PACES

Pacing Up the Energy Transition

Case studies + 7 WPs NWA-ORC 2020/21

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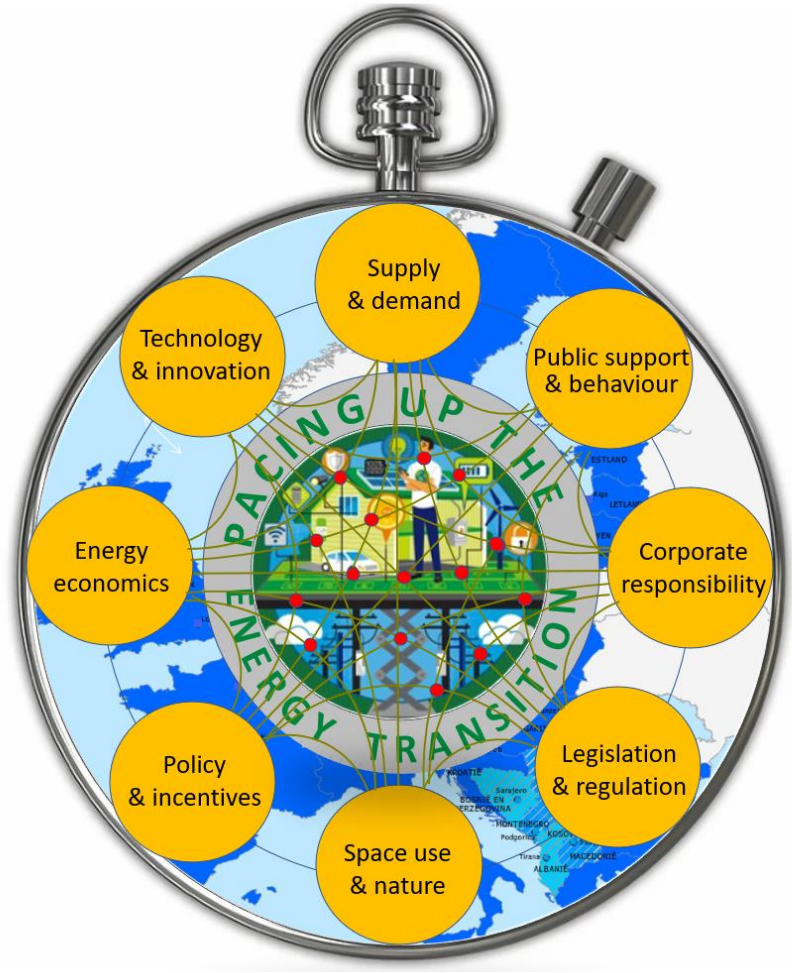

PACES case studies

Introduction

The two case studies that integrate the separate work packages are central in PACES as they approach the wickedness of the energy transition from two opposite directions. Acknowledging the interdisciplinary character and the complex behaviour of the energy transition, the first case, on a specific technology – hydrogen – starts with the well-established methodology of integrated assessment modelling, enriched with insights gained from detailed techno-economic analysis (IAMC, 2021). The scientific challenge of this case study is to expand and develop this relatively standard method with tools and modules that reflect the interdisciplinary and complexity lens inherent to PACES. We do so by integrating approaches from other disciplines into the core operation of the technology-rich TIAM-ECN model, focusing on uncertainty, non-linearity, and cross-disciplinary feedbacks. The second case study, focused on a specific region, the province of North Holland, is centred, first and foremost, around the concept of emergent complexity. It starts with developing models that aim to balance the interdisciplinarity and multiplicity of scales and jurisdictions of actors while paying particular attention to non-linear feedbacks and uncertainties inherent in the region's energy transition. The scientific challenge of this approach is to create small- and medium-scale models that, on the one hand, simulate output within the range of reality and, on the other hand, are flexible enough to generate unexpected insights. During its entire course of five years, the PACES project endeavours to let these two distinct scientific premises gradually approach each other by establishing interactions between them and enhancing each of them by each other's findings and breakthroughs. The simultaneous undertaking of both these approaches increases our understanding of how we can pace up the energy transition, internationally and nationally in the Netherlands.

The Postdocs, who also play a central role in developing the POLDER methodology (see below), will also coordinate both case studies, including modelling activities, and the POLDER co-design and co-creation activities carried out by the whole team of both scientists and stakeholders.

The Hydrogen Case

The first PACES case study, on hydrogen, is of critical importance for the Netherlands, since the country, and the province of North Holland in particular, faces a number of key questions, the answers to which remain for the moment obscure. For example, if massive wind parks will be deployed on the Dutch and other parts of the North Sea, it is unsure whether this wind energy capacity should be complemented with hydrogen production that is likewise located offshore or should perhaps be placed onshore (in which case hydrogen production could also directly be fed with dispersed onshore renewable electricity generation from units with a wide variety of capacities of e.g. either wind, solar or geothermal energy production). Alternatively, the Netherlands may rely to a large extent on hydrogen imported from abroad, in which case the question becomes whether Dutch ports (in Amsterdam, Den Helder, Eemshaven, Rotterdam and/or IJmuiden) can play a role similar to that exercised today for the purpose of facilitating imports of oil and gas. The full title of this case study is therefore "Localized versus Globalized Hydrogen: examples of Europe and Africa", concisely referred to as 'the hydrogen case' (Case H_2). Case H_2 is undertaken in close collaboration with the International Renewable Energy Agency (IRENA), our main international partner, based in Bonn and Abu Dhabi. IRENA co-funds the PACES project by delivering an in-kind contribution in terms of instructing the two PhD candidates hosted by IRENA and providing part of their supervision where necessary (see attached letter of support).

Powerful momentum is building up for hydrogen as an essential energy carrier, complementing an increased supply and demand of electricity generated from renewable energy resources, especially in industries that require high energy densities. Europe and, in particular, the Netherlands are exercising leadership in the broad diffusion of hydrogen-based technologies and options to produce hydrogen, either with fossil-fuel-based plants equipped with CCS ('blue H_2') or through electrolysis of water with renewable electricity as input ('green H_2'). If indeed the world moves towards a massive deployment of hydrogen-producing and -consuming technologies, one of the leading questions will be whether hydrogen production will become a localized economic activity close to where hydrogen is being consumed or a globalized one with large-scale hydrogen generation plants located at places with the highest renewable energy potential (Fraunhofer, 2016; IRENA, 2019; van Wijk and Wouters, 2019). In the latter case, low power production costs are combined with high costs of (inter-)continental infrastructure to transport hydrogen.

The thrust of Case H_2 is ubiquity of hydrogen production possibilities (through, e.g., solar, wind or geothermal energy, fossil fuels with CCS, or even nuclear power), and the, possibly even larger, diversity in the level of centralization at which this hydrogen can be produced (IEA, 2019; IRENA, 2019). At the centralized end of the spectrum, a world can be envisaged where hydrogen is produced in a few locations, much like current crude oil and natural gas production. At the other extreme of the spectrum, it could well turn out that, in the future, hydrogen will be produced at the micro-level (IEA, 2019; IRENA, 2019), that is, in a very decentralized fashion down at the city, neighbourhood or even household level. In between these two extremes almost all forms and combinations are also quite realistic, at least from a technological point of view. It is the ambition of PACES to explore this spectrum and to explore several of the multiple options in more detail.

In Case H_2, it is investigated, through energy systems modelling, which of the alternative futures will develop cost-optimally for hydrogen production and use in Africa and Europe, and what the consequences of these scenarios could be for both (sub-)national policy makers and international analysts in industry. Based on the analysis of these possible hydrogen futures, public servants and representatives from the private sector worldwide could design policies and strategies inspired by the insights of this research, including actors in both national governments and companies as well as international bodies like the EU (EC, 2020). In a highly centralized hydrogen system, (North) Africa is a likely region for large-scale hydrogen production. The solar irradiation in the Sahara is twice as high and is better distributed over the year than at higher latitudes like in the Netherlands. With energy system models with a sufficiently high geographical resolution, we will research where in Africa hydrogen can best be produced, with what technologies, by what means it can best be transported to Europe, via which entry points (e.g., Amsterdam, Marseille, or Rotterdam) it should be imported, and how the cost gains of hydrogen production in Africa compare to the costs incurred as a result of the required additional transport and distribution infrastructure (or, alternatively, whether electricity should be transported cross-continentally for localised hydrogen production). In a more decentralized form of hydrogen production, European countries, including the Netherlands, would become more self-reliant in fulfilling their hydrogen needs. Countries in Africa may follow suit and, in their turn, complement the expansion of renewable electricity with domestic hydrogen production and use in a wide variety of power or heat applications. We will investigate to what extent decentralized hydrogen production in Africa may (or may not) differ from that in Europe, how local conditions may shape the means of production, use, and H_2 applications in African countries, and to what extent Europe can assist in African hydrogen technology deployment as part of overseas development aid. Techno-economics research assists the energy systems modelling work. The latter needs detailed hydrogen cost and efficiency figures and an in-depth understanding of how these costs and efficiencies could improve over time due to, e.g., learning-by-doing, R&D, and economies of scale (see e.g. Rivera-Tinoco et al., 2012).

In practical terms, we will implement this collaboration by letting two PhD students spend each 3-6 months at IRENA as part of their 4-year dissertation tracks. The purpose is that they participate in ongoing IRENA activities, for example by contributing to data acquisition, report writing, undertaking applied analysis, and/or performing expert surveys, while simultaneously working on their scientific research and using their work and findings at IRENA to produce at least one article in a peer-reviewed international academic journal. The WP2 PhD student will actively use either the TIAM-ECN model or the MESSAGE-based model employed by analysts at IRENA. The WP3 PhD student will undertake techno-economic analysis of hydrogen production and consumption methods, in close synergy with the modelling work of WP2. This way, the modelling efforts based on TIAM-ECN or MESSAGE can benefit from the research findings of the techno-economic assessments performed under WP3. While financially fully renumerated by the PACES project, both PhD students are enabled to use office facilities at IRENA as guests and possibly employ locally available databases and contact with stakeholders. These permissions will serve the energy systems modelling and techno-economic research and will help to deliver on the POLDER approach (**POL**icy **D**ecisions-support and **E**vidence-based **R**easoning, fig. xx) undertaken in WP1. Complementary, we also envisage that one or more IRENA employees pay a research visit to UvA during the course of the PACES project to deepen the collaboration further and participate in the stakeholder activities of Case H_2.

The Province of North Holland Case

The second case study (Case P-NH) is dedicated to researching the opportunities for pacing up the energy transition in North Holland (NH). NH is one of the twelve provinces of the Netherlands, harbouring one of the country's main economic centres and home to several major private sector entities as well as some main European port activities. The province of NH, of which about half of the area has agricultural land use, includes the country's capital Amsterdam and the larger Amsterdam Metropolitan Area (AMA), thereby representing 10% of the Dutch population.

Essentially all aspects of the national energy transition are at play in North Holland, including the industrial, commercial, residential, and transportation sectors. The Province of NH is our primary national co-funding partner (see attached letter of support), which finances PACES by 10% of its total budget.

Introduction

The need for a transition to a just energy system with renewable resources that reduce CO_2 emissions to combat climate change is widely recognized. Global ambitions are clearly formulated in the Paris Agreement achieved through the UNFCCC (COP-21, 2015) and have been articulated to European (Green Deal: EC, 2019), Dutch (Climate agreement, 2019), and regional (e.g. RES-NHN, 2021; RES-NHZ, 2021; Hydrogen Valley, 2021) use. The implementation of these ambitions and plans, however, is exceptionally challenging because 1) it is a multi-level undertaking that lacks clear agreements on mandates, 2) it is a multi-scale problem with actors ranging from individual households up to large international companies and political structures, 3) the energy transition needs public and private investments while it is not clear who will pay what, and 4) all kinds of dependencies exist that cannot be studied by one single discipline but need an integrated interdisciplinary approach. Altogether, this makes the transition a truly wicked problem, which may need a different approach from the typical Dutch tactic that is based on consensus, which generally leads to procrastination if no consensus is reached.

Case P-NH possesses geographical boundaries at an intermediate scale: subnational and supra-individual. Thus, it ties to the (inter-)national frameworks (EU, international large companies, Dutch government), on the one hand, and municipalities, single companies (SME's), and households, on the other hand. The case includes public and private actors of different sizes and with different impacts. The involvement of many actors at different scales ensures and allows the analysis of the high level of "wickedness" of the energy transition problem.

Research aims and questions

The main scientific aim of Case P-NH is to identify key actors and understand their internal and external interconnections and feedbacks that determine the speed of the energy transition in the province of North Holland. Namely, we focus on (overlapping) jurisdictions and goals. We use this knowledge in the iterative POLDER approach as a basis for collaborative learning (transformational learning) to co-design and test a range of possible interventions that will accelerate the energy transition. We will give special attention to the following applied questions:
- What infrastructure changes are needed and where? How is this evolution related to the dynamics of the transition of energy use? In North Holland, networks of electricity, heat, and (natural or potentially hydrogen) gas have separate infrastructure and are managed by different stakeholders. As the Netherlands abandons the use of natural gas (RVO, 2017), new solutions for heavy industry and heating of buildings are needed and, in some cases, already partly implemented (collaboration with WPs 3, 6, and 7).
- What is the most effective role of the government of North Holland to speed up the energy transition? Can top-down facilitation and investments stimulate bottom-up emerging processes? (collaboration with WPs 4 and 5).
- What is the best model for collaborative learning? The energy transition is considered a dynamic process that is, at the local scale of province of North Holland, also driven by social, economic, and technological developments from beyond the geographical boundaries. As wicked problems have a short prediction horizon, there is not one big solution to be expected that can solve all problems of the energy transition occurring in the next 30 years. So, how can we make use of multi-dimensional monitoring for adaptive decision making?
- How can we involve both facts and values in our evaluations of intervention? POLDER concepts are based on evidence-based reasoning, whereas policy decisions always involve both values and facts (Dietz, 2013). Participation of stakeholders and citizens in participatory modelling will hopefully help overcome this problem, especially if attention is paid to issues related to the implementation of the interventions (Voinov et al., 2014).

Methodological approach

Participatory modelling with the POLDER approach will be central in this case study. POLDER will allow us to articulate the project between the scientists and the stakeholders, as well as integrate the seven work packages (WPs) in the PACES project.

The iterative process in POLDER consists of a cycle of five steps, as shown in Figure x. **Step 1** is the data preparation and co-design process among scientists and stakeholders to identify, rank, and balance the most important aspects, actors, and processes of the energy transition, focusing on external drivers and internal feedbacks. It uses information from the information base (see below) with literature, real-life data, and expert stakeholder knowledge.

Step 2 is the development of the digital twin, the POLDER systems model, a range of different models (involving e.g. differential equations, agent-based techniques, and multiplex networks) that mimic the dynamics of internal relations in the context of external drivers and the implementation in a computer simulation model. It receives input from the WPs and will produce feedbacks from the system-level dynamics back into the WPs. **Step 3** is the co-creation step with interpretation and evaluation of model results together with stakeholders to: (a) initiate extra iterations in the POLDER process or (b) to test additional scenarios and to design interventions for pacing up the energy transition. This step will involve regular meetings and workshops between the PACES scientists and the stakeholders. **Step 4** represents the feedback loop into the WPs and uses computer simulations to predict the efficacy of interventions iteratively, evaluate these, and design new interventions. **Step 5** is the output of the POLDER system for pacing up the energy transition.

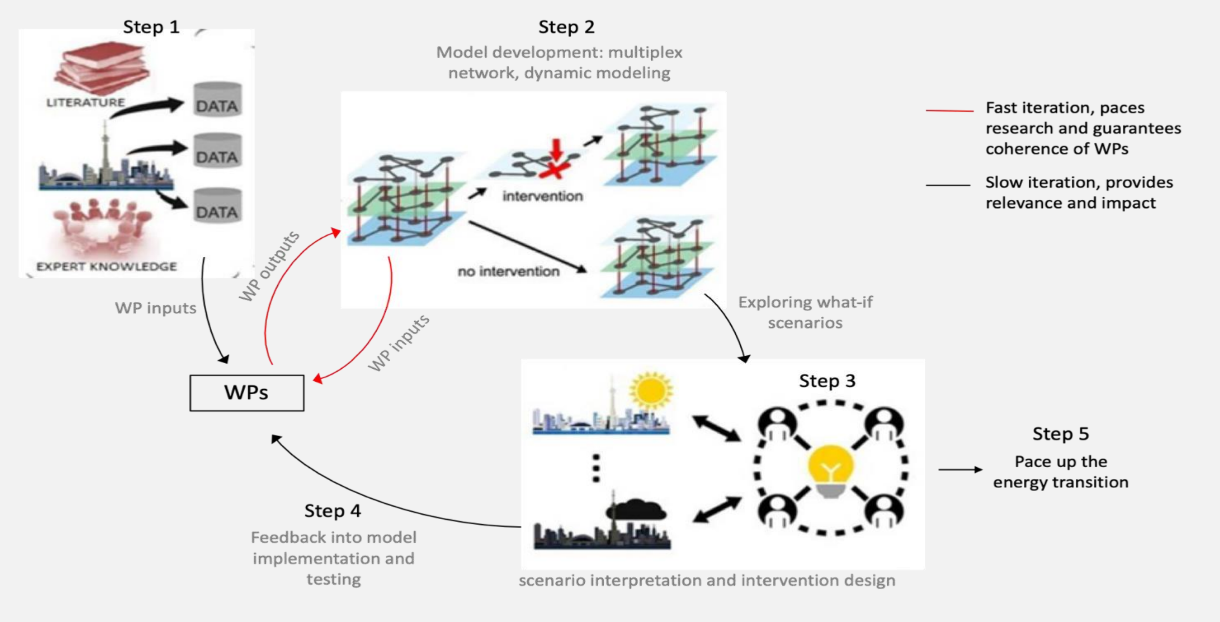

Fig xx, The POLDER approach (**POL**icy **D**ecisions-support and **E**vidence-based **R**easoning)

In close connection with POLDER-activities we foresee some supporting activities that will be carried out in close collaboration with the various WPs and stakeholders:

- As part of Step1: Build a multi-scale factual information base and infographics, as a general reference in communication processes. It focuses on the local and regional evolution of energy use and production in a national and global context. It provides information on various energy sectors and CO_2 footprints at scales of households up to complete supply chains. The information base will be updated regularly with new information.
- As part of Step2: Determine multiple networks, seen from different perspectives, and their topology with focus on homo-/heterophily and functional complementarity. The set of networks includes a broad array of domains such as governance and mandate; interests and value; attitude and trust; knowledge and information; investments or subsidies and economic benefits; space for agriculture or solar parks; energy production and consumption. Special attention is given to the feed-backs between these domains. Case P-NH will be carried out as a continuous process over the whole duration of the project. It may evolve in unpredictable ways as a result of new insights of the involved scientists and stakeholders and the developments in the world relevant for the province of North Holland.

Involvement of stakeholders and connection with WPs

This part still needs to be written.

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6.2 Description of the work packages

Work package number	1
Work package title	POLDER systems models
Work package leader	Vitor Vasconcelos
Involved partners	All stakeholders
Start date	M1
End date	M60

Objectives

The pace of the energy transition will ultimately depend on the complex interactions between socio-political and economic, biophysical, and technological domains. Therefore, we must generate a deep understanding of the development within domains and, critically, of the mechanisms, bottlenecks, and potential accelerants that operate at the interfaces between domains. A participatory modelling approach (1) that combines cross-disciplinary research and close collaboration with relevant stakeholders involved in and impacted by the energy transition is necessary to understand the impact of cross-sector interactions and the resulting system-level dynamics.

This work package aims at developing the POLDER approach ((**POL**icy **D**ecisions-support and **E**vidence-based **R**easoning) to analyze opportunities for pacing up the energy transition with a focus on trans-disciplinary participatory model development. The methodology is tested by applying it to the following research questions:

- How do the dynamic, cross-domain interactions respond to unexpected changes and targeted governance interventions? For instance, for a given intervention, to what extent can change in attitudes and behaviours of civil society that interact with the other domains (e.g., market dynamics) impact the energy transition, and how do spatial constraints play into that equation?
- Which cross-domain interactions slow down or impede the energy transition, with a potential of generating cumulative damages, or serve as accelerants (e.g., biophysical suitability for implementing technological innovations in the context of political and community support or opposition)?
- How do different policy options tradeoff among the security, resilience, and sustainability of the energy transition?

Methodology

Energy resource dynamics investigated as dynamical systems are traditionally described by (differential) equations that define the evolution of the systems in terms of supply and demand (2). They can exhibit complex behaviours like hysteresis (3) or flip between alternative stable states in response to perturbations (4). Managing complexity is a familiar problem in global change policy (5) and of permanent concern for resource provision where planners adaptively control supply-demand to suppress chaos or unstable orbits (6). The complex interactions across social, ecological, and technological domains have significant implications for the security, resilience, and sustainability of resource provisioning systems (7), such as the energy system. However, these interactions are not yet understood in the context of sustainability transformations under real-world conditions (8). Describing these dynamics requires extending such frameworks to include multilayer networks of interlinked agents and localized sectoral systems and identify and distinguish common drivers, domino effects, and feedbacks between observed responses (9).

WP1 will develop an assemblage of dynamical multiplex models ("POLDER systems models"), combining multiplex networks and systems dynamics modelling (10), where the elements are managed to achieve agent- or stakeholder-oriented objectives (e.g., a fast rate of deployment). The POLDER systems models will be developed such that the internal definition of the modules, i.e., their level of description and detail, can be varied and adapted over time without compromising the connectivity with other parts of the POLDER system. This modular structure will allow us to incrementally increase the complexity of analysis in each domain while keeping computational complexity in check. While domain-specific analyses developed in each WP will be self-contained modules, and domains will evaluate empirical relationships between state variables, they will produce outputs for and use inputs from the other modules. In the search for bottlenecks, the POLDER systems models will analyze the dynamic interactions between the domains.

Description of research activities

Policy targets and scenarios will build on the decarbonization scenarios developed as part of the case studies. By adopting a Complex Adaptive Systems perspective, we consider nonlinearities in system evolution in response to

top-down policy decisions and their impact on stakeholder goals, generating bottom-up, emergent responses from the different elements in both case studies. The POLDER systems model will identify and rank the multiple feedbacks regarding their impact on pacing up the energy transition.
Productive interactions (co-design and co-creation) POLDER articulates the project between the PACES scientists and the stakeholders, and, with both case studies, it integrates the seven work packages in the PACES project. All stakeholders involved in PACES will contribute to evaluating the scenarios, interpreting the outputs produced by the model, and designing governance interventions tested in additional model iterations.
Contribution to project WP1 is highly involved in both case studies. It contributes by developing the POLDER approach, especially from a modellers perspective, while focussing on integrating the remaining WPs.

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Work package number	2
Work package title	Global 1.5°C target
Work package leader	B. van der Zwaan
Involved partners	IRENA, Prov-NH, PBL, EZK, NZKG, IIASA, IEA-OECD, IEW
Start date	M1
End date	M60

Objectives

The first main aim of WP2 is to gain insight into whether, how and to what extent means to speed up the energy transition at the (sub-)national level can translate into pacing up the energy transition at the global scale, with which we aim at informing the modelling community as well as international climate analysts and negotiators. If some local energy transition acceleration methods (e.g. as tested in North Holland) can be duplicated internationally – by which the wickedness of the energy transition challenge would be reduced – they can deliver impact across the world and therefore facilitate reaching the Paris Agreement. Inversely, the second main scientific and practical goal of WP2 is to inform local initiatives for deep CO2 emission cuts of developments at the global level, since the success of the former is invariably impacted by the latter. On the methodological level, the third objective of WP2 is to fundamentally improve IAMs, which are extensively used by the IPCC in analyses of scenarios that meet climate targets to control the global temperature increase to at most 1.5°C (IPCC, 2018).

Methodology

The IAM used in PACES is TIAM-ECN, an established global energy systems model with which we can investigate what the impacts on greenhouse gas emissions are from fundamental changes in the energy system. TIAM-ECN is a technology-rich linear optimization model that identifies cost-minimal energy system scenarios under a set of exogenous constraints. It is an established global IAM (IAMC, 2021) operated and maintained at TNO Energy Transition, based on the TIMES generator (Loulou and Labriet, 2008). TIAM-ECN encompasses energy use in all main sectors and its input database includes hundreds of processes simulating energy conversion from resource extraction to end-use. In TIAM-ECN the world is broken down in 36 separate geographical entities (van der Zwaan et al., 2018). TIAM-ECN has been employed to provide long-term projections for many different technologies, including in transport (see Rösler et al., 2014) and power generation (Kober et al., 2016), and has been used to investigate global technology diffusion (van der Zwaan et al., 2016). A recent study was dedicated to CCS (Dalla Longa et al., 2020), pertinent for PACES because CCS deployment requires CO2 networks.

Description of research activities

The overarching research activity of WP2 is to expand TIAM-ECN towards a tool that allows for the modeling of complexity features. IAMs often poorly represent ongoing developments, which WP2 intends to correct, such as in the field of electricity and heat networks (input from WP4 and WP6), the large-scale production of hydrogen as energy carrier (expertise from IRENA and feedback from WP5), the land-use impacts from renewable energy resources (results from WP7), and the massive deployment of daily and seasonal energy storage options (elements from WP4-7, and expert judgment from IRENA). The research of WP2 will let TIAM-ECN reflect that electricity generation and supply are undergoing a fundamental change: highly centralized large-scale power plants are partly replaced by a more decentralized system of largely intermittent renewable forms of power production (WP4-6). TIAM-ECN will be adapted so that it simulates that in future electricity grids variable demand will need to be matched by variable supply, for consumers who simultaneously act as producers (prosumers). While the core methodology behind TIAM-ECN remains that of a central planner who minimizes overall energy system costs to deliver the energy services required to operate our modern economy, WP2 will fundamentally improve TIAM-ECN to represent the changing nature of electricity, heat and other networks from highly centralized to decentralized production, and to characterize the multiple types of energy storage options necessitated to compensate for the diffuse introduction of intermittent decentralized energy resources such as based on solar and wind energy (output delivered to IRENA, and WP4 and WP6).

Productive interactions (co-design and co-creation)

Even more important than the fundamental improvements and updates that the TIAM-ECN model will be subjected to, are the productive interactions with the PACES partners realized in WP2, which enable employing the revised version of TIAM-ECN to achieve the WP2 objectives and answer key energy and climate policy questions. With scenarios developed with our partners, we assess whether current developments in the field of energy networks and storage, as well as the large-scale introduction of hydrogen, pace up the energy transition. Notably for the hydrogen case study WP2 will subject the TIAM-ECN scenarios to the POLDER process (interactions with IRENA, Prov-NH, PBL, EZK, NZKG, IIASA, IEA-OECD, IEW; IRENA hosts one PhD student). In WP2 the local results of other WPs, such as regarding the effectiveness of policy interventions or the speed of technology adoption, are tested in terms of their relevance for achieving the global 1.5°C target. The insights developed under WP5 and WP6 will be used to improve TIAM-ECN, while its outcomes can serve as benchmark for the studies undertaken under WP7. Techno-economic data obtained in WP3 serve as input for TIAM-ECN.

Contribution to project

WP2 assumes a central position in PACES by providing the global perspective required as universal benchmark for all WPs, since the purpose of each WP is to contribute to increasing our understanding of how to accelerate the energy transition to reach the international Paris Agreement goals. The PACES case study on hydrogen will be particularly relevant for WP2, and vice-versa, since TIAM-ECN is particularly fit for investigating whether it is more cost efficient to render hydrogen production a localized economic activity or, inversely, a globalized one. Strongly distributed green electrolysis-based hydrogen production may be more expensive than highly centralized production in regions with lots of sun or wind, but the former obviates the need for large-scale hydrogen transmission and distribution infrastructure, so that it could still be the cost-optimal solution. TIAM-ECN can be ideally employed to answer questions like these (improved scenarios can serve IIASA, IEA-OECD, IEW). WP2 also is instrumental in achieving the objectives of our other impact pathway case study, on accelerating the energy transition in the Province of North Holland. For example, if research with TIAM-ECN suggests that highly centralizing hydrogen production at the global level is optimal and hydrogen demand in North Holland is expected to grow, then port activities in Amsterdam need to be expanded accordingly to allow for large-scale hydrogen imports, possibly also for the European continent. Inversely, if certain means of energy transition acceleration (such as local hydrogen production in NZKG or at the North Sea) rapidly scale up, these may have international consequences that can be tested with TIAM-ECN.

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Work package number	3
Work package title	Techno-economics
Work package leader	B. van der Zwaan
Involved partners	IRENA, Prov-NH, PBL, EZK, NZKG, IIASA, IEA-OECD, IEW
Start date	M1
End date	M60

Objectives

The main objective of WP3 is to determine whether new low-carbon energy carriers as well as associated transport, distribution and storage technologies can become economically competitive with fossil fuel usage and, if not, how high CO2 taxation needs to be in order to bridge the gap and reach competitive break-even. Through techno-economic studies, projections are made for when and under what investments clean energy technology can achieve competitivity with incumbent energy options. This WP also aims at expanding traditional techno-economic research with new tools and apply it to innovative energy options to further the deployability of new energy technology so as to accelerate the energy transition.

Methodology

WP3 uses the methodology of learning curves, that is, constructing, interpreting, unpacking, and applying them. Learning-by-doing has long been recognized as an essential mechanism behind technology cost reductions and has received scientific attention for decades (Arrow, 1962). Techno-economic research using learning curves as expression of learning-by-doing can be used to assess the future opportunities of e.g. solar fuels, in which CO2 and H2 obtained through electrolysis are converted into synthetic energy carriers. Based on analysis with learning curves for system components, it was shown that competitivity can be reached before 2050 for a diverse set of solar energy options, including hydrogen, syngas, methanol, and diesel (Detz et al, 2018). Much is left to be understood regarding whether, how, and when solar fuels become competitive alternatives for fossil fuels. A value of 20% for the learning rate is the median value reported in the literature for a large range of energy technologies (McDonald and Schrattenholzer, 2001). It has been observed for e.g. PV and microwave ovens (Nemet, 2006; Detz et al., 2020). Yet lower values have also been observed, notably for mature technologies or options for which learning-by-doing is constrained by components that do not learn (Ferioli et al., 2009). Also large power plants tend to be characterized by low learning rates, which suggests that one may increase the learning rate by smartly choosing a technology's unit size (Sweerts et al., 2020). This WP has the essential task, through the methodology of learning curves, of exploring how cost reductions for renewable hydrogen and other solar fuels) can be stimulated, so as to speed up their widespread use and thereby pace up climate change mitigation.

Description of research activities

Techno-economic analysis is essential for the development of both case studies on North Holland and hydrogen (co-design and co-creation with Prov-NH respectively IRENA). WP3 determines the price tag associated with new clean energy technology like hydrogen, as it is determinant for (provincial) governments' preparedness to invest in and/or subsidize the transformation of various economic sectors towards carbon neutrality in regions like North Holland. In the first track of WP3 (with IRENA, Prov-NH, PBL, EZK, NZKG) we intend to answer one of the central questions for the development of green hydrogen technology: the extent to which its production costs can be reduced, either by technological progress that can be exercised anywhere, or by optimally exploiting local physical or socio-economic conditions. WP3 assesses physical conditions such as the intensity of solar irradiation or wind potential in a given geography, on the basis of which more hydrogen can be generated with a specified installed electrolysis capacity. WP3 researches socio-economic conditions like the costs of labor and financial risks expressed by the cost of capital, which are both important cost components for hydrogen production facilities. The second track of WP3 (particular relevance for EZK, Prov-NH and PBL) researches the currently poor knowledge base of technology learning opportunities, while they are essential elements for inclusion in policy design. We also assess how to better understand the way in which one can influence the learning curve, so that a major obstacle to the energy transition – technology costs – can be overcome. The third track of WP3 (interaction with and insights from WP5; Prov-NH as important stakeholder) targets another major gap in our knowledge of cost-reducing innovation mechanisms for low-carbon energy technologies, related to their incapacity to deal with behavioural matters. We do so because public acceptance towards innovative technologies and associated costs is key for realizing their large-scale deployment.

Productive interactions (co-design and co-creation)

The technologies researched in WP3 are selected through an interactive process, after which we subject them to analyzing their techno-economic characteristics and evaluating the potential for learning-by-doing as expressed by learning curves. The central approach for these interactions is POLDER (WP1; insights from IRENA, Prov-NH, PBL, EZK, NZKG; internship of one PhD student at IRENA). The results that WP3 generates are used as input to the analyses undertaken in WP2 and both cases. For WP2 these results are essential, since one cannot generate reliable scenarios without the use of up-to-date technology input data for costs and efficiencies (revised scenarios serve IIASA, IEA-OECD, IEW). For both cases the outcome of WP3 is important for determining what regionally, at the provincial level, as well as at the scale of networks, for a variety of energy carriers, the most suitable options

are for large-scale technology deployment and infrastructure design. WP3 and WP5 along with the two case studies will be undertaken jointly in an iterative and coordinated manner, which enables contrasting the additional costs incurred by the use of clean fuels such as hydrogen against the willingness-to-pay for a cost difference by consumers wishing to contribute to mitigating climate change.
Contribution to project WP3 is the technology expertise hub for PACES and delivers techno-economic data for both case studies, on hydrogen and the Province of North Holland respectively, as well as for the various WPs. It delivers insights regarding the extent to which the costs of new energy technologies and supporting infrastructure such as energy networks can be reduced during the forthcoming decades, since cost reductions are essential components of the success of a possible acceleration of the energy transition.

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Work package number	4
Work package title	Overcoming paralysis caused by complexity
Work package leader	John Grin
Involved partners	Prov-NH, Alliander, NZKG, LNV, PBL, Citizens
Start date	M1
End date	M60

Objectives

The scientific objectives of WP4 are 1) to better understand how complex networks may produce inertia and hamper the energy transition, and 2) to explore how interventions in governance, legislation and (trans-)national markets may help to pace up the energy transition, with emphasis on complexity theory.
It will do so through focusing on the province of North Holland's efforts of coordinating, mutually tuning, and spatially facilitating two Regional Energy Strategies (RES NH-North and RES NH-South) and the industrial Cluster Energy Strategy Noordzeekanaalgebied (CES-NZKG) and last but not least coping with public debate and public support. Therefore, the WP's societal objective is to advice stakeholders (in co-creation) by generating options, evaluating their consequences and exploring the roles the province of North Holland can play. This leads to the following research questions:

1) What hybrid energy system is envisaged in existing plans, and how does it perform in terms of economic, energetic and infrastructural efficiency, land use, and public support?
2) What are key merits, drawbacks and limits of these plans, what options are there to achieve a more optimal hybrid energy system, and what institutional and infrastructural demands on RES, provincial, national and (trans-)national level do they imply?
3) Given the findings in terms of question 2), what are key lessons for coordination within and between RESs, and between RES and (trans-)national actors, arrangements and infrastructures?

Methodology

The province of North Holland must coordinate actors 'vertically' (between different scales: (inter-)national, regional and local) and horizontally, between multiple actors at the same level of scale (RES-CES; grid-grid etc.). Actors at these various levels (from an energy corporation around a village to international operators, like Tennet) are embedded in in a variety of networks consisting of actors and structural elements (such as infrastructure, governance arrangements (Grin, 2020), legislation (Bartl, 2017), and (trans-)national markets (Bohnsack et al, 2020)) that end to reproduce the incumbent system and inhibit change. These, mutually interacting, complex networks deny direct, linear interventions and inhibit transformation.
To deal with such 'wicked problem' (Rittel & Webber, 1973), involving many, closely intertwined dimensions (demographic, economic, environmental, social, and technological), factual uncertainties and diverse perspectives, a transdisciplinary methodology is appropriate: integrating the variety of disciplinary analyses of the just mentioned intertwined dimensions through systems analysis and evaluate the outcomes in terms of a predetermined set of core criteria, reflecting the diverse perspectives.
More specifically, in order to generate and evaluate options we will draw on interactive design methodology (Grin, 2020) and participatory modelling, further developed as the POLDER approach in WP1 and in a broader context extensively described by Moallemi et al. (2021). In this process we will specifically pay attention to values of stakeholders and aspects of implementation of possible solutions (Voinov et al., 2014).

Description of research activities

1) Information gathering by document analysis, expert interviews and network analysis to map the key actors and energy generation assets, their structural context (legal provisions, governance arrangements, market structure and infrastructure) and the linkages between these components of the envisaged hybrid energy system (spatial and temporal depiction of flows of information, money and energy).
2) Co-design workshops will be organised, involving actors (to be) engaged in the subsystem, citizens and societal organizations, independent, innovative (legal, economic, technical etc.) experts and key actors from the RESs and Province NH with the purpose to evaluate and adapt the mapped network topologies and set criteria for model evaluation.
3) Formalization of the above gathered information by complex adaptive systems modelling and sensitivity analysis to relate emerging dynamics to key components and interactions in the system.
4) Based on model results and in co-creation with stakeholders we will evaluate model performance with respect to the set criteria and identify options for interventions that can be iterated in the POLDER process. With stakeholders we will also focus on possibilities to implement interventions.

These steps will be re-iterated at any point when needed, using the evaluation of options in one round to adapt, enrich or re-define the options to be considered in a next. This matches well with the kind of incrementalist policy making (Termeer & Metze, 2019) fitting the problem and sought by the province.

Productive interactions (co-design and co-creation)

The co-design and co-creation steps mentioned above and important contributions to the research of WP4. While science can take advantage of the participation of stakeholders that are constantly confronted with the complexity of the energy transition, participatory modelling is expected to contribute to knowledge exchange and

collaborative learning of the whole team, including stakeholders. From the introduction under "Objectives" it is clear that there are numerous stakeholders of which the Prov. NH, Alliander, NZKG, LNV, PBL, and citizens are the most important ones.
Research activities are strongly interwoven with Case P-NH where especially WP3 (techno-economic dynamics), WP6 (energy markets and hybrid networks), WP5 (people's willingness to change) and WP7 (space use for energy infrastructures).

Contribution to project
In the pre-discussions with the Province of North Holland, problems with governance of multiple, intertwined, complex networks at different levels have been mentioned as one of the major issues that could potentially be improved to pace up the energy transition. This is why we developed this WP which is strongly interwoven with Case P-NH. This WP contributes to the aims of accelerating the energy transition by specifically addressing the complexity and analysing the potential to improve governance by:

- yielding insight into the way in which this complexity produces inertia;
- yielding insight in how transformation of governance arrangements and other structures may help overcome inertia
- translating such insights for the practice of P-NH, provinces generally and other actors.

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Work package number	5
Work package title	Citizens' willingness to change
Work package leader	Prof. Dr. Frenk van Harreveld
Involved partners	RIVM, TNO, Alliander
Start date	M1
End date	M60

Objectives

The main objective of this WP is to gain insight into the psychological underpinnings of sustainable behaviours as this is paramount to a successful energy transition. As discussed in Case H_2, hydrogen is an energy carrier that may be produced in small, decentralized locations close to where hydrogen is being consumed. We investigate how the attitudes of citizens of Noord-Holland relating to this technology interact with one another, with acceptance of policymaking, behavioural change and with willingness to accept and pay for decentralized hydrogen production and storage near their homes[1]. Furthermore, we investigate how these psychological variables interact with economic, legal, political, and technological variables in a complex system. Finally, we provide tested interventions that can accelerate the transition by increasing citizens' acceptance of, and willingness to pay for, decentralized hydrogen production.

Methodology

Although attitudes are often key predictors of behaviour, this relation is not self-evident, certainly in the context of sustainable behaviours[2]. We recently formalized models about properties of attitude dynamics and their relation to behaviour[3 4 5 6]. We conceptualized attitudes as networks, consisting of evaluative reactions (nodes) and interactions between them. While there is some work on the topic of attitudes towards hydrogen attitudes[7], this work has not employed a broad systemic approach, which is most applicable, given the complexity of the matter.

Here we investigate how different attitudes that relate to a transition decentralized energy storage (e.g. risk perceptions in relation to the storage technology, attitudes towards climate change, trust in government and technology, perceived social norms, perceived responsibilities of citizens, public and private partners, financial considerations etc.) interact within a complex system. We thus enrich the psychological system well beyond earlier work on attitude networks. A second important extension lies in our investigation of the *temporal dynamics* of the system. In modern society, with its rapid technological developments and vast amounts of information, attitudes are continuously in flux. To our knowledge, no empirical research focused on the temporal dynamics of complex systems of attitudes and related economic, political, technological, and legal factors. In this research we fill this lacuna, enhancing the validity of the 'digital twin' we are developing. Finally, we develop and test interventions (e.g. campaigns, activism) that can facilitate the transition towards a decentralized hydrogen production and storage.

In this project we combine qualitative and quantitative research. We use focus groups and interviews with experts and citizen groups to determine the most important attitudes (and related psychological variables) in the present context. We design a comprehensive survey that allows us to obtain larger samples, which will be translated into attitude networks. We design and test interventions[6] (e.g. campaigns) aimed at generating change in behaviour and citizen's willingness-to-pay for a transition towards decentralized hydrogen production and storage.

Description of research activities

This WP consists of 4 phases over the course of the 4-year PhD project.

Phase 1 (Year 1): In the first phase, we gain insight into the relevant psychological variables. Focus groups with citizens from Noord-Holland as well as interviews with experts will shed light onto most prevalent thoughts, feelings, perceptions etc. that relate to citizen's willingness to adopt (and pay for) decentralized hydrogen production and storage. This phase is defined by a close collaboration with a research project at RIVM (National Institute for Public Health and the Environment) named DIRECT[8] in which (among other things) citizen's attitudes towards solar energy are investigated.

Phase 2 (Year 2 and 3): Next, we will generate a survey to tap into consumers' attitude networks. We will distribute this survey 6 times throughout a period of 2 years among a large sample of North-Holland citizens. Here we collaborate closely with partners from all the other WPs to obtain insight into how citizen's attitudes interact with technological, economic, legal, and political aspects of the energy transition and integrate these insights in the survey.

Phase 3 (Year 3) : The network dynamics obtained in Phase 2 will provide insight into what variables in our survey cluster with willingness to pay and acceptance of policy making regarding the transition to decentralized energy production and storage. We will design and test interventions, like in our earlier work on plastic use[6]. In the last waves of our survey, we will experimentally test the effectiveness of different persuasive tools aimed at enhancing consumers' willingness to pay and acceptance of policy-making aimed at a transition towards decentralized hydrogen production and storage.

Phase 4 (Year 4): After the quantitative approach in phases 2 and 3, we will return to the more qualitative approach in Phase 1 by presenting the persuasive tools that were developed and tested in Phase 3 to similar citizen groups and experts as used in Phase 1. We thus gain more insight into which persuasive tools are most

realistic to employ on a larger scale. In this last phase the focus furthermore is on dissemination of the obtained results throughout the project.
Productive interactions (co-design and co-creation) The stakeholders involved in this proposal play a key role in obtaining insight into the attitudes and behaviours of citizens. We will collaborate with RIVM researchers from project DIRECT[8], which investigates the application of large-scale solar panel applications. The PhD-student in this WP will work at RIVM 1 day a week. RIVM has access to relevant citizen groups and a desire for insight into relevant concerns these groups may have and how these concerns relate to other relevant variables. The contribution of RIVM will be in terms of man hours and resources (access to citizen groups and experts).
Contribution to project The attitudes we investigate are related to technological, economic and political developments and therefore insights from the other work packages will continuously inform our investigation into consumer attitudes and behaviours vis-à-vis decentralized production and storage of hydrogen. Conversely, the insights into what factors are important in relation to willingness to change drawn from this work package will also inform the other work packages. This WP will provide key insight into the acceptance of risks that may be associated with hydrogen storage by Noord-Holland's citizens and a willingness to (at least in the short term) pay more for the sustainable alternative. The current WP will not only provide insight into the complex interplay of the variables relevant to this willingness to pay and acceptance, but also into how these can be enhanced most effectively.

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Work package number	6
Work package title	Market Stability
Work package leader	Cees Diks
Involved partners	P-NH, Alliander, CBS, EZK, RIVM
Start date	M1
End date	M60

Objectives

The overarching goal of this WP is to identify optimal market designs and policy measures to pace up the energy transition. To accomplish this, sub-goals are to obtain insights into (1) optimal post-transition energy markets to aim for, (2) how to keep energy markets acceptably stable during the transition, controlling the risk of price instabilities and/or market failures (3) how to account for uncertainties in the outcomes of the policies considered, and (4) to explore potential measures for system monitoring and early warning signals for impending market failures.

Methodology

This workpackage examines the dynamic interactions within and between the electricity market, heat networks and the hydrogen market. Each of these markets is a complex ecosystem with its own underlying distribution network that is evolving over the longer run, while at shorter time scales dynamic feedback effects become increasingly complex. The relevant insights needed to control or steer such a complex system can only be obtained by taking an integrated, multi-scale perspective on the system as a whole, while at the same time keeping track of the relevant local interactions. This requires an integrated multi-scale complex systems approach (Ball, 2012). Under the current developments towards a hybrid system of energy production, storage and transportation, involving at least the electricity, heat and hydrogen markets, these markets are becoming more and more intertwined, so that dynamics- and policy- related questions can only be meaningfully analysed in the context of an overarching complex system that encompasses all the relevant energy sub-markets simultaneously, as well as their interactions.

Agent-based modelling (ABM) has been successful in many economic sub-fields so far, and is gaining acceptance among economists and policy makers fast. After stock markets, housing markets, and inflation targeting it is now also permeating energy market modelling (Tesfatsion, 2018). In WP6 we therefore study the dynamics of the evolving complex hybrid energy market using ABMs, in which the actors, i.e. the producers, consumers, prosumers and net maintainers are represented by interacting heterogeneous agents. The models are naturally represented as multiplex networks in which the nodes represent the actors and the links in the network represent their interactions (Mattsson et al. 2021). The ABM framework allows studying the joint dynamics of demand, supply and prices in evolving energy markets, in the realistic situation where the interacting agents are heterogeneous in their expectations and/or actions.

Methods from nonlinear time series analysis for complex dynamical systems will be used to explore potential system monitoring tools and early warning signals for impending instability or market failures.

Description of research activities

Across the project, specific instantiations of ABMs are used to perform simulations for multiple purposes; besides developing simulation models, this WP will investigate informative measures of energy security (cf. Neelawala et al., 2019), market instability and early warning signals for impending market failures (cf. Diks et al., 2019).

In order to construct the dynamic, multiplex, network ABMs, crucial information on the multiplex energy network in the (physical) province NH as well as the behaviour of consumers and decision makers is needed. The ABM models developed iteratively within the joint POLDER approach are calibrated using data on heat sink/source networks (P-NH), power grids (Alliander), behaviour and attitudes (RIVM) and energy transition monitors (CBS/EZK). The proposed POLDER approach ensures that the partners and stakeholders will be actively involved during the entire duration of the PACES project, with a focus in the early phase (first two years, roughly) on the preparation and integration of this data in the models, and in the later phase (last two years) on identifying and collecting new types of data, as deemed needed by the progressive insights obtained within the POLDER approach.

Productive interactions (co-design and co-creation)

The POLDER approach is an iterative process, involving the consortium partners as well as stakeholders with an interest in policy/scenario analysis. Using the POLDER approach, the ABMs will be iteratively improved based on the feedback from the partners and stakeholders, and based on interactions between the WPs. As a result, during the lifetime of PACES - and possibly for many years after - the ABMs will evolve from relatively simple dynamic models into complex dynamic multiplex networks that can be used by the stakeholders to address policy-related questions at an ever-increasing level of spatial and temporal detail.

The POLDER approach developed in WP1 provides a crucial method for iterative co-creation involving partners and stakeholders within WP6. At the same time WP6 strongly interacts with the case studies and the other WPs. The connection with the case P-NH is particularly strong, since this focuses on dynamic multiplex network models for the Province NH, and as such directly relates to the research questions in that case study, e.g. related to what changes in infrastructure are needed. The latter also involves land-use issues, incentivising interaction with WP7.

Likewise, specific governance questions for NH will ensure interaction between WP6 and WP4, while question related to the effects of behaviour, acceptance and attitudes will trigger interactions between WP5 and WP6. In the interactions with WP6, it both receives relevant input to improve the model from the WPs / case studies, while it returns simulation results regarding specific questions as well as overall increasingly detailed simulation performance.
Contribution to project This work package is highly integrated with the case studies, around which the project is centred. Specifically, regarding case study P-NH: the province North-Holland currently faces a transition towards a hybrid energy market (Concept-RES NHN, 2020). The underlying physical energy infrastructure of North-Holland can serve as the skeleton of the ABM, making the ABM directly suitable for scenario analysis in the case study; and regarding case study H2: the North Sea Canal Area, as part of their ambitious energy transition plans, aims at becoming a major hydrogen hub over the next years (Vermeulen, 2021). WP6 is involved with the case study H2 by the development and application of measures for market (in)stability and early-warning signals in the context of both national and international hydrogen markets.

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Work package number	7
Work package title	Spatiality: the energy transition in multifunctional landscapes
Work package leader	Elisabeth Krueger
Involved partners	Prov NH, PBL, LNV, NZKG
Start date	M1
End date	M60

Objectives

The transformation of technologies, policies, markets, civil society attitudes, and governance strategies related to the energy transition will ultimately manifest in scarce Dutch physical space. It is therefore crucial to understand potential synergies, which could help reduce the footprints and space demand for different land uses, such as energy production/transmission, food production, water protection, nature conservation areas, and urban spaces. Given the variable scales at which these domains operate, the aim of this work package is to identify the scales at which multifunctional landscapes bear their greatest potential for synergistic effects, and what the main spatial constraints are from a multi-domain perspective by answering the following scientific questions:

- How do the different social, ecological, and technological domains interact in space through co-location, interdependence, and competitive or synergistic effects?
- What is the optimal spatial scale at which synergistic effects arise among the domains affected by the energy transition?
- Can we identify spatial patterns that minimize tradeoffs and maximize synergies? In particular, where can energy, water and food production be integrated with human well-being and ecosystem health in multifunctional landscapes?
- Can we identify spatial patterns that predict the potential of behavioral spillover from supportive to initially unsupportive communities to accelerate the adoption of renewable energy infrastructure?

Insights into these synergistic effects will help accelerating the energy transition.

Methodology

We will use Energy Potential Mapping (EPM) to analyze the production potential for renewable energies of the Prov-NH. Using this method, the properties of a specific area are translated into maps that depict the potential for energy generation and supply as a stack of layers above and below ground (1). The EPMs are overlaid with maps of physical and socio-political constraints, such as land reserved for food production, leisure, or nature protection, across a range of future scenarios as proposed in Spatial Transition Analysis (STA) (2). These methods will be enriched and expanded to include

- the detailed data on market dynamics (WP6), attitudes and behavior of civil society (WP5), and exploration of multilevel governance in the region (WP4),
- the spatial embeddedness of the Province of North Holland into the national and European energy landscape,
- the effects of pattern and scale (3) analyzed using spatial analysis and modeling tools, applied to interdependent infrastructure sectors (4) (in collaboration with WP1),
- social interaction processes of evolving consumers - producers – prosumers (5) (in collaboration with WP1).

Description of research activities

WP7 will integrate the insights from WPs 2-6 on the various domains to spatially map the energy landscape for the Province of North Holland. Each domain will be mapped as a layer, and we will use spatial analysis and modeling tools to identify hotspots for energy production (wind and solar), transmission, and CCS/CCU, given an area's biophysical potential, the importance for agricultural production, industry, nature protection, and the spatial characteristics of sociopolitical and economic factors, such as groups, organizations, and businesses in support of, or opposing the implementation of energy projects in their local communities (e.g., NIMBY attitudes). Geospatial and network connectivity maps will be combined to investigate intra- and inter-domain interactions across localities and regions, in close collaboration with both Postdocs working on multiplex networks of the energy transition landscape and on the modeling of inter-sector dynamics of stocks and flows. We will analyze the physical space demand, as well as the footprints of each layer as its impact diffuses in space. For example, renewable energy infrastructure, such as a wind turbine or transmission line, has a physical space demand, but its impact diffuses in space and into other domains, such as people's visual perceptions and attitudes, thereby creating a cross-domain spatial footprint. Overlaying heat maps of the multiple domains will help identify spatially intersecting domains for different target years in the future.

Productive interactions (co-design and co-creation)

Current conditions and future scenarios of land uses in the province of North Holland (Case NH) will be elaborated with the relevant municipal and regional stakeholders involved in land management and planning (Prov NH, NZKG, municipalities), agriculture and nature protection (LNV), areas for implementing the Regional Energy Strategy (PBL), and constraints of electricity networks (Alliander, Tennet). In a co-creation process with these stakeholders and other work packages (mainly WPs 1, 4, 5, 6), priorities for spatial planning and development will be identified,

and conflicts and interactions will be anticipated. The trajectories for achieving these spatial scenarios will be simulated, and potential pathways, additional bottlenecks, and feasible timing of policy interventions will be identified together with the entire stakeholder group involved in the POLDER approach.
Contribution to project The spatiality of physical and socio-political constraints, such as public resistance, play an important role in determining and accelerating the pace of the Regional Energy Strategies implementation. Spatial constraints identified in this work package will be relevant as input to the other WPs (in particular WP1). This work package will create insights in how to minimize tradeoffs and maximize synergies resulting from space use, thus contributing to the efficiency of planning and the acceleration of implementation. Insights obtained for the Province of North Holland are likely to be largely applicable to other provinces; the methods used (EPM and STA) have partially been applied to other areas of the Netherlands.

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