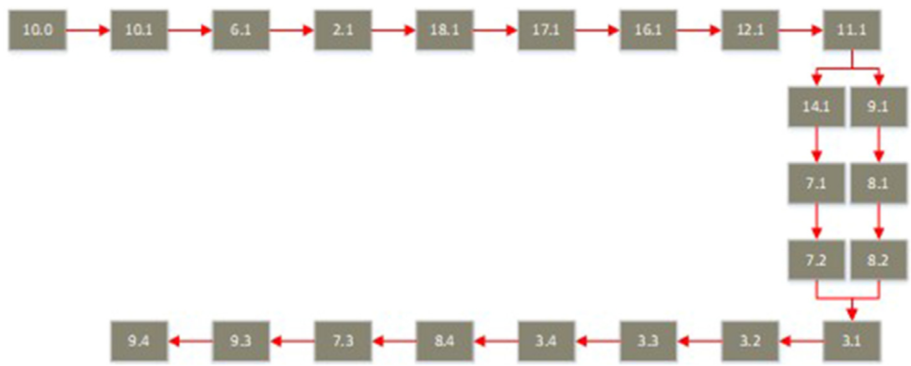


Figure 8. Critical Path Target scenario 3 (source: own presentation).

Load development:

→ Key question: How are private energy consumption and the feed-in of electrical energy into the public grid by private households developing?

Possible projections:

- Steady continuation: Continuation of the current development; for heat pumps, penetration of 3% and 21% in existing and new buildings for 2030; 33% electric vehicles and electric storage units with a penetration of >20% should be in operation
- Climate targets: Acceleration of development; for heat pumps, penetration of 50 % and 100 % in existing and new buildings for 2030; 66 % electric vehicles and electric storage units with approx. 12 GWh should be in operation

ICT:

→ Key question: Which plants are controllable, which are observable and how fast do plants have to be able to react and from which performance class do they have to be controlled?

Possible projections:

- Standstill: is based on the current status quo; the expansion with intelligent communication technology will not be further promoted; the existing need for expansion of the energy grids is largely covered by conventional grid expansion; grid-related ICT will not be given greater consideration; controllability of systems (91% of PV systems); proportion of controllable consumers (direct control of consumers by the operator of the control system is not possible); Smart meter (rollout)/communication connection Smart meter (progressing slowly); connection of the control center (hardly any grid automation to date); degree of (distribution grid only equipped with ICT at a few points); integration technologies (communication solutions largely standardized and prescribed by the regulator); asset management including Data management (data infrastructure is not yet adapted to current requirements)
- Grid-related ICT expansion: standardization will continue and existing standards will be harmonized; through standardized communication, energy supply companies can offer new services; controllability of plants (new plants connected to the grid can all be controlled; intelligent control will be extended from decentralized generation plants to storage facilities); smart meter (rollout)/communication connection smart meter (there are more and more BSI protection profiles; individual solutions can be replaced more and more; rollout rate of smart meters approx. 68 %; area-wide installation of smart meters by 2032; communication connection via IP infrastructure or PLC; communication via bidirectional interfaces); share of controllable consumers (increase in electro mobility and growing spread of storage; load management is becoming more attractive for all users); degree of networking (creation of an intelligent energy supply system; connection and communication via standardized bidirectional interfaces/communication gateways); connection of the control center (vertical exchange between transmission system operators and distribution system operators for greater grid security; horizontal communication between neighboring distribution system operators; ICT-based grid management concepts and decision logic have been further developed and put into practice); asset management including Data management (relevant data for the optimal use of assets is provided automatically; flexible and reliable information retrieval; data management becomes an integral part of the process chain; automatic grid status recognition); integration techniques (standards for syntactic and semantic interoperability are used in practice; reference model for information exchange for the systems is available; integration is increasingly taking place via the cloud; prerequisites for new business models have been created)

Standardization:

Here, standardization is understood to mean the unification of ICT components, semantics and energy data and also uniform processes in the Smart Grid.

Possible projections:

- Politics delays standardization: innovative developments are no longer brought into standardization; standards remain at a standstill; ICT is implemented only cautiously Projection is hostile to innovation and very slow
- No cooperation between market players: individual solutions from full-service providers dominate; attempt to take a dominant position and displace incompatible products parallel to proprietary ICT systems
- Politics forces standards: possibly standards simpler and less innovative and typically German; specification of minimum solutions high interoperability but standardization not in line with the market

Table 4. Target scenarios 1–3.

Topic	Scenario 1	Scenario 2	Scenario 3
PV expansion	36 GW	36 GW	47.9 GW
WTG expansion	35.2 GW	35.2 GW	33.95 GW
Decentralized	43.5 GW	68.9 GW	95.2 GW
Sector coupling			72.7 TWh

Table 5. Dimensions project designetz.

No.	Dimension
1	General information about the organization
2	Strategy, management and regulation
3	Asset management for distributed generation plants
4	Value chain
5	Plant, change and configuration management
6	Grid operations/Fault Clearance Management
7	Grid components
8	Grid control systems
9	Grid automation
10	Grid Planning
11	General technology
12	Data management
13	Forecasting systems
14	Plant communication and control modules (incl. ICT)
15	Information exchange and communication
16	Business Continuity Management (BCM)
17	Threat and vulnerability management
18	Risk management
19	Information Security Management System (ISMS)

- Industry consensus drives standardization: international, innovative standards introduced; rapid implementation of ICT systems high interoperability (ideal situation) [7].

Political environment:

By political framework conditions we mean laws, regulations, support measures as well as the actions of ministries, offices, etc. that currently directly or indirectly affect the energy sector. These are framework policy measures that intervene in, promote, inhibit or even prevent current developments in the energy sector.

Three projections are conceivable here:

- Classical policy: The basis is centralized fossil-fuel power generation; modernization of legislation for stronger competition on the energy markets; but no promotion or subsidization of decentralized expansion Reduction of generation monopolies
- Complexity trap: ambitious objectives cannot be achieved by an inadequate body of legislation; lack of coordination between R&D projects makes it difficult to pool knowledge and thus use it effectively
- Political leadership: Politics takes the lead in shaping the energy vision; laws and regulations fit together and lead to market-based implementation; monopoly-like structures have been strictly regulated or dissolved consistent continuation of the approaches from 2010 with extensive requirements in energy law

Table 6. Target state per target scenario.

No. of Dimension	Scenario 1/Target State	Scenario 2/Target State	Scenario 3/Target State
1	3	4	5
2	3	4	5
3	3	4	5
4	3	4	5
5	3	4	5
6	3	4	5
7	3	4	5
8	4	5	5
9	2	3	4
10	3	4	5
11	3	4	5
12	3	4	5
13	3	4	5
14	3	4	5
15	4	5	5
16	3	4	5
17	3	4	5
18	3	4	5
19	3	4	5

3.3. Step 3: Prescenarios

The scenarios that have been developed in the Green Access project are used as a basis.

3.4. Step 4: Target Scenarios

Target scenarios were developed in the project in cooperation with all project participants. The development procedure will not be discussed further here, but only the results will be presented. In this context, the technology option realistically means that the technologies used for the consideration of the target scenarios will continue to be used and installed continuously, i.e. unchanged from the current point in time. In the case of the technology option optimistically, the use of the technologies increases if the option is used to achieve the climate targets. It is therefore a form of classification, which is reflected in the installation figures for the technologies in Table 1.

3.5. Step 5: Dimensions

The dimensions have already been defined during the development of the maturity model in consultation with the project partners and are intended to address the essential aspects of the project that ultimately appear necessary to characterize the maturity of Green Access. Table 2 summarizes these dimensions (Flore and Marx Gómez, 2020a, b).

3.6. Step 6: Maturity Levels

The development of maturity levels has also already been done in the context of maturity model development.

Basically, the following five maturity levels were determined based on a literature research:

- Level 1: Beginning (standard level in the maturity level model.)
- Level 2: Repetition (The company implements new functions within a domain that enable it to achieve and maintain grid modernization).
- Level 3: Integration (The implemented grid modernization functions are rolled out company-wide).
- Level 4: Optimization (The implemented functions will be further optimized and used to further improve the company's performance).
- Level 5: Preservation (The Company breaks new ground with its new developments and promotes the state of the art in the domain).

The five levels of maturity have been individually formulated for each dimension.

3.7. Step 7: Analysis

In Step 7 of the analysis of the maturity levels per scenario and dimension, the actual state, the target state (per target scenario) and the development steps over time per scenario and dimension were worked out. The results are shown in Table 3.

Dimension	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	(x)	x				x		x											
2		(x)				x					x								
3		x	(x)				x	x				x	x	x	x	x	x	x	
4		x	x	(x)							x			x					
5		x			(x)						x								
6		x	x			(x)		x	x		x		x	x					
7		x			x		(x)	x	x		x	x		x	x	x	x	x	
8		x	x					(x)	x		x	x	x	x	x	x	x	x	
9		x				x	x		(x)		x	x		x	x	x	x	x	
10		x								(x)	x				x	x	x	x	
11		x				x					(x)								
12		x									x	(x)				x	x	x	
13		x									x	x	(x)	x	x	x	x	x	
14		x						x			x	x		(x)	x	x	x	x	
15		x													(x)		x	x	
16		x													x	(x)	x	x	
17		x															(x)	x	
18		x																(x)	
19		x									x				x	x	x	x	(x)

Figure 9. Complexity Matrix of Designetz. * The (x) in Figure 2 means: If only dimensions are considered, the influence of a dimension on itself must be disregarded; at the layer of the developmental steps, the influence of a dimension on itself must necessarily be considered.

3.8. Step 8: Complexity Matrix

In this step, all dependencies or influences were examined, on the one hand at the layer of the dimensions and on the other hand at the layer of the individual development steps. This can be seen in the matrix Figure 2. The matrix should be read in such a way that the horizontal dimensions exert influence and the vertical dimensions are influenced (Flore et al., 2019).

The influences were evaluated quantitatively. The simple evaluation at the layer of the dimensions can be graphically represented as follows in Figure 3.

At the layer of the development steps, the evaluation was further deepened using a developed algorithm (Flore et al., 2019). The following assumptions were initially for the development of the algorithm:

- Assumption 1: Paths to lower developmental steps in other dimensions are possible: Each dimension has developmental steps from 1 to 5, which follow one after the other. Nevertheless, it is possible to achieve lower development steps in other dimensions, as in the example from 1.3 to 2.2.
- Assumption 2: Only necessary dependencies are considered: If an element of the migration path is dependent on another element that is already contained in the path, the embedded dependency is not considered. In the example, the path from 1.3 to 2.4 is not considered, because this dependency is included in the path from 1.3 to 2.2 and 2.3 to 2.4. Nevertheless the path from 1.4 to 2.4 is considered, because the other predecessor of 2.4 can be reached without developing Step 1.4.
- Assumption 3: There are no loops: The predecessors of an element are interpreted as absolute and absolutely necessary, so that if 1.3 in the example were a successor of 2.3, there would be an endless loop between 1.3, 2.2 and 2.3.

The next step is to clarify the effects of the quantitative evaluation. Each development step should be evaluated with a development capability and the effort for the development itself should also be considered. In addition, the ability to perform other development steps should influence the evaluation.

Therefore, the following three assumptions were made about the developmental capability of a step:

1. if two steps have the same basic conditions despite the effort required for the development, the resulting value should reflect this and better evaluate the step with less effort
2. if two steps have the same basic conditions despite the number of new steps that make them possible, the step that enables more successors (with the same effort) should be better evaluated.
3. if two steps have the same basic conditions, but one enables more successors directly and the other enables the same number of successors indirectly after a further development step, the direct release should be better evaluated.

These assumptions can be formalized as follows:

1. the effort e(s) represents the effort required to develop a new system and must be inversely proportional to the development capability of s
2. the development capability of a step is influenced by its successors and its development capability.
3. the reduction factor r is intended to achieve a better evaluation of the direct successors and to multiply the development capability of the indirect steps. Therefore $0 < r < 1$.

The development capability *c(s)* of a development step without a successor as $c(s) = \frac{1}{e(s)}$, where *e(s)* is the effort for step s, is described in Formula 1. Then the successor records $T_s^i = \{t_{s1}^i,\ t_{s2}^i, \ldots, t_{sm}^i\}$ for step s with $i = 1, \ldots, n$ defines the order of successors ($i = 1$ for direct successors), n the highest order of successors and m the number of successors of the same order. For the successors of order i, r_i should be the reduction factor. After this, the second and third assumptions from the previous section are made by using the term $r_i \cdot \frac{1}{e(t_{sj}^i)}$ is added.

So it is overall:

Figure 10. Presentation of the influences on the layer of the dimensions.

$$c(s) = \frac{1}{e(s)} + \sum_{i=1}^{n} r_i \cdot \sum_{j=1}^{m} \frac{1}{e(t_{sj}^{i})}$$

Formula 1. Algorithm

The more "dense" successors there are for a process, the higher is the determined algorithm value. Development steps with a high algorithm value are therefore particularly time-critical, since many other development steps depend on it and a delay therefore has a high impact on the entire process. On the other hand, the acceleration of these time-critical development steps can have a positive effect on the entire process.

With this algorithm value it is possible for the DSO to determine the time critical development steps and to control them especially.

The following values were obtained for the development steps in Green Access when using the algorithm (Figure 4).

Thresholds for the algorithm value were defined for better comprehensibility. Three categories were defined: low influence (white; values c(s) < 2), medium influence (grey; values $2 <$ c(s) < 5) and high influence (green; values c(s) > 5).

In the Green Access case study, only six development steps have an algorithm value >5: These are development Steps 2.1 and 2.2, 11.1 and 11.3, 12.1 and 15.4. These six development steps therefore have a blatant influence on the entire roadmap. Progress in the development of these dimensions as well as the continuous monitoring of successes is essential for the successful progress of the roadmap.

In principle, it can be observed that the first development steps per dimension tend to be green or grey (there are many more possible successors in the beginning) and tend to become white in the course of development (the number of possible successors decreases), which seems logical.

The development steps 11.3 and 15.4 exhibit a particular criticality: They are algorithm values >5 (marked green in Figure 4), but they are not at the beginning of the development of a dimension, but already at an advanced development in the dimension. Accordingly, these development steps are technical prerequisites for many other dimensions (e.g. development Steps 3.4, 8.4 and 16.4 depend on 15.4). It follows that development steps 11.3 and 15.4 must be located very early in the roadmap so that other dimensions can start their development at all (Flore et al., 2019).

The quantitative evaluation at the layer of the dimensions can be visualized in a Treemap diagram. For each dimension five development steps are shown (e.g. 1.1, 1.2, 1.3, 1.4 and 1.5). Depending on the calculated algorithm value, the size of the box is determined in the Treemap diagram (Figure 5). The larger the algorithm value, the larger the box. The greater the value, the greater the influence of the

Algorithm result for c(s) for the development steps of Designetz				
1.1: 1,94	**1.2:** 1,88	**1.3:** 1,75	**1.4:** 1,50	**1.5:** 1,00
2.1: 5,47	**2.2:** 5,49	**2.3:** 4,13	**2.4:** 4,25	**2.5:** 3,23
3.1: 2,50	**3.2:** 2,99	**3.3:** 3,98	**3.4:** 3,47	**3.5:** 1,00
4.1: 1,94	**4.2:** 1,88	**4.3:** 1,75	**4.4:** 1,50	**4.5:** 1,00
5.1: 3,00	**5.2:** 1,88	**5.3:** 1,75	**5.4:** 1,50	**5.5:** 1,00
6.1: 4,24	**6.2:** 2,69	**6.3:** 1,88	**6.4:** 1,75	**6.5:** 1,50
7.1: 2,12	**7.2:** 2,25	**7.3:** 2,63	**7.4:** 1,50	**7.5:** 1,00
8.1: 3,19	**8.2:** 3,50	**8.3:** 2,97	**8.4:** 3,94	**8.5:** 1,50
9.1: 3,09	**9.2:** 3,19	**9.3:** 1,75	**9.4:** 1,50	**9.5:** 1,00
10.1: 1,94	**10.2:** 1,88	**10.3:** 1,75	**10.4:** 1,50	**10.5:** 1,00
11.1: 3,87	**11.2:** 5,75	**11.3:** 4,05	**11.4:** 4,11	**11.5:** 3,47
12.1: 4,78	**12.2:** 1,88	**12.3:** 1,75	**12.4:** 1,50	**12.5:** 1,00
13.1: 3,06	**13.2:** 4,12	**13.3:** 3,73	**13.4:** 3,47	**13.5:** 1,00
14.1: 4,69	**14.2:** 3,97	**14.3:** 4,68	**14.4:** 5,12	**14.5:** 2,25
15.1: 4,89	**15.2:** 3,52	**15.3:** 3,53	**15.4:** 5,06	**15.5:** 1,50
16.1: 5,91	**16.2:** 2,98	**16.3:** 3,95	**16.4:** 2,44	**16.5:** 1,00
17.1: 5,35	**17.2:** 3,63	**17.3:** 4,02	**17.4:** 1,75	**17.5:** 1,50
18.1: 4,26	**18.2:** 3,13	**18.3:** 2,75	**18.4:** 3,51	**18.5:** 1,00
19.1: 1,94	**19.2:** 1,88	**19.3:** 1,75	**19.4:** 1,50	**19.5:** 1,00

Figure 11. Algorithm results of designetz.

Figure 12. Presentation of the influences at the layer of the development steps.

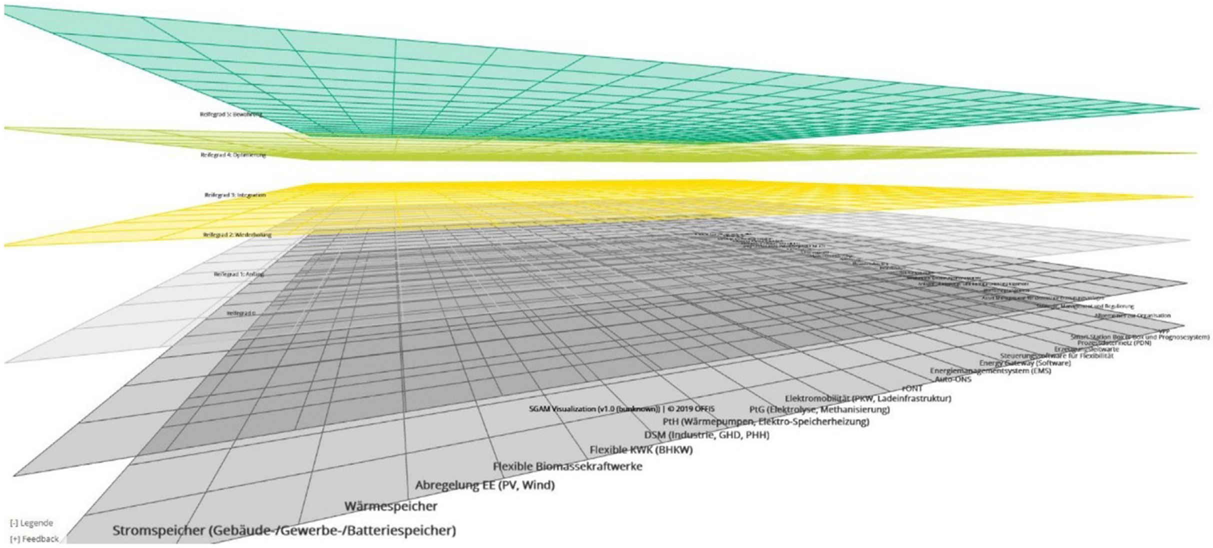


Figure 13. Roadmap Designetz (source: own presentation).

development step on the overall roadmap. This form of presentation allows the proportions of the development steps to each other to be clearly visualized.

3.9. Step 9: Roadmap

A roadmap was then drawn up for the Green Access project covering the entire process, which is presented visually as follows (Figure 6).

The presentation of the roadmap is a 3D visualization. The technologies used or required are entered in the bottom line and the dimensions that are being considered are shown on the right-hand side. The five layers of the 3D visualization are the five maturity levels. In order to be able to display the roadmap, boxes are now set in which dimension which technology must be used in which dimension in order to reach a respective maturity level. These different points are completed with arrows according to the direction and order of development, thus creating a complete roadmap. The 3D visualization offers the advantage that it can be presented interactively for the customer, it can be rotated and viewed from all sides and also only single layers can be displayed.

3.10. Step 10: Criticality

Finally, each of the three target scenarios was examined for critical processes and a critical path was outlined.

As an example for target scenario 3, the flow chart (represented as a network without duration) for the critical sequence of development steps for all dimensions is as follows (Figure 7). The process is illustrated using a simplified network diagram. All development steps of the dimensions are displayed as boxes. The small red boxes with the red numbers are a numbering system that indicates the sequence in which the various development steps must be carried out.

The critical path is shown in Figure 8. The critical path for the entire schedule is based on the determination of the sequence (as shown in Figure 7) plus consideration of whether there is still a free buffer for operations or whether there is a hard sequence where each deviation leads to an overall delay.

4. Case study Designetz

4.1. Step 1: Key Factors

The scenarios were developed by the RWTH Aachen University (IAEW) as part of the project and are briefly presented here for the sake of completeness.

The following points have been identified as key factors here - also by specification of the project assignment:

- Development of renewable energies
- Development Flexibility Penetration
- Sector coupling

In general, the following key factors can also be mentioned:

- Standardization
- Political environment

4.2. Step 2: Extreme Projection

The complete elaboration of the maximum expression was recorded in a separate document in the project and is not discussed here in detail.

4.3. Step 3: Prescenarios

The final scenarios were developed by the RWTH Aachen University (IAEW) in cooperation with some other project partners.

4.4. Step 4: Target Scenarios

The scenarios developed by RWTH Aachen University (IAEW) in cooperation with other project partners are used as a basis. The development procedure will not be discussed further at this point.

The identified target scenarios represent scenarios relevant for the project with regard to expansion paths for RE plants, the development of flexibility and the use of sector coupling.

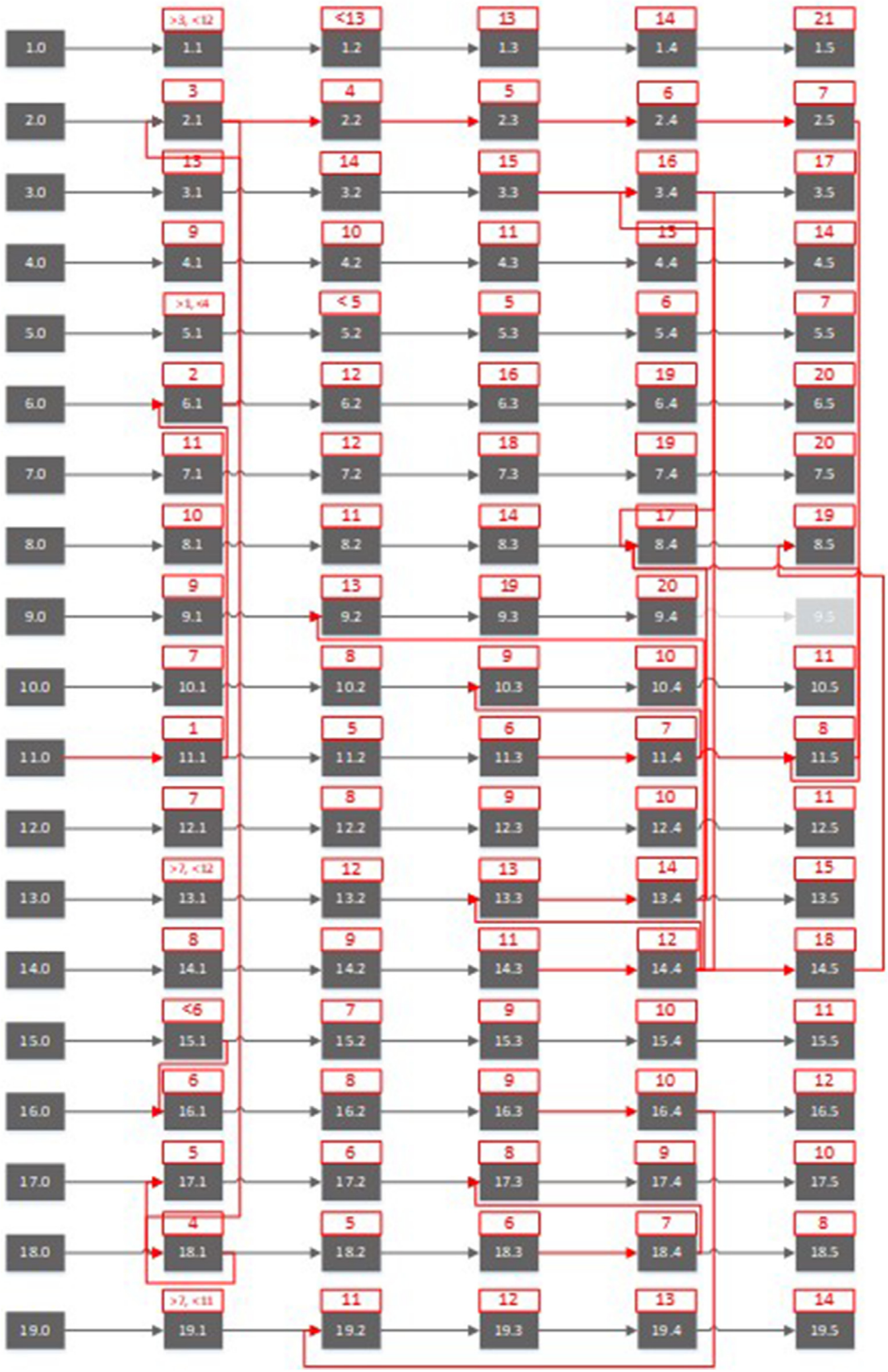


Figure 14. Roadmap target scenario 3 (source: own presenation).

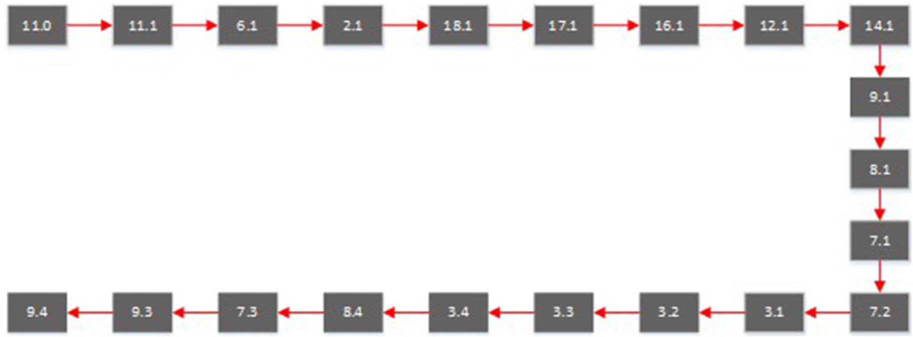


Figure 15. Critical Path Target scenario 3 (source: own presentation).

The basis for all three scenarios was the Electricity 2030 Grid Development Plan, for which deviating and supplementary assumptions were made in order to ensure a consistent scenario framework. To ensure comparability of the use of flexibility across all scenarios, the conventional power plant park (consisting of thermal power plants and hydraulic storage facilities) is identical in all scenarios.

The different scenarios are considered with the target year 2035.

Overview of the target scenarios in case study Designetz in Table 4.

4.5. Step 5: Dimensions

The dimensions have already been defined during the development of the maturity model in consultation with the project partners and are intended to address the essential aspects of the project that ultimately appear necessary to characterize the maturity of Designetz. Table 5 summarizes these dimensions (Flore and Marx Gómez, 2020a, b).

4.6. Step 6: Maturity Levels

The maturity levels were the same as in the Green Access case study (see Chapter 3.6) and were worked out here for the other dimensions within the framework of maturity model development.

4.7. Step 7: Analysis

In Step 7 of the analysis of the maturity levels per scenario and dimension, the actual state, the target state (per target scenario) and the development steps over time per scenario and dimension were worked out. The results are shown in Table 6.

4.8. Step 8: Complexity Matrix

In this step, all dependencies or influences were examined, on the one hand at the layer of the dimensions and on the other hand at the layer of the individual development steps. This can be seen in the matrix Figure 9.

The influences were evaluated quantitatively. The simple evaluation at the layer of the dimensions can be graphically represented as follows in Figure 10.

The algorithm, which was developed to evaluate the quantitative influences of the development steps, was already presented in Chapter III.h. Figure 11 shows the results of the calculation.

The quantitative evaluation at the layer of the dimensions can be visualized in a Treemap diagram. For each dimension five development steps are shown (e.g. 1.1, 1.2, 1.3, 1.4 and 1.5). Depending on the calculated algorithm value, the size of the box is determined in the Treemap diagram (Figure 12). The larger the algorithm value, the larger the box. The greater the value, the greater the influence of the development step on the overall roadmap. This form of presentation allows the proportions of the development steps to each other to be clearly visualized.

4.9. Step 9: Roadmap

A roadmap was then drawn up for the Green Access project covering the entire process, which is presented visually as follows (Figure 13). The 3D visualization is the same as in Green Access. In this graphic, only the corresponding technologies and dimensions were entered for Designetz and the corresponding boxes were set there and supplemented with arrows.

4.10. Step 10: Criticality

Finally, each of the three target scenarios was examined for critical processes and a critical path was outlined.

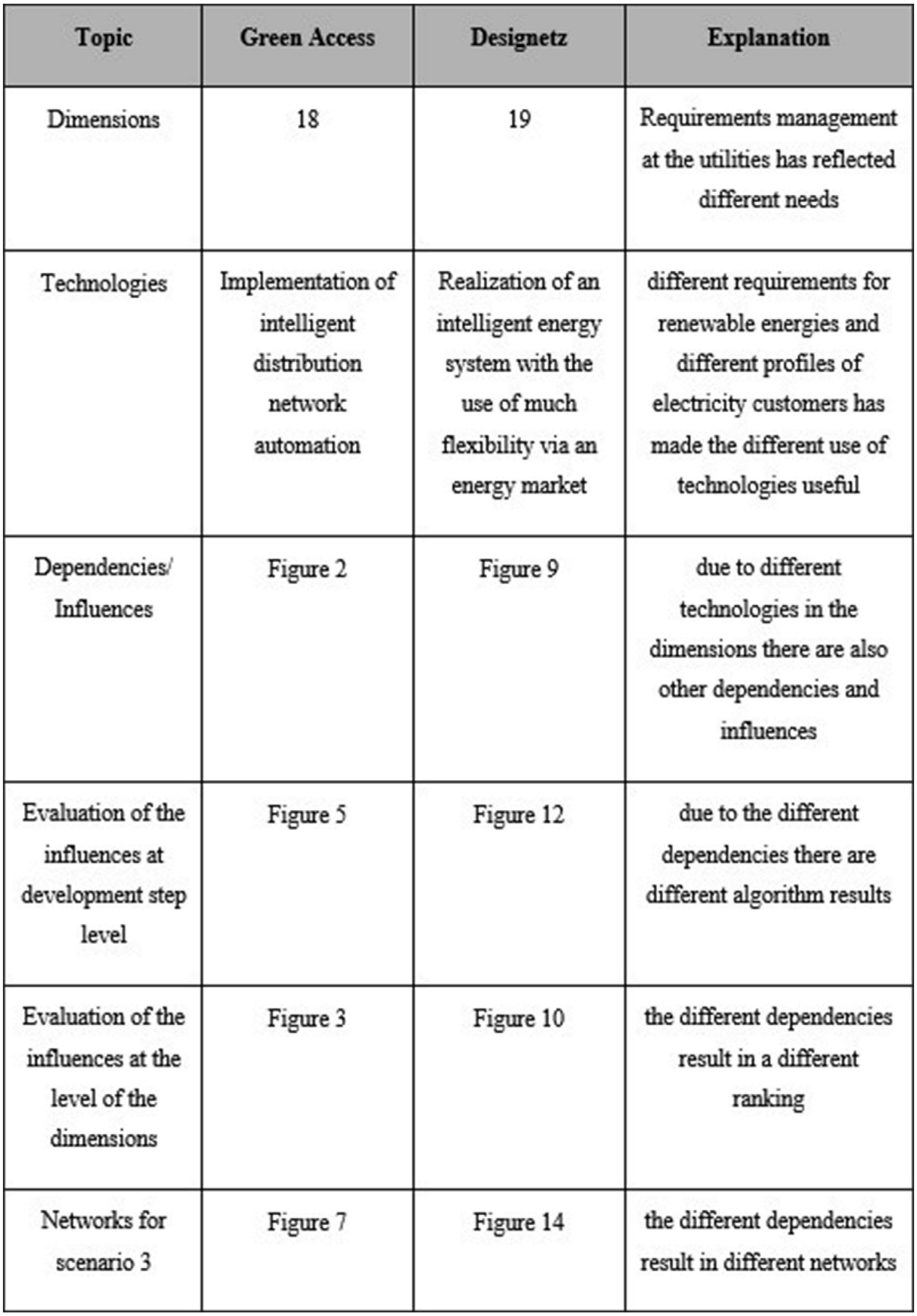
As an example for target scenario 3, the flow chart (represented as a network without duration) for the critical sequence of development steps for all dimensions is as follows (Figure 14). The process is illustrated using a simplified network diagram. All development steps of the dimensions are displayed as boxes. The small red boxes with the red numbers are a numbering system that indicates the sequence in which the various development steps must be carried out.

The critical path is shown in Figure 15. The critical path for the entire schedule is based on the determination of the sequence (as shown in Figure 14) plus consideration of whether there is still a free buffer for operations or whether there is a hard sequence where each deviation leads to an overall delay.

5. Comparison of the two case studies

In principle, different insights can be gained from the creation of the migration paths for the two case studies:

- Improvements in individual dimensions should not be made haphazardly, but rather a developed sequence in the form of roadmaps should be observed in order to avoid disruptions and impairments in the processes.
- Special attention should also be paid to the critical path.
- Similarly, attention should be paid to the different development speeds of the dimensions that lie on the critical path.
- With the quantitative analysis the very influential dimensions could be identified.
- With the qualitative analysis, particularly influential individual developmental steps could be identified on a layer deeper than the dimension.
- A good prerequisite for the individual planning of a DSO is an individual location determination by means of a maturity level model and migration paths adapted to this.



Topic	Green Access	Designetz	Explanation
Dimensions	18	19	Requirements management at the utilities has reflected different needs
Technologies	Implementation of intelligent distribution network automation	Realization of an intelligent energy system with the use of much flexibility via an energy market	different requirements for renewable energies and different profiles of electricity customers has made the different use of technologies useful
Dependencies/ Influences	Figure 2	Figure 9	due to different technologies in the dimensions there are also other dependencies and influences
Evaluation of the influences at development step level	Figure 5	Figure 12	due to the different dependencies there are different algorithm results
Evaluation of the influences at the level of the dimensions	Figure 3	Figure 10	the different dependencies result in a different ranking
Networks for scenario 3	Figure 7	Figure 14	the different dependencies result in different networks

Figure 16. Differences between the two Case Studies.

In comparison, it can be said that due to the different use of technologies in the two case studies, other dependencies and influences and, as a result, different roadmaps have emerged. Already in the quantitative analysis of the influence, although very similar dimensions are in the top five ranks, they are not the same or in a different order. It is striking that dimension 14 of case study 2 (which is divided into dimensions 11 and 14 in case study 1) is not to be found in the first five ranks of the quantitative analysis. Similarities, but also some differences, can also be seen in the quantitative analysis at the layer of the individual development steps. Development Steps 2.1 and 2.2 are found in both case studies, as well as 15.4, but all further development steps with a calculated value >5 are different. In both case studies there are still developmental steps from dimension 11 (case study 1)/dimension 14 (case study 2), but not the same developmental steps.

Finally, a statement is to be made as to whether the evaluation was able to determine whether the decisions of the actors are better with the use of the model than without it. Unfortunately, this question cannot be answered unambiguously, since the execution of the migration paths could not be evaluated concretely, but only their conception. Due to the large scale of the implementation of the migration paths in the own company and the long time period that this will take, this could not be considered in the context of this dissertation. Basically, we came to the conclusion that the mere fact of dealing with the dimensions and their dependencies makes a company sensitive to possible problems and pitfalls and therefore the maturity model created, and the related migration paths, are definitely helpful for future strategic decisions of a DSO. Pitfalls or development steps that require special attention are also pointed out.

The differences between the case studies can be summarized again in an overview (see Figure 16).

6. Conclusion

Based on an extensive literature research and expert interviews, a procedural model for the development of migration paths was presented. This process model was subsequently applied in the Green Access project and in the Designetz project.

The basis for the development of migration paths was a previously developed maturity model (which was also previously applied in the Green Access and Designetz projects).

The findings from the developed migration paths and in particular the dependencies, influences, their assessments and the critical paths can be incorporated into further work with utilities or other partners. The comparison of the various migration paths that have been developed on the basis of different project objectives and different technologies to be used is also revealing. This also resulted in different influences, dependencies and a different evaluation of the influences that were compared.

Since the migration paths are based on the current state of research and technology, they are naturally limited in time. If there are new technological advances or if the DSO pursues a different technological concept, the migration paths must be revised on this basis and the dependencies must be re-analyzed. As a recommendation, a control of the migration paths for all 2–3 is proposed.

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

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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