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Review article

Diagnosis of the implementation of smart grid innovation in The Netherlands and corrective actions☆

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ABSTRACT

With its potentially disruptive nature, the smart grid can be viewed from both a transformational and an innovation systems perspective. Synthesising these, a research approach is adopted in which a Technological Innovation System (TIS) analysis is combined with a transformational perspective to identify a broader range of success and failure factors. This study analyses smart grid innovation system development. The main research question is: What systemic and transformational failures are identified in the development of smart grid innovation in the Netherlands from 2001 to 2021 by combining TIS and a transformational perspective? The question is answered by mapping the events to TIS functions and identifying both 'systemic failures' and 'transformational failures'. Transformational failures are linked to events outside the smart grid TIS that work against the alignment and harmonising of activities within the TIS. Results show that the smart grid innovation system experienced three periods and that it suffers from various structural and transformational failures. TIS functions like knowledge diffusion, and the creation of legitimacy were only fulfilled to a limited extent. Consequently, smart grid innovation is currently still not considered a mainstream technology in the energy transition, and there is little attention to the role of end-users. The study ends with suggestions for future research, including the suitability of the research approach for other contexts and when applied to other energy system innovations.

1. Introduction

Recently, in many countries, the electricity sector has witnessed a change towards using Renewable Energy Systems (RESs) [1]. This change can arguably be seen as an initial phase of system-wide transformative change. In this phase, the central theme is the technical and economic validation of RESs as a feasible option which prompts diffusion in electricity systems [2]. Recently, this theme is changing because the concern is not merely phasing out fossil fuel resources but also the electricity system's overall functioning [3]. In this regard, the integration of RESs requires balancing between demand, supply and storage, ensuring power quality, avoiding congestion in transmission, distribution, and storage systems. These requirements and related problems challenge the operation of electricity grids to reconsider all parts of the supply chain, not just generation [4].

To this end, the smart grid concept was introduced to improve the functionality of electricity systems [5]. This concept aims to support decentralised electricity technologies mainly in generation, system operation and ideally also transmission in both national and international grids [6].

Precisely describing a smart grid appears challenging. The smart grid can be implemented in several ways depending on the application [7]. However, there is a general consensus regarding its main features [8]. Focusing on these features helps in understanding the disruptive nature of smart grids. The smart grid can be understood as a rebranded definition of a power distribution system with renewables, automation, and power electronic converters. More recently, smart grids are being rebranded again as cyber–physical systems, or even as microgrid clusters [9].

Whenever the definition of smart grid is leveraged to bi-directional high voltage transmission, its scope also covers HVDC-based super grids with voltage source converters [10]. The key characteristic of a smart grid is bi-directional active-controlled power flow at the distribution level [11]. This implies that consumers become prosumers of energy

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Nomenclature

Abbreviations

ACM	Netherlands Authority for Consumers and Market
DLC	Direct Load Control
DSO	Distribution System Operator
DSM	Demand Side Management
EDSEP	Experiments decentralised, sustainable electricity production
EMS	Energy Management System
IPIN	Innovation Programme Intelligent Grids
MEP	Environmental Quality of Electricity Production
NMP4	Fourth Dutch National Environmental Policy Plan
RES	Renewable Energy System
RET	Renewable Energy technology
RVO	Netherlands Enterprise Agency
SEC	Smart Energy Collective
SET-Plan	Strategic Energy Technology Plan
TIS	Technological Innovation System
TKI	Top Consortium for Knowledge and Innovation
TSO	Transmission System Operator

equipped with distributed RESs. Dealing with a bi-directional power flow requires including other concepts like flexibility in the electricity system to deal with balancing issues [4]. Flexibility, in turn, can be realised by multiple technologies like storage devices, vehicle-to-grid systems, and the microgrid concept. Modern IT structures, control strategies, and Energy Management Systems (EMS) are the backbone of smart grid design [12].

Fig. 1 presents a typical smart grid. This is based on the authors' understanding of smart grids based on state of the art in academic works [13]. This visualisation helps to discuss its transformative nature. As Fig. 1 illustrates, a smart grid includes the concept of Demand-Side Management (DSM), which comes from the end-users' response to balance the generation and load [14]. A microgrid concept can also be considered to be present in the distribution system. Although microgrids can exchange power with the main grid in the grid connect mode, distributed generation (DG) of electricity can go along with this to make microgrids independent from the main grid in an autonomous configuration. This takes place within the Point of Common Coupling (PCC), if required [15].

The transmission level of the electricity grid is equipped with EMSs, modern Supervisory Control and Data Acquisition (SCADA) systems, and advanced data processing software such as Advanced Distribution Automation (ADA) for controlling and monitoring purposes. These technologies improve DSM by sending and receiving data from the distribution level [16].

Transformative and disruptive characteristics of smart grids can be outlined as follows. First, smart grids introduce new ways of balancing demand and supply. This allows for new modes of ownership and decentralised production. For example, ownership of production can be in the hands of individual households or of citizen collective entities such as energy communities [17]. These energy communities have the potential to influence incumbent structures and institutions of the traditional, centralised electricity system model [18]. Smart grids are therefore associated with disrupting and changing the current hegemonic mass-market logic supporting incumbent firms and with supporting niche markets focusing on small groups of prosumers [19]. However, achieving such a disruption would require adopting new technologies to facilitate direct trading, demand response and local balancing which would, in turn, disrupt the business models of incumbent firms [20].

Another potential disruptive feature of the smart grid is its economic efficiency. Currently, traditional business models related to electricity generation are mainly based on centralised fossil fuel-based electricity generation. The key economic value of smart grids stems from optimising and adjusting electricity usage [18]. In addition, there is increasing demand for a higher quality of supply in terms of electrical harmonics, variation in voltage magnitude and continuity of service among consumers [21]. In the presence of modern communication infrastructures such as ADA and SCADA, electricity companies have to become more capable of rapidly detecting and handling supply quality problems. This creates more opportunities to gain economic value from increased system reliability [18]. Consequently, these changes in revenue streams will attract new actors to facilitate demand response, create flexibility for system operators (e.g., by means of aggregators), and install new equipment or services for customers as well as system operators [17]. The purpose of this new configuration in electricity systems is not merely sustainability but also moving towards goals related to other values (e.g., creation of local energy markets and fostering energy democracy) [22]. Based on this information, the smart grid can be considered as a disruptive (transformative) innovation [23].

Many studies on Renewable Energy Technologies (RETs) apply systemic and transformational approaches. This includes [24] in which systemic problems in developing RETs are analysed, mainly in European countries. Even though this study reviewed the most market and systemic failures [25], it did not cover transformational failures. In addition, in various countries, key parts and elements of smart grid systems such as energy storage technologies [26] and electric and hybrid-electric vehicles [27] have been analysed to identify barriers and drivers.

Furthermore, studies have been conducted to analyse smart grid development in the Netherlands by focusing on its central components. These include identifying the motivations and needs of energy communities in forming virtual power plants [28], the role of 'information flows' and smart grid technologies in creating sustainable energy practices [29] and the hurdles for new entrants to invest in the smart grid market [30]. Furthermore, smart grid projects have been analysed from the lens of institutional design [31], and institutional regulations applicable to smart grid deployment projects [32].

Transformative change in the energy sector entails a long journey that can take various pathways. However, these pathways are typically non-linear, unpredictable, complex and chaotic [33]. Taking a retrospective empirical approach, this study tries to uncover and explain the pathway for smart grid innovation, focusing on events that contributed to the current situation of smart grid innovation in the Netherlands. It does so by using Technological Innovation Systems (TIS) as a theoretical perspective, and by adopting a systemic and transformational failures perspective. In summary, this study attempts to answer the following question, " What systemic and transformational failures are identified in the development of smart grid innovation in the Netherlands from 2001 to 2021 by combining TIS and a transformational perspective?" This question is answered by using historical event-history analysis to identify both systemic failures inside the smart grid TIS and transformational failures outside this TIS. The critical point is that external factors such as policy measures influence the TIS internal performance and the other way around. The interaction between the technological system and the socio-technical system provides a holistic picture of the dynamics of factors. This aids in comprehending the relationship between technological innovation system failures and external transformational failures.

This study contributes to the acceleration of the understanding of the transition of electrical systems by taking a new approach and

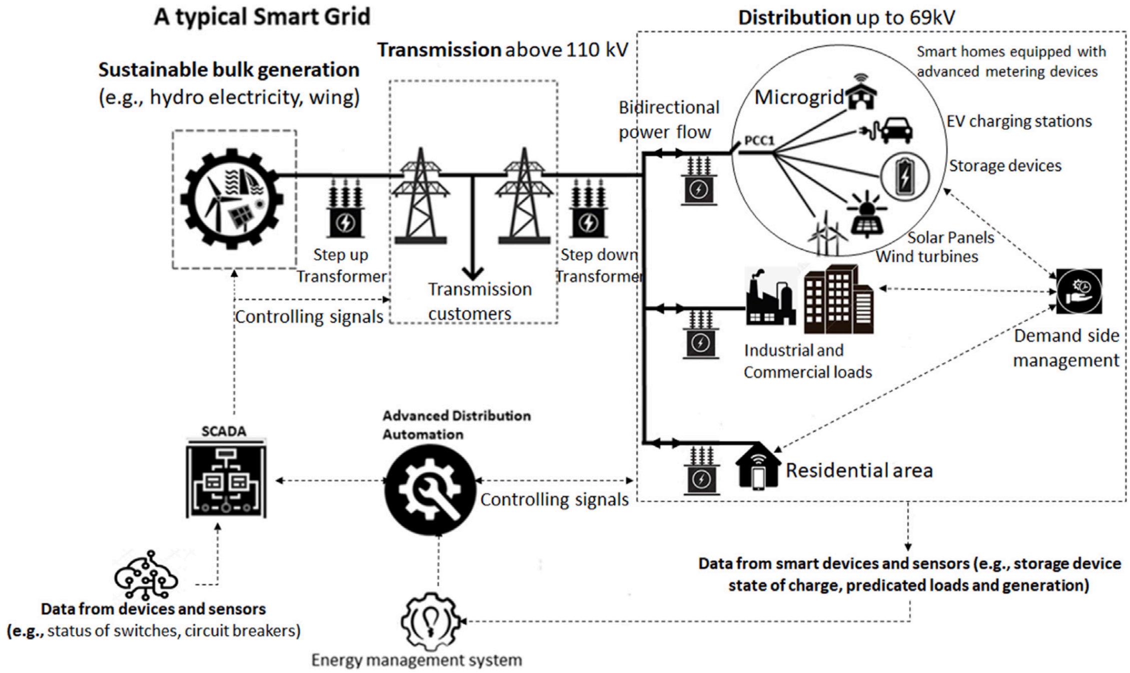

Fig. 1. A typical Smart Grid containing Microgrids and equipped with SCADA, ADA and EMS.

examining smart grid innovation from the perspectives of technological innovation and sustainable transition. The study's findings can be of use to policymakers who want to develop unified policies to address previous policy deficiencies in smart grid introduction.

The literature review shows that smart grid innovation has thus far not been studied from a holistic socio-technical system perspective. It has also received scant scholarly attention in terms of systemic and transformational failures that impede the introduction of smart grid innovations. Analysing a case study on smart grid innovation in a country whilst using a longitudinal research design can be useful and aid academic research agendas. This particularly holds for showing how to apply a technological innovation system perspective to smart grid innovation whilst mapping systemic and transformational failures.

This study is structured as follows. Section 2 presents the theoretical framework, which includes TIS, systemic and transformational failures. Section 3 explains the required steps for the analysis. This includes research design, case selection, data collection and treatment, and data analysis, i.e., identification and mapping of systemic and transformational failures, and validation of the results. In Section 4, the results of the longitudinal analysis are presented. Section 5 discusses the main findings and compares the findings with some other European countries by using quantitative metrics. This Section also provides policy suggestions to address the identified failures. Finally, the study concludes in Section 6 by answering the research question and proposing suggestions for future research.

2. Technological innovation system and failures in innovation

The concept of Technological Innovation has its root in evolutionary economics and was introduced by Carlsson and Stankiewicz [34] to elaborate on the nature of technological changes. Later the concept of the Technological Innovation System developed as an analytical tool for illustrating and understanding the dynamics of technological innovations [35]. In the case of developing smart grid technologies, many recurring themes and events have been reported in several studies [36]. Focusing on the dynamics that led to the current situation of the smart grid in the given country or region helps to find the problematic patterns.

This is also the reason why TIS was adopted for analysing smart grid system innovation in this study. A TIS perspective can be used to assess or evaluate smart grid performance, innovation system growth, and decline. However, TIS should be seen as using a focused analytical lens that does not reflect on all aspects that are relevant to smart grid as a socio-technical system in a holistic sense. This implies that the causal drivers and barriers of smart grid development should be analysed in a broader societal context. Policies, regulatory settings, and user practices, for example, should be considered to understand the external performance of smart grid innovation. Consequently, this study employs a framework [37] to analyse the smart grid's technological innovation and transformative nature. By integrating a transition perspective into TIS, this framework will broaden the environment of TIS. This allows, for example, to also address attention to failures related to governance and policy arrangement externally to TIS. These are part of a wider set of failures that are classified under the term 'transformational failures'. They complement systemic failures obtained from the (internal) TIS analysis. These failures are explained in Section 2.2.

2.1. System functions and feedback loops

TIS explains the process by which an emerging technology develops [38]. The central idea is that innovation develops and diffuses within a system, a so-called technological innovation system, or TIS [39]. A TIS consists of actors, technologies, institutions, and networks (configurations) of them (more details of these main building blocks of a TIS can be found in [40]). These are called structural elements. These structural elements are built up by specific processes such as knowledge development and market formation. These processes are called 'system functions' [38]. Clear indicators can be defined to analyse each system function. Table 1 shows the list of functions and examples of these indicators [41].

Within system thinking, feedback loops determine the dynamics of the systems [42]. It is a feature of a system where the output of one

Table 1
Functions of innovation system and their indicators [40].

Functions	Examples of indicators
F1: entrepreneurial activities	Commercial experiments, business opportunities, new entrants and established firms and portfolio expansion for companies
F2: knowledge development	Investment in R&D projects (learning-by-searching), patents, publications, laboratory experiments (learning-by-doing) and increasing in the number of researchers in universities and firms
F3: knowledge diffusion	Workshops, conferences, joint projects, networking activities, end-users' experience with new technologies and reports of projects
F4: guidance of the search	Setting ambitious goals by decision-makers, increasing the expectations of a technology, technological guide and changing in belief system of decision-makers regarding a technological innovation
F5: market formation	New standards, tax exemptions, Overall changes in the market environment for a technology and increase in number of users of a given technological innovation
F6: resource mobilisation	Investment and subsidies, development of required infrastructure and availability of experts (mobilisation of human resources)
F7: creation of legitimacy	Political lobbies against or in favour of a certain technological innovation, activities to convince the government to support or hinder a technology, and increases in the number of NGOs and private sector companies that support or hinder a technological innovation

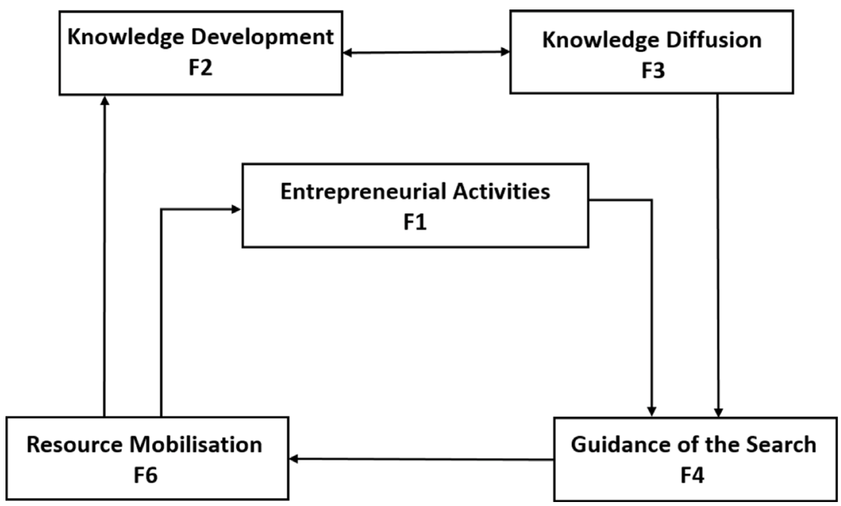

Fig. 2. Feedback loops in the Science and Technology Push Motor.

node eventually affects the input of the same node. All systems' dynamics can be explained by understanding how the feedback loops interact. Positive (or self-reinforcing) and negative (or self-correcting) feedback loops are the only two types that interact to create dynamics [43]. While large socio-political systems contain many feedback loops, the behaviour of systems are controlled by only a few of these loops [42].

Development and growth of a TIS can be explained by the cumulative causation in which different functions reinforce each other [40]. Suurs distinguished particular feedback loops, which are called motors of innovation [44]. In addition, there are four distinct stages in the development of a TIS. Fig. 2 exemplifies the concept of a feedback loop for the first stage of TIS development. In each of these stages, another typical motor of innovation can be observed [45]. The four main stages and motors of innovation are:

- The 'science and technology push motor' refers to a feedback loop in which knowledge development and diffusion have a central role. Policy makers support the innovation via R&D support, and the innovation is developed and tested via experimental projects and R&D programmes. The main functions in this phase are knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], and resource mobilisation [F6].
- The 'entrepreneurial motor' refers to a feedback loop in the following stage which is typically characterised by growth in the number of active entrepreneurs. These active entrepreneurs try to legitimise the innovation [F7] and mobilise more financial resources [F6] or change the institutions favouring innovation. In addition, market formation [F5] becomes important knowledge development [F2] and knowledge diffusion [F3], which were significant functions in the preceding stage, are still important.
- The 'system building motor' refers to a phase in which there is an increase in infrastructural development, institutional re-configuration and actor networks. During the system building motor, entrepreneurial activities [F1], knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4], resource mobilisation [F6] and creation of legitimacy [F7] play dominant roles.
- The 'market motor' refers to a feedback loop in the last stage. In this phase, the innovation has institutionalised into society, and the main function is market formation [F5]. All other functions also play a role in this feedback loop, except for creation of legitimacy [F7] because the market environment is partly created by formal regulations.

2.2. Systemic and transformational failures

Assuming the systemic nature of innovation, there are problems and weaknesses within a TIS that are due to poor structural conditions (i.e., weak infrastructure, institutions, or actor networks) [46]. This is referred to using the concept of systemic failures [47], which develops a rationale for the occurrence of problems in a given TIS. To address these and other failures a complementary approach was developed to identify the failures that impede or slow down transitions towards sustainability besides systemic TIS failures. Weber and Rohracher [37] argue that due to the long-term nature and the different character of societal transformation compared with processes in the TIS, other kinds of failures should also be considered for addressing broader socio-technical systems change. These additional types of failures mirror recent debates on the sub-optimal performance of the innovation process in stimulating innovation activities towards reaching desired long-term transformative changes. These failures are strategic in nature, and they target the need for appropriate innovation policies to stimulate and prioritise the process of transformative changes. The four transformational failures are 'directionality failures', 'reflexivity failures', 'policy coordination failures', and 'reflexivity failures' [37]. The details of transformational and systemic failures are outlined in Table 2.

3. Research design and methodology

In this study, a longitudinal research design is used to analyse the development of smart grids in the Netherlands over the 2001–2021 period. By the end of 2019, around 31 residential smart grid projects focusing on the role of various actors (e.g., end-users, technology providers, and system operators) had either been initiated or had already been finalised, resulting in a large number of reports and text documents [48]. In addition, the case of smart grid in the Netherlands has scientific value because its development has different and contradictory aspects. For example, EV infrastructures [49] and smart meter technologies are being developed with a promising pace [50]. However, other aspects, such as the renewable energy diffusion rate or demand side management market, lagged behind other comparable European counties [51,52]. Understanding the origins of discrepancies in the development of smart grid technologies facilitates comprehension of the electricity system's transition process.

This study uses event-history analysis as developed by Van de Ven and Poole [53]. This method has been applied in previous TIS studies to identify patterns of technological development by using qualitative data (see, for example, [54]). A standard and procedure were used for identifying the events, mapping them, and assigning them to the TIS functions. During event-history analysis, simple incidents and events are distinguished. Here, an incident is seen as an empirical observation. However, an event is categorised as a critical moment that explains the formation of a pattern. Following this standard prevents choosing certain events subjectively [53].

After finding the events, they are sorted by date in chronological order. They are then categorised into system functions. To map events to certain functions, events are evaluated by the indicators of each function. For example, a new standard would serve as an indicator of a market function. Mapping the standard-related event to the market function means that the market's current state is affected by the event. This usually leads to another event(s). Eventually, the pattern of events is shaped.

One important criterion for mapping an event into transformational elements is that transformational factors are usually outside the TIS. They are typically found in the policy domain or social domain. These transformational elements eventually influence TIS functions. This stresses the importance of the formation of patterns in mapping a given event into certain transformational elements. For example, a lack of shared vision between policymakers may lead to undermining the guidance of research inside a TIS.

In brief, mapping an event into a function is to observe a change in the function status within a feedback loop system. The accurate mapping of the events by using an indicator requires in-depth knowledge of the TIS case study. Therefore, the results of the study are validated by interviewing smart grid TIS experts to reduce subjectivity.

Fig. 3 illustrates the steps for the analysis of systemic and transformational failures in the development of innovation. The analysis measures the system functions and identifies systemic TIS failures in the innovation-oriented stage. This links up with the system's internal functioning failures. In the transformational-oriented analysis, transformational failures are identified by searching for failures that hinder transformative change to fulfil specific societal needs.

3.1. Data collection

Collecting relevant data begins with choosing a TIS boundary [55]. This study treats smart grid innovation systems as integrated systems. It implies including all technologies in the supply chain from generation to end-users. Although various technologies such as PV, storage devices, and DSM technologies [4] certainly compete for more resources or legitimacy and sometimes complement each other, the smart grid can be considered as an individual yet integrated system [56]. Therefore, in this study, other complementary innovations, including smart meters, RETs, and storage devices, are treated as required necessary infrastructures, not as individual technologies.

The primary resource for the qualitative analysis pertains to official documents and reports from governmental and scientific organisations and archives of news articles and scientific papers and websites. Official documents are obtained from database of the Netherlands Enterprise Agency (RVO), reports on the official website of the Ministry of Economic Affairs and Climate Policy, publications in the European Commission, and reports from the International Energy Agency (IEA) and European Patent Office. The main resource for news articles is the Nexis Uni database. Scopus, Web of Science, and Google Scholar are used for scientific papers by searching with Boolean search operators for "Smart Grid", "Microgrid", and "Smart energy system" in combination with "Netherlands" and/or "Dutch".

In the initial search, 185 news articles, reports, and journal publications were found. The exclusion criteria were then put into practice. The study boundary and the authenticity of the data served as the primary criteria. A few resources were excluded because they referred to certain smart grid technologies without considering how these technologies affected overall smart grid deployment (i.e., as an integrated system). These articles discussed a distinct technology, making it hard to determine the pattern of events. Moreover, some news articles were excluded because the validity of their sources could not be verified. The selection of the documents involved reading, interpreting, and textual analysis of summaries and abstracts of text documents.

The system functions and transformational components are used to categorise and store historical events in a database. The relationship between the events was discovered using the chronological order of the occurrences. Finally, the experts evaluated the early patterns of the events to ensure their validity. Some events and documents were eliminated on the advice of experts because it was impossible to verify them. Additionally, relevant resources were added via snowballing and feedback from experts. Finally, 21 news articles, 33 governmental reports, and 37 journal publications were used for the analysis.

3.2. Mapping events to the system functions

According to Hekkert and Negro [38], retrieving all relevant data for TIS studies is impossible in practice. Hence, in the data reviewing process, attention should be paid to finding key events and turn-

Table 2
Summary of systemic and transformational failures adapted from: [25,37].

Systemic failures	Transformational failures
Infrastructure failures refer to the absence (or weakness) of required physical and knowledge infrastructures to promote the innovation	Directionality failures refer to lack of creation of a shared vision for the role of innovation in solving societal challenges
Institutional failures refer to the absence (or weakness) of sufficient institutions (e.g., regulations, legislation, standards, values and social norms) to support the innovation	Demand articulation failures refer to a lack of space for learning and anticipation of users' preferences
Network or Interaction failures refer to the absence (or weakness) of sufficient interaction, networking and trust between actors	Policy coordination failures refer to the lack of coordination across various policy levels which can lead to incoherence in policy implementation or deviation from strategies
Capability failures refer to the absence (or weakness) of relevant actors, competencies and capabilities to utilise available infrastructures	Reflexivity failures refer to the lack of continuous monitoring and anticipating the progress of transition

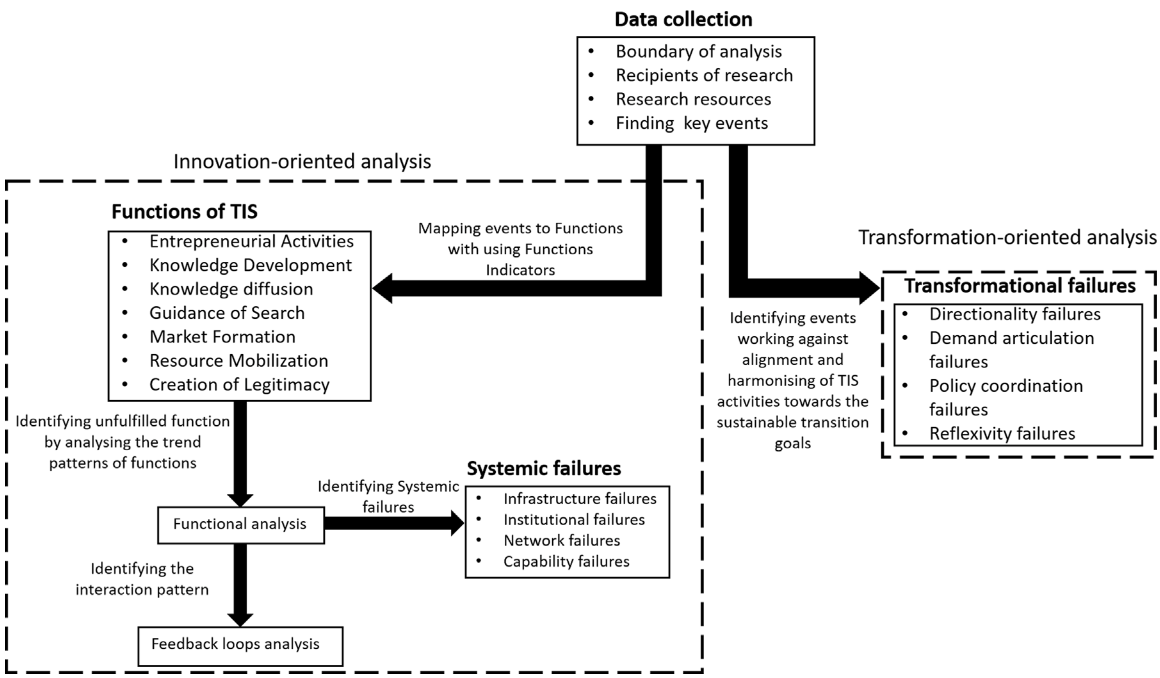

Fig. 3. Method for the analysis of the causes of systemic and transformational failures in the development of innovation.

ing points, such as a rapid change in the number of entrepreneurial activities. System function indicators are used as a heuristic tool to identify meaningful events and link them to corresponding functions. In the TIS analysis, an event can be considered an instance when it has some public importance or rapid impact on actors, institutions, or technology. After identifying the events, they are compared with the function indicators to determine the best match. For example, the initiation of certain research projects with a large number of involved actors can be considered a meaningful event linked to the knowledge development function (i.e., '[F2]'). This knowledge development may lead to technological advancements.

3.3. Identifying failures

With respect to systemic failures, a TIS analysis can be conducted to explore where these failures occur. As Bergek et al. [57] argue, neither functional analysis nor structural analysis constitutes a sufficient basis for identifying failures. Consequently, Wieczorek and Hekkert [25] argue that functions attach meaning to structures and that meanings generate structures. Therefore, in this study, an integrated structural–functional analysis is applied. This holds that unsatisfied TIS functions are analysed through the lens of structures. The trend pattern technique is used to identify the fulfilment of a function. Here, events related to different functions are subjected to quantitative analysis based on their accumulated numbers [35].

The trend pattern in this study is displayed by the number of positive and negative events for each function. In addition, the most important quantitative indicators of smart grid development are presented in Section 5. The level of TIS function fulfilment in the Netherlands can be compared to that of other European countries using the data provided by this quantitative analysis.

After the function analysis, the systemic innovation policy framework proposed in [25] is used to identify and discern systemic failures to identify the causes of problems in the Dutch smart grid TIS. Table 3 shows the indicators used for identifying systemic failures. These indicators pertain to the absence or incapability of relevant actors, the absence or poor quality of institutions, the absence or inadequacy (malfunctioning) of infrastructures, and a lack of interaction between actors [25].

Table 3
Identifying systemic failures based on functional–structural analysis of an innovation system [25].

Evaluated functions	Indicators of structural elements	Indicators of systemic failure
Functions1–7	Actors: government, NGOs, knowledge institutes, companies and civil society	Relevant actors are absent or may lack necessary competences
	Institutions: rules, regulations, norms, and expectation	Specific institutions are absent or are considered as weak
	Interactions: individual or organisational contacts	Interactions are missing or quality of interactions are considered to be weak
	Infrastructure: physical, knowledge or financial	Specific infrastructures are absent or infrastructures are considered to be weak.

With respect to transformational failures, the classifications provided by Weber and Rohracher (see [37] and Table 2) offer useful guidance. To apply this approach in identifying transformational failures, attention is paid to considering the system as a whole. As conceptualised by Weber and Rohracher [37], transformational failures can be perceived as blocking mechanisms embedded in wider societal systems [58]. They were retrieved as the bottleneck working against sustainable transition goals rather than failures hindering the innovation system from serving innovation and market purposes [59].

For this study, two steps are taken to assess the transformation procedure towards a decentralised electricity system. First, the analysis distinguished between the key events that comprise all parts of the socio-technical system in the broader sense (e.g., policy coordination elements) and the events that are linked to structural innovation system elements (e.g., institutions) at the TIS level [60]. The overarching events in the broader sense level determine how TIS functions are appropriately aligned and harmonised. For example, if policies are misaligned at different levels of government and if visions are misaligned (e.g., between different economic sectors or policy domains), then the likelihood of realising the required institutional settings to promote technology adoption is considered as low [60].

3.4. Identifying feedback loop between TIS functions

Although the trend pattern method enables studies to observe to what extent functions are fulfilled, it is also necessary to conduct an additional interaction pattern method for providing qualitative explanations for the observed sequence of events and constructing a storyline. Moreover, having cumulative causation in mind, this method facilitates understanding the role of system functions within chains of events. It can be used to identify feedback loops between certain TIS functions [44].

As a result, a combination of trend and interaction pattern methods is adopted in this study. The trend pattern method is used to identify significant changes in the number of functions' events to distinguish between different periods and the fulfilment of TIS functions. In addition, the interaction pattern technique is used to unfold the feedback loops between TIS functions. The aim is also to observe cumulative causality in this regard. The interaction analysis aims to reveal whether interaction between the TIS functions results in the construction of a complete innovation motor [39].

3.5. Validation

To increase the validity of the research and avoid weaknesses resulting from a researcher's single viewpoint, the findings are validated through triangulation. To this end, results were discussed and validated with experts and practitioners who have participated in key events of the smart grid innovation journey. The experts that were consulted are shown in (see Appendix Table A.1). In order to encourage the interviewees to express their opinions freely and to obtain more information, a semi-structured questionnaire was developed. The guidance of the semi-structured interview can be found in Appendix Table A.2. Following the validation interviews, any discrepancies in the analysis were resolved by discussing the conflicting viewpoints and reaching a consensus by using the guidelines explained in Section 3 as the common ground. The results of the interview are reflected in Sections 4 and 5. The interviewees' inputs include correcting the mapping of events to TIS functions, interpreting events, and giving more data regarding the identified event.

4. Results: chronological overview of key events

4.1. First period: 2001–2012

Several structural elements for the Dutch smart grid TIS existed before 2000 in terms of actor networks, technology and institutions. However, the adoption of the Fourth Dutch National Environmental Policy Plan (NMP4) by the National Government in early 2001 was a notable event leading to a considerable chain of events. The plan's goal was to accelerate sustainable transitions in areas like sustainable electricity and mobility and green resources [F4] [61]. This visionary plan was relevant to the smart grid because one of its major goals was to increase energy efficiency and focus on renewable energy (interviewee #5). This ambitious plan proclaimed that environmental issues were in need of a transformation approach in various technological, economic and socio-cultural domains [62]. Consequently, the Ministry of Economic Affairs became responsible for the implementation of NMP4 in March 2001. The Ministry was looking for a conducive condition for businesses to contribute to the transition in the energy system [63]. Therefore, it started encouraging research into different fields, including smart grid technologies via the Innovative Research Programme for Electromagnetic Power Technology (in Dutch: Innovatief Onderzoeksprogramma Elektromagnetische Vermogenstechniek, IOP-EMVT) [64]. This program included the 'Intelligent Power Systems' project, which was conducted by Delft University of Technology and Eindhoven University of Technology and funded by SenterNovem, an agency of the Ministry (interviewee #1) [F2, F6] [64].

These fundamental research projects initially focused on technical aspects of smart grids, including standards for the quality of grid voltage connected to intermittent distributed generators, stability analysis, algorithmic forecasting of uncertain demand, and remote power flow measurement and voltage regulation by smart sensors [65]. However, these projects were later expanded into a new research area within the Energy Research Subsidy (In Dutch: Energie Onderzoek Subsidie, EOS). This research was conducted on ICT, consumer behaviour, and social and market development (interviewee #1) [F2, F3] [66]. The EOS and

IOP-EMVT programmes together had budgets of over 30 Million Euros annually from the Dutch government and the Dutch Research Council (in Dutch: Nederlandse Organisatie voor Wetenschappelijk Onderzoek) (2008–2011) [F6]. Together, they formed the cornerstone of smart grid experimentation in 2002–2011 period [66].

This knowledge development led to encouraging entrepreneurial activities [64]. Such entrepreneurial activities can be perceived from two angles. First, some entrepreneurial activities can be seen as grassroots initiatives, defined by Seyfang & Smith as "networks of activists and organisations generating novel bottom-up solutions for sustainable development; solutions that respond to the local situation and the interests and values of the communities involved" [67, p. 150]. In this respect, Dutch grassroots initiatives for generating renewable energy first developed in the 1980s and 1990s. After some years of stagnation, these research programmes opened a window of opportunity for them. For instance, local farmers participated in the "Farmer Seeks Neighbor" project by getting loans for solar panels from local communities in 2006 [68]. In the same year, the civic climate activist group "Urgenda" was established by two Erasmus University Rotterdam academics representing Dutch citizen interests in a fast transition towards a sustainable society. Urgenda earned a reputation later, in 2019, for winning the Urgenda Climate Case urging the national government to take a more active stance to combat climate change [69]. In fact, as elaborated by Oteman et al. [68], growing grassroots activities had the potential to increase local acceptance of renewable resources as well as to provide financial benefits to local energy cooperatives. Therefore, this study considers increase in the number of grassroots activities as entrepreneurial activities [F1] and market formation (interviewee #3) [F5]. It is also a positive indication of smart grid institutionalisations and as cultural change in favour of it (interviewee #1) [transformational element as demand articulation].

Second, another way to look at entrepreneurial activities is by considering the business sector's commercial activity [70]. There are positive indications of growth in the Dutch smart grid domain with new companies emerging, such as Almende, an engineering company working on R&D solutions applicable to several domains of ICT, or existing firms expanding their portfolios to cover smart grid-related projects (interviewee #5). An example is the Tenergy group which was established to work on the digitisation of electrical systems with expertise in ICT, the energy market, power imbalance, and data measurement since 2004 [F1] [71].

At the same time, a net metering scheme, 'Environmental Quality of Electricity Production' (MEP), was introduced by the national government to stimulate the adoption of RETs (particularly for small solar energy producers) [72]. The scheme was connected to the EU Directive No. 2003/55/EC (PbEG L 176) and the national Electricity Act 1998 and the national Gas Act 2000. MEP played a very positive role in capacity growth of PV systems until 2013 [F4] [73]. Moreover, actors had the opportunity to share knowledge and experiences during MEP. By using a multi-actor simulation tool (FleXnet), actors could discover and share the outcomes (technical and economic) from the integration of distributed RESs into the electric grid under different scenarios (interviewee #1) [F3] [74].

The cycle of positive events did not last long. Over the 2004–2012 period, three national government coalitions collapsed (i.e., in July 2006, in February 2010 and in April 2012), resulting in inconsistent energy (transition) policies. Moreover, government coalitions often only had short-term priorities influenced by policies that supported economic growth (interviewee #2). During the process of reaching a compromise between economic interest and environmental sustainability concerns, the former gained the upper hand due to the global financial crisis [75] (2008–2010) [transformational directionality failures], and after 2007 the NMP4 policy had reached a point of stagnation [-F4]. During this time, Dutch policies were criticised for being incapable of incentivising investment in smart grid innovation (interviewee #5) [61].

As an illustration, contradictory policies led to the partial implementation of the MEP scheme. MEP aimed to stimulate renewable and combined heat and power generated electricity by subsidising per kWh of locally produced renewable energy [76]. Renewable energy and Combined Heat and Power producers could receive a subsidy up to ten years to compensate for market price difference between the production costs of these types of energy systems and conventional energy systems. However, in 2007, the Dutch government decided to terminate the scheme based on the assumption (which later proved to be wrong) that the Netherlands would meet its renewable energy target in 2010 with ongoing subsidised projects (interviewee #4) [transformational reflexivity failure] as well as having ran out of subsidy budget because of the many requests that were made [61].

After 2005, the Dutch government perceived the potential of smart meters for facilitating energy saving and stimulating the introduction of tariff schemes [77]. The EU Directive 2006/32/EC [78] on energy efficiency and services also helped the Dutch national government justify the smart meter's mandatory roll-out (interviewee #2). However, this top-down approach by the Dutch government, which ignored consumer preferences and privacy rights, encountered a public protest in 2009. The rollout of smart meters failed after a judge ruled against the government because smart meter installation was considered to infringe on the right to privacy [transformational demand articulation failure] [79].

Another factor that contributed to shortening the cycle of positive events was the initiation of the liberalisation of the Dutch energy market in 2004. This led to increased competition and lowering of electricity pricing as a result of privatisation and removal of natural monopolies in the electricity system's operation by unbundling the system operation from potential market activities such as production and supply [80]. Studies about the effects of unbundling and privatisation on the energy market show little consensus on this matter, though [81]. The liberalisation of the Dutch energy market resulted in suspending sustainable energy innovation system activities in terms of R&D and knowledge development (interviewee #5). Moreover, the liberalisation in the Netherlands happened in a fairly non-transparent way. In an insecure environment, energy companies searched for cost-saving and business-as-usual activities, meaning that they reduced risky and challenging plans linked to smart grid innovation (interviewee #5) [82]. The effect was that certain research programmes were terminated, and almost no demonstration pilots or field tests subsidised via the EOS scheme took place until 2009 [-F2] [83].

However, the liberalisation of the energy market can be considered a double-edged sword. In 2007, the separation of electricity generation and delivery from the management of the regional electricity grid can be seen as a contributing factor for weakening the incumbent producers, therefore creating room for the emergence of new suppliers (e.g., Oxxio company in 2006) and the introduction of Distribution System Operators (DSOs) [84]. Furthermore, structural changes in electricity markets were auspicious for the future of smart grids [85]. After the liberalisation of the energy market, electricity-supplying or energy service-providing companies switched to activities linked to customers by, for example, focusing on intelligent networks (interviewee #4) [F1].

The EU's Strategic Energy Technology Plan (SET-Plan) began in 2008, which was a turning point in the development of smart grids. The smart grid became one of the main topics of this plan. [86]. Policymakers of the EU believed that energy efficiency would become a promising way to reduce greenhouse gas emissions and secure energy supply [transformational element as a direction creation] [64]. This was a motivation for the European Commission to move forward with smarter, more integrated, and decentralised forms of energy delivery for consumers. In hindsight, this can be considered a stepping stone for the development of low-carbon technologies in which specific attention is paid to bringing down costs and boosting efficiency [64]. For the implementation of the SET Plan the ERA-Net Smart Energy Systems

Initiative started to coordinate and facilitate deep knowledge sharing between regional and European smart grid initiatives by financing joint projects (2008–2014) (interviewee #1) [F4, F6] [87]. In the Netherlands, this was used by the Ministry of Economic Affairs to establish the Intelligent Networks Task Force 1 in October 2009 [88]. Its goals were to provide coherent strategies for Intelligent Grids, to draw up an action plan for the realisation of Intelligent Grids in the Netherlands, and to organise cooperation between interested parties at the national level to the necessary extent. Two years later, Task Force 1 released a discussion document, "Towards intelligent grids in the Netherlands". It emphasised moving ahead on making Dutch electricity grids 'smart' by using solar energy under the assumption that home use would become more affordable than traditional energy pricing. This was considered a critical moment for smart grid innovation because government legitimised it for the first time (2011–2012) [F7] [88].

Fig. 4 summarises the key events observed during the first period (2001–2012). The positive and negative elements are indicated by '✓' and '∗', respectively. The turning point emerged as the Dutch government showed enthusiasm (with at least four key positive events) in capturing the potential of the smart grid innovation. This led to providing universities and other education institutes with resources that were essential to engage in experimental research and develop and diffuse knowledge (with seven positive events) about smart grids. The analysis of this period does not show any positive event to create considerable momentum for increasing market demand. Some entrepreneurial activities are visible with three positive events. However, these three events did not lead to creation of legitimacy. In general, the role of [F2], [F4] and [F6] were most visible and together formed a positive feedback loop, which is an indicator for a 'science and technology push motor'. The main missing function was knowledge diffusion [-F3]. This leads to a lack of feedback from society to stimulate the guidance of the search [-F4] in the proper direction. Not fulfilling the requirements for knowledge diffusion [-F3] is indicated by the lack of platforms for learning about smart grid [systemic infrastructure failure] as well as a lack of actors stimulating knowledge diffusion [systemic capability failure]. In addition, several transformational elements had a negative outcome in this phase.

4.2. Second period: 2012–2016

Entrepreneurs and early adopters of smart grid technology began to play a central role in the launch of demonstration and pilot projects beginning in 2012. Theoretically, the successful growth of a TIS depends on expectations and promises and on the willingness of firms to participate in high-risky projects [44].

To realise the SET plan and comply with European legislation in modernising the national 1998 Electricity and Gas Act, the Dutch government took the next step in 2011. NL Agency, a Dutch public sector agency and responsible for developing road maps to sustainability, innovation, international business, and cooperation, commissioned "Guidelines for applying laws and regulations for the Smart Grids Innovation pilot projects" [F4] [89]. These pilot projects were to be organised under the Innovation Programme Intelligent Grids (in Dutch: Innovatieprogramma Intelligente Netten; IPIN), which launched a series of key events [F4]. From early 2012 until late 2015, at least twelve demonstration pilots were carried out to explore the potential of integrating technological innovations in terms of demand response, storage devices, and DGs. The Ministry of Economic Affairs supported these projects, investing around 63 million Euros [F6] [90,91]. IPIN and related supportive schemes (e.g., the Sustainable Energy Production Incentive Scheme (SDE) in 2013) benefited from the relative political stability in the Netherlands after a new government coalition (Rutte II) came into power (2012–2017) [75]. This led to the establishment of the so-called "National Energy Agreement for Sustainable Growth" (2013), which contained the provision of energy conservation and boosting energy from renewable sources (interviewee #3) [92]. Having this as a meta-governance structure helped to keep a shared vision and avoid discrepancies during the experimenting period [93].

In parallel, the formation of the Top consortium for Knowledge and Innovation (in Dutch: Topconsortium Kennis & Innovatie; TKI) in 2012 reflected institutional change for smart grids that stimulated increased coordination between the government, private sector, universities, and research centers (interviewee #5) [transformational element as policy coordination] [94]. TKI also contributed to entrepreneurial activities by sharing knowledge and research plans with other TKIs or research organisations in the top sectors[1] [F1] [96].

Before setting up and implementing IPIN projects, twenty companies founded the Smart Energy Collective (SEC) [97]. SEC aimed to set up large-scale demonstration projects in the field of intelligent energy networks in the Netherlands and overseas. It had the ambition to take the lead in smart grid services and networks. At the time, it was the most comprehensive initiative in the Netherlands working on the development of intelligent energy services with approximately 5000 private and business consumers [F1] [98]. Organisations involved in SEC included private sector companies like ABB, Alliander, Enexis, Eneco, and Essent, but also the DSO Stedin and the Transmission System Operator (TSO) TenneT [99].

Other networks and initiatives were established shortly after IPIN demonstration pilots began in order to jointly develop testing grounds. More than 30 companies joined Netbeheer Nederland (the branch organisation of the Dutch grid operators) smart grid projects to set up living labs in various regions across the country [100]. A good example is Power-Matching City in the city of Groningen [101], where smart meters, decentralised energy technologies (e.g., solar PV, wind and hybrid heat pumps) and ICT infrastructure were installed for a few households to test stabilisation and optimisation of the system [100]. Regional initiatives such as the New Energy Business Community (in the Northern part of the Netherlands), Smart Energy Technologies & Systems (in the Twente region in the Eastern part of the country), the Amsterdam Innovation Motor, and the Utrecht Sustainability Institute were either empowered by IPIN demonstration pilots or directly involved in IPIN itself. This also applied to citizen-led energy cooperatives like TexelEnergie and LochemEnergie (interviewee #2) [transformational element as demand articulation] [94]. Furthermore, almost simultaneously, other kinds of entrepreneurial activities targeted local initiatives. In this regard, REScoopNL, the federation of Dutch energy communities, was founded in 2013 to empower local communities and citizen working on local energy production ambitions. This includes the installation of wind turbines, solar panels, and hydroelectric power plants, as well as the provision of knowledge and the sharing of the financial risk associated with community-led projects [F1] [68].

Besides an increase in entrepreneurial activities in the (2012–2016 period), some elements of market formation came to the fore. For example, actors participating in the IPIN demonstration pilots realised that setting new standards is essential because interoperability between testing sites was vital for scaling up. Dutch technology suppliers also needed to strengthen their worldwide efforts to capitalise on the international smart grid market [102]. Therefore, parties in the IPIN demonstration pilots tried to adopt the Open Smart Grid Protocol to assure reliable delivery of command and control information for smart meters, solar panels and other smart devices (2012) [F5] [103].

In addition to the observed positive results of IPIN (e.g., an increase in entrepreneurial activities), negative events had occurred. The first pertained to relative exclusion of end-users from the learning process during experiments (interviewee #2). Although a number of IPIN demonstration pilots certainly included end-user acceptance and behaviour as key themes at the start of the project (e.g., in Smart Grid Lochem [104]), end-user behaviour, acceptance, and involvement

[1] The Dutch government identified nine sectors in which the Dutch economy is particularly strong. More details can be found in [95].

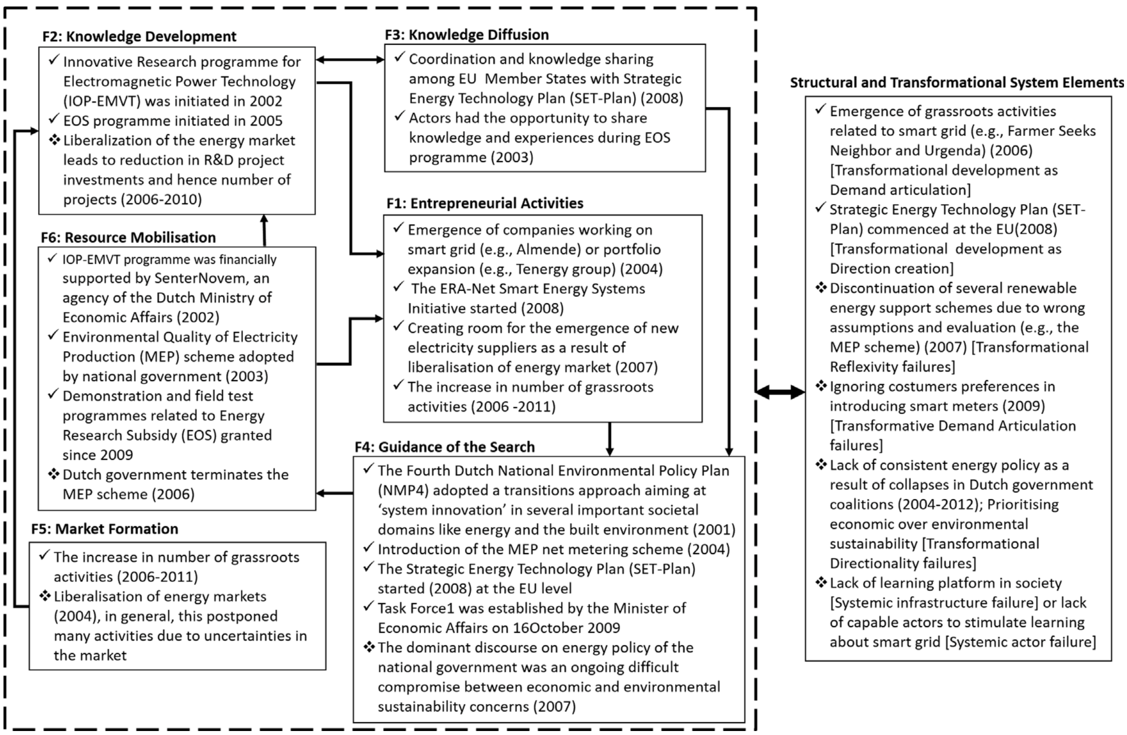

Fig. 4. Overview of functions and failures in the first period (2001–2012).

did not receive sufficient support and attention, also not in knowledge dissemination after IPIN had ended [105].

The dominant top-down approach delineated why the outcomes from the projects were limited to technical validation. A critical point here is the short-sighted consideration of smart grids by developers as a tool to maximise the efficiency of the system and subsequently to impose top-down technological solutions [106]. IPIN demonstration pilots and similar experiments were typically designed by IT-based initiatives or organisations (e.g., ICT Group Netherlands and iLeco) from the Dutch energy top sectors [107]. Reviewing the title of the IPIN demonstration pilots [48] reveals a predominant technical and engineering approach with a focus on the supply side of the electricity system but with little attention to the demand side. This also meant the exclusion of end-users from technology design [107], and their needs and desires for transition [transformational demand articulation failures]. This is also shown in a study by Planko et al. [108] who found six networks in smart grid innovation in the Netherlands as Testing and Development Network, Standardisation Framework, Device Standardisation, Industry Association, Product and Service Development, and Knowledge Exchange. There were no end-user networks found among these networks.

Furthermore, the dominant role of some actors constrained knowledge development by other actors. As stated in an official report [88] in the majority of projects DSOs played the main role. This was considered undesirable by other actors because the dominant role of the DSO deprived other parties from providing certain technical services (interviewee #3) [-F5].

The second issue concerns poor knowledge diffusion. In the IPIN demonstration pilots, the process of knowledge diffusion was limited to organisations and initiatives that were linked to either the government or energy sector incumbents [109]. Therefore, constraints were placed on start-ups to access reports of projects because they were made confidential or were not released at all [-F3]. For example, the official evaluation of the IPIN demonstration pilots [110] was not dedicated to the programme individually, provided little detail, and was part of a larger policy evaluation of a number of innovation programmes by the national government. In this report, the performance of the IPIN demonstration pilots was simply stated to be at a "reasonable" level without providing any further details or presenting results in terms of a sound policy evaluation (e.g., addressing programme impact, effectiveness, and cost efficiency). This conclusion about IPIN was confirmed during a validation interview with interviewee #2, arguing that "IPIN was suddenly terminated in 2015 without proper feedback for interested stakeholders including end-users" [transformational reflexivity failure].

In addition, the IPIN demonstration pilots suffered from a lack of actual programmatic control. Interviewee #2 (the former IPIN programme manager) argues that it is hard to call IPIN or its successor, SDE, actual 'programmes' because the philosophy behind them was not more than the proverb, "To seed a field, and then see what flowers grow". "However, a gardener was missing out". [transformational reflexivity failure].

The national government agency RVO was aware of the shortcomings of knowledge diffusion and the exclusion of end-users. However, when IPIN was first implemented (2012–2014), it attempted to address this issue by organising a series of workshops [91]. These workshops concentrated on themes like reflecting on users' feelings, doubts, visions, and experiences and opening up discussions and communications with end-users [F3].

The third adverse point pertained to a number of governance obstacles. For example, although developed technologies allowed the active participation of customers in demand response, there were no financial incentives due to static electricity prices (interviewee #2). Furthermore, regulations served as an obstacle for peer-to-peer electricity trading because actors in the electricity market are required to obtain a legal permit to supply energy [31]. Moreover, in some cases, actors needed flexibility in market and grid activities. For instance, some experiments required controlling storage and generation

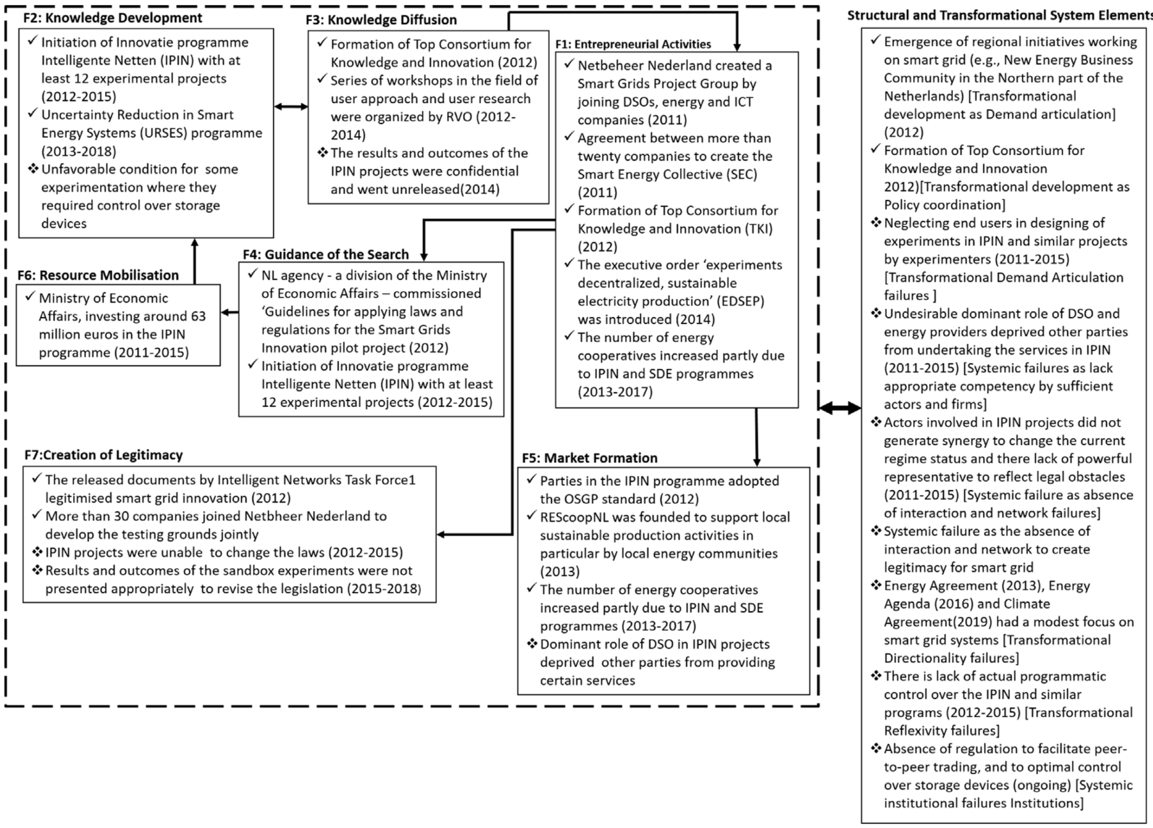

Fig. 5. Overview of the of second period (2012–2016).

activities simultaneously, which meant that the re-bundling of grid operation and market activities were needed. Regulations governing the conduct of DSOs did not allow system operators to take control over storage devices in terms of ownership and operation. This led to unfavourable conditions for the experiments and knowledge diffusion [-F2, -F3] [111].

Last but not least, actors involved in IPIN demonstration pilots were not able to mobilise capacity and neither generated synergy with the aim to change the current embedded regional and national electricity systems [111]. The IPIN management made one attempt to infer institutional change. "We made an inventory of the legal obstacles, and it was submitted to the legislator" according to the IPIN demonstration pilots coordinator (interviewee #2). However, public authorities were not satisfied and argued that they needed many more practical cases before taking action [-F7]. In addition, interviewee #2 stated that actors need to take more action in order to be heard by regulating authority and that there is a need for a powerful representative to reflect on the needs actors have in the energy market [-F7] [112].

As can be observed in Fig. 5, the national government was actively involved in the smart grid innovation system to initiate demonstration projects and to support the projects by implementing schemes having subsidies and grants. Moreover, various entrepreneurial activities took place (with five positive events). However, entrepreneurial activities alone could not legitimise the smart grid. Although the government continuously fed the innovation system, this was due to high interest in the government for sustainable development rather than entrepreneurial activities or creation of legitimacy by the entrepreneurs (see the negative outcome of [F7] in Fig. 5). This was due to the systemic failure as the absence of actor interaction and networks. Resource mobilisation by government programmes prevented the system from breaking down and cascading negative events (interviewee #1). In addition, although the market function experienced two positive events, it could not contribute to the guidance of the search in the desired direction due to the substantial number of systemic failures, mostly in terms of ignoring end-users' needs, wants and interests, and the absence of powerful actors in creating a strong network. This is linked to the dominant role of DSOs in IPIN demonstration pilots and systemic failures occurring, indicating a lack of appropriate competency by sufficient actors and firms. In addition, the quality of experimentation suffered from a lack of customer incentives and regulations that hindered peer-to-peer electricity trading [systemic institutional failure]. In general, quite a number of failures and the absence of a positive feedback loop were observed over 2012–2016.

4.3. Third period: 2016–2021

During the third period, a considerable number of transformational failures occurred, followed by a new approach for experimentation (e.g., sandbox experiments, upscaling the projects, and experimenting to reach new socio-technical arrangements).

Upscaling the projects (e.g., from the IPIN demonstration pilots) became an important discourse among policymakers by the end of 2015 [113]. The focus of the projects during the second period was on technical feasibility. However, the IPIN demonstration pilots were ultimately unable to create a market, nor did IPIN result in any transformative change (interviewee #2) (except for some projects arguably being replicated elsewhere in the Netherlands) [114]. The demonstration pilots faded after IPIN had ended, public funding stopped, and sufficient user demand had not yet been created [115].

To this end, after 2015, RVO in cooperation with the Top consortium for Knowledge and Innovation (TKI) Urban Energy, continued investment in research programmes to explore how smart grids could potentially be deployed [114]. Concurrently, the smart city concept became popular, reflecting the common belief towards scaling the projects. Moreover, large gatherings at both the EU and national level took place focusing on smart cities shifting the attention away from smart grids to a higher level of aggregation, also including other sectors than the electricity sector. This is showcased by events like Amsterdam's smart city event 2016 and the Conference on "Smart, Innovative & Sustainable urban mobility" [115] [F3].

Although RVO and TKI supported the scaling approach to smart grids, a policy directionality failure was evident at this time. The smart grid as an innovative concept was not embraced or sufficiently legitimised by the government. Notably, the 2013 Dutch Energy Agreement [116] had a modest focus on decentralised systems, and measures were aimed at supporting large investors and incumbents in the electricity sector. As discussed by Oteman et al. [68], this meta-governance arrangement was mostly based on the economic attainability of the energy transition, employment opportunities, and profitable investment. Additionally, the majority of the actors involved in the strategic design of the Energy Agreement were the national government, the traditional energy sector, and business representatives, who paid little attention to small-scale bottom-up projects carried out by local stakeholders, grassroots energy communities, or start-ups in smart grid innovation (interviewee #5). A similar approach was visible in the 2016 Energy Agenda [117] and later in the 2019 Climate Agreement [118], in which the main theme in the electricity sector was production from large-scale offshore wind, solar, and hydrogen [transformational directionality failure] [68].

Aside from the downside of the 2013 Dutch Energy Agreement, it also stated that "To realise the energy transition, the legislation needs to be providing a consistent framework to provide investors with long-term security. In addition, legislation needs to facilitate innovation". This meant that legislation needed to provide sufficient space to enable desired new developments, in particular, when it comes to energy generated from RESs [119]. To this end, the Gas and Electricity Acts were to be revised. Consequently, the national government established a legislative agenda entitled "streamlining, optimising, and modernising " [120]. Eventually, this resulted in an executive order entitled "experiments decentralised, sustainable electricity production" (EDSEP) (2015). This allowed experiments contributing to the energy transition to deviate from certain stipulations regarding the specific electricity provision of the national Electricity Act 1998 [F2] [121].

EDSEP helped to develop and carry out so-called 'sandbox experiments' to resolve issues observed during the implementation of the IPIN demonstration pilots. Sandbox experiments are "tools" (i.e., small-scale demonstration pilots) for new socio-technical arrangements by providing regulatory exemptions for experimenters [122].

By introducing EDSEP, DSOs, the Netherlands Authority for Consumers and Markets (ACM), and tax authorities started to collaborate to facilitate experimentation. For example, Smart Grid Westland, Aardehuizen, Schoonschip, and Endona were approved under EDSEP (see [120] for details on the experiments in 2015–2019 period). Implementing EMS with dynamic tariffs and installing PV panels formed the main technical configuration within these experimental projects [121].

Legal exemptions were allowed for a maximum of ten years. EDSEP applies to specific articles of the Electricity Act; other regulations must be applicable. In general, exemptions are allowed for the projects that pursue increasing utilisation of renewable energy systems, enhancing the current energy infrastructure, and increasing the involvement of energy users in energy supply [111]. This meant that there had to be a lot of cooperation between agencies in order to decide if a project was eligible for an exemption. Although the programme was not finalised at the time of conducting this study, a number of issues emerged. The first issue encountered pertained to RVO not transparently explaining what the regulations entailed to DSOs and the ACM [120]. Moreover, compartmentalisation within DSOs and energy companies negatively influenced the progress of the sandbox projects because inconsistent decisions were made and in parallel [transformational policy coordination failure]. For example, a certain project could get approval for exemption from a DSO, although the ACM was not convinced (or the other way around) [122].

The case of 'Windpark Kloosterlanden' in the municipality of Deventer in 2015 illustrates this issue. The current electricity tariff code compelled newly constructed wind turbines to be connected to the nearest medium voltage substation. However, partners in the project, particularly energy providers, requested an exemption to connect the wind turbines to a specific medium voltage grid, which was not the nearest. The reason for such an exemption was to install wind turbines close to the energy demand in the smart grid with proper control of it. Local customers also supported this request, according to the energy supplier manager [123].

Nevertheless, the ACM did not grant the exemption on the grounds that exemption is only a temporary solution and precedents can arise. To support this argument, the ACM argued that this case was an opportunity for the grid operator to request an amendment to the electricity tariff code instead of asking for an exemption. In response, Liander (the responsible DSO) considered the rejection of the exemption as very unfortunate because it undermined the pilot project goals. Its manager believed that the project only needed a short-term solution for experimental purposes. Changing the code was considered a long-term process that should be done in consultation with other system operators and their federation 'Netbeheer Netherland' (interviewee #2) [transformational policy coordination failure] [123]. However, Liander took the decision of the ACM to heart and started a lobby to have this connection method adopted into legislation. This was eventually achieved in 2020 with the addition of Article 23 (2) in the Electricity Act [Structural system development as a revision of institutions] [124].

Related to these failures is the absence of lobby organisations and intermediaries to accelerate the law revision process. The efficiency of the experiments to make a long-term impact was undermined because RVO reports project progress to the Ministry of Economic Affairs and Climate Policy from its own perspective (interviewee #2). Experimenters are hardly asked to provide their inputs for revising regulations [transformational reflexivity failure]. Furthermore, RVO, the ACM, the DSOs, and the project developers were working in parallel worlds in which a shared vision regarding the goals and process was badly missed [75]. There was no communication channel supported by a lobbyist representative or intermediaries in different decision-making units. Nor was there any coordination of the activities [111]. "Energie Samen" was founded in 2018 as a national federation to resolve this issue for local community energy collectives. It is the successor to REScoopNL and a few other community energy federations. Its goal is to strengthen community energy initiatives and projects and to represent them in negotiations and lobbying vis-à-vis the government and, in particular, the regulatory authorities [F7] [120].

The analysis also reveals a lack of policy coordination between the EU and national government, particularly in terms of transposing EU directives into national legislation. For example, the EU obligates its Member States to provide the right for system users to access the electricity network indiscriminately (e.g., Directive 2009/72/EC of the European Parliament and the Council) [125]. This guarantees Third Party Access (TPA) for users that threaten the goals of experiments at the national level. Inasmuch as TPA implies that users have their own suppliers, the business models of experiments are undermined because their generation capacity will be constrained to the projected demand. Some parts of production cannot be used if users choose other energy suppliers than the energy provided by the energy suppliers involved in the experiment. In general, according to interviewee #5, the Ministry of Economic Affairs is too slow to transpose the EU packages [transformational policy coordination failure]. For example, the EU's Clean Energy Package [126], which includes the concept of energy sharing, should have already been transposed by the end of 2020 but is currently only expected to be transposed by 2024.

The opposite also happens when EU legislation tries to increase demand response, but national legislation deprives Dutch customers of the initial incentives. For example, the EU directive 2012/27/EU states that the network tariff should encourage demand response and promote system flexibility [127]. However, currently, the Dutch Electricity Act does not allow tariffs based on users' capacity and dynamic network tariffs. In addition, DSOs and aggregators could provide flexibility for the network by means of direct load control [128]. However, this option is also obstructed by Dutch national law. Applying direct load control by a DSO means rewarding a selective number of users for taking part in direct load control (i.e., implying a discount on their electricity bill). This can be considered as discrimination between customers because the DSO can only provide direct load control for consumers living in an area with grid constraints or congestion problems [129]. Obviously, this lack of coordination between the national and European levels limits experimenters' control over experimental projects [transformational policy coordination failure].

The implementation of DSM plans is also complicated by the regulatory setting that currently exists in the EU and the Netherlands [130]. The Electricity Act and EU Directives emphasise the importance of 'efficiency' in network management [131]. However, the DSOs' activities must be unbundled from the supply and production market as a result of liberalisation. Using DSM by DSOs can directly influence the electricity market. Furthermore, current methods for calculating the DSO's tariffs can discourage the end-user from adopting the DSM plans. End-users should be provided with transparent information about the financial value of the flexibility [130]. This is a challenging task for DSOs because the value of flexibility depends on the system condition at other electricity system levels and not only on the local condition. The current tariff setting is calculated based on the system connection level (e.g., 230/400 V) rather than on the customers' exact location [129].

Evaluating the current status of smart grid innovation indicates that the approach to running experiments has changed after the termination of the IPIN demonstration pilots in 2015 (interviewee #2). For instance, it was visible in the 'Uncertainty Reduction in Smart Energy Systems' research programme [F4] that ran from 2013 until 2018 [132]. The aim of this programme was to reduce uncertainties for actors in smart energy supply chains [133]. To this end, projects gained insight from social and behavioural sciences to analyse the cause and nature of uncertainties in smart grids [134]. Following the new approach for experimentation, as of September 2020, the Dutch government allows entrepreneurs to apply for financial support under the "Renewable Energy Transition" scheme in Dutch: "Hernieuwbare Energietransitie", (HER+) [135]. Similarly, the national government subsidises projects contributing to the development of improved (self-learning) control systems for energy use and advanced control systems. This programme is called "Mission-driven Research, Development and Innovation" (in Dutch: "Missiegedreven Onderzoek, Ontwikkeling en Innovatie", MOOI) and it began in August of 2020 (interviewee #3) [F2, F4, F6] [90]. The national programmes were also backed by funding from EU frameworks programmes (e.g., Horizon 2020 and NER 300) (2013–2020) [F6] [136]. Over the same period, the number of energy cooperatives tripled (2017–2020). This was partially due to the available funding programmes [137]. Moreover, "Local Energy Monitor" [137] which monitors community energy sector performance annually shows that most of the energy firms, such as Alfen N.V. (an LLC), have been expanding their activities into EV charging product developments and upscaling of the energy storage since 2017 (interviewee #4) [F1, F5].

Rolling out the essential infrastructures and institutional changes indicate favourable developments that are promising for the future of smart grids in the Netherlands. In this regard, the Royal Netherlands Standardisation Institute (in Dutch: Nederlands Normalisatie Instituut) published its "Smart grid standardisation roadmap", "the IEC/TR 63,097" in 2017. This document is used as a guiding principle for future smart grid experiments [F5] [138].

Another example of existing infrastructure is the high adoption rate of EVs in the Netherlands (reaching 34% of the market share in 2022) [139]. This is a result of the National Agreement (2019) commitment to electrification and the allocation of a 250 million euro stimulus to promote electric driving by the end of 2025 [140]. Provinces and municipalities have recently been active in setting-up extensive tenders to increase the number of charging stations. As a result, installing public charging infrastructure with open protocols, and smart charging without government investment is becoming the new norm [141].

In addition, for the first time in Europe, all Dutch DSOs and TSOs worked in partnership to create an online congestion management platform for the Dutch grid operators (GOPACS) [142]. This platform has been in operation since 2019 and successfully addresses the TSO-DSO coordination issue by requesting flexibility from the market to reduce congestion in the electricity grid. The platform considers DSOs' grid situation in coordination with the balance in the national electricity grid [143] [F5].

Furthermore, regarding smart meter installation, currently, the Netherlands can be considered one of the European frontrunners in rolling out smart meters despite having encountered initial setbacks (see Section 4.1). A 2021 study [79] shows the diffusion rate of the smart meter is at 85%, meeting the 2020 goal [developing structural system infrastructure]. Despite this rapid adoption, DSOs can hardly use data from smart meters for smart grid management purposes because of the current privacy legislation. To solve this problem, the Dutch DSOs developed a code of conduct approved in May 2022 by the Dutch data privacy authority [144].

The graphical summary of the events in Fig. 6 shows the absence of creation of legitimacy [-F7] and the existence of a substantial number of transformational failures (with six negative events). Lack of creation of legitimacy deprives the completion of a positive feedback loop because connections between creation of legitimacy [F7], guidance of the search [F4], and market formation [F5] are missing (interviewee #4). This resulted in a missing connection (network) between the government and interest groups to effectively establish the required institutions to support the whole smart grid innovation system. The failure to create legitimacy [-F7] indicates a systemic failure in networking between the smart grid supporters. Like the first period, knowledge diffusion is not developed [-F3] due to the absence of interactions between entrepreneurs, effective networks, and learning infrastructure. Similar to the second period, there are several failures and no positive feedback loop.

5. Discussion

The following findings are discussed in relation to the study's goal of identifying systemic and transformational failures in the development of smart grid innovation in the Netherlands in the 2001–2021 period by combining TIS and transformational perspectives. The analyses of the three periods show that in the first period a positive feedback loop could be observed in the form of a science and technology push motor. However, no positive feedback loop was observed in the second and third periods. In these two periods, systemic failures led to the weak fulfilment of some functions and the absence of certain linkages between functions. In all periods, the Dutch national government was motivated and intensified innovation activity in smart grid technology. The national government's adoption of the NMP4 in 2001 showed that smart grid-related technologies caught the attention of policymakers as promising technology. Supporting IPIN demonstration pilots in the second period revealed the same motivation. In the third period, this continued with support for socio-technical experimentation under EDSEP executive order.

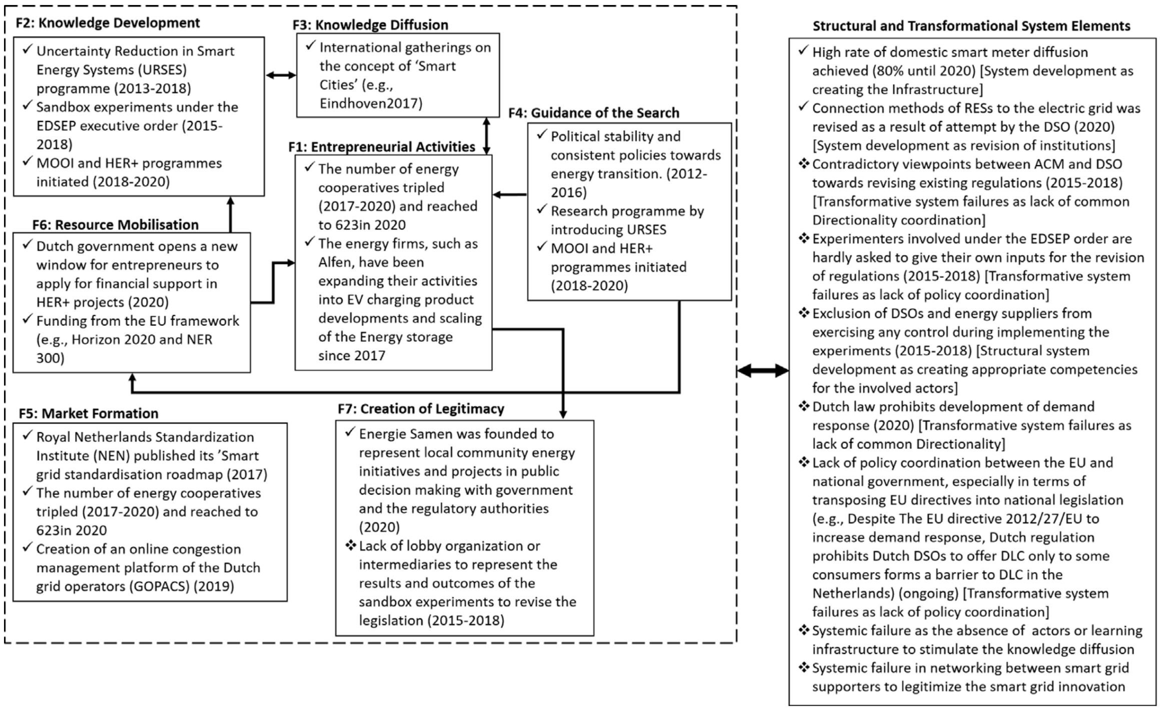

Fig. 6. Overview of functions and failures in the third period (2016–2020).

In the first period, setting up support programmes like IOP-EMVT by the national government and investing in R&D projects facilitated the acceptance of the smart grid, at least, among a small network of scientists and early adopters (interviewee #3). Consequently, the number of involved firms and scientists working on the smart grid gradually increased. However, the small-sized network of entrepreneurs suffered from a lack of leadership and the near absence of learning platforms for the diffusion of smart grid knowledge (2001–2012). In general, entrepreneurs lacked a proactive mentality, and government and research institutes were in the lead of innovative projects, with firms taking more of a passive role (interviewee #5).

Similar trends characterised the second period (2012–2016), but it was somewhat more intensive than the first period in terms of fulfilment of entrepreneurial activities. Initiating the IPIN demonstration projects increased entrepreneurial activities in terms of the number of new entrants and established firms involved in the projects. The IPIN demonstration pilots could potentially work as a learning platform for entrepreneurs and end-users. However, this was not realised because designers predominately focused on technical improvement while ignoring end-users' preferences (interviewee #2). Demand-side support and standardisation were still underdeveloped. This meant that the created niche market could not significantly impact building the required infrastructure and institutions. As explained by Ten Heuvelhof and Weijnen [30], building the infrastructures for market formation involves actors making a substantial investment in the market, which is risky because the return on investment depends on end-users' preferences and uncertain regulatory conditions.

Large-scale projects are considered necessary to influence the incumbent electricity system. This also requires a larger and more powerful actor-network to legitimise the smart grid TIS. This finding complements the findings by Van Summeren et al. [28] that energy cooperatives and other bottom-up initiatives in the Netherlands struggle to play their preferred role with respect to their needs and values because they have to comply with energy sector incumbents.

The third period started in response to the required structural changes (e.g., the need to remove regulatory barriers for proper experimentation). However, this had not been realised by 2021 due to a number of significant transformational failures. Experimentation in this period signalled that overcoming systemic failures is not only about the fulfilment of smart grid TIS functions but also about harmonising and alignment of activities outside the smart grid TIS. Here, a sound example concerns the contradictory viewpoint between the ACM and the DSO in revising the existing regulations in the Deventer wind park case. This is also shown by Lammers and Heldeweg [31] who hold that decision-making in smart grid projects in the Netherlands is complex due to the diversity of stakeholders. Based on this study's results, this complexity influences the collective action between regulatory authorities and system operators besides actors directly involved in the projects. Interviewee #5 elaborated on the market formation issue by stating that there is a lack of proactive mentality among business enterprises to adopt new business models like peer-to-peer trading. DSOs also experience a net capacity problem. Therefore, they have to improve the grid capacity, which leaves them with little financial capital to invest in smart grid innovation structurally.

In summary, legislation, technology and business did not work in tandem, with technological advancement. Projects and market development suffered from the slow adaption of legislation, and slow growth of business potential for smart grid innovation. What did not help either was the Dutch national government (unlike the European Union), lacking a vision and a structural innovation support programme (interviewee #5). The national government's approach to smart grid innovation was rather haphazard, lacking strategy, and changing suddenly between government administration terms, giving entrepreneurs, DSOs and research institutes little certainty on what to expect with regard to setting up the next smart grid innovation projects. Neither was there sufficient attention to scaling results of pilot demonstrations (interviewee #2).

Systemic failures resulting from a lack of networking between actors, interactions between entrepreneurs, and legitimising smart grid are crucial and must be addressed. Networking and interaction between actors can be improved by creating branch associations that impact policymakers and society [145]. This interaction can also influence the knowledge diffusion process. In addition, interactions between actors (both companies and consumers) dramatically increase by sharing knowledge during demonstration projects. However, it is recommended that the goals and strategic policies of the demonstration projects be defined before starting the projects. In designing strategic policies, specific attention should be paid to end-users and raising their awareness.

To legitimise the smart grid, it is recommended that involved companies and other actors like energy communities take collective action to lobby and create legitimacy. This, in turn, can convince the government to emphasise the rule of the smart grid in the legislation. Then, current legislation and regulations can be adapted, and economic policy instruments can be made available to support smart grid start-ups to survive the "valley of death".

To address the identified policy coordination and demand articulation failures, the following should be considered. These failures are reflected in the Dutch Energy agreement (2013) and Climate Agreement (2019), in which the Dutch government preferred to support centralised RESs. This is not surprising because the transition task forces and platforms are dominated by incumbents, which support centralised RESs. Support for RES innovations by incumbents means that they shape the public policy in a manner that is not disruptive to their business [18]. According to interviewee #2, this issue is rooted in the fact that there is no urgency among decision-makers or end-users to seriously consider adopting smart grid and related technologies, infrastructures, and services. Directionality and coordination transformational failures can be removed if support for the centralised RESs is downscaled and more focus is put on establishing local and regional, decentralised systems. This can lead to further smart grid legitimisation. Consequently, the legitimiSed smart grid can improve the identified reflexivity failures because, if the smart grid is legitimised, the results of demonstration projects (such as IPIN) must be evaluated more thoroughly.

Although the results derive from a case study reflecting a single nation, there is reason to believe that similar results may also be found in other countries with similar characteristics, in particular in other North-Western European countries like Germany, Denmark, or Norway [146]. A comparable study in South Korea examined the development of the smart grid through a governance and innovation system lens [147]. Empirical studies from these countries have revealed similar failures hindering smart grid innovation system development. They pertain to knowledge sharing, acceptance issues, complexities in introducing suitable regulations, or a lack of legal definition, which harms practical operations and hinder the mainstreaming of a potentially mature smart grid innovation (i.e., energy storage; [148]).

These studies highlight the importance of designing a structured approach, tools to facilitate multidisciplinary knowledge exchange, and incentives to ensure a level playing field. The Dutch case complements results from studies in other countries by tracing issues to overarching transformational failures and showing how they occur in practice and impact innovation system development. Arguably, similar transformational failure might be found in fairly comparable countries with the government having the desire to stimulate and implement smart grid innovation (i.e., with similar institutions, technological innovation visions, and socio-political conditions).

Table 4 provides various smart grid deployment metrics for the Netherlands and four other EU countries to complement this study's qualitative findings. The selected metrics also serve as indicators of TIS functions. The overall deployment of the smart grid is reflected in metrics like CO_2 emission per capita and demand side flexibility market.[2] In terms of these metrics, the Netherlands' adoption of the smart grid lags behind that of other European countries. Programmes focusing on physical infrastructures like the roll-out of smart meters, the development of charging stations for EVs stations, and the storage capacity display encouraging numbers. The deployment of the smart grid, however, necessitates more than these infrastructures because each TIS depends on all institutions and actors working together [149]. Moreover, there are fewer patents, a key indicator for determining the development of knowledge. The number of collaborative interactions with other countries during the projects shows that knowledge sharing between Dutch project and projects in other countries is less than between smart grid projects in other countries. Due to the limited degree of interaction, this may lead to fewer lobbying activities to legitimise the smart grid.

The level of concentration of DSOs[3] and the number of companies and organisations involved in the projects can be used to interpret the fulfilment of entrepreneurial activities. A medium concentration of DSOs in the Netherlands indicates average success in unbundling electricity networks and fulfilling entrepreneurial activities. This was observed during smart grid projects in the Netherlands (e.g., in IPIN), when a few DSOs played the dominant role. Moreover, the number of companies and organisations in smart grid projects also confirms the moderate speed of fulfilment of entrepreneurial activities. The comparative analysis also indicates that the Netherlands' total investment in smart grid projects is among the highest in the EU. This supports the qualitative analysis's conclusion that the Dutch government offers a variety of financial support schemes to run smart grid projects.

With a futuristic approach, the market's slow demand-side flexibility development can be problematic soon. Due to the increased percentage of renewable energy before 2050, the congestion problem in the Dutch power system will significantly increase [157]. More demand-side flexibility is necessary to solve this issue. Demand-orientation policies will probably become more dominant so that demand-orientation will compete with or even take the place of supply-orientation, which is still the dominant policy in the Netherlands [158]. Policymakers can use the success of the adoption of EV innovations as an example to encourage the use of other smart grid technology [149]. To that purpose, the Dutch polder model's culture of collaboration in public decision-making and knowledge development between the government, private parties, and local government can be potentially also used in other (energy) infrastructures [159].

Despite the merits of this study, two major shortcomings of the used integrated framework (see Section 3) compromise the accuracy of the analysis. First, the willingness, values, preferences, and position of end-users in the existing and future market are not thoroughly examined while looking for TIS development and transformational failures. Any transition in an electricity system cannot be realised by only providing comfortable and affordable technologies. To elaborate on this way of thinking, as Kemp and Van Lente argue [160], sustainability transitions through sustainable technology adoption require a dramatic change in the values and criteria of customers in addition to changes in technologies and infrastructure to accommodate these values and intentions. For instance, adopting smart grid related technology like installing solar panels by end-users can assist in reducing CO_2 emissions. However, more production at the end-user side means that DSOs have to cope with increasing net congestion problems. Taking electricity system operators, end-users are expected to accept the constraints of new technologies and start behaving and using electricity differently. However, this often does not match well with end-users' current behaviours, lifestyles, and social practices. It cannot be expected that end-users will change these overnight after adopting smart grid technology. It instead requires an adaptive process in which technology changes to accommodate behaviours and social practices. However, according to sociological and psychological research [146] minor changes in the latter can be achieved but are difficult to attain and maintain.

The second methodological problem occurred in identifying the transformational failures as there is no systematic way to retrieve all relevant transformational failures. Merely defining the transformational failures as a descriptive method is insufficient because sustainability is a complex normative problem that is rooted in actors' paradigms (i.e., basic beliefs) [161]. The paradigms of each actor determine what actions or practices are considered reasonable and legitimate. For example,

[2] Information on how to interpret 'low', 'medium', and 'high' rankings can be found in [52].

[3] Low concentration means that they are mainly small, local DSOs and the three largest DSOs usually deliver less than 50% of distributed power. Very high concentration means that there is only one DSO company [150].

Table 4
Comparing indicators of smart grid development in the Netherlands and four other EU countries until 2021.

Metric	The Netherlands	Germany	Norway	France	Denmark
Population (millions) [151]	17.53	83.13	5.40	67.5	5.85
Total investment in smart grid projects per capita (EUR/capita)	10	4.5	6	4	16
Total electricity power generation (GWh) [152]	117,440	250,385	39,412	530,418	32,793
Renewable generation percentage (%) [51]	34.8	41.80	98.80	23.25	78.14
PV penetration rate (%) [51]	11.8	10.9	0.1	3.6	5.0
Wind power capacity in relation to overall power capacity (%) [51]	14.7	25	7.49	6.76	39.1
Offshore capacity in relation to overall power capacity (%) [51]	5	3	0.01>	0.01>	12
Number of electric vehicles per 1,000 population [49]	21.7	15.7	117.3	11.6	24.7
Number of charging station per 1000 EV [49]	200	38	30	68	20
Absolute capacity of operational electrochemical storage (MW) [153]	37	570	6	19	2
Capacity of operational electrochemical storage by population (W/capita) [153]	2.11	9.02	1.19	0.28	0.341
Smart metering rolling out (%) [50]	85.2	15>	98	80–90	80
CO_2 emissions per capita (tonnes) [154]	8.06	8.09	7.57	4.74	5.05
Number of patents related to smart grid technologies per million population [155]	0.75	29.7	6.8	1.4	6.32
Electricity market potential for demand side flexibility [52]	low	medium	low	medium	low
DSOs level of concentration [150]	medium	low	low	very high	low
Number of participations in smart grid projects per capita [156]	18	8.1	18	6.1	28.7
Number of companies and organisations involved in the smart grid projects [156]	476	835	245	680	430
Number of collaborative interactions with other Eu countries during smart grid projects per 1000 population [156]	0.31	0.42	0.87	0.41	3.02

a lack of coordination between different policy levels may happen because each level has a different vision regarding sustainability. This misunderstanding of the causes of transformational failures may result in poor policy design.

6. Conclusion

By using an integrated framework in which TIS structural elements, functions, and failures are combined with a transformational perspective, this study explains the development of the smart grid innovation system in the Netherlands. Results show that this went through a couple of stages of experimentation. Although knowledge development [F2], guidance of the search [F4], and entrepreneurial activities [F1] were found to have experienced the largest number of positive events, the functions of knowledge diffusion [F3] and creation of legitimacy [F7] had limited positive events. The weakly fulfilled functions are linked to systemic failures in terms of a lack of infrastructure to stimulate knowledge diffusion, failures in terms of the absence of interactions and actor networks to legitimise smart grid innovation, and failures in the absence of institutions (e.g., regulations) for experimentation purposes or market formation.

Moreover, market formation [F5] presents the potential for scaling up, for example, with the adopted standards and implemented infrastructures such as smart meters. However, systemic and transformational failures hinder smart grid innovation from developing into market concepts that can readily be commercialised. The implication is that resources [F6] for the projects still mainly come directly from the Dutch national government and from EU innovation investment funds, and the market plays a marginal role in feeding further experimentation.

The scientific novelty of this study lies in the combined analysis of TIS functions, systemic failures, and transformational failures. The results show that these three elements have influenced each other in the case of smart grids in the Netherlands. Transformation failures in the broader socio-technical system outside the TIS led to problems in TIS functions and to systemic failures. This study is also relevant to current debates on mission-oriented innovation policy [162]. In the case of smart grids in the Netherlands, it is shown that the influence of policy programmes and policy steering has been of considerable importance throughout all three studied periods. However, it is also shown that, in spite of stimulation programmes, misalignment between the actors involved, such as policymakers, entrepreneurs, energy cooperatives, business firms, and end-users, can lead to systemic failures and can severely slow down TIS growth.

Smart grid analysis shows why developing improved methods of analysis is necessary. The inability of TIS to reflect on the failures caused by the preferences and willingness of end-users is a major limitation of TIS functions and transformational failures. Therefore, it is essential that future research designs incorporate psychological and sociological factors.

Moreover, methodological shortcomings hamper the reliability of recovered transformational failures when tracing the origins of these failures. This is due to the normative nature of transformational failures. As a result, studies should shift their focus to incorporating belief systems (paradigms) into innovation system analysis as the root causes of transformational failures.

Recently, studies took a first step in this direction by proposing policy interventions to overcome transformational failures [163]. Another interesting area of further research is the quantification of the qualitative results of this study in terms of the number of positive and negative events for modelling purposes, for example, to evaluate the impact of each function of the TIS on other functions in a system-dynamic manner.

CRediT authorship contribution statement

F. Norouzi: Conceptualization, Methodology, Writing – original draft, Investigation. **T. Hoppe:** Supervision, Validation, Writing – review & editing, Resources. **L.M. Kamp:** Writing – review, Validation & editing. **C. Manktelow:** Writing – review & editing. **P. Bauer:** Suppervison & coordination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A

See Tables A.1 and A.2.

Table A.1
List of experts for validation interviews.

Experts	Position and expertise	Organisation
1	Assistant Professor with expertise in International and European Law and Multidisciplinary Approaches	University of Groningen
2	Former manager in IPIN demonstration pilots, and advisor with expertise in energy transition	Energy consultancy
3	Assistant Professor with expertise in end-user practices and Sustainable Urban Development	University of Amsterdam
4	Associate Professor with expertise in Modelling of Innovation Systems, innovation management and entrepreneurship	Eindhoven University of Technology
5	Former Chief Technology Officer with expertise in energy transition on the local, national and international level	Energy consultancy and DSO Stedin

Table A.2
A semi-structured interview guide.

Main Theme	Open-ended questions	No. of resolved discrepancies
Events	Is there any moment identified during the analysis that cannot be considered an event? Do you confirm the causality between events?	7
Functions	Do you agree with the method of mapping events to functions? Is there any event mapped to the wrong function? Is there any need for amending the functions' relationships?	10
Systemic failure	Do you confirm the identified unsatisfied system functions? Do you confirm the identified system failures?	5
Transformational failures	Do you confirm the identified transformational failures? Do you agree with the method of mapping events to transformational failures?	6
Missing event or data	Is there any event that is not included in the analysis? Do you add any events to the ones that have already been identified? Do you add more explanations to the events? Do you recommend any resources for retrieving more events?	14

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