SURVEY REPORT

Transactive Energy in the Dutch Context

Koen Kok[1] | **Aliene van der Veen**[2] | **Sjoerd Doumen**[1] | **Pieter Loonen**[3]

[1]Eindhoven University of Technology (TU/e), Electrical Energy Systems, Eindhoven, The Netherlands

[2]Netherlands Organisation for Applied Scientific Research (TNO), Information & Communication Technology, Groningen, The Netherlands

[3]Netherlands Organisation for Applied Scientific Research (TNO), Energy Transition Studies, Amsterdam, The Netherlands

Correspondence
Prof. dr. J.K. (Koen) Kok
Eindhoven University of Technology
Electrical Energy Systems
PO Box 513
5600 MB Eindhoven
The Netherlands
Email: j.k.kok@tue.nl

Funding information
Topsector Energy – System Integration
Netherlands Enterprise Agency – RVO
Order number: TSE7200006

Date: February 2022.

TOPSECTOR ENERGIE
Empowering the new economy

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

TNO innovation for life

Abstract

Transactive Energy (TE) is an energy management approach combining (local) systems control with market-based interactions to realise a more bottom-up coordination. Parties in a transactive energy system coordinate their actions through automated transactions based on exchange of value, where "value" acts as a key operational parameter.

In this paper, we map out the current state of the art in TE and how it can be relevant for the energy system of The Netherlands. Our analysis reveals key challenges for the implementation of transactive energy mechanisms. The Netherlands has a strong eco-system of industrial and knowledge parties developing or applying TE in some form; a good basis for further developments. This is also shown by the projection on The Netherlands' situation and the corresponding SWOT analysis presented. However, short-term innovation activities are highly problem-oriented at the moment, as the current capacity shortages in electricity distribution demand for quick solutions. On a longer timescale, it is important to avoid strings of piecemeal innovations leading to suboptimality. The long-term opportunity is to develop a fully self-organised and bottom-up coordinated energy system integrating multiple carriers.

KEYWORDS

Transactive Energy, Energy Transition, Energy System Integration.

Contents

Management Summary

Transactive Energy (TE) is an energy management approach that combines (local) systems control with market-based interactions. In different locations in the world, practical and theoretical knowledge has been obtained regarding this approach. Development of transactive energy concepts and technology has been triggered by the decentralization of electricity generation and the subsequent need to decentralize control and coordination in the energy system as well. In the future grid, high numbers of energy consuming or producing devices, currently just passively connected, have to become actively involved in coordination tasks, both locally and on a system-wide level. Transactive energy is a way to realise a more bottom-up coordination by combining systems control with transactions. Parties in an energy system coordinate their actions through automated transactions based on exchange of value, where "value" acts as a key operational parameter.

In this white paper, we map out the current state of the art in TE and analyse how TE can be relevant for the future energy system of The Netherlands. Industrial initiatives and scientific literature are analysed, discussed and compared to provide an overview of the state-of-the-art in transactive energy.

We identified a lack of interaction between academia and industrial pilots. Reports on industrial initiatives barely refer to scientific literature and there are barely any scientific reports published about the industrial initiatives.

Analysis of the scientific literature on the subject reveal five key scientific challenges related to the implementation of transactive energy mechanisms: market design, agent strategies, information and communication technology (ICT), adoption and settlement. Market-design challenges include ensuring market stability and scalability, and the design of mechanisms for multi-objective decision making. Key enablers for agent strategy optimization are good forecasting and risk management. The most important ICT challenges are realising non-functional requirements such as scalability, reliability (including resilience) and security. The three adoption factors have been identified as: integratability in the current system, acceptance and interoperability. Solving these is fundamental for a successful implementation of TE in the real world. The settlement challenge is related to tariff design. The way in which proof of delivery of a flexibility service is established is one of the important open questions.

The Netherlands has a strong eco-system of industrial and knowledge partners developing or applying TE in some form. This is a strong basis for further developments. This is also shown by the projection on The Netherlands' situation and the corresponding analysis of Strengths, Weaknesses, Opportunities and Threads (SWOT) presented in the white paper.

Current short-term innovation activities in this field are highly problem-oriented. The lack of electricity distribution capacity available to connect new (renewable) generation assets as well as new or expanding electricity consuming connections is an urgent problem. It is occurring in a large portion of the country and is hampering the energy transition at the moment. Innovation is now increasingly driven by these acute problems and therefore highly short-term problem-oriented. On a longer timescale, it is important to avoid strings of piecemeal innovation steps. Therefore we advise to stimulate medium-term innovation actions targeted at breakthrough research and innovation designing a future-proof integrated energy (distribution) system. One or more lighthouse projects should develop and field-demonstrate a full end-to-end blueprint for such an integrated energy system that is multi-carrier, multi-scale, and multi-temporal.

Long-term opportunity is to surf the digitization wave further towards a fully self-organised and bottom-up coordinated energy system. Scientific research is needed on how to apply cutting-edge knowledge and technology from e.g. cyber-physical systems of systems, complexity science to create a Web of Energy Cells that allow an dynamic clustering of assets producing and/or absorbing/consuming energy using self-organisation techniques in coordination and control.

1 | INTRODUCTION

1.1 | This document

Through the *Topsector* policy, the Dutch government aims to strengthen the international position of nine industry sectors performing among the world's best. The policy stimulates cooperation between industry and knowledge institutes by making an extra contribution to universities and companies that jointly set up structural research and development projects. Ultimate goal is to get innovative products or services onto the market more quickly.

The Topsector Energy (TSE) is one of these nine top sectors and operates as a driving force behind innovations needed for the energy transition, i.e. the transition to an affordable, reliable, safe and sustainable energy system. Within the TSE, the System Integration (SI) program focuses on system-level innovations as described in the Multi-annual Mission-driven Innovation Program titled "A robust and socially supported energy system" (MMIP 13). Part of this program is the development of knowledge and technology to support a more interactive and intelligent energy system that combines bottom-up and top-down organization, e.g. based on an *holarchic* architecture.

Transactive Energy (TE) is an energy management approach combining (local) systems control with market-based interactions. Development of transactive energy concepts and technology has been triggered by the decentralization of electricity generation and the resulting need to decentralize control and coordination in the energy system as well. In the future grid, high numbers of energy consuming or producing devices have to become actively involved in coordination tasks, both locally and on a system-wide level. Transactive energy is a way to realise this type of more bottom-up coordination by combining systems control with transactions. "Value" is then becoming a key operational parameter, while parties in an energy system coordinate their actions through automated transactions based on exchange of value. In section 2 we provide a deeper explanation of Transactive Energy.

TE makes a good fit with the holarchic approach to energy systems integration. In different locations in the world, practical and theoretical knowledge has been obtained regarding TE. The goal of this study is (i) to map out the current state of the art in TE and (ii) to analyse how TE can be relevant for the future energy system of The Netherlands.

TE research and development has predominantly been targeting energy transition challenges in the electricity system. Hence, defining literature, and also state of the art literature, is mainly focused on applications in electricity. Therefore, we place the electricity system in the center of our investigations. Subsection 5.4 is one of the places in this document where we zoom in on an integrated energy system including other energy carriers.

In this document, we will start out introducing the methodology followed in our survey in the next subsection (1.2). The concept of Transactive Energy is explained in section 2. Then, in section 3, we describe the state of the art in TE on the basis of a number of pilot or operational implementations and the scientific literature. Further, we present a mapping of the eco-system of parties in The Netherlands (section 4), a projection on the Dutch situation (section 5), and a SWOT analysis as compiled with a diverse group of experts during an on-line workshop (section 6). Finally, an advice to the Dutch Topsector Energy is formulated in section 7.

1.2 | Methodology

As explained in the introduction, the goal of this study is (i) to map out the current state of the art in TE and (ii) to analyse how TE can be relevant for the future energy system of The Netherlands. To attain these goals, we executed the following steps:

1. Analysis of a number of European initiatives that each led to a pilot or an operational system with a clear transactive element (described in subsection 3.1).
2. Analysis of scientific publications on TE and identification of the key scientific challenges addressed in this literature (subsection 3.2).
3. Analysis of the gap between the industrial initiatives and the scientific literature (subsection 3.3).
4. Mapping of the eco-system of parties in The Netherlands based on a larger list of projects, alliances and initiatives having a transactive element and aimed at unlocking energy flexibility (section 4).
5. Projection of the results of the previous steps on the Dutch situation, against the wider European background (section 5).
6. Discuss the preliminary outcomes of the above and perform a joint SWOT analysis with a diverse group of experts during an on-line workshop (section 6).
7. Formulation of an advice to the Dutch Topsector Energy for their System Integration Program (section 7).

To be able to map the current state of the art to the future Dutch energy system, we introduce **two axes of Transactive Energy development** (see Figure 1) to describe Transactive Energy solutions introduced in an existing energy system:

- The first axis describes the level of **improved transactive participation and self-organisation**, meaning more consumers and producers are participating in transactive mechanisms and, in that way, are increasing opportunities for self-organisation. If all connected consumers and producers are active (or at least are able to become active) in transactive mechanisms, the solution is said to be *inclusive*. If only larger parties, say, retailers or traders can participate, a transactive mechanism is said to be *exclusive*.
- The second axis describes the level of **improved transactive coordination** meaning that new coordination objectives are resolved with transactive mechanisms. If the solution only provides access to existing markets (e.g. to players lacking access before) it is a *platform-only* solution. If a solution introduces a market-based approach to trade one or more new or more specialized products to balance demand and supply (e.g. more local or on a smaller or longer time frame) we call it a *new market*. New market solutions include:
  - market-based alternatives for grid reinforcement and top-down congestion management / redispatch.
  - markets introducing specialized products e.g. energy with a specific source of origin or location that enables

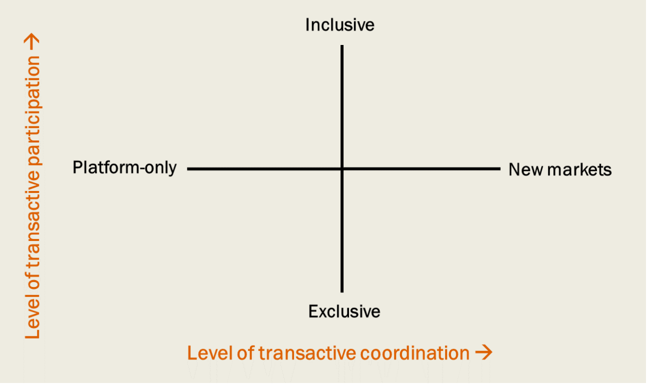

FIGURE 1 Two axes of Transactive Energy development: transactive participation and transactive coordination.

market parties and grid operators to fulfill their (heterogeneous) needs.
- market-based alternatives for grid connection requirements (e.g. power quality, inertia) and contracts (kWMax and transport tariffs).
- Multi-objective market mechanisms introduced to coordinate the optimization of multiple objectives at the same time (e.g. multi-timescale, multi-local or multi-carrier).

Note that, these two axes can only be seen in an existing energy system, since they describe the increase of transactiveness in a system when introducing a mechanism or a change of market rules. We chose this approach since it is not possible to create a uniform scale of transactiveness for all energy systems in the world since energy systems are very heterogeneous: e.g. the market dynamics in two countries with a double-sided auction can be very different under influence of country-specific rules such as regulated tariffs and taxes.

Further, the two axes should be seen as rather descriptive and not as a judgement of a solution. The purposes of the description with the two axes is to make clear what a new platform or mechanism entails: is it a way to increase participation of smaller players or is it an introduction of a new market-based coordination mechanism? In the SWOT-analysis we further look into the pros and cons of both improved transactive participation and improved transactive coordination.

Note further that the number of objectives an approach addresses has been made part of the horizontal axis in Figure 1. Generally, there are always multiple objectives in a TE system, as each market participant has its own reason to participate with a corresponding objective, such as: minimizing energy cost, maximizing revenue from generation or storage assets, etc. Additionally, there will be global and, sometimes, local objectives from the energy-system and (local) network perspectives. TE allows for combinations of these global and local system objectives. The number of objectives could have been chosen as an additional axis in the Figure. We chose not to do so for reasons of simplicity. In section 5.4, we discuss possible coordination objectives in more detail.

In Section 3, the *two axes of Transactive Energy development* are used to plot a number of industrial initiatives implementing a transactive energy solution in existing energy systems and to describe the state-of-the-art in scientific literature. In Section 5 the two directions of development are used to analyse the possible benefits of TE used in the context of the current situation of the Netherlands: what are the starting-points in the Dutch energy system, when is a solution exclusive and platform-only and when is it inclusive and introducing new markets and products? In Section 6, a SWOT analysis is performed for Transactive Energy solution implemented in the Netherlands with a focus on either *improved transactive participation and self-organisation* or *improved coordination*.

2 | WHAT IS TRANSACTIVE ENERGY?

In this section we introduce the concept of Transactive Energy. What does it entail and how has it developed? First the context (energy transition, system integration) is described, second Transactive Energy in this context is defined and compared against alternatives such as price-reactive systems. Finally a short history on the development of Transactive Energy in academia is given and its relation with developments in industry and regulation is explained.

2.1 | The Energy Transition, System Integration and the Electricity Distribution Grid

The transition to a fully sustainable energy system poses great challenges to the energy infrastructures throughout the world. In order to meet targets set in the Paris agreement, large investments, for instance, in renewable energy sources, electrification and system integration are needed. “Energy system integration refers to the planning and operating of the energy system ‘as a whole’, across multiple energy carriers, infrastructures, and consumption sectors” [35]. By linking the main energy carriers in our energy system — electricity, heat, cold, gas, fuels — with each other and with the end-use sectors, the energy system as a whole can be optimised instead of taking measures for energy efficiency and decarbonisation in each sector independently. Further, integrating energy systems is a way to realise the transition in sectors that are harder to decabonize: transport, industrial processes and heat supply, for instance. Energy carrier shifts – to electricity, to green gas – form an important part of this strategy.

The electricity distribution grids are playing a pivotal role in the transition, as distribution grids (1) form a pre-requisite for electrification, (2) are the connecting point for decentralized renewable power generators, (3) enable flexibility and demand management, and (4) are key in enabling customer participation in the energy transition [3]. To harness this potential, the current electricity infrastructure needs to be rigorously re-engineered into an integrated and intelligent electricity system, the so-called smart grid. Hence, the needed investment level for these distribution grids is substantial as well. In Europe alone[1], the required investment in the power distribution grids is estimated to be 400 billion Euros for the 2020 to 2030 time frame [3].

Much of the flexibility potential in the distribution grids is currently still to be unlocked. This flexibility can be utilised for multiple purposes, including energy trade position optimization (e.g., portfolio balancing by Balance Responsible parties), TSO Ancillary Service Provision (e.g., the different reserve markets), and DSO congestion management. Note that all these purposes enlarge the capacity of the energy system to incorporate renewables. Note further that DSOs are having only limited access to flexibility in the current regulatory framework. Managing flexibility in a market-based way provides opportunities to provide market signals to motivate changes in energy supply and demand, and to prioritize the different, possibly conflicting, objectives for which flexibility is utilized.

2.2 | Definition of Transactive Energy

In the future grid, coordination mechanisms have to ensure that high numbers of energy consuming or producing devices, currently just passively connected to the energy infrastructures, become actively involved in coordination tasks, both locally and on a system-wide level. Transactive Energy (TE) has been proposed as a way to approach this challenge in a way that is scalable, efficient and predictable in its operation, while ensuring privacy and customer choice. Because of the challenges arising in the electricity infrastructure as described in section 2.1, research and development related to TE have predominantly been targeting coordination in the electricity system. Hence, the defining literature is geared towards electricity as well.

In [8], a characterization of a TE system is given as follows: “in a distribution-level transactive energy management system, mid to small-sized [energy] consuming or producing devices automatically negotiate about their actions with each other, with devices in the physical network, and with dispatch systems of energy suppliers through efficient and scalable electronic market algorithms”. In the USA, the GridWise Architecture Council adopted the following definition of Transactive Energy: *“a set of economic and control mechanism that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter” [4]*. Key elements of this definition are:

- **Value as a key operational parameter:** This means that “operational decisions are made through an exchange of value-based information captured in transactions between participants” [8]. The value-based information is not limited to money.
- **Combination of control and economic mechanisms:** The transactions made between participants lead to control

[1] EU27+UK

actions regarding electricity consuming, producing or storing devices. Intelligent devices controlling a local system or device take control actions based on economic mechanisms.

- **Across the entire electrical infrastructure:** This means that the definition is valid "from the transmission level with its bulk generation and transport of electricity down to the distribution system and the variety of connected customers." [8]. Note that in locations where well-functioning markets for wholesale electricity and transmission system services are in place, the transmission-level of the electricity system already functions as a transactive energy system. The challenge is to introduce TE in the distribution level of the electricity system as well. The electricity distribution networks exhibit higher levels of complexity with vastly higher numbers of network nodes and connected customers.
- **Dynamic balance of supply and demand:** Hence, timescales are down to, and including, the real time.

It has been argued that the Transactive Energy approach has clear advantages over other types of smart grid coordination, such as direct control, price reactive systems and centralized optimization, in terms of customer privacy, scalability, and efficiency. See the box text below for an explanation. Further, the use of transactive or market mechanisms introduces self-organisation in complex systems of interacting actors. Well-designed market mechanisms yield so-called Pareto optimal outcomes through simple interactions between players in the system though these mechanisms. An outcome is Pareto optimal if there is no other solution that makes the situation for one player better off without making at least one other player worse off. In this way self-organisation emerges on a system level as a result of a multitude of rather simple interactions between actors in the system.

The Transactive approach leads inherently to a distributed software architecture, where local issues are dealt with locally by software that is interacting in its local context, while interacting with the rest of the system using transactions. Multi-agent systems and holonic architectures can be used implementing the TE approach. Further, note that, from the viewpoint of mathematical optimization, market systems are a form of multi-party distributed optimization that yield (Pareto) optimal solutions. Further note that, transactive energy mechanism include both competitive (e.g. double-sided auction) and cooperative mechanisms (e.g. coalition formation such as in [42]) and hybrid forms. Market-based control is used as an equivalent of Transactive Energy (see 2.3), and should therefore be read in a broader context than just competitive mechanism. Especially in smaller markets with less liquidity purely competitive mechanisms are mostly not feasible.

2.3 | Seminal developments

Both in the United States and Europe, TE research has had a strong focus on intelligent agent-based innovation in household equipment and field demonstrations involving grid operators, energy supply companies, power technology companies, and regulators. Seminal work has been performed by two research groups independently, one in the USA [5] and the other in Europe [6]. Both groups developed and field demonstrated similar concepts of *transactive control* or *market-based control* in a power systems context, based on multi-agent systems and double-auction electronic markets. Over the last few years, researchers from both groups are engaging in vision-building and agenda-setting activities related to TE (see, for instance, [8, 9]).

Transactive Energy compared to other distributed energy management approaches

The "smart energy management matrix" has been introduced to classify demand-side energy management approaches and to debate the advantages of TE [8, 7]. This box text is adapted from [8]. The matrix classifies approaches into four main categories, with the vertical axis distinguishing if an approach makes decisions on local issues locally or centrally, while the horizontal axis plots whether an approach uses one-way or two-way communications. Figure 2 shows this matrix with four general classes of energy management approaches filled in: top-down switching, price reaction, centralized optimization, and transactive control and coordination.

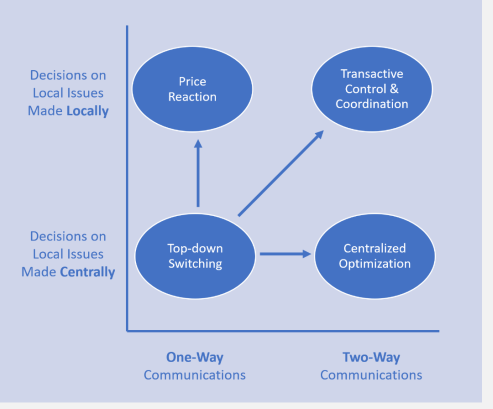

FIGURE 2 The Energy Management Matrix [8]

Top-Down Switching: This quadrant contains the classical demand-response programs where, typically in a certain grid area, one device group is switched simultaneously following a broadcasted signal. This is the simplest demand-response approach, and it has been used successfully for decades in different parts of the world, e.g. to remotely switch off water heaters or air conditioning systems during peak load periods. The approach does not unlock the full response potential of devices, as the device state is not taken into account and expected system reaction can only be estimated through statistics. As a result, the operation is based on worst-case scenarios. Further, the method ignores the consumer altogether. It does not take user preferences into account and interferes with the autonomy of energy consumers.

Centralized Optimization: In this quadrant, local decisions are still made centrally, but communications are two way. Here, a complex optimization engine oversees all flexible demand and supply in the smart grid cluster under consideration (such as a virtual power plant or a local grid segment). Based on available information and taking into account the global and, perhaps, local control goals, the optimizer searches for the best solution for the whole system. All relevant local data need to be communicated to the optimizer, that in a later step communicates control signals or schedules to the field. This type of method is able to fully unlock the response potential of the individual devices and, as direct control is performed, the system-level reaction of the response cluster is known when a response is triggered. The autonomy issue of the top-down switching approach remains, and a privacy issue is added as detailed local information is now communicated. Further, communicating all relevant local information to a central point severely limits scalability. The approach also does not respond gracefully to failures in communications or in the central optimizer.

Price-Reactive Systems The price reaction approach is based on one-way signaling of a dynamic price to end users. At certain intervals, a new electricity price or a price profile for the coming hours is sent to an automation system at the premises. This price profile is displayed for the user, or used by an automation system, to adjust equipment operations. Benefits of this approach include 1) simple one-way communications, 2) no issues regarding privacy or autonomy, and 3) an easily implementable approach in regions having an electricity wholesale market due to the availability of a day-ahead or intraday price profile from this market.

Using the price signal, the operation of responsive devices can be optimized economically by a local intelligent controller that is owned by and/or under the consumer's control. Such a controller would thus be able to increase the consumer's loads during low-priced periods, and generation during high-priced periods, while accounting for device states and user preferences. In this way, the controller has the opportunity to unleash the full response potential. To bill the customer according to the prices signaled, a communicating electricity meter needs to measure usage at a resolution appropriate to track response from the price signal. The recent technology developments in advanced metering are providing solutions to mitigate the privacy risks.

These characteristics have advantages compared to the central optimization case; however, the reaction of a demand-response pool to each price reaction signal is difficult to predict without knowing each device's state and end user's preferences.

Transactive Control and Coordination: The transactive control quadrant offers distinct advantages in integrating flexible devices in the electricity operations. Here, smart homes, buildings, and industrial sites engage in automated market trade with others at the distribution system level and with representation of the bulk system. Communications are based on prices and energy quantities in a two-way negotiation.

Analogous to the price reaction approach, the operation of the flexible devices is optimized economically by a local intelligent controller (or agent) under the control of the end user. This controller receives price information and takes the device state and user preferences into account to operate local demand and supply resources. This is the same as the price reaction approach except that, before the price reaction takes place, the local controller communicates the available flexibility combined with their preferences and conditions to an electronic marketplace through a market transaction (price/quantity bid). Consuming devices communicate their willingness to pay, while producing devices communicate the price for which they are willing to produce.

Since all resources participating in the market communicate their intended reaction to a range of price levels, the pool reaction to a range of price signals is known up front and the market mechanism can determine the price for an appropriate balance of supply and demand. From the end user's or energy consumer's point of view, the local energy management system agent acts on behalf of the user or consumer to bid into the market and reacts to the resulting market price signals. Unlike the centralized optimization approach, no direct outside control is involved here. However, from a system perspective, the participants engage in coordinated control actions. With this approach, demand response moves from influencing, with an uncertain overall response, into market-based control with a collaboratively derived dynamic price as a control signal to trigger a predictable system reaction. This is why this approach is sometimes referred to as market-based control or transactive control. A highly scalable system is obtained when the bids are digitally represented such that bids can be aggregated together. The processing and communication time then scales with the height of the aggregation tree instead of with the number of devices participating. Further, the approach protects the end user's privacy as the bids communicate only information about energy quantities and prices. When these bids are aggregated on the level of a house, a building, or an industrial site before being communicated externally, the information exchanged is comparable to that of a metering system collecting near-real-time data as described for the price reaction approach above. And unlike the centralized optimization approach, no complicated models of the devices, consumer behavior, or preferences have to be exchanged or maintained.

In summary, TE approaches are able to access the full response potential of flexible devices, provide greater certainty about the momentary system reaction, realize an efficient market with proper incentives, and protect the privacy of the end user whose devices participate in the energy management task.

3 | STATE OF THE ART OVERVIEW

In this section, industrial initiatives and scientific literature regarding TE applications in the electricity sector are analysed, discussed and compared to provide an overview of the state-of-the-art: what is the current status of the development of transactive energy solutions in existing electricity systems and what are the open issues?

3.1 | Industrial Initiatives

In order to analyse industrial initiatives leading to TE implementations, a search has been conducted into European industrial initiatives. Criteria for inclusion:

- The initiative has led to a field implementation (e.g. a demonstration or pilot) or is a development towards a commercially operational system.
- The initiative has a clear transactive element: operation is based on agreements regarding energy or service delivery.
- Detailed and publicly available information is available describing the initiative's setup and mechanisms.

Although this overview isn't exhaustive, the initiatives presented here give insight in the current developmental directions followed by industry parties and energy communities in Europe.

3.1.1 | GOPACS

The Grid Operators Platform for Congestion Solutions (GOPACS) is a software platform aimed at mitigating capacity shortages and solving congestion in the electricity infrastructure at any voltage level. In the initiative, the Dutch TSO Tennet cooperates with the four larger DSOs in the Netherlands: Stedin, Liander, Enexis, and Westland Infra.

The GOPACS platform is designed to operate in synergy with one or more intra-day market platforms. The idea behind GOPACS is to add locational information to the orders on the intra-day platform, such that the orders can be used for redispatch actions solving congestion. Initially, the Energy Trading Platform Amsterdam (ETPA), developed and operated by a company with the same name, served as the sole counterpart platform. GOPACS is mainly targetting congestion management in the transmission and mid-voltage network levels.

To understand the working principle of GOPACS, one needs to understand the trade process of an order-book market, the market mechanism predominantly used by European intra-day markets. In an order-book market, buyers

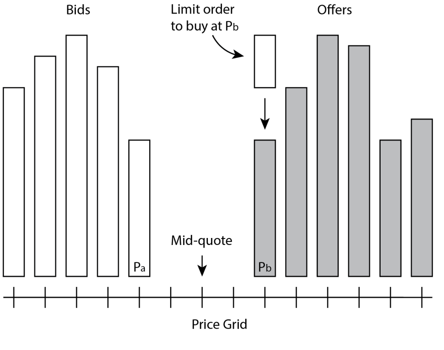

FIGURE 3 The working principle of an order-book market (adapted from [40]).

and sellers are able to place limit orders into the market's order book. Limit orders are bids or offers for a specified commodity volume against a specified price or better. Hence, the stated price is a price limit for the order. Order-book markets implement a form of continuous trade as bits and offers are matched as soon as prices match. In other words, if the best buy order has a higher limit price than the best sell order, these are matched, resulting in a transaction against the price of the sell order, as shown in Figure 3. The orders involved are then removed from the order book and any remaining volume of either the buy or sell order is placed back as a new order against the same price. As possible matches are made as soon as the involved orders are placed in the order book, there is always a price spread between the current best buy and best sell orders. Generally, intra-day electricity markets implement an order-book mechanism for each trading time slot that is open for trades, with slot lengths typically being 15 or 60 minutes. Trade starts when the day-ahead market closes and trade happens continuously until close to the start of each time slot.

GOPACS has been designed as a separate platform that interacts with one or more intra-day market platforms. As a prerequisite, the intra-day platform should allow for traders to add locational information to their orders. Newly entered buy and sell orders having locational information are duplicated into GOPACS and kept up-to-date. As a result, the GOPACS platform holds an order book with locational bids and offers that is always showing a price spread. If there would be a match between a buy and a sell order, the match would have been made in the original intra-day platform leading to removal from GOPACS. The involved DSOs and TSOs use load-flow calculations combined with a continuous forecasting process to identify upcoming congestions. Identified congestions are then registered in the GOPACS platform and the platform then selects and exectutes two or more trades that together solve the congestion.

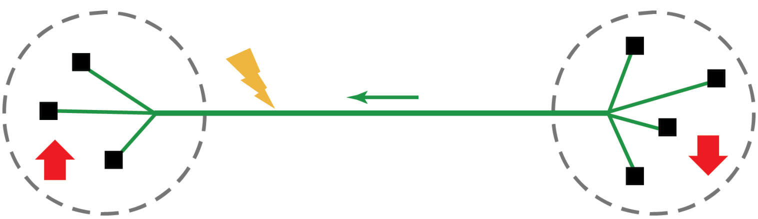

FIGURE 4 Example of an expected network congestion in a tie line between two regions. Figure adapted from [10].

As an example, imagine a network congestion expected few hours in advance for a certain time slot by a distribution network operator (DSO), as depicted in Figure 4. After entry of the details of the congestion in GOPACS, that platform selects one or more sell orders in the order book located in the area behind the congestion point that together solve the expected congestion. That is the left-hand-side region in this example. Then, to restore the system balance, it selects one or more buy orders in the rest of the system for the same energy volume. Per definition, there is a price spread between the selected buy and sell orders indicating the cost for the DSO to let the orders execute and, as a result, solve the congestion [10].

3.1.2 | Quartierstrom Walenstadt

In the Quartierstrom project, a local energy market (LEM) has been piloted in the Swiss town of Walenstadt from 2019 to January 2020. It included 37 participating households including 27 prosumers with a total combined PV capacity of 280 kW and a lithium-ion battery storage capacity of 80 kWh [11, 26, 27]. Using blockchain technology, peer-to-peer trades of solar energy were made within the neighborhood, in this way, allowing participants to buy and sell locally produced solar electricity. The pilot aimed to determine the technical feasibility of a local market and to test the participation and willingness-to-pay of consumers/prosumers.

Key functionality of market design was the possibility for participants to change their own electricity purchase and selling price. The market runs decentralized on a mesh of prototypical smart meters, capable of measuring current, voltages, and frequencies on each of the phases. The meters have been supplied to the participants for this study. On the smart meter, a price slider is implemented with which regular consumers set a maximum purchasing price and prosumers also set a minimum selling price. On top of that, both indicate a willingness to purchase local electricity from neighbours. Every 15 minutes the smart meter creates a bid based on the user's limits and the current electricity consumption. The bid is collected by an order book. In this order book, the bids are ordered from lower to higher sell price and higher to lower buy prices. Bids have a duration of 15 minutes and 15 minutes is also the frequency at which the market is cleared and trades are allocated. Blockchain technology was used for the validation of transactions and settlements, as this would not necessitate a central authority and is scalable to a large number of participants.

The LEM only operated locally. If energy demand could not be supplied locally, the energy was acquired via a utility company [12]. The LEM did not allow for participation in the balancing markets. The goal of the LEM was not to alleviate grid congestion, but trading energy locally could have a positive impact on the congestion. The purchase of locally produced solar power almost doubled. The 37 households covered 33 percent of their electricity demand with solar power produced in the neighborhood. The participating households played a very active role and perceived the electricity market as green, local, and fair.

As the pilot only contained 37 households, it is difficult to make generic conclusions. However, the activity of individuals in the pilots showed interest in the market activity meaning that the concept of a local P2P market could be accepted by the general population [12]. Furthermore, future LEMs should implement a combination of possible agent types which users can select ranging from bidding on behalf of users or full user control. Finally, in a questionnaire, users indicated that they support the general concept of P2P LEMs and have recommended the concept to others.

3.1.3 | Cornwall Local Electricity Market

By creating a local virtual marketplace, the LEM initiated in Cornwall mainly aims to improve grid reliability, make electricity trading inclusive, reduce carbon emissions, avoid investments in grid upgrades, and improve the procurement of flexibility [13, 25]. The project contains a wide range of DER's and more then two-hundred participants (one-hundred businesses and one-hundred residents).

The market is based on a peer-to-peer (order book) energy sales between participants, TSO, and DSO. For residents, this is an automatic process. Offers can be made months in advance in block orders or as hourly day-ahead offers. There is also a quarterly based intraday market. Offers will have a locational tag connecting them to a node in the grid to determine the nodal pricing. The transactions in the Cornwall Local Energy Market pilot are real and tracked using a private blockchain.

The TSO can purchase flexibility from the LEM and use it in the balancing markets but the LEM is not fully integrated in the balancing market. Part of LEM's goal is to alleviate grid congestion and this is achieved with the local day-ahead and intraday market.

3.1.4 | FUSION

FUSION is a local market pilot for large consumers/producers that is planned to go live in 2021 in East Fife, Scotland. FUSION is based on the Universal Smart Energy Framework (USEF), which is a flexibility market architecture integrating prosumers, aggregators and distribution system operators in the existing electricity markets. FUSION is focused on alleviating congestion by activating flexibility bids, reducing the need to upgrade grid infrastructure [29, 28]. The focus is on extending the normal (green) operational mode of the power grid by managing capacity by requesting local prosumer flexibility (the yellow regime), following the USEF operating regime definitions [30].

Bids are based on the USEF framework and use USEF's D-programs for bidding purposes. D-programs are prognosis profiles that take grid topology into account and do not have to be balanced. These D-programs can be contractually arranged or can take on the form of free-bids (FlexOrders). D-programs are determined iteratively. Firstly, D-programs are submitted at 11:00 am the day before with a 30-minute settlement period. Secondly, the list of congestion points is determined. Finally, the D-programs are updated, and the process repeats.

FUSION does not allow participants to join the TSO's balancing markets but does alleviate grid congestion by implementing the green and yellow operating regimes determined by USEF. The pilot does not focus on small-scale end-participants, the LEM is rather connecting larger parties too small to participate in the existing markets individually.

3.1.5 | EPEX Enera

Enera is a local energy market in the area around the German city of Emden that is used complementary to the wholesale and balancing markets. Enera uses the traffic light concept. The green light means that flexibility is offered by aggregators for portfolio optimization in the wholesale market. During yellow light, flexibility is requested by TSO's and DSO's on a contractual basis in local order. Finally, in the red operating phase, flexibility is controlled without a contractual basis. The market framework used is an extension to the EPEX SPOT intraday continuous market and is complementary to the German wholesale and balancing markets[16].

3.1.6 | GridFlex Heeten

GridFlex Heeten is a LEM pilot that ran from 2017 to 2020 in the Dutch town of Heeten [19]. The project included several project partners including Dutch DSO Enexis and the University of Twente. As investing in grid infrastructure is expensive and the extra capacity often remains unused, the goal of the project was to alleviate congestion by shifting consumption to moments with less consumption. The pilot included one community of 47 households of which 100% participated in the pilot. According to the project partners, this pilot was the first to test two different network tariffs models and the first to include sea-salt batteries in a real-life scenario.

The congestion was managed by persuading participants to shift behavior to less congested moments by basing the network tariff on the network congestion. Also, the pilot allowed excess energy to be stored in the sea-salt batteries. Two different network tariffs were used, one only varied the networks transport tariff (note not the networks connection tariff), while the other also set a fixed price of 20.5 cent per kWh on excess solar energy that was sold within the community. Participants received a tariffs prediction for the next 24 hours which was determined by running simulations.

Several important lessons learned from the pilot are to involve partners from the start, the importance of testing in real-life (the simulation had to be tweaked during the pilot) and the behavior of participants can only be partially predicted and remains uncertain. Finally they found that ransport tariffs alone are not enough to profoundly adjust consumer behavior though an effect was still noticeable: the transport tariffs are just a small portion of the energy bill of residential prosumers.

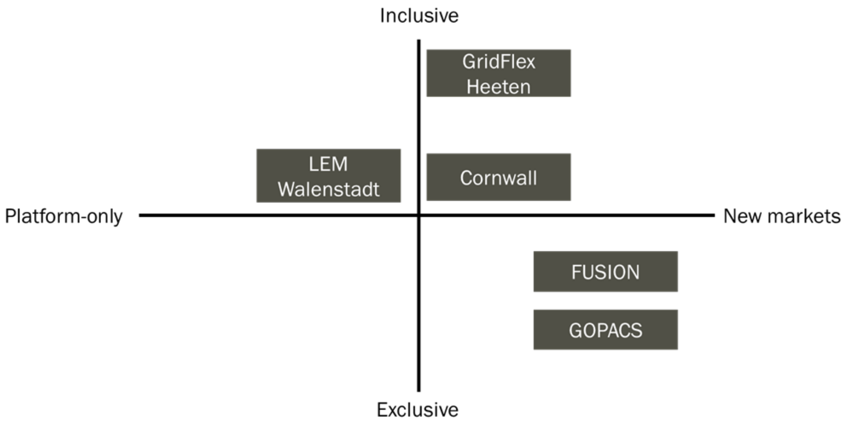

FIGURE 5 Mapping of the industry initiatives on the two axes of Transactive Energy development.

3.1.7 | Findings

Reflecting on the described industrial pilots it can be stated that most pilots focus either on market participation or introduce a transactive solution for a coordination problem. For the Quartierstrom Walenstadt project, the goal was market participation and for GOPACS, Enera and Fusion the main goal was to solve congestion problems by a market unlocking local flexibility instead of reinforcing the grid.

Cornwall combines the two objectives by introducing a continuous auction on which consumers, producers and grid operators can buy and sell. Heeten has a strong focus on inclusiveness but the grid congestion issue is reflected in the grid fee of the community: it implemented in the market as a constraint.

3.2 | Scientific Literature

To explore the open issues in Transactive Energy from a scientific perspective, research problems addressed in selected publications were collected and translated into the scientific challenges presented. The list of scientific challenges is a result of a literature survey on IEEE[2] papers published before 2019 (See Appendix for the list the papers). IEEE articles containing the word combination *'transactive energy'* were selected for the survey. The 'IEEE Explorer' database found 112 results[3]. In addition, we have selected some (early) works on market-based control and transactive control and some articles published elsewhere that we regard as relevant works in TE. A second broader selection was made by searching for *'transactive'* and *'energy'* in IEEE Explorer and Google Scholar. This selection was scanned based on title. If a title did address a problem that was not found earlier, it was added to the selection.

This analysis revealed five key scientific challenges related to the implementation of transactive energy mechanisms: challenges related to market design, agent strategies, information and communication technology, adoption and settlement. We will briefly discuss each of these challenges in the following subsections.

[2]The Institute of Electrical and Electronics Engineers is the largest publisher of scientific papers and articles related to (smart) energy systems.
[3]search date: November 11, 2018

Market design challenges

Market design challenges concern the problem of social welfare optimization in a transactive energy system: how to ensure the economic optimization of the whole system when dealing with multiple heterogeneous objectives of various stakeholders, uncertainty, a continuous-time world, and intelligent transacting parties?

> **Economic social welfare** is economic well being expressed in terms of the sum of consumer and producer surplus. Consumer surplus exists whenever the price a consumer would be willing to pay in terms of their expected private benefit is greater than they actually pay. Producer surplus exists when the price a producer would be prepared to supply at is less than the actual market price[a]
>
> [a]Definition from: https://www.economicsonline.co.uk/Definitions/Economic_welfare.html.

As introduced in 2.2, the toolbox of market design researchers include both competitive and cooperative mechanisms. For both types as for hybrid mechanisms researchers study the effectiveness in terms of social welfare for example by measuring the Pareto efficiency: when an economy has its resources and goods allocated to the maximum level of efficiency, and no change can be made without making someone worse off. See for example [36].

Market design challenges are mentioned widely in scientific literature. Below the challenges we identified in literature survey:

- The *multi-objective decision making* (MODM) challenge concerns the prioritization and valuation of heterogeneous objectives of different agents which should be taken into account in the social welfare optimization. An important aspect of MODM is how to deal with objectives over time: when decisions are made have influence on the social welfare optimization.
- *Ensuring market stability* is the challenge of finding a proof that a market design leads always to social welfare optimization. This implies that it should be a stable solution at all times which is not impacted by gaming or system-related effects e.g. load synchronization and undesirable power oscillations. Pre-condition for Pareto efficiency, and thus social welfare, is competitiveness of the market. In a competitive market, individual actors cannot influence the price (they are tne said to be price takers) and, thus, are not able to game the system for their own interest. If there are limited numbers of players, or if there is a limited group of players with high market power, the markets is not competitive.
- The challenge of *coordination of scale* is about how to ensure that a market is designed such that social welfare optimization is still guaranteed when parties of various scales are active in a market of limited size.
- The market design challenge of *dealing with future events* concerns uncertainties of timing (when), load (kW) and volume (kWh) of consumption or production driven by external forces (e.g. weather, behavior of people or wholesale market clearing) but may include events triggered by internal market forces, such as rebound effects (turning of a process at one point in time will result in extra consumption later).

The market design challenges can be mapped on the two axes of Transactive Energy development, see Table 1. Coordination of scale is typically a challenge for transactive solutions that improve the transactive participation. Multi-objective decision making and dealing with future events are related to improved transactive coordination. Ensuring market stability is relevant for both developments: stability of a mechanisms changes with both improved participation and with improved coordination.

Agent strategy challenges

Whereas the market design challenges focus on the optimization over all objectives, the challenges of *agent strategies* focuses on optimization of the objectives of individual parties to transactions. In most transactive market designs,

Market design challenge	Transactive Energy development
Multi-objective decision making	improved transactive coordination
Ensuring market stability	both
Coordination of scale	improved transactive participation
Dealing with future events	improved transactive coordination

TABLE 1 Market design challenges mapped on the two axes of Transactive Energy development.

a certain degree of intelligence in transactive parties is assumed, based on the assumption that the market design aligns commercial interests with the overall social welfare. In some market designs, aggregation of several transactive parties ('cooperatives') increases the social welfare by reducing the risks of single parties.

The core challenge of agents is *optimization* of their strategies given the characteristics of the assets in a portfolio, the trade rules of the various markets, the forecasts for behavior of other parties in these markets, the forecast of net load, generation and flexibility of bids in the portfolio [77] and the risk profile of the portfolio manager. Important enablers for a successful optimization strategy are good *forecasting* and *risk management*.

ICT challenges

On the one hand, market design implies technical requirements of both communication infrastructure and single components; on the other hand, the ability to have fast and reliable interactions and transactions expands the efficiency of the market. The more advanced the solutions to the technical challenges *scalability*, *reliability* (including resilience) and *security* are, the more effectively TE can be used.

The *scalability* challenge concerns the operational problem of overcoming performance bottlenecks when increasing the scale of either a market design or an agent strategy. The challenge of *reliability* of is about metering and communication processes in TE systems. Since two-way communication is a key characteristic of TE systems, communication failures and lack of information (e.g. metering data) may have negative impacts on social welfare, or even cause a total failure of the system. The consequences of inadequate *security* are similar to the consequences of a limited reliability, ranging from negative impacts on social welfare to a complete failure of the TE system.

Adoption challenges

The three adoption factors *fit to current system*, *acceptance* and *interoperability* are challenges that are less fundamental from an academic perspective, but solving them is fundamental for a successful implementation of TE in the real world. This even means that a less optimal solution to one of the 12 other challenges may be preferred when the adoption factors are considered.

The challenge of *acceptance* addresses the problem of evaluating the conditions under which decision makers are willing to adopt the TE system. Solutions have to fit with the values of a society e.g. about fairness ('no discrimination bias'), ownership of problems ('The causer should pay') and energy as a basic need ('society should ensure everyone can consume enough for basic living').

The challenge of *fit* of TE solutions to *existing* systems addresses whether the participants are able to adopt a TE system. For example, is the TE system compliant with grid tariffs regimes or wholesale market trading rules?

Finally, *Interoperability* is seen as a key enabler to the wide-spread adoption of TE systems. The design of a generic framework that can be applied in many situations is viewed as particularly difficult given that it is already a challenge to design a TE system for a specific (local) situation.

Settlement challenges

Design of the settlement mechanism is often referred to as the *tariff design problem*. This is the problem of 'designing the process where costs of especially regulated business are determined and allocated to customers according to a chosen procedure' [38]. Using a mechanism for optimization of social welfare (the domain of TE market design) is a choice that can be implemented in the tariff design and on the other hand in a (transactive) market design one can take into account the final tariff structure.

The scope of tariff design includes the choice for resolution, nature of the pricing (fixed, varying based on location and/or time) and the costs basis (i.e. future investments in the grid or in (renewable) production and storage facilities). The problem of tariff design is broader than Transactive Energy, however with the introduction of transactive control especially when used for local balancing or grid constraint management an adjustment of the tariff design is probably desirable.

Before defining a tariff design problems the social fundamentals of the transactive parties in the system (the society) should be defined, which is a challenge on its own: the adoption challenge *acceptance*.

Another vital element of the settlement process is the challenge of *quantification of delivery*: the measurement and verification of delivery of energy or an energy service. Metering is an important aspect of the quantification, but investment in appropriate meters for grid-edge devices is mostly not worth it, so alternative quantification methods are explored in the scientific literature e.g. using distributed ledger technologies for registration and calculation of delivery using static rules and statistical approximation [51].

The quantification of delivery is especially difficult for demand side flexibility: when a market participant offers flexibility it is difficult to see if the flexibility was offered because more activity happens behind one meter: it hard to differentiate between regular consumption and offered flexibility. Several methods exists that allow the determination of a baseline each with advantages and disadvantages [18]. There is, however, also a detailed study that suggests that baselines are not suited for local energy markets and a different mechanism should be used [32].

3.3 | Gaps identified

From the brief review on the industry initiatives and the scientific literature we have identified a few gaps between industry and science. Further, we identified a number of general knowledge and developmental gaps. We list those below:

- In scientific studies market algorithms are focusing often on multi-objective decision making while in industry only one to two objectives are taken into account.
- Market design challenges are not mentioned in industrial initiatives e.g. market stability, coordination of scale and dealing with future events.
- The way settlement is done in local energy markets (LEMs) is an important question that is still under debate [32]. How is a demand side response quantified? How is proof of delivery of a flexibility service established? Often these questions aren't answered in pilot reports or in scientific studies.
- ICT challenges are barely mentioned by the industry initatives. Only Quartierstrom Walenstadt has provided a scientific publication on scalability and communication challenges [43]. They found that for their blockchain local energy market enough bandwidth is a prerequisite.
- Pilots often neglect the possibility of market manipulation by participants. As with regular markets, it is possible to manipulate electricity markets. For example a false data injection, where the aim is make market operations inconsistent or gain extra benefits by tampering with measurements [23].
- Industry initiatives are often not fully integrated in the energy system e.g. a coupling with the balancing markets is

lacking, or an energy supplier is still representing the local energy market in wholesale markets. Fit to the current system is therefore still a challenge in up-scaling of many pilots.

- Study of social aspects such as customer acceptance is still open for more research. User acceptance has been studied by Quartierstrom Walenstadt [44] and GridFlex Heeten [19].
- Most initiatives identify legal barriers but none of the projects studies legal aspects in detail. Co-development of regulation and TE solution would be a way to solve the adoption challenge 'fit to current system'.
- Interoperability is barely discussed in both the industry initiatives and scientific literature on local energy markets, which indicates a split between initiatives and experts working on interoperability and on the design of TE solutions.
- In general, we identified a lack of interaction between academia and industrial pilots. Reports on the industrial initiatives barely refer to scientific literature and there are barely any scientific reports published about the industrial initiatives. Also the consortia of a number of the industrial initiatives listed lack scientific institutes. Initiatives having an active scientific partner yield scientific publications providing an more in-depth view in key aspects and outcomes of the pilot.
- The lack of industry-scientific interaction (see the previous point) has resulted in a lack on reporting on industrial pilot results. A reason could be that pilots are still running, however.

4 | ECO-SYSTEM

For an overview of the ecosystem in The Netherlands, we first focus on the electricity sector as there are ongoing initiatives involving TE. At the end of the section, we zoom in on other energy carriers as well.

4.1 | Electricity

To map out the NL ecosystem in TE as applied to the electricity system, we first list projects, alliances and other initiatives involving the electricity system and exhibiting two characteristics: 1) having a clear transactive component, and 2) unleashing distribution-level flexibility. Then we categorise the parties involved.

NL projects, coalitions and initiatives:

- **The Flexible power Alliance Network (FAN)** is an industry coalition that aims to provide open standards for unlocking flexible energy in energy systems. The FAN develops and promotes open standards (currently mainly the Energy Flexibility Interface, EFI), stimulates project developent and organises the FLEXCON conference. Parties: Stedin, Enexis, Alliander, TNO, EXE, Enshared, Nieuwestroom, Ecovat, Recoy, NVDE, Senfal, SmartEn, Technolution, TenneT, Dutch Heat Pump Association.
- **the USEF Foundation** is an industry association developing and promoting the Universal Smart Energy Framework (USEF). This framework is designed to provide a "flexibility market design for the trading and commoditisation of energy flexibility and the architecture, tools and rules to make it work effectively." USEF has been applied in pilots in The Netherlands and abroad. Parties: Alliander, Stedin, ABB, DNV, IBM, ICT Automatisering, Essent.
- **The Grid Operators Platform for Congestion Solutions (GOPACS)** is a software platform used by grid operators to solve congestion in the electricity infrastructure both at the transmission and the distribution levels. GOPACS is an initiative of the Dutch grid operators: TenneT, Stedin, Liander, Enexis and Westland Infra. The other Dutch DSOs Enduris, Coteq and Rendo, support this initiative. ETPA has been involved in the development of the platform.

- **Energy Traders and Energy Service Companies developing demand response in NL** include: Scholt Energy, Priogen, Centrica Business Solutions, ENGIE.
- **Interflex Demo Strijp-S:** InterFlex was an Horizon 2020 financed project that investigated the use of local flexibilities to relieve distribution grid constraints. The Dutch part of the consortium performed a demonstrator in the Strijp-S living lab are in the city of Eindhoven. Dutch parties involved: Enexis, ElaadNL, TNO, Jedlix, Sympower, Croonwolter&dros and TU/e.
- **GridFlex Heeten** was a smart energy community project that, amongst others implemented and tested a local energy market aimed at matching local demand, supply and local energy storage. Partners: Enexis, Energie Coöperatie Endona, UT, Enpuls, ICT Automatisering, Escozon, Buurkracht, DrTen.
- **GO-E** (Built Environment Electrification) is a nationally funded research and development project investigating whether smart flexibility services can offer an alternative for strengthening the electricity grid in the built environment. Parties: Alliander, Enexis, Stedin, ElaadNL, Greenchoice, Recoy, Itho Daalderop, ETPA, Technolution, Phase to Phase, DNV GL, Witteveen + Bos, TU Eindhoven, TU Delft, TNO.
- **TROEF** is a nationally funded research and development project investigating bottom-up energy exchange. Parties: AM, Royal BAM Group nv, ENTRNCE International, KPN, OrangeNXT, Stedin Netbeheer, University of Applied Sciences Utrecht, NEN, Eindhoven University of Technology and Tymlez
- **Equigy**: TenneT, IBM.

We see the parties involved fall in seven broad groups. Below we list the parties mentioned above per category and in alphabetical order.

- **Grid operators:** Alliander, Coteq, Enduris, Enexis, Rendo, Stedin, TenneT, Westland Infra.
- **Market participants:** ENGIE, Essent, Greenchoice, Nieuwestroom, Priogen, Recoy, Scholt Energy.
- **Market operators:** ETPA.
- **Platform operators:** Centrica Business Solutions, EXE, Senfal, Jedlix, Sympower, Entrance.
- **Enabling Technology Providers:** ABB, DrTen, Ecovat, IBM, ICT Automatisering, Itho Daalderop, Phase to Phase, Technolution, KPN, OrangeNXT.
- **Consultancy Firms:** Croonwolter&dros, DNV, Enpuls, Escozon, Witteveen+Bos.
- **Knowledge and research:** Delft University of Technology, Eindhoven University of Technology, TNO, University of Twente, the NL Universities of Applied Science.
- **Standardization**: NEN.
- **Other**: Buurkracht, Dutch Heat Pump Association, ElaadNL, Energie Coöperatie Endona, Enshared, NVDE, AM, SmartEn, BAM.

4.2 | Other energy carriers

A similar analysis for transactive techniques used for other energy carriers is hard to perform, as there are hardly any initiatives targeting the distribution infrastructures and having a clear transactive component. Some early developments using TE for heat systems focused on optimizing energy flows in buildings, e.g. [1]. However, to our knowledge, there is no active R&D line following up these developments.

Therefore, we list a number of parties cooperating in projects and alliances that could be involved in a TE-based project either involving heat, gas, or integrated energy systems. This list is not meant to be exhaustive.

- Energy-sector parties cooperating with, in and around harbours. Harbours including the Port of Rotterdam, Port of Amsterdam, and Groningen Seaports.

- The 38 participants in the Warming UP Collective: heat-supply companies, technology providers, municipalities, knowledge partners.
- Parties involved in operation and expansion of heat networks: Gasunie, WarmtelinQ, Eneco, ENGIE, HVC.
- Knowledge Parties: TNO, PBL, TU Delft, TU Eindhoven.

5 | PROJECTION ON THE NETHERLANDS

5.1 | Projection

Various transactive coordination mechanisms can be found in today's Dutch electricity system e.g. for wholesale energy markets, balancing markets and some solutions for congestion management.

From the perspective of small consumers and producers the energy market is not transactive, they are exposed to mostly flat and sometimes dynamic prices and have no interaction with the transactive mechanisms such as the wholesale market. With the current 'supplier model' it is in general not possible for small consumers to be active on energy markets directly or via a broker/retailer other than their energy supplier.

Improving the transactive participation in the Dutch energy system means therefore that a Transactive Energy solution is introduced that provides abilities to smaller consumers and producers to participate in transactive energy mechanisms i.e. energy markets. This either entails direct participation in existing energy and balancing market or participation in new markets e.g. operated by wholesale market participants. Transactive mechanisms operated by energy suppliers are an improvement in inclusivity (as explained in 2.2 such a hierarchical model can lead to social welfare optimization), but probably this does not provide consumers the ability to employ their transactive behavior fully (see 2.2). When implementing a regulated structure for transactive participation (new Dutch energy legislation, "Energiewet") one should take into account the heterogeneous objectives of consumers (for example, kWMax and self-consumption objectives).

Improving the coordination by introducing transactive energy solutions means solving more problems via transactive mechanisms. In the Netherlands we see most opportunities in the DSO-domain and local market domain since 1) the TSO / national market domain is already to a large extend transactive (however inclusivity can be improved) and 2) the number of issues (especially congestion) are growing in the DSO-domain. Since the DSO-domain is the domain of smaller consumers and producers, solutions to improve coordination should also improve the transactive participation of these parties.

We see also a need for multi-objective mechanisms, solving multiple objectives that use the same solution space or can have a negative impact on each other. For example, the combination of congestion management and balancing management has conflicts [41], [39]. Coordination between grid operators is critical here and a multi-objective mechanism can provide an effective and transparent solution.

5.2 | Changes foreseen with the EU Clean Energy Package

In 2019, the European Commission issued a directive aimed at implementing the Energy Union Strategy described as 'enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers'. This directive is known as the 'Clean Energy package' (CEP) [34]. Two of the five main elements of the package are relevant regarding transactive energy system: (i) a smarter and more efficient electricity market, and (ii) more rights for consumers. The result is that the European Energy Market has adopted already openings for the implementation of Transactive Energy by:

- including the introduction of new roles in the electricity system: e.g. aggregators, energy communities, active prosumers
- defining market-based solutions as preferred for either supply, balancing, redispatch, transport capacity, congestion management. In general, the CEP states: 'Core market principles should set out that electricity prices are to be determined through demand and supply. Those prices should indicate when electricity is needed, thereby providing market-based incentives for investments into flexibility sources such as flexible generation, interconnection, demand response or energy storage.'

Hence, the Clean Energy Package includes elements that drive national regulations to include more transactive mechanisms in their energy system, both regarding improvement of transactive participation and self-organisation as regarding improved transactive coordination.

The Dutch regulator has published the first draft of the new energy regulation (Energiewet) implementing the latest European directives. Regarding improvement of transactive participation and self-organisation the following elements are relevant:

- Consumers have the right to be active meaning that their energy supplier should allow them to produce for own consumption, store energy and sell and supply energy to other consumers independently or in a group and as part of an energy community (*Artikel 2.1.4 actief worden*). This article directly prescribes to improve transactive participation.
- Residential and small commercial consumers can assign a Balancing Responsible Party (BRP) other than their energy supplier. (*Artikel 2.2.9 aanvullende eisen leveringsovereenkomst i.v.m. balanceren*). This article enables more self-organisation.
- Consumers can contract a second energy supplier. (*Artikel 2.1.1 rechten eindafnemers tav leveren*). This article increases the options for consumers to contract energy service providers and so it enables more self-organisation.
- Consumers can contract an independent aggregator (independent from their supplier) that aggregates demand response or energy produced by prosumers. (*Artikel 2.1.2 aanvullende rechten eindafnemers van elektriciteit tav aggregeren*). This article increases the options for consumers to sell their own production on the wholesale market or to sell their demand response services and so it enables more self-organisation.
- Grid operators should collaborate towards optimal, safe an efficient management of the energy system in a way that secures and stimulates effective participation of market participants. (*Artikel 3.5.2 samenwerken*) This article underlines the articles above by making grid operators partly responsible for the improvement of transactive participation and self-organisation.

Regarding improved transactive coordination the proposed Energiewet defines a clear preference for applying market-based solution (above central optimization and tariff solutions) for congestion, balancing and other grid management proposes in the electricity system:

- Grid operators buy energy and energy (flexibility) and capacity services in case of congestion, balancing or in case the grid can be operated more efficiently or to balance grid losses. Procurement of these products or services should be done in a transparent, non-discrimination way and via a market-based procedures that facilitates the participation of all possible market participants (*Artikel 3.4.15 congestie en inkoop flexibiliteit elektriciteit + Artikel 3.4.18 balancering TSB elektriciteit sub 3 + Artikel 3.5.3 aankoop NFOD elektriciteit*)
- Storage should be operated by a commercial party (and not a grid operator) where possible. (*Artikel 3.3.9 ontheffing opslag door transmissie- of distributiesysteembeheerder*)

With these articles the grid operators are pushed to improve the transactive coordination in the grid and are even made responsible to secure inclusivity in these new transactive mechanisms.

With the new Energiewet we expect that there will be more possibilities to develop Transactive Energy solutions either for improving transactive participation or improved coordination. However, specific lower legislation and market rules need to be adapted or developed to pave the path for improvement of both transactive participation and self-organisation and transactive coordination.

5.3 | Expectations

On the short term, i.e. in the next one to five years, we see a need for the development of a multi-objective mechanism for small prosumers. This enables small prosumers to enter the wholesale market and balancing markets and allow then to aide in solving congestion problems. The number of congestion issues is growing and the new energy regulation requires that smaller consumers can enter the wholesale and balancing markets. Whether a completely transactive mechanism is the best solution should be investigated. An alternative to a fully transactive mechanism is for example a combination of an inclusive platform for balancing and wholesale markets combined with dynamic or bandwidth tariffs from the DSO.

Another short term development is energy communities supporting the grid operator. If an energy community is able to solve a congestion problem it should be enabled to do so. Whether energy communities are capable of solving the problems at all time (e.g. during summer holidays or cold winter conditions) and what risk they should take is up for debate.

Longer term developments include more daily grid constraint management that extends the life time of the grid or is part of the grid design (use of flexibility e.g. battery management becomes part of normal (daily) grid operation). In such scenario, the relation between grid users and their grid operator will change drastically and transactive mechanisms can shape this new relation. In such a new relationship grid connection agreement will also change and transactive mechanisms can provide also a solution to align the availability of transportation capacity on the longer term.

Another possible long term development is a change from grid requirements for assets and grid connections to transactive mechanisms that coordinate joint requirements (e.g. grid inertia).

5.4 | Transactive Energy for an integrated energy system

As we wrote in section 1.1, TE research and development has predominantly been targeting energy transition challenges in the electricity system. Hence, defining literature, and also state of the art literature, is mainly focused on applications in electricity. Here, we zoom in on an integrated energy system including other carriers as well.

Characterization of heat infrastructures

Heat networks are predominantly found at the micro and meso levels of the energy system. At the micro level, heat networks supply space heating within homes and buildings and process heat in factories. At the meso level, heat networks can be found connecting homes and buildings to external heat sources, and on industrial sites connecting heat sources with processes needing heat. At the upper-meso level, first steps are made towards a regional heat network connecting a number of existing and new heat networks in the Dutch province of South Holland.

The remainder of this characterization is partly based on [2]. Residential heat networks are still predominantly fed by heat originated from fossil fuels, often in the form of waste heat from another primary process. Heat from waste incinerators is an exception here. Dimensioning of heat networks is critical and overdimensioning, as is common practice in the design of other types of energy infrastructures, leads to higher losses. Heat networks need to deliver their heat at a certain temperature, dependent of the application. Typical temperatures are 90 degrees Celsius for the outgoing stream and 70 for the return flow. Overcapacity leads to higher temperatures in the return flow, resulting in high losses as this heat cannot be recovered. This can lead to counter-intuitive phenomena, for instance, if connected houses are being insulated. Then, the heat demand is lowered, leading to higher infrastructure cost per unit of transported heat.

Valuating heat transported through a heat network is non-trivial. Where marginal cost of other energy carriers are relatively high and fluctuating with demand and supply (electricity, natural gas, for instance), heat as a byproduct from a production process has virtually no marginal cost associated. Traditionally, heat delivered to consumers was coupled to the price for heat from natural gas. However, with natural gas being phased out, this will no longer hold as a benchmark for heat prices. In (local or regional) energy systems where heat is mainly generated as a byproduct, the low marginal cost makes it hard to introduce market mechanisms as a way to match demand and supply. For demand-side flexibility of heat consumers, a transactive mechanism might be useful, but the settlement of prices will probably not be straightforward. A fixed part of the price (presumably set by the regulator) would be needed to amortize capital costs. Note that this would also be the case for large-scale all-solar and/or all-wind scenarios in the electricity system. Since overcapacity in the heat network is not a good idea, undercapacity combined with a hybrid coupling with a heating solution based on hydrogen or electricity may be a solution.

Before operational coordination mechanisms need to be worked out for heat networks within an integrated energy system, the system-level options need to be studied. Meso-level design choices, such as building all-electric houses instead of rolling out heat networks, need to be studied to make informed choices on the direction to follow. To illustrate, we describe two of these choices. Firstly, geothermal energy provides a low-cost option for heat supply to the built environment and other sectors. In the built environment, geothermal wells depend on heat networks to distribute the heat to homes and buildings. Hence the presence of heat networks are a *conditio sine qua non* for this relatively low-cost source of sustainable heat. On the other hand, secondly, modern, well-insulated, houses in The Netherlands, are having low heat demand for space heating. During summer, these houses tend to overheat. Hence a solution with a ground heat exchanger used to store excess heat during the summertime and feeding a heat pump during the winter gives a suitable all-electric solution.

Electricity flexibility as a system integration vehicle

Many of the flexibility options in the electricity system involve conversion of energy to other carriers. If the other energy carrier is infrastructure-based, (capacity) challenges in one infrastructure can be mitigated by using capacity in the other. Combined Heat and Power (CHP) units, for instance in the greenhouse sector or feeding heat networks, establish interaction between the electricity and the natural gas networks. When operated in response to (price) signals originating from the electricity system, capacity shortage in either electricity generation or in the corresponding infrastructure is mitigated by using capacity in the gas system. A similar interaction is expected to occur between electricity and hydrogen through Power to Hydrogen and (round trip) electricity storage options using hydrogen. A similar case can be made for flexible electric vehicle charging and future vehicle-to-grid applications. Here, an overcapacity in the transport sector (i.e. vehicles standing still temporarily) is used to create value based on (temporal) capacity shortages in the electricity sector.

Key differences between infrastructures

Network-inherent storage: Network-inherent storage is the amount of energy (or commodity, so you wish) that is stored in an energy infrastructure, if any. The stored amount may change over time, when the total feed-in to the network is unequal to the total feed-out. Generally, inherent storage is possible in case of gas flows, where it is influenced by the average system pressure. In Electricity networks there is no storage in the network itself. The only form of inherent storage in an electricity system is the inertia provided by the rotating mass of the synchronously-coupled generators. This has a dampening effect on fast fluctuations in demand and supply in a system. Infrastructures for Gas and Heat both have storage inherently in the network. With gas it is usable as a buffer. The pressure in the (transmission) network can be increased preemptively when peak demand is expected (e.g. during a cold winter morning). For heat it isn't possible to use the network storage as a buffering means, as increasing the temperature level of the in-going flow eventually leads to a higher-temperature return flow, with higher losses as a result.

Demand/supply balancing time scales: For electricity, this timescale is very short. Time constants related to the system inertia is in the order of seconds. If there is a sudden drop in supply (e.g. due to a power plant trip or a transmission line outage) the system's 50Hz frequency drops almost instantaneously. This is the main reason for the complexity found in the organization of the electricity markets. The market mechanisms operating on different timescales (futures, day-ahead, intra-day, balancing and reserve markets) are all aimed at keeping or restoring the instantaneous balance between demand and supply in the system.

TE in the integrated energy system

In the light of the above, we expect the future integrated energy system will evolve into a master-follower set-up, where highly-dynamic operational modes in the electricity-part of the system trigger reactions in the heat, gas and transport subsystems. In turn, electricity market prices will be influenced by the interactions with other carriers. For example, if hydrogen prices are high, electrolyzers are willing to pay more for electricity and drive up the market price, even at moments with a lot of solar and wind [33].

Electricity will be very cheap for longer periods on end. In these periods, weather-based renewables will set the electricity prices by producing far more than the traditional type of 'must run' consuming devices and installations consume. Due to sector coupling, the surplus of energy flows into the gas, heat and mobility sectors, using new conversion techniques such as Power to Hydrogen (P2H2), Power to Heat (P2H), where it is stored or used immediately. The longer periods of low-priced electricity will be interleaved with extremely high-priced periods. Then, energy from the other sectors, gas, heat and mobility, the latter through vehhicle to grid (V2G), will unburden the electricity system. During longer periods of low winds and low solar irradiation levels (the Germans call this a "Dunkelfaute") the peak electricity demand will be covered by generation assets operating only a few hours per year. As the CAPEX of these units needs to be earned back in these short periods, their generation prices will be far above their marginal cost. These weather-dependent fluctuations, happening on the time scale of day to weeks will be superpositioned upon the seasonal cyclus. At the same time, short-cycled fluctuations in demand and supply will continuously spark a need for energy flexibility. And this will be in much larger quantities than we see now.

This ongoing integration of energy carriers will happen on the system-wide level, but also locally. Coordination mechanisms will need to operate on multiple time scales, on multiple scale levels, between multiple energy carriers, within the limits of scarce network capacities, and optimizing multiple objectives. On the macro level (i.e energy wholesale and transmission), this type of integrated coordination is already operational using market mechanisms, transactions and dynamic pricing. The challenge is to work out the transactive mechanisms to establish a similar kind of integration at the meso and micro levels as well. As we have seen in TE systems under development for electricity, 'similar' does not mean 'the same' here.

Discussion: Coordination Objectives

Using value as a control parameter opens the possibility (i) to implement multiple coordination goals, and (ii) to let individual players attach their own value levels to specific properties or goals. There are multiple ways in which local or global objectives can be implemented in TE systems. It has to be noted that TE implementations using (near-real-time) monetary value of produced, consumed or stored power readily allow for multiple optimization goals:

- **System-wide balancing:** Using electronic markets, such as double-side auctions, global demand and supply can be matched on different timescales.
- **Congestion Management:** Congestion management can be implemented as (part of) a TE system in multiple ways: as a market-based redispatch (such as in the GOPACS system described above), or constraint-based, when the available network capacity is used as a constraint to the possible outcomes of a market mechanism. The Locational marginal pricing (MLP) mechanism is an example of this.
- **Optimizing self-consumption:** Any price difference between the incoming and outgoing power flows for a prosumer provides an incentive to optimise self-consumption. These price differences can be rooted in tax schemes (e.g. Value-added Tax levied on the incoming flow), subsidy schemes (e.g. as in the German subsidy program for solar PV generation) or caused by time-of-day effects. Massive PV power in-feed lowering electricity prices is an example of the latter.
- **Minimizing network use:** The monetary value of network use consists of fixed and variable costs. In case of electricity, the variable cost mainly consist of network losses. These can be incorporated, for instance, in a local marginal pricing mechanism, leading to an additional incentive to source energy locally. A price component then represents the cost for network losses as incurred by each load put on the system.
- **Ancillary Services:** In a large part of the Western economies, the EU included, ancillary services related to scheduling & dispatch, and the operating reserves are already organised through market-based systems. These services are increasingly delivered by (aggregates of) distributed energy resources.

Other global or local control objectives can not be so straightforwardly connected to monetary value as the ones listed above. The sustainability level of the energy mix is an example here. When marginal energy production cost is driving the price dynamics in a TE system, abundance of sustainable energy from solar and wind is triggering flexible load assets to consume through low energy prices. However, other low-marginal cost production assets, coal-fired conventional plants for instance, are stimulated then as well. In order to let energy consumers influence certain dynamic properties of their procured energy, a labelling system needs to be added to the trade system at hand. To our knowledge, there is no scientific consensus on how to realise such a system. However, a *(near-)real-time certificates of origin* system would add customer choice opportunities for a great variety of properties attachable to energy commodities:

- Carbon emissions
- Ecological footprint
- Generation mix
- Air pollution
- Land use
- etc.

In such a system, energy offered to a TE market can optionally be labelled according to origin, enabling the trade of energy with certain properties. Then, the market system needs to make peer-to-peer trade connections between suppliers and demanders of energy having a particular label or label set. This gives consumers means to ensure a (close-to) real-time guarantee of certain properties of the energy consumed, including those listed above.

Note that a number of challenges need to be overcome to implement such a system effectively and efficiently. The market clearing mechanism will be much more complex and, thus, less transparent for participants. Further, each combination of commodity and label can be seen as a separate, although coupled, market, that needs to have certain trading volume to avoid liquidity problems like price instabilities and proneness to market manipulation.

6 | SWOT ANALYSIS

This section provides the results of a SWOT analysis resulting from a workshop held at March 31, 2021 with various stakeholders in the Dutch energy system including DSOs, energy suppliers and consultants. The analysis consists of two parts, one for each axis of Transactive Energy development (see Figure 1). Both are in context of a shorter-term development foreseen in the Netherlands. The first SWOT analysis (part) focuses on improved transactive participation in wholesale markets. The second on improved transactive coordination in the DSO domain.

6.1 | Improved transactive participation in wholesale markets

The scope of this first SWOT analysis is improved transactive participation in wholesale markets. Meaning current wholesale markets are opened for smaller parties either directly or via a platform that enables consumers and producers to communicate the value of their consumption, production and flexibility and to respond to the result of a transactive mechanism directly linked to the wholesale markets. The combination of improved transactive participation and transactive coordination is left out of scope.

For a SWOT analysis it is useful to define the alternative of the foreseen development. In this case we defined as the alternative that small consumers and producers receive either fixed supply prices or dynamic price schemes from a retailer - a large party that has access to the wholesale market.

- **STRENGTHS:**
  - **Ownership**: A transactive relation with the energy system introduces ownership of smaller parties about energy transition challenges. This is expected to increase the awareness about the impact of their energy usage and behavior on achieving the energy transition goals as a society.
  - **Resiliency**: With the expansion of transactive interactions in the energy system, more control options become available leading to more resiliency. Further, by integrating distributed flexibility options, robustness for outages of individual units decreases, as the individual units are smaller (in comparison with a traditional power plant.)
  - **Observability**: With the expansion of transactive interactions in the energy system, more information on demand and supply becomes available and prognoses of grid operators and balance responsible parties can be improved.
- **WEAKNESSES:**
  - **Redesign ICT Infrastructure**: New administration systems and maybe measurement equipment are required. The ICT architecture needs to encompass the full distribution level of the energy system.
  - **Business case still unclear**: Especially for residential prosumers, there is only a limited business case in the current market environment and setting. Even without the annual net metering currently in place in the Netherlands, price differences might be too small to be attractive for (residential) prosumers.
  - **Redesign of energy market**: New regulation will be required to support transactive mechanisms for example balance responsibility for residential prosumers.
- **OPPORTUNITIES:**
  - **Cost reduction**: Potentially, the market participation of smaller parties can decrease their energy bill. The

societal cost for the energy transition will be lower as well, most probably.
  - **Fairness**: transactive mechanisms provide opportunities to implement 'causer pays' objectives and a dynamic that ensures non-discrimination.
  - **Triggering the right incentives**: For example, incentives for flexibility and renewable investment follow from the mechanism. Note that introducing additional market mechanisms operating in the shorter-term lead to (positive) longer-term economic effects as well.
  - **Redefining local economies**: Opportunities for cross-domain value propositions improve local living environment e.g. exchange energy with neighborhood services. Opens opportunities to redefine the value of energy for small consumers and producers.
- **THREATS:**
  - **Trust:** Loss of trust in the value communicated.
  - **Robustness to extremes:** Non-preparedness for extreme or unexpected cases, while they have more than ever direct impact on consumers.
  - **Motivation:** People are not motivated to participate.
  - **Misuse:** Transactive systems can be used for other purposes than they are design for (gamestop example).
  - **Gaming:** Transactive systems can be gamed, under circumstances.
  - **Increasing complexity:** The complexity of the energy system increases by adding complex interaction of smaller parties.

Whether and to what extend improved transactive participation should be realized in the Netherlands should be answered by reviewing the:

- proportionality of effort: is the effort of changing regulation and implementation of required ICT infrastructure proportional to the gain of the smaller parties and the energy transition goals?
- level playing field for smaller parties given the Clean Energy package directives. According to the clean energy package small prosumers should have the opportunity to be 'active; meaning they have either directly or indirectly access to the wholesale markets.

6.2 | Improved transactive coordination in the DSO domain

For the second SWOT analysis we focus on improved transactive coordination in the DSO-domain. This means that DSOs are introducing new ways to approach network management challenges such as congestion, voltage and grid connection issues. Alternatives to the introduction of transactive mechanisms to coordinate DSO grid challenges are grid reinforcement, top-down control by the DSO or innovative DSO price schemes.

- **STRENGTHS:**
  - **Cost efficiency:** Can be a cost-efficient alternative to grid reinforcement and grid tariffs.
  - **Fair and clear problem ownership:** The causer pays principle can be implemented.
  - **Deal with interdependencies:** Multi-objective mechanisms can solve coordination issues (e.g. between grid balancing by the TSO and congestion management by the DSO).
  - **Service-oriented:** Solutions can be designed more aligned with the consumer experience by offering a more service-oriented mechanism (instead of a commodity-oriented one.)
  - **Locational observability:** transactive mechanisms provide DSOs with a view on the status of the local grid.
  - **Awareness of grid issues:** Users of the grid become aware of the issues the grid operator is facing.

- **WEAKNESSES:**
  - **Cost-effectiveness currently unknown:** Costs and effects are unknown
  - **Increasing complexity:** Complexity increases and with it the probability of error.
  - **Too much abstraction:** Especially in multi-objective markets; the product and its value can become unclear (why do I pay more than yesterday?)
  - **R&D required:** Market mechanism is not available from the shelf. However, also the effect of alternatives as tariff solutions are unknown.
- **OPPORTUNITIES:**
  - **Unlocking flexibility:** If the value of flexibility in low and medium voltage grid is increasing - by using it for more purposes-, more parties have interest in joining new and existing markets and providing their (flexibility) services.
  - **Enable capacity optimisation:** (Early) notification and planning of load and production - as part of a transactive mechanism - enables capacity optimisation of the grid operator.
  - **Deal with increasing uncertainty:** uncertainty of load profile predictions grow, transactive energy can provide a solution.
  - **Collectivity:** Cooperative behavior can get a boost.
  - **Shift from grid access to market access:** The relation between the DSO and grid-connected parties is going to change: focus will be more on enabling market access instead of the right to connect.
- **THREADS:**
  - **Lack of DSO Acceptance:** There is not a good fit yet with the way of working of the DSO ('verzwaren tenzij') vs 'friend of the grid operator').
  - **Increasing dependence on forecasts:** Forecasts can be wrong and depending highly on these introduces a risk.
  - **Energy availability / Price risks:** Consumer is not willing to accept that energy is not always available at a fixed / capped (low) price.
  - **Emergent behavior:** Transactive energy systems can show behavior of that does not depend on its individual parts, but on their relationships to one another. This emergent behavior cannot always be predicted by examination of a system's individual parts and is hard to understand and predict.
  - **Scalability:** Field-demonstrated TE mechanisms have predominantly been performed with relatively small numbers of players. It is unsure how these will scale.

Whether and to what extend improved transactive coordination in the DSO domain should be realized in the Netherlands should be answered by reviewing the:

- Opportunity to unlock flexibility with a transactive mechanism. The amount of unlocked flexibility should be able to solve the DSO grid issues completely otherwise grid reinforcement or (non-voluntary) congestion management is still needed. This also should include a review of the capacity of the DSO to forecast grid issues and to understand the effect of activation of flexibility bids. Also the acceptability of the back-up system (when the transactive market is not functioning due to ICT issues or a lack of available offers).
- The extent to which the resulting market system is competitive. If the competitiveness is low, market participants will be able to influence the market price, which, in turn, may lead to gaming behaviour. Especially in small (e.g. local) sub-markets the number of participants may be too small for a competitive market. The use of a properly-designed tariff structure might mitigate this gaming opportunity.
- The fairness of the mechanism: is the mechanism legal/economical and societal acceptable? This also includes

a review on the understanding of the mechanism. If it is not clear when and why prices go up and down the mechanism is not acceptable.

7 | ADVICE

As explained in the Introduction of this document, the goal of this study is (i) to map out the current state of the art in Transactive Energy (TE) and (ii) to analyse how TE can be relevant for the future energy system of The Netherlands. TE is an energy management approach combining (local) systems control with market-based interactions, as we described in greater detail in section 2. This advice is written for the Topsector Energy System Integration Program, which focuses on system-level innovations as described in the Multi-annual Mission-driven Innovation Program titled "A robust and socially supported energy system" (MMIP 13).

7.1 | How to talk about Transactive Energy?

In Subsection 2.2, we explored the concept of Transactive Energy and in 1.2, we presented a methodology to discuss Transactive Energy developments in existing energy systems. The TE definition and TE development methodology can help to structure discussions about the implementation of TE. For such discussions we identified a few recommendations:

- Be aware that Transactive Energy mechanisms include both competitive and cooperative solutions. Have a good look at the variety of TE mechanisms and choose wisely. Unfortunately, we see a lack of overview of type of mechanisms available for a broader public which may complicate to perform such a TE mechanisms selection.
- Always consider the alternative to the Transactive Energy solution. The Energy Management Matrix is a useful tool to identify alternatives and to spot the key differences that should be discussed.
- Where possible split discussions over the two axes of TE development. Development in improved transactive participation and improved transactive coordination go in especially the DSO domain go hand in hand, but discussion both elements separate help to identify the key issues. In Section 6 we took this approach.

7.2 | Directions for the systems integration innovation agenda

In the following subsections, we describe a research & innovation (R&I) agenda that could be adopted by the MMIP13 innovation program to stimulate TE development and further uptake in The Netherlands. We describe this agenda based on a current trend we see in short-term innovation in the energy sector. From there we argue about the needed focus for the medium and long terms. In this way, we present the high-level R&I agenda as depicted in Figure 6. In terms of funding instruments, the short term developments are either done by the sector parties themselves or funded through the Netherlands Enterprise Agency RVO, the mid-term R&I is typically funded through RVO as well, and the long term research trough the Dutch Research Council NWO.

The short-term part of the agenda is describing a current trend and is included for the sake of the argument we are trying to make. As such, this part is not part of our advice and, therefore, we do not describe it in a separate subsection.

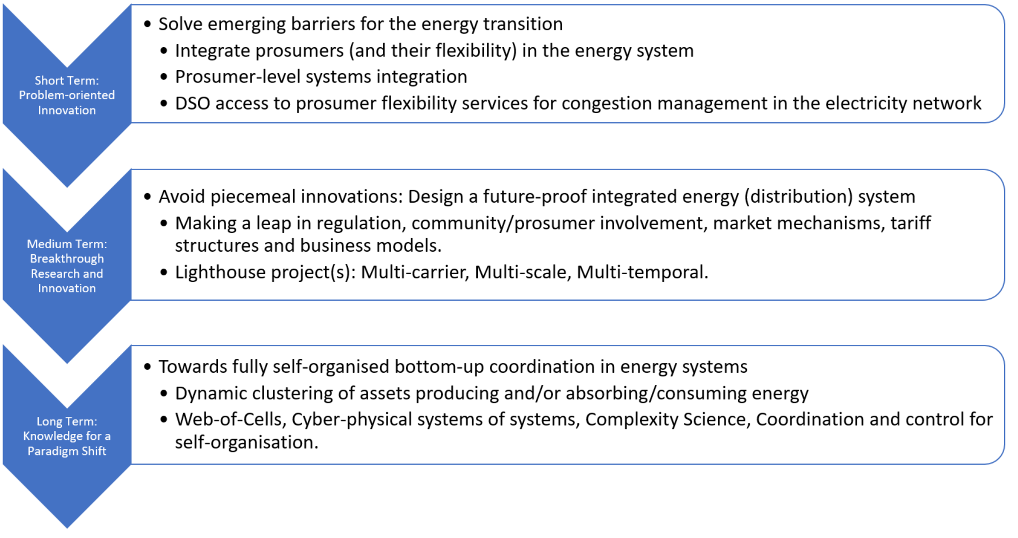

FIGURE 6 High-level Research and Innovation agenda for Systems Integration: some current short-term developments, and recommendations for medium-term breakthrough research and innovation and long-term scientific research.

Short-term: Problem-oriented Innovation

Currently, there are a number of emerging challenges in The Netherlands related to the energy transition and/or the out-phasing of Dutch gas extraction from the Groningen field due to earthquake problems. The most pressing challenge is the lack of electricity distribution capacity available to connect new (renewable) generation assets as well as new or expanding electricity consuming connections. This occurs in a large portion of the country and it is hampering the energy transition at the moment. System integration mechanisms that unlock prosumer flexibility, and give system operators means to manage congestion using that flexibility, are urgently needed. A number of innovation projects are currently underway to provide short-term solutions. These include the GO-E project (developing flexibility activation mechanisms for the DSOs), the Flexibility Market Zuidplaspolder (an operational flexibility market to bridge the time needed for grid reinforcement) and the development of a real-time interface for control of distributed generation and loads by *Netbeheer Nederland*, the Dutch Association of System Operators, to name just a few. These problems were foreseen, however, most policy makers were surprised by the timing in which these developed into developing into (temporal) show-stoppers. As a result, innovation is now increasingly driven by these acute problems and therefore highly short-term problem-oriented.

7.3 | Medium term: Breakthrough research and Innovation

On a longer timescale, it is important to avoid strings of piecemeal innovation steps. Developments as described above are predominantly happening within the current regulatory framework, in the current energy sector order and within the current socio-economic frame. As each innovation step will be taken from the previous one as starting point, there is substantial risk of locking in solutions that give good results on a short scale, but steer towards a sub-optimal system solution in the long run. Therefore, medium-term innovation actions are needed targeted at breakthrough

R&I designing a future-proof integrated energy (distribution) system. An orchestrated innovation leap is needed in regulation, community and prosumer involvement, market mechanisms, tariff structures and business models. One or more *lighthouse projects* should develop and field-demonstrate a complete end-to-end blueprint for such an integrated energy system that is multi-carrier, multi-scale, and multi-temporal.

To describe the difference in short-term development and medium term breakthrough R&I, we look at the example of congestion management for electricity distribution. In current developments in multiple projects, this is approached as a redispatch process, similarly to the process used in transmission. So, first, we let the markets run assuming a copper plate network (i.e. having unlimited capacity) and then we use the remaining flexibility to solve congestion if it occurs. As the easy accessible, and thus cheaper, flexibility is used up in the normal market run, the flex available to solve the congestion will be limited in availability and higher in price. This suffices fine in a setting where congestion occurs in a limited number of places, at a limited number of times and is foreseeable a few hours ahead. However, solving congestion this way in a mid-term business-as-usual scenario, i.e. more frequently and on a much larger scale, will turn out to be highly inefficient. Hence, in a more far-stretching innovation step (a leap if you wish), one would redesign the market mechanisms such that the network capacity serves as a constraint to the market outcome. Market trade and congestion management are then integrated in a single process. Note that this doesn't disqualify the current developments and mechanisms. These are important steps in keeping our energy system stable and reliable and in exploring the changing roles and way of working triggered by the energy transition. However, a thorough R&I effort on the medium term, as described above, is needed to innovate on a system level.

The scientific challenges identified in subsection 3.2 can be used to define the scope of academic research and demonstration calls. A lighthouse project should address all five challenges identified: market design, agent strategies and challenges related to adoption, settlement and ICT. We recommend to study the challenges both from a fundamental scientific perspective as in the context of a demo, pilot or existing implementation. Underexposed by the scientific literature in TE are the legal challenges. As stated above, an innovation leap in multiple disciplines and domains need to be taken. This includes innovation in the legal domain as well. As part of the adoption challenge, special attention should go to user acceptation. Better insights in the societal requirements and in the social innovations needed will help to speed up the development of TE. Nevertheless, society is always in progress and lessons should be learnt from demo and real-life experiences.

In Section 5 we discussed the status of Transactive Energy in the Dutch energy system and explored the next steps to realise an improvement of transactive participation and coordination under influence of regulation and challenges that grid operators and other stakeholders in the energy system face. We identified a number of needs and recommendations:

- A short term need for a multi-objective mechanisms improving the participation of small consumers so they help balancing the grid in the TSO (system-wide balancing) and DSO (congestion management) domains.
- A structured and deep analysis into the impact of various TE market design in comparison to (price-based) alternatives (e.g. grid tariffs). Also hybrid approaches TE embedded in an innovative tariff design should be evaluated.
- A further development of the role of energy communities. Some of the industrial initiatives described, are expanding market mechanisms from the wholesale and transmission level downwards into the distribution grids. At the other side of the system, local energy communities are evolving their ways to make their local subsystem greener and more efficient, e.g. by developing ways to exchange energy locally. These two developments should be brought together to accomplish synergy.

Additionally, it is recommended to investigate alternatives for the use of time slots in markets and coordination mechanisms. Already in the current wholesale market setup, time slots are posing a challenge. Frequency swings can be seen around the start of each hour and, albeit to a lesser extent, around 15, 30 and 45 minutes past the hour.

Event-based TE mechanisms should be investigated as an alternative.

Finally, we came across several industrial initiatives that lack scientific publications communicating design and implementation choices, as well as results such as the performance of the piloted system. As this hinders transfer of knowledge and, thus, scientific progress, we advise funding bodies to expect thorough scientific publications on systems design, performance and lessons learned from higher-TRL (industrial) pilot projects.

7.4 | Long Term: Knowledge development for a paradigm shift

The energy systems of the Western economies are already among the most complex man-made systems. Systems integration and the integration of the edges of the system, i.e. the prosumers and the currently passively-operated energy distribution networks, only adds to this complexity. Long-term opportunity is to surf the digitization wave further towards a fully self-organised and bottom-up coordinated energy system. Scientific research is needed on how to apply cutting-edge knowledge and technology from e.g. cyber-physical systems of systems, complexity science to create a Web of Energy Cells that allow an dynamic clustering of assets producing and/or absorbing/consuming energy using self-organisation techniques in coordination and control.

Abbreviations

- **BRP:** Balancing Responsible Party
- **CAPEX:** Capital Expenditure
- **CEP:** Clean Energy Package
- **CHP:** Combined (generation of) Heat and Power
- **DSO:** Distribution System Operator
- **EPEX:** European Power Exchange
- **ETPA:** Energy Trading Platform Amsterdam
- **GOPACS:** Grid Operators Platform for Congestion Solutions
- **ICT:** Information and Communication Technology
- **IEEE:** Institute of Electrical and Electronics Engineers
- **LEM:** Local Energy Market
- **MMIP:** Multi-annual Mission-driven Innovation Program
- **MODM:** Multi-objective Decision Making
- **NFOD:** Non-frequency Supporting Services (in Dutch: niet-frequentieondersteunende diensten)
- **PV:** Photo-voltaic (solar panel)
- **PH:** Power to Heat
- **P2H2:** Power to Hydrogen
- **P2P:** Peer-to-peer
- **R&D:** Research and Development
- **SI:** System Integration
- **SWOT:** Strengths, weaknesses, Opportunities and Treads
- **TE:** Transactive Energy
- **TRL:** Technology Readiness Level
- **TSE:** Topsector Energy
- **TSO:** Transmission System Operator

- **USEF:** Universal Smart Energy Framework
- **V2G:** Vehicle to Grid

Acknowledgements

The authors wish to thank the team that runs the Systems Integration Program of the Dutch Topsector Energy, and especially Mart van Bracht, Michel Emde and André de Boer, for the opportunity to do this survey and the discussions we had during the writing of this report. Further, we thank Steve Widergren, Hayden Reeve, Abhishek Somani and Daniel Boff from the Pacific Northwest National Laboratory (PNNL), one of the United States Department of Energy national laboratories for our topical and procedural discussions and valuable feedback on an early draft of this document. Further, we thank David Chassin, chair of the Grid Integration Systems and Mobility group at the SLAC National Accelerator Laboratory in Stanford in the United States for valuable input to the scientific literature survey.

And, last but not least, we sincerely thank the group of sector experts that participated in the Workshop for their feedback on the concepts presented and their input to the SWOT Analysis and NL Projection. This group included the following people:

- Jan-Peter Doomernik, Enexis
- Michel Emde, Topsector Energie
- Albert Molderink, Nieuwestroom
- Dieuwke Martens-Bakker, Antea
- Marcel Postema Alliander
- Wilbert Prinssen Technolution
- René Troost, Stedin
- Arjan Wargers ElaadNL
- Arjen Zuijderduijn, Stedin

8 | REFERENCES

[1] O. van Pruissen, A. van der Togt, and E. Werkman, "Energy efficiency comparison of a centralized and a multi-agent market based heating system in a field test," *Energy Procedia*, vol. 62, pp. 170–179, 2014, 6th International Conference on Sustainability in Energy and Buildings, SEB-14. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1876610214034092

[2] L. de Vries, personal communication.

[3] Deloitte, E·DSO, and Eurelectric, "Connecting the dots: Distribution grid investment to power the energy transition - final deliverable," Monitor Deloitte, Tech. Rep., January 2021.

[4] D. Forfia, M. Knight, and R. Melton, "The view from the top of the mountain: Building a community of practice with the gridwise transactive energy framework," *IEEE Power and Energy Magazine*, vol. 14, no. 3, pp. 25–33, 2016.

[5] D. J. Hammerstrom, R. Ambrosio, J. Brous, T. Carlon, D. Chassin *et al.*, "Pacific northwest gridwise testbed demonstration projects – part i. olympic peninsula project," Pacific Northwest National Laboratory, Richland, Washington 99352, Tech. Rep. PNNL-17167, October 2007.

[6] K. Kok, C. Warmer, and R. Kamphuis, "PowerMatcher: multiagent control in the electricity infrastructure," in *AAMAS '05: Proceedings of the 4th int. joint conf. on Autonomous Agents and Multiagent Systems*, vol. industry track. New York, NY, USA: ACM Press, 2005, pp. 75–82.

[7] J. Kok, "The PowerMatcher: Smart coordination for the smart electricity grid," Ph.D. dissertation, VU University Amsterdam, 2013, naam instelling promotie: VU Vrije Universiteit Naam instelling onderzoek: VU Vrije Universiteit.

[8] K. Kok and S. Widergren, "A society of devices: Integrating intelligent distributed resources with transactive energy," *IEEE Power and Energy Magazine*, vol. 14, no. 3, pp. 34–45, 2016.

[9] S. Widergren, K. Kok, and L. Tesfatsion, "Transactive energy systems," Webinar, 2016. [Online]. Available: smartgrid.ieee.org/resources/webinars/past-webinars

[10] L. Hirth and S. Glismann, "Congestion management: From physics to regulatory instruments," Kiel, Hamburg, Tech. Rep., 2018. [Online]. Available: http://hdl.handle.net/10419/189641

[11] L. Ableithner, A. Meeuw, S.Schopfer, V. Tiefenbeck, F. Wortmann, and A. S. Glismann, "Quartierstrom - implementation of a real world prosumer centric local energy market in walenstadt, switzerland," ZBW – Leibniz Information Centre for Economics, Tech. Rep., May 2019. [Online]. Available: http://hdl.handle.net/10419/189641

[12] L. Ableitner, V. Tiefenbeck, A. Meeuw, A. Wörner, E. Fleisch, and F. Wortmann, "User behavior in a real-world peer-to-peer electricity market," *Applied Energy*, vol. 270, 2020, cited By 3. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85085289046&doi=10.1016%2fj.apenergy.2020.115061&partnerID=40&md5=44eda07029790a41d01f12947ef1b237

[13] Centrica, "Cornwall local energy market," 2020. [Online]. Available: https://www.centrica.com/innovation/cornwall-local-energy-market

[14] C. Corinaldesi, D. Schwabeneder, G. Lettner, and H. Auer, "A rolling horizon approach for real-time trading and portfolio optimization of end-user flexibilities," *Sustainable Energy, Grids and Networks*, vol. 24, p. 100392, 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2352467720303234

[15] Y. Du and F. Li, "A hierarchical real-time balancing market considering multi-microgrids with distributed sustainable resources," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 72–83, 2020.

[16] EPEX Spot, "Local flexibility markets," EPEX Spot, Tech. Rep., 2019. [Online]. Available: https://nordicelforum.org/wordpress/wp-content/uploads/2019/12/3A-NEMF_EPEXSPOT.pdf

[17] M. Farrokhseresht, N. G. Paterakis, H. Slootweg, and M. Gibescu, "Enabling market participation of distributed energy resources through a coupled market design," *IET Renewable Power Generation*, vol. 14, no. 4, pp. 539–550, 2020.

[18] R. Fonteijn, P. H. Nguyen, J. Morren, and J. G. H. Slootweg, "Baselining flexibility from pv on the dso-aggregator interface," *Applied Sciences*, vol. 11, no. 5, 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/5/2191

[19] GridFlex, "Op weg naar een lokale energiemarkt," GridFlex, Tech. Rep., 2020. [Online]. Available: https://gridflex.nl/wp-content/uploads/2020/09/267-whitepaper-v0.2.pdf

[20] G. Hoogsteen, J. L. Hurink, and G. J. M. Smit, "Demkit: a decentralized energy management simulation and demonstration toolkit," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2019, pp. 1–5.

[21] P. Hou, G. Yang, J. Hu, and P. J. Douglass, "A network-constrained rolling transactive energy model for ev aggregators participating in balancing market," *IEEE Access*, vol. 8, pp. 47 720–47 729, 2020.

[22] I. Lampropoulos, T. Alskaif, J. Blom, and W. van Sark, "A framework for the provision of flexibility services at the transmission and distribution levels through aggregator companies," *Sustainable Energy, Grids and Networks*, vol. 17, p. 100187, 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2352467718300432

[23] S. Mohammadi, F. Eliassen, and Y. Zhang, "Effects of false data injection attacks on a local p2p energy trading market with prosumers," in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2020, pp. 31–35.

[24] K. Nakayama, R. Moslemi, and R. Sharma, "Transactive energy management with blockchain smart contracts for p2p multi-settlement markets," in *2019 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2019, pp. 1–5.

[25] N. Nicholas, "Centrica to pilot blockchain in local energy market," May 2018, [Accessed: 16-September-2020]. [Online]. Available: https://www.smart-energy.com/industry-sectors/policy-regulation/blockchain-technology-centrica-lo3-energy/

[26] ——, "Switzerland pilots world's 'first-of-its-kind' local electricity market," February 2020, [Accessed: 16-September-2020]. [Online]. Available: https://www.smart-energy.com/industry-sectors/smart-grid/switzerlands-walenstadt-pilots-worlds-first-of-its-kind-local-electricity-market/

[27] P. Europe, "Field test of switzerland's first local electricity market concluded," February 2020, [Accessed: 16-September-2020]. [Online]. Available: https://www.pveurope.eu/installation/field-test-switzerlands-first-local-electricity-market-concluded

[28] S. E. Networks, "Unlocking the value of local network flexibility," SP Energy Networks, Tech. Rep., 2020. [Online]. Available: https://www.spenergynetworks.co.uk/userfiles/file/Fusion_Fact_Card_Visual_Version.pdf

[29] E. Mian and R. Versmissen, "Fusion usef implementation plan," SP Energy Networks, Tech. Rep., February 2020. [Online]. Available: https://www.spenergynetworks.co.uk/userfiles/file/FUSION_USEF_Implementation_Plan.pdf

[30] *USEF: The Framework Explained*, USEF Foundation, Arnhem, the Netherlands, 05 2021. [Online]. Available: https://www.usef.energy/news-events/publications/

[31] K. Zhang, S. Troitzsch, S. Hanif, and T. Hamacher, "Coordinated market design for peer-to-peer energy trade and ancillary services in distribution grids," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 2929–2941, 2020.

[32] C. Ziras, C. Heinrich, and H. W. Bindner, "Why baselines are not suited for local flexibility markets," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110357, 2021. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032120306456

[33] R. de Kler, F. van de Beek, and A. van der Veen, "Roadmap for the introduction of a low carbon industry in the rotterdam region," ERA-Net ACT project - Enabling a Low-Carbon Economy via Hydrogen and CCS, Project Deliverable D5.2.6, September Project Deliverable D5.2.6; 2020, project Deliverable D5.2.6.

[34] European Commission, "Clean energy package for all europeans," 2019, [Accessed: 17-February-2021]. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=null&WT.ria_f=3608&WT.ria_ev=search

[35] ——, "Powering a climate-neutral economy: An eu strategy for energy system integration," 2020, cOM(2020) 299 final.

[36] H. R. Varian, *Microeconomic Analysis*, 3rd ed. New York: Norton, 1992.

[37] S. Chakraborty, T. Baarslag, and M. Kaisers, "Automated peer-to-peer negotiation for energy contract settlements in residential cooperatives," *Applied Energy*, Dec. 2019.

[38] L. Similä, G. Koreneff, and V. Kekkonen, "Network tariff structures in smart grid environment," *VTT, Espoo, Tech. Rep. VTT-R 03173–11*, 2011.

[39] A. Stawska, N. Romero, M. de Weerdt, and R. Verzijlbergh, "Demand response: For congestion management or for grid balancing?" *Energy Policy*, vol. 148, p. 111920, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421520306315

[40] M. E. Paddrik, R. Haynes, A. E. Todd, W. T. Scherer, and P. A. Beling, "Visual analysis to support regulators in electronic order book markets," *Environment Systems and Decisions*, vol. 36, no. 2, pp. 167–182, 2016. [Online]. Available: https://EconPapers.repec.org/RePEc:spr:envsyd:v:36:y:2016:i:2:d:10.1007_s10669-016-9597-2

[41] K. Poplavskaya, M. Joos, V. Krakowski, K. Knorr, and L. de Vries, “Redispatch and balancing: Same but different. links, conflicts and solutions.” in *2020 17th International Conference on the European Energy Market (EEM)*, 2020, pp. 1–6.

[42] W. Tushar, T. K. Saha, C. Yuen, M. I. Azim, T. Morstyn, H. V. Poor, D. Niyato, and R. Bean, “A coalition formation game framework for peer-to-peer energy trading,” *Applied Energy*, vol. 261, p. 114436, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261919321245

[43] A. Meeuw, S. Schopfer, A. Wörner, V. Tiefenbeck, L. Ableitner, E. Fleisch, and F. Wortmann, “Implementing a blockchain-based local energy market: Insights on communication and scalability,” *Computer Communications*, vol. 160, pp. 158–171, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140366419314318

[44] L. Ableitner, V. Tiefenbeck, A. Meeuw, A. Wörner, E. Fleisch, and F. Wortmann, “User behavior in a real-world peer-to-peer electricity market,” *Applied Energy*, vol. 270, p. 115061, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261920305730

A | PUBLICATIONS USED IN THE LITERATURE ANALYSIS (SCIENTIFIC CHALLENGES SECTION)

[45] Yerasyl Amanbek, Yrys Tabarak, HSVS Kumar Nunna, and Suryanarayana Doolla. Decentralized transactive energy management system for distribution systems with prosumer microgrids. In *2018 19th International Carpathian Control Conference (ICCC)*, pages 553–558. IEEE, 2018.

[46] M Babar and PH Nguyen. Analyzing an agile solution for intelligent distribution grid development: a smart grid architecture method. In *2018 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, pages 605–610. IEEE, 2018.

[47] Matthew Davison, Jesse Cranney, Terry Summers, and Christopher D Townsend. Decentralised energy market for implementation into the intergrid concept-part i: Isolated system. In *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, pages 80–87. IEEE, 2018.

[48] Matthew Davison, Jesse Cranney, Terry Summers, and Christopher D Townsend. Decentralised energy market for implementation into the intergrid concept-part 2: Integrated system. In *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, pages 287–293. IEEE, 2018.

[49] G. De Zotti, S.A. Pourmousavi, et al. Utilizing flexibility resources in the future power system operation: Alternative approaches. In *IEEE Int. Energy Conference (ENERGYCON)*, pages 1–6, 2018.

[50] ML Di Silvestre, P Gallo, MG Ippolito, E Riva Sanseverino, G Sciumè, and G Zizzo. An energy blockchain, a use case on tendermint. In *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, pages 1–5. IEEE, 2018.

[51] M.L. Di Silvestre et al. Transparency in transactive energy at distribution level. In *AEIT International Annual Conference*, pages 1–5. IEEE, 2017.

[52] P.H. Divshali, B.J. Choi, and H. Liang. Multi-agent transactive energy management system considering high levels of renewable energy source and electric vehicles. *IET Generation, Transmission & Distribution*, 11(15):3713–3721, 2017.

[53] G. Ghatikar, J. Zuber, E. Koch, and R. Bienert. Smart grid and customer transactions: The unrealized benefits of conformance. In *IEEE Green Energy and Systems Conference (IGESC)*, pages 7–14. IEEE, 2014.

[54] Rahim Ghorani, Mahmud Fotuhi-Firuzabad, and Moein Moeini-Aghtaie. Optimal bidding strategy of transactive agents in local energy markets. *IEEE Transactions on Smart Grid*, 10(5):5152–5162, 2018.

[55] A. Hahn, R. Singh, C Liu, and S. Chen. Smart contract-based campus demonstration of decentralized transactive energy auctions. In *IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pages 1–5. IEEE, 2017.

[56] J. Hu, G. Yang, C. Ziras, and K. Kok. Aggregator operation in the balancing market through network-constrained transactive energy. *IEEE Transactions on Power Systems*, 2018.

[57] Q. Huang, T. McDermott, et al. Simulation-based valuation of transactive energy systems. *IEEE Transactions on Power Systems*, 2018.

[58] S. Katipamula, J. Haack, G. Hernandez, B. Akyol, and J. Hagerman. Volttron: An open-source software platform of the future. *IEEE Electrification Magazine*, 4(4):15–22, 2016.

[59] VVG Krishnan, Y Zhang, K Kaur, A Hahn, A Srivastava, and S Sindhu. Cyber-security analysis of transactive energy systems. In *2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, pages 1–9. IEEE, 2018.

[60] Fernando Lezama, Joao Soares, Pablo Hernandez-Leal, Michael Kaisers, Tiago Pinto, and Zita Vale. Local energy markets: Paving the path toward fully transactive energy systems. *IEEE Transactions on Power Systems*, 34(5):4081–4088, 2018.

[61] Jiayong Li, Chaorui Zhang, Zhao Xu, Jianhui Wang, Jian Zhao, and Ying-Jun Angela Zhang. Distributed transactive energy trading framework in distribution networks. *IEEE Transactions on Power Systems*, 33(6):7215–7227, 2018.

[62] J. Lian, H. Ren, Y. Sun, and D. Hammerstrom. Performance evaluation for transactive energy systems using double-auction market. *IEEE Transactions on Power Systems*, 2018.

[63] W. Liu, J. Zhan, and C.Y. Chung. A novel transactive energy control mechanism for collaborative networked microgrids. *IEEE Transactions on Power Systems*, 2018.

[64] Z. Liu, Qiuwei Wu, K. Ma, M. Shahidehpour, Y. Xue, and S. Huang. Two-stage optimal scheduling of electric vehicle charging based on transactive control. *IEEE Transactions on Smart Grid*, 2018.

[65] F. Lombardi, L. Aniello, S. De Angelis, A. Margheri, and V. Sassone. A blockchain-based infrastructure for reliable and cost-effective iot-aided smart grids. 2018.

[66] A. Makhmalbaf, D.J. Hammerstrom, Q. Huang, and Y Tang. Valuation diagramming and accounting of transactive energy systems. In *IEEE Conference on Tech. for Sustainability (SusTech)*, pages 1–7. IEEE, 2017.

[67] T. Morstyn, A. Teytelboym, and M.D. McCulloch. Bilateral contract networks for peer-to-peer energy trading. *IEEE Transactions on Smart Grid*, 10(2):2026–2035, 2019.

[68] Thomas Morstyn, Alexander Teytelboym, and Malcolm McCulloch. Designing decentralized markets for distribution system flexibility. *IEEE Transactions on Power Systems*, 2018.

[69] Md Salman Nazir and Ian A Hiskens. A dynamical systems approach to modeling and analysis of transactive energy coordination. *IEEE Transactions on Power Systems*, 2018.

[70] H. Neema, J. Sztipanovits, Martin B., and E. Griffor. C2wt-te: A model-based open platform for integrated simulations of transactive smart grids. In *Works. on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, pages 1–6. IEEE, 2016.

[71] Alexandros I Nikolaidis, Charalambos A Charalambous, and Pierluigi Mancarella. A graph-based loss allocation framework for transactive energy markets in unbalanced radial distribution networks. *IEEE Transactions on Power Systems*, 34 (5):4109–4118, 2018.

[72] J. Qiu, J. Zhao, H. Yang, and Z.Y Dong. Optimal scheduling for prosumers in coupled transactive power and gas systems. *IEEE Transactions on Power Systems*, 33(2):1970–1980, 2018.

[73] Farrokh Rahimi and Farrokh Albuyeh. Applying lessons learned from transmission open access to distribution and grid-edge transactive energy systems. In *IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pages 1–5. IEEE, 2016.

[74] Mohammad Rayati, Sanaz Amirzadeh Goghari, Zahra Nasiri Gheidari, and Ali Mohammad Ranjbar. Robust and dynamic transactive energy system using tsypkin–polyak theorem. *IET Smart Grid*, 1(2):57–65, 2018.

[75] Yahya Kabiri Renani, Mehdi Ehsan, and Mohammad Shahidehpour. Optimal transactive market operations with distribution system operators. *IEEE Transactions on Smart Grid*, 9(6):6692–6701, 2017.

[76] H Wang, N Good, EA Martínez Ceseña, and P Mancarella. Co-optimization of a multi-energy microgrid considering multiple services. In *2018 Power Systems Computation Conference (PSCC)*, pages 1–7. IEEE, 2018.

[77] Y. Wasa, K. Hirata, and K. Uchida. A dynamic contract mechanism for risk-sharing management on interdependent electric power and gas supply networks. In *11th Asian Control Conference (ASCC)*, pages 1222–1227. IEEE, 2017.

[78] S. Widergren, J. Sun, and L. Tesfatsion. Market design test environments. In *IEEE Power Eng. Society General Meeting*, pages 6–pp, 2006.

[79] Qiuwei Wu, Mohammad Shahidehpour, Canbing Li, Shaojun Huang, Wei Wei, et al. Transactive real-time electric vehicle charging management for commercial buildings with pv on-site generation. *IEEE Transactions on Smart Grid*, 10(5):4939–4950, 2018.