Switching tracks: Railway stations as sites for renewable energy generation in the Netherlands

by

Rory Foyle

A Master's Thesis

Submitted to the Faculty of Spatial Sciences

University of Groningen

In fulfilment of the requirements

For the Degree of Master of Environmental and Infrastructure Planning

August 2023

Student number

3940861

Supervisor

Charlotte Miller, MSc.

Date of submission

August 17th, 2023

Contact

r.t.foyle@student.rug.nl

rorytffoyle@gmail.com

Abstract

Due to the low power density of renewable energy sources and the competition of land uses in the Netherlands, there is a need for an integration of energy landscapes. Transport infrastructure can be used both for its primary purpose in transportation and for the generation of renewable energy. This research aims to find the technical and socio-institutional feasibility of the use of railway station rooftops for the generation of renewable energy using a mixed methods approach. This approach combines interviews with staff members in key organisations relating to the Dutch energy and railway systems with solar resource analysis using geographic information systems. To do this, a systems transition theory perspective is taken, highlighting the interconnectivity of society's socio-technical systems. This lens is used to examine the case study of the Hogesnelheidslijn-Zuid, the only high-speed railway line in the Netherlands. Results of the quantitative analysis of available rooftop space show an abundance of exploitable solar resources, particularly on one of the six stations studied, Barendrecht. Results of the qualitative analysis show an improving energy governance system, accompanied by an increasing prevalence of local energy initiatives. However, there remains institutional ambiguity in many aspects, including whether or not government and government-owned organisations should focus on developing a few large- or many small-scale renewable energy projects to meet targets. This is compounded by the localisation of energy landscapes, which these organisations must also address and the need for urgent results.

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List of abbreviations (in alphabetical order)

Term	**Abbreviation used**
Carbon dioxide	CO_2
Centraal Bureau voor de Statistiek (Central Bureau for Statistics)	CBS
European Union	EU
Geographic information systems	GIS
Greenhouse gas	GHG
Hogesnelheidslijn	HSL
Hogesnelheidslijn-Zuid	HSL-Zuid
Hogesnelheidslijn-4	HSL-4
Institutional Analysis and Development	IAD
Intergovernmental Panel on Climate Change	IPCC
International Energy Agency	IEA
National Renewable Energy Laboratory	NREL
Opwek van Energie op Rijksvastgoed (Generation of Energy on Government Real Estate)	OER
Photovoltaic	PV
Public-private partnership	PPP
Regionale Energie Strategie (Regional Energy Strategy)	RES
Stimulering Duurzame Energie en Klimaattransitie (Stimulation of Sustainable Energy Production and Climate Transition)	SDE++
United Nations	UN

Note. Format: Dutch (English if necessary) - Abbreviation

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Introduction

A background of spatially inefficient renewable energies

Time is running out in societies trying to switch to renewable energy sources and, in places like the Netherlands, space is running out as well. Climate change, and the detrimental effects it has on our planet and way of life, has spurred on innovation in the age of "sustainable development". The scientific consensus is that the emission of greenhouse gases (GHGs) must be rapidly curtailed to prevent more of the devastating effects of climate change, which we have already begun seeing around the world (Davidson, 2019). The rapid expansion of renewable energies is necessary to meet energy demand while moving away from polluting fossil fuels (Sayigh, 2020). Attempting to accelerate this shift through innovation has come with its own set of challenges. Physical, technical, social, and institutional constraints are factors which, when combined with varying levels of ability and willingness of various societal actors to switch to renewable energy sources, prevent rapid action in decarbonizing global and national economies. In the Netherlands, each of these factors presents itself in different contexts to different extents, which makes the ambitious national and European Union (EU) targets to drastically reduce carbon dioxide (CO_2) emissions by 2050 more difficult to achieve (Klimaatwet, 2019; Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 2021). Chief among these constraints on renewable energy development is physical, as the Netherlands is the second most densely populated country in the EU following only Malta (*World Population Prospects - Population Division - United Nations, n.d.)*. This abundance of people on what is a relatively small area of land makes maintaining current land uses very difficult while, at the same time, trying to expand the penetration of renewable energy sources into the energy mix (since renewable energy sources need more space than traditional fossil fuel sources to generate the same amount of energy). Expansive solar farms and wind parks are currently a necessity in the energy transition, and this energy generation, transportation, storage, and usage all come with spatial considerations.

Through the emission of GHGs, human activities have led to a warming of the planet of approximately 1.1°C compared to 1850-1900 levels (I.P.C.C., 2023). This long-term increase in average global temperatures has been accompanied by an increase in extreme weather events in every region of the world (Saura et al., 2023) and is referred to here as *climate change*. Fossil fuels or hydrocarbons, such as coal, gas, and oil, are the largest contributor to climate change and account for 75% of global GHG emissions and 90% of global CO_2 emissions, itself a harmful GHG (United Nations, n.d.). These fossil fuels make up the main source of power for many electrical energy systems, and about 57% of global GHG emissions in 2016 were attributed to the energy sector, excluding energy used for transportation (Scheidel & Sorman, 2012; Smil, 2006). Similar statistics are true of the Netherlands, where, in 2021, natural gas, coal, and oil accounted for more than 63% of the country's generated electricity and an even larger portion (over 86%) of the total energy supply (International Energy Agency, n.d.-a). Despite this reliance on fossil fuels, both the Dutch government and the EU have set ambitious, legally binding targets. The Dutch government aims to reach 49% GHG emissions reduction by 2030 and 95% GHG emissions reduction by 2050 compared to 1990 levels (Klimaatwet, 2019). To reach these targets, the implementation of low-carbon renewable energy technologies has ramped up in recent years to capture energy from sources such as wind and solar. In 2021, renewable energy sources supplied more than 36% of the Netherlands' total electricity usage (International Energy Agency, n.d.). Despite the necessity of this energy transition, the expansion of renewable energies has its limits; the continued development of wind and solar farms comes into conflict with the lack of space for renewable energy infrastructure in the Netherlands.

The power density (measured in W/m^2) of renewable energies such as wind and solar is much lower than that of fossil fuels like gas and coal (Scheidel & Sorman, 2012; Smil, 2006). This generally means that extracting the same amount of energy using renewables (such as wind and solar) requires vastly more area than using coal-, oil-, or gas-based generation methods. In the province of Groningen in the Netherlands, one of the less densely populated provinces (257 people/km^2 compared to the national average of just over 519 people/km^2), the space available for renewable energy generation is still insufficient to cover the province's energy usage using current technological measures (Centraal Bureau voor de Statistiek, n.d.; Sahoo et al., 2022; *World Population Prospects - Population Division - United Nations*, n.d.). This is due to exclusionary land uses, population density, and a lack of available space (Sahoo et al., 2022). To address this, the spatial integration of energy landscapes in the Netherlands has been pursued as a method of furthering the energy transition while maintaining existing land uses. An example of this is the placement of wind turbines on farmland to combine renewable energy production with agriculture, which can be found throughout the country. These forms of spatial integration are already contributing to the Dutch energy mix through onshore renewable energy, such as that of the wind farm at the Slufterdam at Rotterdam Maasvlakte (Heijden & Blok, 2020). Aspects of this multi-functionality of (energy) landscapes in the Dutch context have been studied extensively and have seen widespread use, particularly in the combination of wind energy production and agriculture. Despite this, the prospect of squeezing more renewable energy infrastructure into the already dense landscape of the Netherlands remains a technical, social, and institutional challenge which this paper aims to analyse and address.

This paper focuses on solar energy which, alongside wind, is likely to continue increasing its share of the Dutch electrical energy mix in the future due to increased investment, subsidies, and tax cuts offered by the Dutch state. In particular, this paper looks at the use of solar photovoltaics (PVs) to harness solar radiation and how they can be integrated into the Dutch landscape. Solar PVs or solar cells are a form of technology that converts solar radiation directly into electrical energy, which can then be distributed and used for a myriad of societal functions. A number of solar PVs put together create a solar panel or module, which can be used as part of an array to generate larger amounts of electricity (Jäger-Waldau, 2018). It has been and continues to be a rapidly growing industry, with the technology also having seen vast improvements in efficiency over the last number of decades (National Renewable Energy Laboratory [NREL], n.d.). New installations are now consistently cheaper than new coal- or gas-fired power plants in many countries throughout the world (International Energy Agency, 2020; Jäger-Waldau, 2018). This rapid expansion of the use of solar panels, among other renewable energies, indicates the corresponding acceleration of the global energy transition, as discussed in the 'Theoretical framework'.

Relating to spatial integration in the Netherlands, the placement of solar panels, as well as other renewable energy technologies together with other land uses, demonstrated how land can effectively be used for multiple purposes at the same time. As an example, the placement of solar panels on building rooftops has seen a spike in popularity and usage in the Netherlands in recent years (Bellini, 2023b). In addition, national-level subsidies and initiatives continue to encourage the uptake of solar energy systems. Examples include that of the Dutch SDE++ (Stimulering Duurzame Energieproductie en Klimaattransitie/Stimulation of Sustainable Energy Production and Climate Transition), which grants subsidies to private companies and nonprofits that generate renewable energy, or the reduction of value added tax on residential solar systems to 0%, as of January 1st, 2023. The placement of solar PVs on rooftops can be seen as an integration of energy landscapes, as the same land area can be used for two purposes at once: electrical energy generation and business, living, etc. It is this multi-functionality of space which this paper discusses in depth and for which worked sample calculations are presented. In particular, this study assesses this integration as related to the use of train station roofs and platform shelters for solar energy generation using solar panels.

The focus, the research question, and the scientific and societal relevance

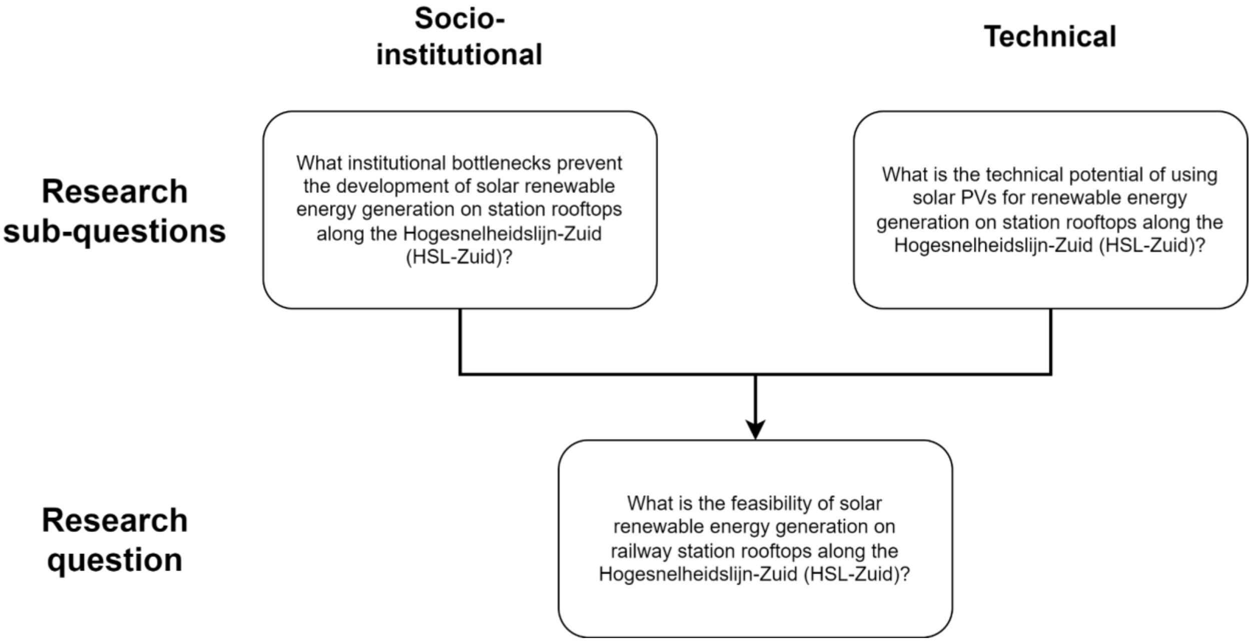
While some studies have regarded transport infrastructure as an exclusionary land use (Sahoo et al., 2022) railways have been the site of much innovation concerning renewable energy production (Mitrofanov et al., 2021). These innovations include solar panels on train station roofs, alongside railways, in between the tracks (Chen et al., 2022; Euronews Green, 2023; Jaffery et al., 2014) and vertical axis wind turbines which harness the power of the air displaced by passing trains (Chilugodu et al., 2012; Kumar et al., 2015), as well as sound and vibration energy harvesting (Hosseinkhani et al., 2021). These various methods of renewable energy generation offer opportunities for the integration of transport and energy infrastructure for more efficient use of space. In many applications, the use of renewable energy generation mechanisms has been researched to support the development of monitoring, signalling, switching, and communication systems relating to railway usage (Hosseinkhani et al., 2021). In addition to supporting these relatively low energy intensity railway functions, there may remain untapped potential in the use of renewable energy generated on existing railway infrastructure for either improved electric train system efficiency or grid connection and distribution. Some evidence suggests that renewable energy generated along railway infrastructure could be put back into the railway catenaries to improve the electrical efficiency of the trains (Oñederra et al., 2020). However, it is also the case that any larger-scale renewable energy generation sites would likely need to be connected to the grid if the energy generated could not be used locally for functions such as monitoring or switching. Despite these intricacies, these possibilities present societal relevance as a window of opportunity for the combination of land uses and more efficient use of space.

This paper looks at the railway transport network of the Netherlands as one of its objects of study. This is done using the case of the Hogesnelheidslijn Zuid (HSL-Zuid). The HSL-Zuid is the Dutch portion of the Hogesnelheidslijn (HSL) from Amsterdam Schiphol Airport train station to Antwerp Central train station. This paper examines the ways in which solar panels could be integrated into the line's existing (railway network) infrastructure: both on a technical and physical level, and at the level of socio-institutional barriers. This examination uses a mixed methods approach, including both qualitative and quantitative methods of data collection and analysis to answer two research sub-questions relating to the integration of solar PVs in the existing railway infrastructure of the HSL-Zuid. The challenges preventing the installation of solar PVs on railway infrastructure, including railway station roofs are examined. Particularly, this paper examines the institutional and social/societal barriers, as well as the physical possibility of using station rooftops for solar energy generation. This is aimed to show the possibility of further integration of renewable energies into what are already very dense landscapes through the use of a calculated example.

The primary research question of this paper is: "What is the feasibility of solar renewable energy generation on railway station rooftops along the Hogesnelheidslijn-Zuid (HSL-Zuid)?". Finding a useful answer to this question requires a further expansion and clarity on what "feasibility" in this sense really means. To answer such a broad question, this paper looks at the railway and electrical energy networks as large societal sub-systems (as discussed in the theoretical framework), which enables the split between the social, institutional, and technical aspects of the systems. These three aspects are addressed through the use of two research sub-questions: one which examines the social and institutional, and another which examines the technical feasibility and potential of the integration of solar PVs into railway infrastructure. To address the socio-institutional side, the first research sub-question is: "What institutional barriers prevent the development of solar renewable energy generation on railway station rooftops along the Hogesnelheidslijn-Zuid (HSL-Zuid) in the Netherlands?". The second research sub-question, looking at the technical feasibility of this integration is: "What is the technical potential of using solar PVs for renewable energy production on station rooftops along the Hogesnelheidslijn-Zuid (HSL-Zuid) in the Netherlands?". Combined, these two sub-questions aim to answer the primary research question on the feasibility of this integration, as illustrated in Figure 1.1 on the next page.

Figure 1.1

Visualisation of the two research sub-questions being used to answer the primary research question of the paper



To investigate these two complementary research sub-questions, this paper uses a mixed methods approach, combining institutional analysis with geospatial analysis to examine the institutional and physical conditions necessary to allow for the integration of solar PVs into the railway network. This is done using a case study of the HSL-Zuid in the Netherlands. Semi-structured in-depth interviews are the method of qualitative data collection used to answer the first sub-question relating to the institutional bottlenecks preventing this development. Quantitative geospatial analysis, using geographic information systems (GIS) of spatial data related to the stations "along" the HSL-Zuid, is done to answer the second research sub-question concerning the physical feasibility. By looking at the social and institutional side on the one hand and the technical side on the other, this paper aims to expand both on the discourse surrounding the integration of energy landscapes, as well as the mixed-method research of the energy system. It is intended that this mixed methods analysis can add value to the many discourses surrounding institutional analysis, the integration of renewable energy, and the research methods thereof. Furthermore, this article aims to add to the body of scientific literature on the topics of spatial integration, institutional harmonisation, and the mixed methods approach to research of a case study.

Background of the case

Since beginning its modern industrialised development as a country in the 19th century, the Netherlands has become a veritable network society (Vleuten & Verbong, 2004). Instrumental in its development was the use of multiple networks, both physical and institutional, which allowed for easier transportation. Among these networks is the railway network of the Netherlands, whose infrastructure quality is touted as one of the world's best (*Railroad Infrastructure Quality by Country, around the World*, n.d.). Of this network, there is only one section of track which can accommodate high-speed rail traffic, and that is the Hogesnelheidslijn-Zuid (HSL-Zuid), a part of the Hogesnelheidslijn (HSL). The HSL is a high-speed railway line which connects Amsterdam Schiphol Airport to Antwerp Central Station. This international railway line can be split into its Dutch and Belgian components, those being the Hogesnelheidslijn-Zuid (HSL-Zuid) in the Netherlands, and the Hogesnelheidslijn-4 (HSL-4) in Belgium.

This line, stretching from Amsterdam to Antwerp, does not run continuously between the two. For certain stretches of the track in the Netherlands, for example, the line uses the same railways as lower-speed traffic from other lines, such as in the greater Rotterdam metro area, where the HSL-Zuid officially stops outside the city near Rotterdam West and begins again at Barendrecht. This division of what is and is not designated as the HSL-Zuid is important, as, unlike the rest of the Dutch railway network, the day-to-day management of the HSL-Zuid is carried out by a private consortium, Infraspeed, not the national railway management agency, ProRail. Additionally, this means that there are no stations "along" the HSL-Zuid, as such, since the stations are managed by NS Stations and ProRail, while Infraspeed maintains the HSL-Zuid. Although, in an official, legal capacity, no train stations are technically situated "along" the HSL-Zuid, a number of stations are included in this analysis to aid in comparability to the Beijing-Shanghai case study done by Chen et al. (2022).For ease of reference, the stations under study in this paper are described as being "on" or "along" the HSL-Zuid, despite the legal distinction.

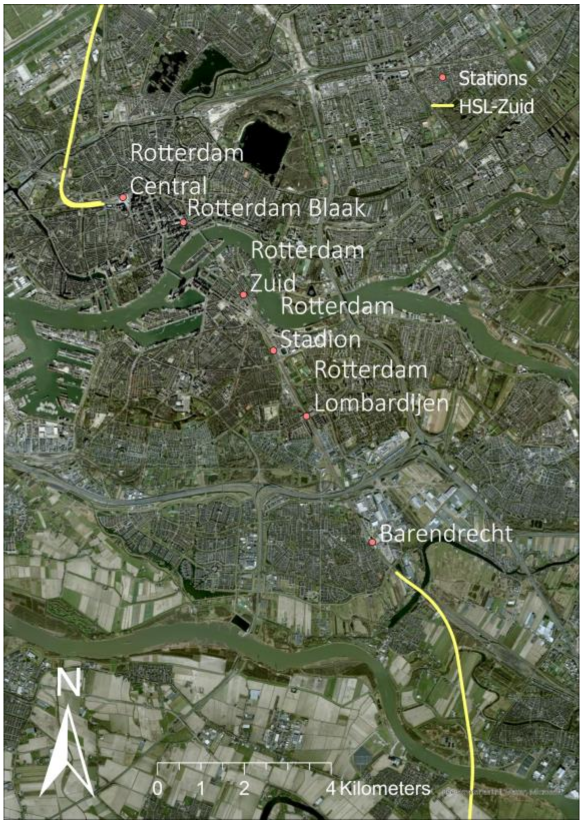
Figure 1.2

The HSL-Zuid, including all of the stations between Schiphol Airport and Belgium

Note. Only those stations with high-speed stops are given labels.

Figure 1.3

A closer look at the many stations in Rotterdam

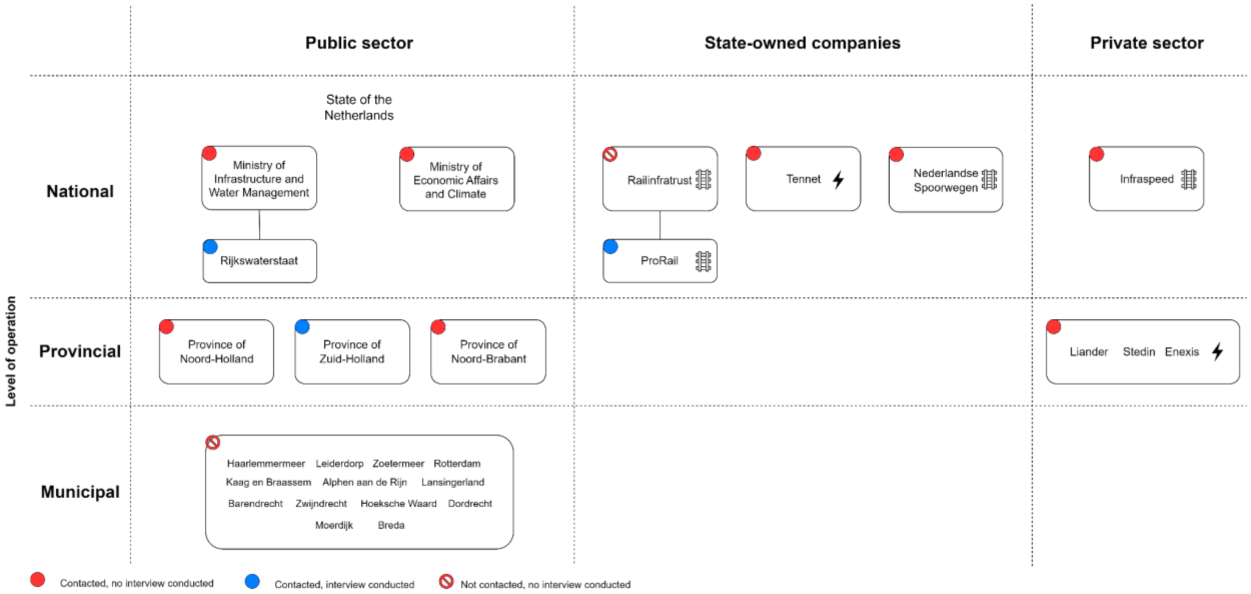


Note. The HSL-Zuid officially stops by Rotterdam West, which is partly why there are no stations "on" the HSL-Zuid.

ProRail is the national organisation in charge of managing the railway network of the Netherlands. It is a private limited company, and a subsidiary of Railinfratrust, which is completely owned by the Dutch state, with shareholding done by the Ministry of Infrastructure and Water Management. ProRail is in charge of the maintenance, renovation, expansion, and safety of the railway network, as well as rail traffic control and allocation of railway capacity, and has exclusive rights to assets necessary for that, including land, rails, platforms, shelters, energy infrastructure, etc. relating to the network (*Over Ons*, n.d.). The organisational arrangement, demonstrating the public, state-owned, and private sector stakeholders relevant to the planning of the railway and energy systems of the Netherlands, is illustrated in Figure 1.4. Included in the figure are also key stakeholders involved in managing large-scale infrastructure (projects), Rijkswaterstaat, and legislation relating to climate policy and carbon-reduction programmes, the Ministry of Economic Affairs and Climate Policy. Rijkswaterstaat is the executive branch of the Ministry of Infrastructure and Water Management, responsible for the maintenance and safety of a large number of large-scale infrastructures throughout the country. These stakeholders are important in programmes relating to government attempts to reduce carbon emissions, generate renewable energy, and bring about a clean transition, such as the Opwek van Energie op Rijksvastgoed (OER, or the "Generation of Renewable Energy on Government Assets") programme, a programme aimed at the generation of renewable energy on government properties.

Figure 1.4

Visualisation of the key stakeholders involved with the transport, energy, and planning systems of the Netherlands



While there is a push to make government organisations and the country as a whole more sustainable, certain sectors, such as the railway transport sector, are already ahead of schedule. The majority of the Dutch train network is powered using overhead electrical lines, with the entire Nederlandse Spoorwegen/Dutch Railways (NS) fleet being electrified. This stands in contrast to the many diesel-powered train systems of other countries in Europe and around the world. On top of this, since 2017, NS has supplied all of the electricity for its trains using renewable sources (*Green Energy for Train, Bus and Station | Sustainability | About NS | NS*, n.d.). This use of clean energy sources means that public transport in the Netherlands is already ahead of schedule when it comes to meeting national renewable energy targets. The use of electricity to power the majority of the Dutch train network means that the maintenance of the energy infrastructure, on top of the maintenance of the railways themselves, is important to allow for continued train travel throughout the country. As seen in Figure 2.1, there is considerable interrelation between the railway transport and energy systems of the Netherlands due to this reliance of the railway network on electricity from the grid, with a contract between NS and Eneco guaranteeing electricity supply (*Green Energy for Train, Bus and Station | Sustainability | About NS | NS*, n.d.).

The HSL-Zuid illustrates the interrelated nature of the railway, energy, and planning systems, and the necessity to involve more societal actors. As ProRail puts it, the HSL-Zuid is a special piece of track (*ProRail en de HSL-Zuid*, n.d.). This is because there are more stakeholders involved in its management than with most of the rest of the Dutch railway network. As mentioned above, although the main management of the HSL-Zuid is done by ProRail, the day-to-day management is done by a private consortium known as Infraspeed. Infraspeed is a consortium which began between multiple market parties, including the construction companies of Koninklijke BAM NBM, Siemens Nederland, Fluor Daniel, and two finance agencies: Charterhouse Project Equity Investments and Innisfree Ltd. Together, these parties formed Infraspeed BV, which was created to pursue the design-build-finance-maintain (DBFM) contract for the HSL-Zuid. It won this project with the best bid in the procurement process in 2001, after which construction began on the line. Construction took five years, between 2001 and 2006, after which maintenance stayed in the hands of Infraspeed. This maintenance contract lasts until the end of 2030. The current plan is for ProRail to take over full responsibility for the superstructure of the HSL-Zuid from the beginning of 2031. This DBFM contract, where only the operation is left up to other parties, is a prime example of a public-private partnership (PPP). In fact, at the time of its being awarded, this was the largest PPP in Dutch national history (Hetemi et al., 2021).

Relating to spatial integration, there are two key infrastructure projects along the HSL which relate directly to the use of solar panels on railway network infrastructure, including stations and along the railway line. The first is that of Rotterdam Central Station, which underwent a renovation, as mentioned previously. This renovation included the installation of over 9,000m^2 of solar cells on its 28,000m^2 roof. In this case, the required renovation and remodelling of the Rotterdam Central Station was used as a window of opportunity to include renewable energy generation in the station's new form, thereby spatially integrating the functions of the railway station with renewable energy generation. While this stands as an example of the integration of solar power with a railway station on HSL, there is also an example of the integration of solar power with track infrastructure, demonstrated by the Peerdsbos Solar tunnel on the Belgian portion of the HSL, the HSL-4. The Peerdsbos railway tunnel is another example of railway infrastructure being used to tackle multiple challenges at once. The Peerdsbos is a forest located just outside Antwerp. Here, there was a need to protect the forest from the noise and air pollution of the railway traffic, as well as the traffic on the adjacent E19 highway (which led to the construction of the tunnel over the railway track). After construction, at a later stage, solar panels were placed on the tunnel's flat roof to allow for the generation of renewable energy in addition to the protection of the forest from noise and the railway from falling trees. Although this is not an example of exploiting windows of opportunity as they occur, since the solar panels were used after the construction of the tunnel, it shows the utility of planning which allows for future adaptation to more sustainable infrastructure development.

Theoretical framework

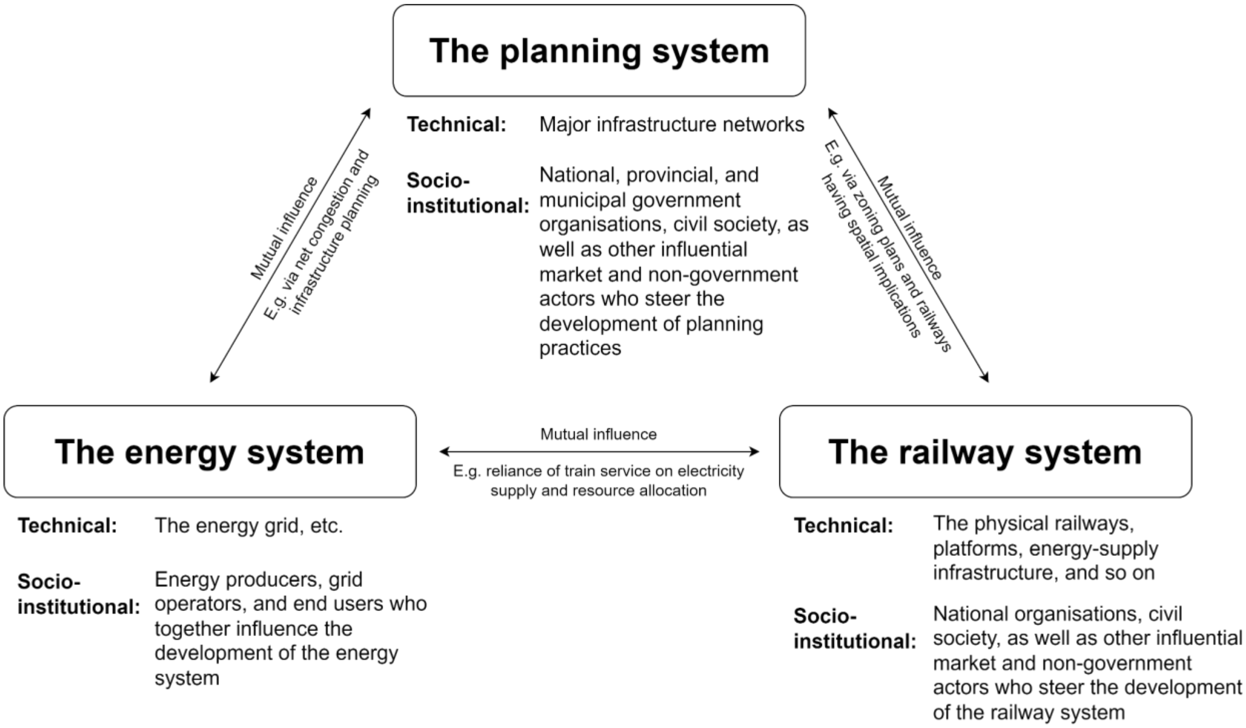
Systems

In this paper, systems and transition theory acts as the analytical lens, providing a perspective which allows for the viewing of the energy and transport systems and their planning and governance as a socio-technical system (Kern & Smith, 2008; Meadowcroft, 2009). Utilising systems theory allows for a clear delineation of the object of study. Systems theory is based on the idea that within society there exist a number of interrelated systems, both large and small. A system is a collection of the linkages between elements necessary to fulfil a societal function (Geels, 2004). This is true of socio-technical systems, socio-ecological systems, and societal systems more broadly. An example of one such system is the electrical energy system of the Netherlands, which this paper takes as one of its systems of focus. Systems theory has previously been used by many scholars to study energy systems (Kern & Smith, 2008; Markard, 2018). An energy system can be viewed as a large socio-technical societal sub-system. Linkages and elements of systems can be technical, social, or institutional in nature, all of which undergo change in periods of transition (Geels, 2004). This study aims to analyse all of these elements in the case of the transport and energy systems of the Netherlands. Cross-sectoral infrastructure development in particular requires the analysis of multiple complementary and partially overlapping systems and sectors, which is why multiple large societal sub-systems are taken into account. This is illustrated in Figure 2.1, where three systems: the planning, energy, and railway systems of the Netherlands are taken as the three primary systems important to the analysis of cross-sectoral railway-renewable energy infrastructure development.

Each of these systems, through their interaction, is necessary for the proper and ongoing functioning of the other. Each of these systems will have to undergo fundamental change, some of which has already begun. For the electrical energy system of the Netherlands, for example, the societal function of the system is that of providing energy to the almost 18 million inhabitants, countless businesses, industries, transport systems, and everything else which requires electricity to operate in the country; all these functions will (soon) need to be met with energy from renewable sources (Kern & Smith, 2008). Although the system currently supplies electricity for all of these different uses with a 99.999% success rate (*Homepage NL*, n.d.), the need for change towards sustainability will require new methods of electricity generation, transportation, storage, consumption, and importantly, management. The transition from traditional methods of energy provision to newer methods (such as wind and solar) also requires a transformation in the dominant 'rules of the game', as will be discussed later (Meadowcroft, 2009). The concepts and frameworks found in systems and transition theory literature – including multi-phase, multi-level, multi-actor and multi-causal – which are vital to our understanding of the energy transition, will be discussed in detail in the 'Transitions in each of these aspects' section of this paper (Loorbach et al., 2008). Before doing this, however, we must first look at the nature of systems themselves.

Figure 2.1

Interaction between the multiple complex systems involved in realising cross-sectoral infrastructure projects involving the railway and energy systems



Note. This visualisation of the many systems involved in infrastructure development relates to the idea of *nested hierarchies* in systems theory (Geels, 2002), where each system is interrelated and in some senses a sub-system of another. In this case, the energy and railway systems of the Netherlands are sub-systems of the planning system, which encompasses many sectors and systems as well as the actors vital to them.

Important to any understanding of systems theory is the idea that society itself is made up of a number of large, complex, adaptive systems. The above graphic shows the three systems essential to this analysis. Although for the sake of the illustration, the idea of a "planning system" is separated from the other systems, this does not truly reflect the functioning of socio-technical systems or the real world. In the Netherlands, this can be illustrated using the example of an organisation such as ProRail, responsible for the maintenance, safety, and (if needed) expansion of the railway network. ProRail is a vital stakeholder in the Dutch railway system, not least because of its planning functions. ProRail is the primary planner of railway maintenance, renovation, remodelling, and so on, with their role also including the on-the-ground maintenance work, as well as big-picture planning. For the ease of demonstration, the "planning system" is separated from the energy and railway systems in the figure above, but it must be noted that planning overlaps heavily with systems such as the energy and railway systems, which require intense planning from actors in those systems to operate. This is why, under the 'socio-institutional' aspect of the planning system non-governmental parties are mentioned, including actors such as ProRail and Tennet, each vitally important to planning in the railway and energy systems respectively.

As mentioned above, systems are collections of linkages between elements. This linkage between elements within systems can also be applied to entire systems themselves, which are all inter-related to greater or lesser extents. Society itself is a system of systems, a collection of elements which, in differing ways, relate to one another. The energy and railway systems are two such systems and form the focus of this paper. As seen in Figure 2.1, these systems influence each other in a number of ways which make them interconnected in planning, despite sectoral separation. Possibly the most evident connection between the energy and railway systems is that the majority of the Dutch railway network is reliant on electricity to run its trains. This electricity has to be generated somewhere, then transported to the overhead railway lines to be consumed by trains for propulsion. This is a microcosm of the current energy system.

The Netherlands and most of the world today can be described as consisting of a second-generation energy landscape (de Boer & Zuidema, 2016; Noorman & de Roo, 2011). Second-generation energy landscapes, of the three generations of energy landscapes described by Noorman & Roo (2011), are characterised by their intensive use of generally high power density energy sources such as oil, gas, or coal, where energy production and consumption are spatially detached (de Boer & Zuidema, 2016; Kann, 2015; Noorman & de Roo, 2011; Pasqualetti, 2012). This spatial disconnect between energy generation and usage reinforces the passive roles of the public in the provision of energy, and runs counter to the spatial integration of energy landscapes, as will be discussed in the following sections (de Boer & Zuidema, 2016).

Technical

Switching from the current fossil-fuel-dominated energy system to an energy system designed around and reliant on renewable energy sources will require major shifts in the physical and technical structure of the energy system. Renewable energy sources have characteristics not typical of fossil fuel sources that make their integration into the current electrical energy system a rather complex task (Verzijlbergh et al., 2017). The known intermittency (the variability and reliability) of renewable energy sources cause friction through their integration into the energy system (Verzijlbergh et al., 2017). This starkly contrasts the always-on-demand nature of fossil fuel energy sources such as gas-fired power plants, which can begin generating electricity on short notice, making them excellent for ensuring supply meets demand (Greenfield, n.d.). Renewable energy sources, on the other hand, vary greatly in terms of their energy output due to atmospheric processes over large and small spatial and temporal scales (Verzijlbergh et al., 2017). This intermittency makes renewable energy sources more difficult to integrate into the existing energy system than traditional below-ground fossil-fuel-sourced energy (Erdiwansyah et al., 2021).

The increasing demands on space and time only compound the problem of intermittency in renewable energy sources. The energy transition will come with an enormous change in the generation and consumption of energy, with much of the change being in the proximity between the two, as well as an increase in the number of distributed generation inputs into the distribution grid (Manfren et al., 2011; Zegers et al., 2015). This also requires a shift in the transmission-distribution interface, particularly due to the current grid congestion of both levels in many parts of the Netherlands (Bellini, 2023a; *Grid Capacity Map - TenneT*, n.d.; Zegers et al., 2015). The current (Dutch) energy system can largely be described as a second-generation energy system (de Boer & Zuidema, 2016). In this energy system, there is a disconnect, particularly spatially, between energy generation and energy use (de Boer & Zuidema, 2016). Any true energy transition will account for this, as the long-distance transportation of always-on-demand energy is something which lowers efficiency, as transporting electricity over long distances leads to energy loss (DeSantis et al., 2021). This footloose link between energy production and energy consumption ultimately "prevents people from developing more active attitudes towards energy generation and consumption" (Burch, 2010; de Boer & Zuidema, 2016, p. 172). However, as a switch to more distributed generation inputs from ‘prosumers’ occurs, the management of these many, new, small-scale inputs presents challenges for grid management in a continued *'decentralisation'* or *'localisation'* of energy landscapes (Jakimowicz, 2022).

The electricity grid of the Netherlands can be split up into the transmission system and the distribution system. It is the connection of these systems, the high-voltage transmission system and the lower voltage distribution system which allows for continued energy provision in the Netherlands. However, "[t]he current upward trend in renewables participation will demand even more flexibility from the energy systems" (Gallo et al., 2016, p. 800). These two parts of the energy grid, the transmission system and the distribution system, are operated by different parties. The transmission systems operator in the Netherlands is Tennet, the state-owned company responsible for operation and management of the high-voltage grid. While Tennet operates the national high-voltage grid, a multitude of parties, including organisations such as Enexis, Stedin, and Liander, act as distribution system operators, managing the lower-level electricity networks throughout the country. The railway system of the Netherlands requires a constant supply of electricity to continue functioning. Although increased implementation of battery technologies could aid in this, the combination of railways and their electrical energy demand, via overhead lines, shows a prime example of a 'double vulnerability paradox', meaning that the proper functioning of the railway system is reliant on the proper functioning of the electrical system (Vleuten & Verbong, 2004). It exemplifies the utility of the existing second-generation energy system of the Netherlands where energy is (essentially) always available. The supply of clean energy for the Dutch railway system is currently being filled by wind farms in the Netherlands, Sweden, Finland, and Belgium (*Green Energy for Train, Bus and Station | Sustainability | About NS | NS*, n.d.). This supply would need to remain uninterrupted as more local supplies come on-line to guarantee train travel for passengers.

Social

The energy system is a complex web of actors and networks (de Boer & Zuidema, 2015). Chief among these actors (and actor networks) are the managers, governors, and operators involved with the day-to-day management of the energy system on its different levels. Providing electricity for the proper functioning of modern society requires the cooperation of many societal actors; it is not just a matter of connecting the wires or the simple rollout of renewable energy sources in the energy transition. Multiple actors and stakeholders are involved in the provision of electricity in the Netherlands. In the Dutch context, organisations are vital to the management of the energy system and therefore the energy transition. Organisations are here defined as "material entities typically possessing personnel, offices, budgets, a legal personality, and so forth" (Bhandari, 2019, p. 114). These include Tennet, the national transmission system operator, the many distribution system operators, including Enexis, Stedin, and Liander, as well as direct governmental organisations such as the Ministry of Economic Affairs and Climate Policy, all of whom have a hand in planning, operating, managing, and governing the energy system of the Netherlands.

However, there are an even wider range of stakeholders and actors involved with the energy system and its transition, principal among them being the public. Despite the fact that most people may be "accustomed to playing a passive role in energy procurement" (de Boer & Zuidema, 2016, p. 172), the increasing prevalence of local energy initiatives and cooperatives in the Netherlands every year over the past decade shows the important emergence of a new attitude (Hufen & Koppenjan, 2015; *Lokale Energie Monitor 2022 | HIER*, n.d.; Oteman et al., 2017). Traditional top-down and managerial planning approaches often do not enable effective planning given the complexity of such a multi-actor system as the energy system (Boer & Zuidema, 2015; Etzion et al., 2017). As such, we need to turn towards more area-based, area-oriented, and context-dependent planning approaches (Boer & Zuidema, 2015). Fostering energy citizenship provides a step towards this, a step that is increasingly regarded as vital to the energy transition (Korjonen-Kuusipuro et al., 2017). Energy citizenship relates to the active, rather than passive, participation of the public, not just in individual energy projects, but in the ongoing energy transition as a whole. The “socialisation” of energy production systems is a key aspect of the energy transition (Devine-Wright, 2012) and something which any further integration of railway and energy infrastructure would have to address head-on.

While this paper discusses the feasibility of governance for renewable energy integration into the rail network, this should not be seen as a one-size-fits-all proposition. Despite looking for the possibility of integration of renewable energy and railway infrastructure in the case of the HSL-Zuid, it is not a recommendation for a top-down approach to rolling out solar PVs on every square metre of relevant, available space. On the contrary, in light of the abundance of relevant literature on the topic, this paper also looks towards the necessity of integrated and publicly-inclusive planning which encourages energy citizenship. "An area-based approach to fostering the 'energy transition' has the potential to improve understanding of the factors that contribute to the viability of innovative energy initiatives" (de Boer & Zuidema, 2015, p. 1). These innovative, small-scale, and local energy initiatives are vital to long-term change, as will be discussed later.

Institutional

Institutions, just like the actors and organisations that create, maintain, and disrupt them, are essential to the understanding of any socio-technical system. In the case of the Dutch energy system, as discussed above, the actors involved are both subject to and able to change the formal and informal institutions which determine their actions. To continue with this line of reasoning, it is first imperative to begin with a shared understanding of what an institution is. Unlike organisations, institutions can be understood as the formal and informal rules and norms that influence the behaviour of humans and organisations (Ostrom, 2005). Institutions are vital to the understanding of environmental and resource management regimes (Young et al., 2008). Regimes relating to environmental and resource management can be seen as institutions or sets of institutions and are components of governance systems at all levels (Young et al., 2008). Organisations, as discussed in the 'Social' section above, are those entities influencing and influenced by these institutions, as organisations can be seen as networks of human actors. Each of these organisations is governed by a set of internal and external institutions, formal and informal, including codified and uncodified rules, norms, and values. Imperative to any long-term structural change in society is change in organisations and institutions. This leads to considerations of how institutional change occurs. In this paper, the action of individuals and organisations in changing institutions (or the '*rules of the game*') or interpreting and changing the interpretation of institutions is referred to as the '*play of the game*' (Spijkerboer et al., 2019). This refers to "actors' ideas, interpretations, and deliberations regarding how rules *should* be reframed, ignored or abolished" (Spijkerboer et al., 2019, p. 1595). 'Institutional work' is an important concept here, and is "the purposive action of individuals and organisations aimed at creating, maintaining, and disrupting institutions" (Lawrence & Suddaby, 2006, p. 215).

Human action and inaction shape institutions. Essential players in shaping institutions and actors' interpretation of institutions are known as '*policy entrepreneurs*' (Huitema et al., 2011). Policy entrepreneurs are those groups or individuals who "instigate, implement, and sometimes block transitions" (Huitema et al., 2011, p. 718). These front-runners can affect transitions in many ways, including the detection and exploitation of windows of opportunity, network management, coalition building, venue shopping, and idea development (Huitema et al., 2011). All of these roles are important in this analysis of the roles of individuals and organisations involved with the energy transition, both inside and outside the energy sector. To differing degrees, and in different ways, all of these roles must be taken on by actors directly involved with the management of the energy system. In the case of the modern energy system, there must not only be a switch from a hydrocarbon/fossil fuel-based energy system to a renewable energy system, but also a shift from a sectoral approach to project realisation to a more integrated approach, where individuals and organisations exploit windows of opportunity, build coalitions, and develop new innovative ideas. The current sectoral, "*siloed*" approach to project development, means that many windows of opportunity are left unexploited, as demonstrated by Warbroek et al.'s (2023) paper on unexploited windows of opportunity in the energy and climate adaptation sectors.

The silo approach to infrastructure development has been and continues to be pervasive in the Netherlands. However, there also remain examples of innovative cross-sectoral projects which involve the development of renewable energies in other areas. This includes the placement of solar PVs on highway noise barriers and embankments, water reservoirs, and building roofs, and of wind turbines on agricultural land and offshore. A recent example is that of Rotterdam Central Station, the renovation of which was completed in 2013, including integrated solar panels as a part of its glass roof. Projects like this highlight the integrative possibility of renewable energies with existing railway and other transport infrastructure.

As lauded by researchers Bosman & Rotmans (2016), the Netherlands is already spearheading an integrated, bottom-up strategy to switch from fossil fuels to renewable energy sources by taking on a facilitatory position that allows for radical innovation. However, other researchers also provide evidence that many windows of opportunity are left unexploited in what could be cross-sectoral projects (Warbroek et al., 2023). According to Warbroek et al. (2023), this is due to the creation and maintenance of sectoral *action situations* by sectoral institutional arrangements in which actors are likely to act in sectoral ways. One aspect of this paper is to test whether or not sectoral institutional arrangements guide the realisation of projects relating to the railway network of the Netherlands and how, if at all, this can be helped in order to maximise the space available for renewable energy generation on land. A recent update in this regard was the introduction of the Opwek van Energie op Rijksgrond (OER) programme. Under this programme, government-owned land and real estate assets have been made available to the 30 Regional Energy Strategy regions responsible for generating a total of 35TWh of on-land renewable electricity by 2030. These assets have come from a number of national-level authorities, including The Ministry of Defence, Rijkswaterstaat, Rijksvastgoedbedrijf (the Central Government Real Estate Agency), Rijksdienst voor Ondernemend Nederland (the Netherlands Enterprise Agency), Staatsbosbeheer, and ProRail. A number of ProRail assets are currently being used in projects as part of the OER programme, none of which are along the HSL-Zuid proper (*Projecten*, n.d.).

The OER programme can be seen as a prime example of policy in environmental governance. Environmental governance is "the set of regulatory processes, mechanisms and organisations through which political actors influence environmental actions and outcomes" and "is synonymous with interventions aiming at changes in environment-related … institutions, decision making, and behavio[u]rs" (Lemos & Agrawal, 2006, p. 298). Since the 1960s/70s, there has been a decline in the status of governments as the primary agents of environmental governance, coinciding with the emergence of the modern environmental state, the blurring of lines between and within the public and private sectors, and the state's loss of steering ability (Lemos & Agrawal, 2006; Mol, 2016; Peters & Pierre, 2006; Stoker, 1998). This change has involved the dilution and spread of power from central governments to other market and civil society actors, which has also meant change on an institutional level. This change has involved a shift from government to governance, two poles on a continuum of governing types (Jordan et al., 2005). The two terms – government and governance – are not synonymous. While government refers only to the actors and actions of the state, governance also includes the actions of non-state actors, including both market and civil society-based actors such as businesses, communities, and other non-government organisations (NGOs), in the steering of societal development (Lemos & Agrawal, 2006).

In this shift since the 1960s, more and more non-governmental actors have gained influence over actions relating to the environment. With this rise of new, actively involved stakeholders, governments around the world have shifted their approach from more traditional 'command-and-control' regulatory environmental policy to '*new environmental policy instruments*' (Jordan et al., 2005). These are softer policy instruments which allow more freedom to other societal actors to coordinate amongst themselves to meet societal goals with less government involvement (Jordan et al., 2005). A key development in this new era of governance is the increased use of public-private partnerships (PPPs), which is considered to be "a form of structured cooperation between public and private parties in the planning, construction, and/or exploitation of infrastructural facilities in which they share or reallocate risks, costs, benefits, resources and responsibilities" (Koppenjan, 2005, p. 137). This form of cooperation has often been used throughout the Netherlands in the construction of large-scale infrastructure, such as for the designing, construction, and maintenance of the HSL-Zuid.

Transitions in each of these aspects

To analyse the problem of creating a carbon-neutral energy system and the means by which this can be achieved given the current spatial and temporal constraints in the Netherlands, the challenges must first be clarified and defined. As mentioned briefly above and outlined in detail in the IPCC's latest report (I.P.C.C., 2023), unsustainable energy use is one of the myriad human activities which continue to contribute to the increasing emission of GHGs. The transformation of socio-technical systems which underpin core sectors such as energy "is essential if human activities are to be brought back within ecological boundaries" (I.P.C.C., 2007; Meadowcroft, 2009; Millennium Ecosystem Assessment (Program), 2005). In other words, fundamental change is required to address how and how much energy is generated and consumed, as well as how generation and consumption are spatially linked. In order to achieve this, there is a need for a transition of global energy systems, which currently rely predominantly on fossil fuels.

A transition can be defined as "a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms" (Rotmans et al., 2001, p. 16). The energy system is just one of these complex societal sub-systems but contributes massively to global GHG emissions and humans' effect on the planet as a whole. This paper looks closely at two of society's complex sub-systems to investigate how they might undergo transition simultaneously. These sub-systems are the energy and transport systems (and the planning thereof). More specifically, this paper examines the railway transport and the electrical energy systems of the Netherlands, and how integration/harmonisation between the two might produce co-benefits by allowing for the multi-functional use of land.

The main system of focus in this theoretical framework is the energy system, as it is currently undergoing an *energy transition*. The *energy transition*, in this paper, is defined as "those transitions in the electricity sector that are characterised by an accelerated diffusion of intermittent renewable energies" (Markard, 2018, p. 628). Over the past few decades, as evidence of the increasing threats posed by human-induced climate change began to grow with increasingly undeniable evidence, there has been an increase in the use of renewable energy sources for electricity generation throughout the world. The term, 'renewable energy sources', in the context of the energy system, is used to refer to both non-finite resources (solar, wind, hydro) and the technologies by which these resources can be used to generate electricity (solar photovoltaics, wind and hydro turbines, etc.). It is these renewable energy sources on which any carbon-neutral society must base its energy production (Ray, 2019). Other "renewables" include certain sources of biogas, wood, etc. These materials may also be used in an unsustainable manner which can lead to other consequences, such as deforestation, as has happened in many parts of the world at different times due to reliance on wood for energy.

However, this transition implies far more than a simple and straightforward rollout of renewable energy technologies, as problems have arisen with conventional managerial approaches in the past (Etzion et al., 2017). It requires a shift in business models, markets, electricity prices, load curves, and in consumption, as well as other aspects of the energy system which is a contested and political process (Salomaa & Juhola, 2020). It also implies a shift of governmental policy, and furthermore, the changing of all three of the social, technical, and institutional aspects of systems as discussed in the previous sections (Geels, 2004). In relation to the complex matter of defining the energy transition, different scholars disagree on the fundamental nature of what constitutes a transition or transformation in a societal system (Meadowcroft, 2009; Salomaa & Juhola, 2020). While some view transitions as non-structural, unradical, or superficial (Salomaa & Juhola, 2020), others see transitions as processes of gradual, but structural and radical change (Rotmans et al., 2001; Geels, 2004). This is the case despite a significant number of authors calling for structural, long-term change in societal systems. Therefore, although we here call the necessary shift from fossil-fuel energy sources to renewable energy sources the 'energy transition', the 'energy transformation' may be an equally apt term, and the two will be treated as interchangeable during this paper. In essence, regardless of how gradual or abrupt, radical structural change can and must occur imminently to bring societal processes back within ecological boundaries. This paper examines stations which could double as sites of renewable energy generation, a possible action which could be taken to make an impact right now or in the near future. It is not concerned with what actions would do the most good with the least cost, or what aspects of change are most essential

Sustainability transformations, or transformations towards sustainability are an example of what Rittel & Webber (1973) first described as *wicked problems* (Etzion et al., 2017). Wicked problems are problems which cannot be simply defined, have indirect causal relationships, and are socially complex, among other characteristics (Rittel & Webber, 1973). These characteristics of wicked problems can easily be applied to climate change and the problems posed by it, such as the necessity to shift to renewable energy sources, and so on. The central problem of each of these interrelated and complex topics is difficult to define. This, along with the involvement of many systems and actors, makes them socially complex issues, calling for multiple potential pathways which do not rely on conventional managerial and top-down approaches (Etzion et al., 2017). All of this complexity is compounded by the fact that sustainability itself is an often ill-defined term, and one which it is important to contend with when it plays a leading role in research methodology (Salomaa & Juhola, 2020). With this in mind, this paper takes sustainability, based on the idea of sustainable development from the Brundtland Report, to mean the ability to meet "the needs of the present without compromising the ability of future generations to meet their own needs", with a focus on multi-sectoral sustainability (Brundtland, 1987, p. 6; Salomaa & Juhola, 2020). In this way, it must be acknowledged that any transition or transformation in a societal system to more sustainable practices does not have negative externalities and spill-overs into other systems and sectors (Salomaa & Juhola, 2020). Herein lies one of the fundamental complexities of planning, especially in a country where space is tight and renewable energy generation is not the only problem driven by the climate crisis to contend with.

The multi-level nature of system transitions

The multi-level concept of transition theory highlights three levels and posits that it is the continued interaction between these levels that is characteristic of long-term societal change (Rotmans et al., 2001). These levels are the niche, regime, and landscape levels of systems (see Figure 2.3). On the niche level, small-scale innovations and initiatives occur. Over time, these experiments can influence the dominant regimes of the system under study on the meso (middle) level. These regimes are the next level up and represent the dominant 'rules of the game', institutions, as well as networks of actors relating to the system and its governance. Above this is the landscape level. This level represents the long-term societal trends relating to the system. The three levels influence and interact with one another, with the regime level often inhibiting change at the beginning of transitions (Loorbach et al., 2008; Rotmans et al., 2001). On the niche level, small-scale experimentation can occur, leading to variations and deviations to the status quo (Rotmans et al., 2001).

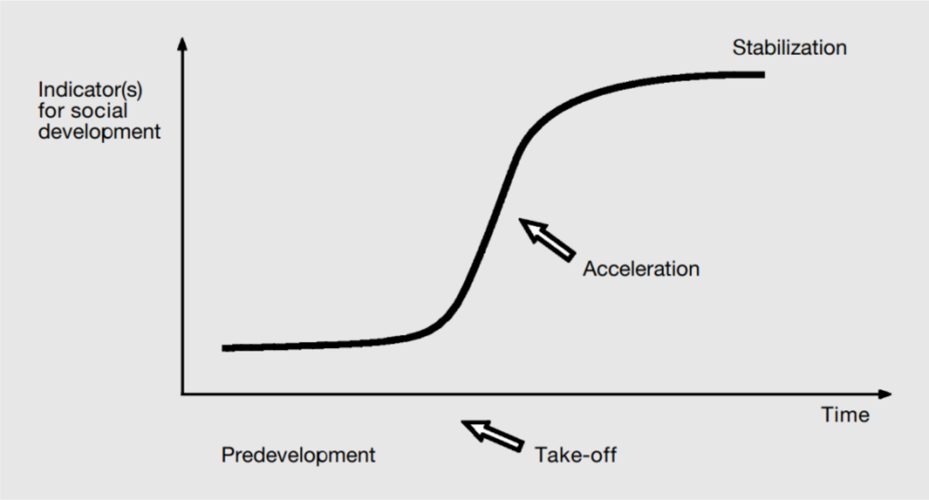
Niche-level innovations such as increased efficiency of solar PVs can, over time, lead to momentum which influences the dominant regime through niche-regime interactions (Loorbach et al., 2008). This is also true of landscape level developments, such as the adoption of the 2015 Paris Agreement by 196 parties on the global stage, which is widely regarded as a momentous event in global efforts to combat climate change. The combination of small-scale innovations and initiatives (niche) to combat parts of the problem relating to climate change with the wider societal attitudes towards cutting down GHG emissions (landscape) influence the dominant regimes which affect how action takes place. The interaction between the levels is instrumental in transitions in socio-technical systems. Applying this to the energy system allows for visualisation of the ongoing developments relating to energy and conceptualises the multi-layered nature of issues involved in the energy transition. In the case of the energy system of the Netherlands, where fossil fuel use is dominant and cross-sectoral project realisation could be improved, applying the multi-level concept of transition theory gives a perspective on how small-scale projects can influence the dominant 'rules of the game' in the medium and long term.

The multi-phase nature of system transitions

Transitions can be split up into four stages, referred to as the predevelopment, take-off, acceleration, and stabilisation phases (Rotmans et al., 2001; see Figure 2.2). These phases represent different stages of transition from an old to a new regime. In the case of the energy transition and the changes that need to occur in the energy system in order to combat climate change, the current or "old" regime is characterised by a reliance on below-ground, fossil-fuel, hydrocarbon energy sources such as gas, coal, and oil. It is also characterised by a sector-based approach to project and target realisation, where GHG reduction takes place sectorally (Warbroek et al., 2023). A new regime will have to be reliant on renewable energy sources, which many governments, including in the Netherlands, are working towards, with an ever-increasing share of renewable energy technologies in their energy mix. However, this paper argues that another important development will have to be the increasing use and realisation of integrated energy projects; projects which are cross-sectoral, and address multiple issues at once. The shift from hydrocarbons to renewable energy sources and from silo approaches to integrated approaches of project realisation occurs in four stages (see Figure 2.2). These stages are the predevelopment, take-off, acceleration, and stabilisation phases. At present, some scholars argue that due to the increasing adoption of renewable energy technologies and management systems thereof, many countries can now be seen to be in phase two of the four-phase transition: take-off (Laes et al., 2014).

Figure 2.2

The four stages of system transitions



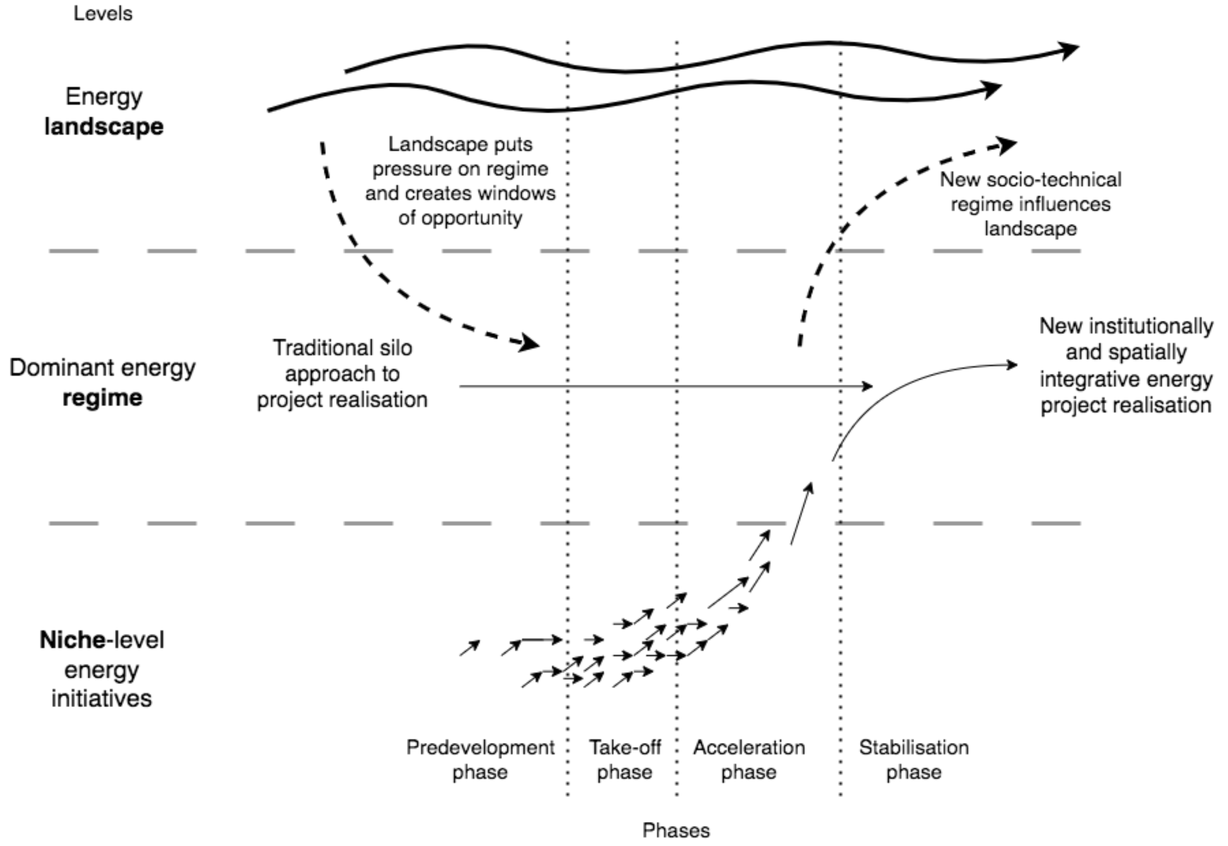
Note. Source: Rotmans et al. (2001).

Applying these phases to the energy transition shows the recent take-off of more sustainable methods of energy production and crucially, of integrative energy governance and institutions. This includes the take-off of more diverse explorations of integrative energy projects which aim to tackle multiple cross-sectoral issues at once. An example of this is biogas-powered rural heating from manure that also reduces soil nitrogen levels (Warbroek et al., 2023) which addresses two ongoing societal issues in the Netherlands at once. An energy system based mainly on renewable energy sources and steered using more integrative governance strategies, in contrast to the current energy system of the Netherlands, represents a new dynamic equilibrium. Although the idea of equilibrium is contentious in the theoretical realm of transition theory, a shift from the current energy paradigm (based predominantly on below-ground fossil fuels and sectoral 'silo thinking') to integrative governance of above-ground renewable energy sources is required in order to reduce GHG emissions. Although the specificities of the energy system in 2050 may be unknown (e.g. what are the most favourable solutions/strategies to reach carbon neutrality), it will be substantially different from the energy system of today (Loorbach et al., 2008).

This shift has already begun with the uptake of an increasing use of renewable technologies and also of integrated project realisation. This can be shown in examples of station renovation and remodelling implemented to diversify and expand into the realms of energy generation and climate adaptation. This is done by integrating land-use functions and has been seen in places like Rotterdam Central, Delft Campus and the Groningen Main Station that is currently under construction. These examples show the beginnings of a take-off in renewable energy and integrated project realisation. Distributed experimentation of this kind can lead to small wins that can generate momentum (Etzion et al., 2017; Weick, 1984). Despite these cross-sectoral developments, institutional arrangements can restrict further integration, especially for novel and innovative technologies. Examples of complexities include the often costly nature of new technologies, the expense of small-scale energy projects (when compared to large-scale developments which benefit from economies of scale), and the expansion of the project scope which is often associated with increased risk and complexity. Examples of such missed opportunities include using urban residential heat grid development for the simultaneous implementation of climate adaptation measures, and the reduction of soil nitrogen levels by using manure for rural heat generation (Warbroek et al., 2023). The missed opportunities represented by these examples indicate a trend of maintaining sectoral divisions, while missing out on windows of opportunity.

Figure 2.3

A multi-level, multi-phase perspective of innovations in the socio-technical energy system



Note. Based on the work of Geels (2004).

Figure 2.3 is a visualisation of the multi-phase and multi-level aspects of the energy system and its transition. Combining the multi-phase and multi-level concepts in analysis of the energy transition shows the current rapid uptake of renewable energies in the energy sector, as well as the increasing prevalence of cross-sectoral projects attempting to use windows of opportunity and address multiple societal issues at once. This new, renewable energy-based and integrated approach has been influenced by both niche-level energy initiatives and projects (e.g. the A50 highway solar noise barriers project or Delft Campus energy neutral train station), as well as large-scale landscape level change typified by international agreements and general cultural awareness (e.g. Paris Agreement). These two levels interact with, influence, and are influenced by the regime level and the currently dominant 'rules of the game'. These rules are being challenged and interpreted in new and different ways by the actors looking to take rapid and effective action to forward the energy transition.

The multi-actor and multi-causal nature of system transitions

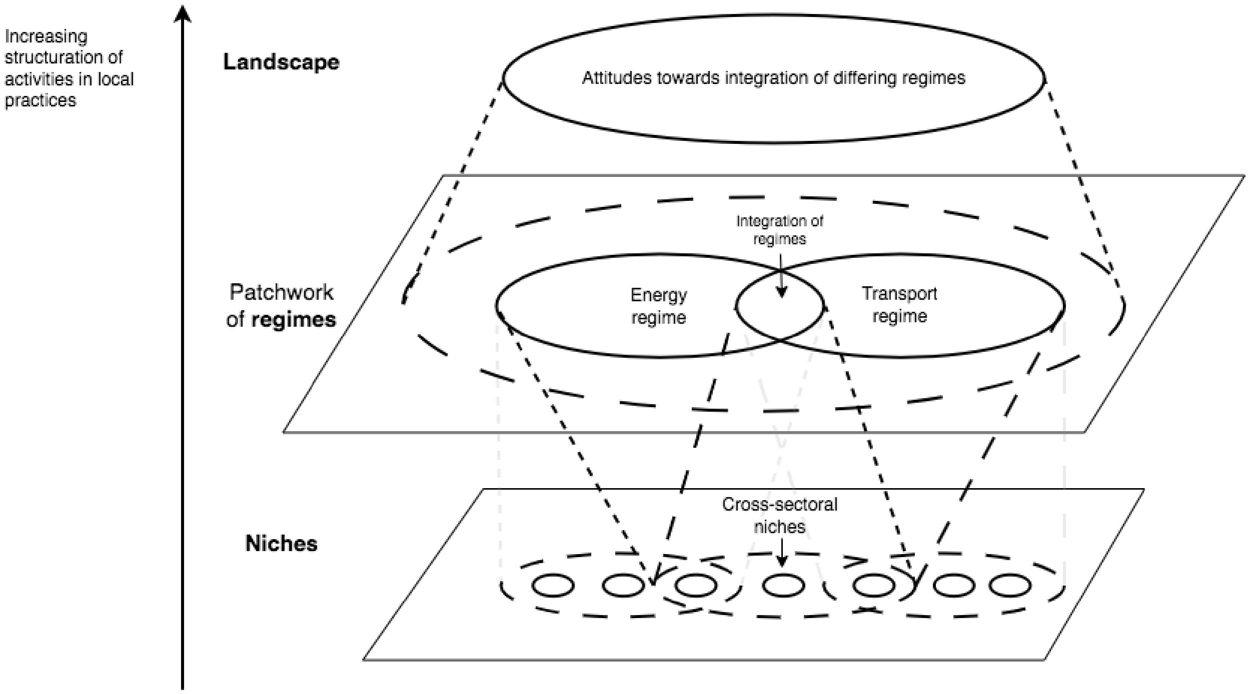
Transitions "are inherently social issues, and therefore governance strategies should involve a wide range of actors" (Loorbach et al., 2008, p. 11). From a transition management perspective, this acts as normative guidance. Understanding the necessity of multi-actor involvement in developments relating to the energy transition is key when hoping to realise innovative cross-sectoral energy projects such as the one discussed in this paper. In the case of the energy, railway, and planning systems of the Netherlands, there are a multitude of actors involved to differing extents, each with their own perspective, knowledge, expertise, interest, and value, etc. The necessity of involving relevant and interested actors and stakeholders from an early stage within projects must be acknowledged (Cuppen et al., 2016), as well as the utility of coalition building and networking as methods of expanding horizons and improving project outcomes (Huitema et al., 2011). The turn towards area-based planning in the energy system comes with its own set of new stakeholders, namely the public, that need to be involved (see 'Social' section). This can add complexity, as hierarchies, institutions, and ways of working will need to change, which also relates to the multi-causal nature of the energy system.

Although by itself, the concept of multi-causality may not be as analytically important as the other concepts previously discussed, the need for an emphasis on the complex and blurry nature of issues relating to sustainable development is evident. From a systems perspective and when speaking of large socio-technical systems such as the energy system, it is imperative to highlight the difficulty faced by decision-makers, particularly in the government realm, in steering long-term societal developments (Loorbach et al., 2008). This is exacerbated by the multi-actor nature of any large socio-technical system and the historic shift from government to governance, with many more actors outside the realm of the government now wielding power in steering long-term societal development (see 'Institutions' section).

A shortcoming of many of the conceptualisations of systems and transition theory, particularly regarding the multi-level concept of transitions, is that diagrams show a rather simplified upscaling of ideas from the niche to the regime to the landscape level within particular systems/sectors. However, cross-system or cross-sectoral idea generation and upscaling can occur. Identifying sectors such as energy and transport as different regimes fails to account for the upscaling of cross-regime or cross-sectoral niche-level innovations. In the figure below (Figure 2.4), you can see an alteration of the idea of nested hierarchies introduced by Geels (2004), with the inclusion of niches from other sectors and cross-sectoral niches, which themselves can be upscaled and influence the regime level. In the case of the transport (railway) and energy systems/regimes and the focus of this paper, cross-sectoral transport-energy innovations provide an opportunity to exploit windows of opportunity for more integrative governance techniques and capitalise on combinations of infrastructure to save space.

Figure 2.4

Nested hierarchies of the transport and energy regimes, the upscaling of cross-sectoral niches, and the integration of regimes



Note. Based on the work of (Geels, 2002).

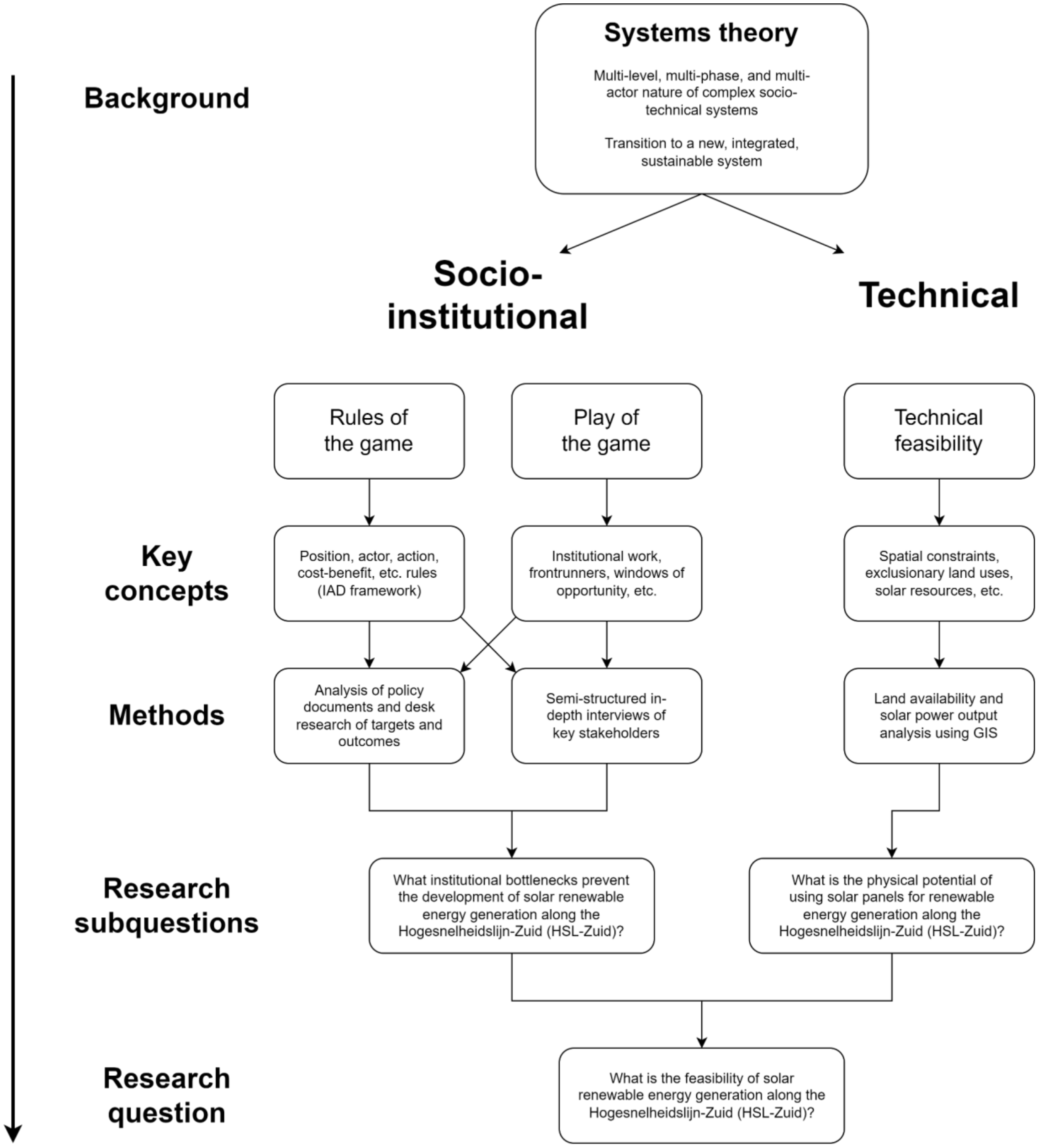
A setting for analysis

To briefly summarise what has been discussed, manifold elements are necessary to fulfil the societal function of providing electricity. These elements can broadly be divided into the technical, social, and institutional aspects of the system (Geels, 2004). The technical aspect of the energy system includes the physical infrastructure needed to generate, transport, store, and use energy. The social aspect of the energy system includes the actors involved in managing, maintaining, using, and changing the system. The institutional aspect is characterised by the organisation, governance, and expertise surrounding the other categories and generally refers to the 'rules of the game'. To briefly illustrate this, the societal function of electrical provision has the boundaries of ensuring that enough energy is being generated during times of high demand and to avoid excess energy from being produced during times of low demand. This management requires all of the above: physical infrastructure, actors to manage, and institutions to ensure the methods of management are kept in check and culminate in the seamless provision of energy to users. It is not simply a collection of interlinked technologies, but the interplay between all of these three aspects of a system that results in a desirable societal outcome. This paper is aimed at examining each of these three aspects.

Figure 2.5 on the next page is a visualisation of the conceptual model that is guiding this entire research, based on the theory which has just been highlighted and examined. The primary theoretical frame which acts as the basis of this research is the distinction between the technical, social, and institutional aspects of complex socio-technical systems, and the need for each of these three aspects to change. For the sake of research methods and analysis techniques, these three aspects have been re-categorised into two: the technical on the one hand, and the socio-institutional on the other, since the actors involved in a social sense are also those actors creating, maintaining, and disrupting the institutions which guide them. This multi-aspect nature calls for a mixed methods approach, which is outlined in the following section and which informs the conceptual model which is shown in Figure 2.5. These two (re-categorised) aspects are analysed using a different research method and are used to answer each of the two sub-questions, thereby answering the primary research question. Following the figure from top to bottom shows that systems theory, including system transitions and the multi-level, multi-phase, and multi-actor and multi-causal concepts of system transitions, acts as the basis on top of which the research takes place and is thus analysed and evaluated.

Figure 2.5

Conceptual model



Methods and methodology

Mixed methods is the use of both quantitative and qualitative methodologies in a single study (Salehi & Golafshani, 2010; Tashakkori & Teddlie, 1998) and have been used extensively in the past, often when analysing a complex object of study (Kallemeyn et al., 2020; Maxwell, 2016; Ponce & Pagán-Maldonado, 2015; Poth, 2018). Many strands of social scientific thought accept the use of mixed methods for the inquiry of complex phenomena (Shan, 2022). These positions range in the "strength" of their philosophical foundations but provide reasoning as to why a researcher may choose to employ a mixed methods approach (Shan, 2021). Due to the complex, adaptive, and multifaceted nature of the problems with transition in the Dutch socio-technical energy, railway, and planning systems, a mixed methods approach is the most suitable, given its utility in studying complex phenomena. Each of their technical, social, and institutional aspects affects the others, as technical limitations influence social and institutional action, and vice versa, both within and between systems. Despite the relationships between these aspects, there remains an extent to which they can be separated and analysed. For the purposes of research, this paper splits up the three categories of socio-technical systems: technical, social, and institutional, and re-categorises them into two: the technical and the socio-institutional. This paper addresses these aspects by taking a methodological pluralist stance to the research methods used.

To study each of these aspects, this paper uses a different research sub-question, one aimed to give insight into the technical aspect of spatial integration, and one aimed to give insight into the socio-institutional aspect. These two research sub-questions are answered using research methods suited to the nature of each of the phenomena which they are based on (i.e. methodological pluralism). Of the two research methods used in this paper, one is quantitative, while the other is qualitative. On the quantitative side, the analysis looks at the physical potential of integration, while on the qualitative side, the analysis looks at the social and institutional bottlenecks preventing this integration. These phenomena are related, but not identical. Therefore, this use of two research methods on two different phenomena cannot be considered *methodological triangulation* due to the methods being used on different phenomena (Hussein, 2009; Mitchell, 1986; Polit & Beck, 2008). Rather than leading to converging or diverging findings about one phenomenon, these two research methods relate to different but complementary objects of study, supplementing the results of each individually to create a fuller picture of the system under study (Heale & Forbes, 2013). In this case, rather than simply analysing the physical potential of solar along the HSL-Zuid, the institutional bottlenecks preventing such a development are also addressed, and the combination of these complementary lines of inquiry is intended to lead to more insight into the system as a whole.

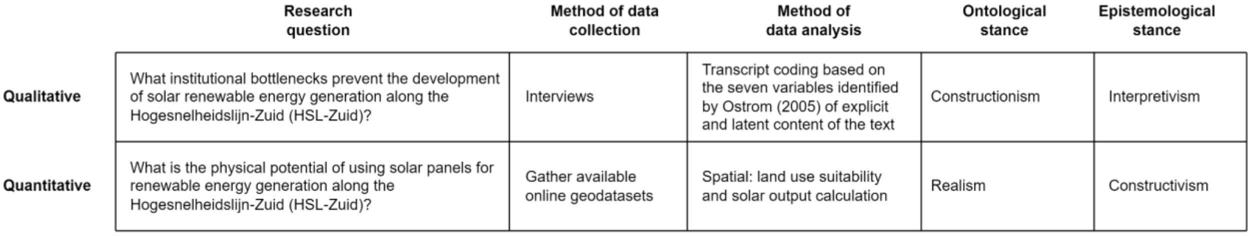
This mixed methods approach, using two separate research (sub)questions, helps to better illustrate the breadth of the technical and social-institutional challenges that prevent further spatial integration and realisation of the energy transition in the Netherlands. However, before outlining the details of each of the research methods used to answer these research questions, the details of the ontological and epistemological foundations which allow for this research in the first place are outlined as follows. For the purposes of this research paper, this involves using two distinct ontological and epistemological stances for each of the two research methods, due to the stark difference in the nature of the phenomena being studied using each. Despite this difference, and despite this epistemological and ontological pluralism, there exists some foundation which guides the research methods chosen in this paper. As detailed by Ghiara (2020) on the work of Hacking (1999) and Moussa (1993) about women refugees, "realism and constructivism, even though based on contrasting assumptions, provide compatible observations" (Ghiara, 2019, p. 18). These two assumptions and "worldviews" are the foundation of the two research methods used in this paper: one dealing with the physical, "real" world, and the other dealing with people's interpretations and values associated with that world. "The idea of women refugees is embedded in a complex system of institutions, advocates, newspaper articles, court decisions, and immigration proceedings" (Ghiara, 2019, p. 18, based on the work of Hacking (2001), and Moussa (1992)). Like women refugees then, the railway and energy systems of the Netherlands are more than just their physical embodiment. They are embedded in a complex system of institutions, advocates for their change, newspaper articles, court decisions, and other proceedings. This paper is aimed at addressing both an aspect of its physical manifestation, as well as the institutions and other social factors which affect and surround these systems.

Diving slightly more into the philosophical stances taken for this analysis reveals an apparent disconnect between the realist ontological perspective of the quantitative approach and the constructionist ontological perspective of the qualitative approach. Although this may be the case, it raises the question of whether mixed methods research can be considered a combination of the qualitative and quantitative "paradigms" or a new paradigm by itself (Ghiara, 2019). It is a fruitful debate on the ontological, epistemological, axiological, and methodological nature of different paradigms in the social sciences. While this could be seen as an example of pragmatic thinking of "what works" in relation to the object under study – or, any more thoughtful approach to pragmatic inquiry (Hall, 2013) – it can also, rather simply, be seen as the use of complementary research methods given the nature of the phenomena under study. In the case of the research undertaken in this paper, geospatial analysis is employed to discover the "true" potential for solar energy (or as close to true as reasonably possible, given the inaccuracy of some assumptions made, e.g. that every solar module will last 25 years, and measurements taken, e.g. the use of Google Earth for rooftop area measurement rather than in-person measurement). Rather than asking experts through questionnaires or interviews what they believe the possible potential to be in the case of the 6 stations under study, geospatial analysis is done to get a more accurate representation of that reality. Similarly, for the socio-institutional context, experimentation was not conducted, given the social and highly subjective nature of the subject being discussed and studied. Despite this categorization and justification of the methods used, this paper in no way aims to create a matrix or typology of the link between certain phenomena and the research instruments which "should" be employed to study them.

Instead, this combination of paradigms often considered to be incommensurable (realism and constructivism, and qualitative and quantitative) is used to illustrate the complementary nature their insights can provide to one another (Cupchik, 2001). Rather than determining whether mixed methods research is a new paradigm or a mix of many, this paper aims to use quantitative geospatial analysis to examine the physical potential solar output of station rooftop solar systems and qualitative institutional analysis to examine the socio-institutional bottlenecks preventing it from occurring. On the quantitative side, Schuurman (2002) emphasises that GIS and, by extension, quantitative geospatial analysis are influenced by social parameters, but that this does not detract from its utility in spatial process modelling. For institutional analysis, the emphasis on social processes and the human-centric nature of institutions is evident, as outlined in this paper's theoretical framework. Together, the use of qualitative and quantitative methods, along with the methodological and philosophical underpinnings on which these research methods rely, have the opportunity to give insight into the various aspects of the complex nature of the energy transition in the Netherlands.

Figure 3.1

Outline of research questions and associated methods and methodology



	Research question	Method of data collection	Method of data analysis	Ontological stance	Epistemological stance
Qualitative	What institutional bottlenecks prevent the development of solar renewable energy generation along the Hogesnelheidslijn-Zuid (HSL-Zuid)?	Interviews	Transcript coding based on the seven variables identified by Ostrom (2005) of explicit and latent content of the text	Constructionism	Interpretivism
Quantitative	What is the physical potential of using solar panels for renewable energy generation along the Hogesnelheidslijn-Zuid (HSL-Zuid)?	Gather available online geodatasets	Spatial: land use suitability and solar output calculation	Realism	Constructivism

Note. This figure shows the methods of data collection, the method of data analysis to answer the research questions and the ontological and epistemological stances associated with each line of inquiry.

Qualitative data collection and analysis

To study the socio-institutional setting which allows for cross-sectoral planning between the energy and railway transport systems, in-depth interviews with staff from a number of the relevant organisations were conducted. This method was used to understand not only the 'rules of the game' (which was supported by a non-systematic literature review of policy documents relevant to the Dutch energy transition, spatial integration, and the railway network), but also the 'play of the game' (how actors interpret and engage with the 'rules of the game'). In-depth interviews were chosen due to a lack of time, resources, and availability to partake in ethnographic study, and to allow for deeper questioning and analysis of meaning, understanding, and interpretation than surveying would allow. In-depth interviewing was also done to partially replicate the conditions of study employed by Spijkerboer et al. (2019) in their analysis of the highway transport network of the Netherlands. Interviews, rather than focusing on observation of real-time situations as they unfold, allowed for the time to investigate in depth the understandings, meanings, and interpretations held by different actors. In the case of this research, this important aspect cannot be overlooked, since imperative to the realisation of infrastructure projects and planning practice more generally is an understanding not only of the rules, but also the 'play of the game'; the analysis of which interviews encourage over other research methods.

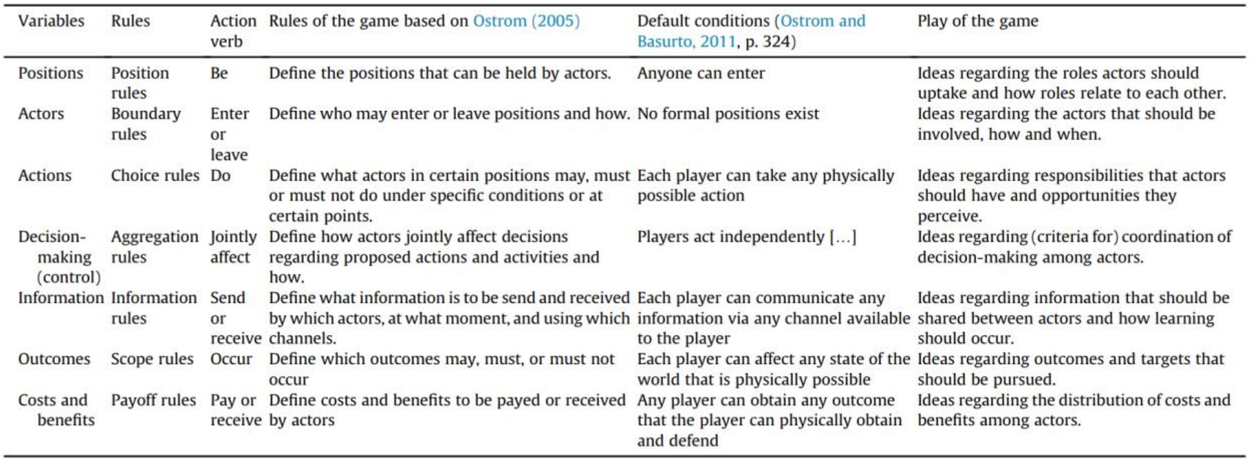
Four semi-structured in-depth interviews were conducted with staff from the Dutch national railway maintenance company, ProRail, Rijkswaterstaat (the executive branch of the Ministry of Infrastructure and Water Management), and the Province of Zuid-Holland, through which the HSL-Zuid passes. Together, these stakeholders represent some of the main actors who would be involved in further integration between railway maintenance/(re-)development projects and projects aiming to further the energy transition, particularly in the case of the HSL-Zuid. Interview questions used were formulated primarily to question interviewees based on the seven variables and rules outlined in the Institutional Analysis and Development (IAD) framework developed by Ostrom (2005). In particular, this paper follows the operationalisation used by Spijkerboer et al. (2019) in their analysis of solar PV integration into Dutch highway infrastructure, based on the IAD framework, discursive institutionalism, and an emphasis on the 'play of the game' in addition to the 'rules of the game'.

Interview participants were selected based on their willingness and ability to partake in an in-depth interview. While all of the stakeholders outlined in Figure 1.4, besides the many municipal authorities, were contacted as part of this research, only a small number of them responded to contact and were also available for participation in an interview. The primary limitation arising from this selection process was the omission of a number of stakeholders from the analysis. These omissions include the many municipalities through which the HSL-Zuid passes (the authorities of which could have given valuable insight into a more local perspective), and Infraspeed, the company in charge of day-to-day management of the HSL-Zuid. Firstly, in the case of the municipalities, their omission was partly organised to recreate similar conditions of study to those in the study by Spijkerboer et al. (2019), where no municipal-level authorities were interviewed. Secondly, an interview was not conducted with contact persons from Infraspeed due to contractual limitations. These, alongside the relatively low number of interviewees, are the most important considerations which may limit the precision, accuracy, and insight of this analysis. These decisions, as well as others, and their effect on the analysis, are discussed in the 'Reflection and limitations of the study' section of this paper.

The qualitative analysis of interviews involves the examination of interview transcripts through the coding of speech according to the seven rules and associated variables of the IAD framework (Ostrom, 2005; see Figure 3.2). Codes of each of the seven variables were assigned to quotes from the interviewees based on their latent content, as can be seen under the 'rules' and 'play of the game' sections in Figure 3.2. This was done to understand and capture the underlying meaning of the data, the results of which were then coded again using 'manifest coding' to identify various rules and ideas within each of the seven variables (Babbie, 1995; Spijkerboer et al., 2019). This combination of latent, followed by manifest coding was used to first understand the 'play of the game', based on the interviewees' ideas and interpretations of the rules, and then to categorise these into ideas or concepts which could be compared with those of other interviewees. In total, this involved the conducting, transcribing, and coding of in-depth interviews (each lasting at least one hour). This institutional analysis approach allowed for the use of semi-structured interviews which were participant-focused, with questions tailored to the interviewee's expertise and position. Like Spijkerboer et al. (2019), the ideas and perceptions mentioned in just one of the interviews are not used to inform the results of this paper. Although this may lead to a low number of insights due to the low number of total interviewees, it is hoped that it should improve the validity of the results. Only concepts brought up by two interviewees are taken as results. The full table, including all of the insights and codes taken from each of the interviews, can be found in Appendix A.

Figure 3.2

Analytical approach for studying the 'rules of the game' and the 'play of the game'



Variables	Rules	Action verb	Rules of the game based on Ostrom (2005)	Default conditions (Ostrom and Basurto, 2011, p. 324)	Play of the game
Positions	Position rules	Be	Define the positions that can be held by actors.	Anyone can enter	Ideas regarding the roles actors should uptake and how roles relate to each other.
Actors	Boundary rules	Enter or leave	Define who may enter or leave positions and how.	No formal positions exist	Ideas regarding the actors that should be involved, how and when.
Actions	Choice rules	Do	Define what actors in certain positions may, must or must not do under specific conditions or at certain points.	Each player can take any physically possible action	Ideas regarding responsibilities that actors should have and opportunities they perceive.
Decision-making (control)	Aggregation rules	Jointly affect	Define how actors jointly affect decisions regarding proposed actions and activities and how.	Players act independently […]	Ideas regarding (criteria for) coordination of decision-making among actors.
Information	Information rules	Send or receive	Define what information is to be send and received by which actors, at what moment, and using which channels.	Each player can communicate any information via any channel available to the player	Ideas regarding information that should be shared between actors and how learning should occur.
Outcomes	Scope rules	Occur	Define which outcomes may, must, or must not occur	Each player can affect any state of the world that is physically possible	Ideas regarding outcomes and targets that should be pursued.
Costs and benefits	Payoff rules	Pay or receive	Define costs and benefits to be payed or received by actors	Any player can obtain any outcome that the player can physically obtain and defend	Ideas regarding the distribution of costs and benefits among actors.

Note. Source: Spijkerboer et al. (2019), joining the seven variables used to analyse the 'rules of the game' as outlined by Ostrom (2005) and (Ostrom & Basurto, 2011) with the 'play of the game'. Misspellings are copied from the cited author's work.

To understand the 'rules' as well as the 'play of the game', desk research was combined with this interview analysis to come to an understanding of the institutional setting which enables and/or restricts the possibility of spatial integration. While much of the desk research, mainly involving the national-level targets relating to renewable energy generation, local ownership, etc. is presented in the theoretical framework section of this paper, it also informs the 'Results' section on the 'Background of the case'. The data gathered during the interviews are discussed in detail in the 'Qualitative findings' section and lead to the paper's final results and conclusions. While the data gathered during desk research acts as an analytical backdrop, the data gathered and analysed from the interviews (combined with the data gathered from the quantitative spatial analysis) acts as and informs this paper's primary set of findings.

Quantitative method of data collection and analysis

To study the technical setting which allows for the integration of renewable energy generation with railway infrastructure, quantitative geospatial analysis was carried out to find the technical/physical potential of the spatial integration of solar renewable energy infrastructure with the HSL-Zuid. As outlined previously, the generation of renewable energy comes with spatial considerations, as there is a finite amount of space available in the Netherlands. These spatial considerations mean that spatial integration of land uses is preferential, involving the multi-functional use of space. Due to these spatial considerations, quantitative geospatial analysis presented itself as the most suitable analysis type. The analysis takes a realist ontological position, with the theoretical assumption of the existence of an objective physical reality about which knowledge can be gained using observation and research. Epistemologically, this paper takes a constructivist stance. With this in mind, while the use of geospatial analysis aims to provide insight into the physical reality of the world around us, it must also be acknowledged that other research methods, including different data collection and analysis techniques, could likely lead to different results, and that the results presented in this paper are open to interpretation and contingent on the researcher.

With that being said, the quantitative method used in this paper draws on that of Chen et al. (2022) to analyse the technical feasibility of using solar photovoltaics in the railway infrastructure of the HSL-Zuid. However, instead of following the mathematical formula by which Chen et al. calculate the solar output, the 'Area Solar Radiation' tool in ArcGIS Pro (a geographic information systems (GIS) software) provided ample ability to reproduce an accurate calculation of the available solar resources at every location under examination for the year of 2023. These raw solar resources could then be converted into likely possible energy output, given some of the same assumptions and rates used by Chen et al. (2022). These assumptions included a 25-year lifespan of solar modules, with a per-year linear degradation rate of cell efficiency of 0.4%, as well as a rooftop packing factor of 0.86. This assumes that 86% of the available rooftop space is used for the placement of solar PVs. A change was made to the type of solar cell used for calculation from the n-type monocrystalline silicon cell used by Chen et al. (2022) to a multicrystalline silicon cell, due to more recent available data about its efficiency (National Renewable Energy Laboratory, n.d.). Despite the manufactured efficiency of such a cell being marketed at 23.23%, this can vary due to climatic and geographic factors (Huld et al., 2010; *Jinko Solar-Tiger Neo*, n.d.). Although long-term averages can result in a positive bias of approximately 3% of efficiency, the expertise of the researcher to adequately address these biases through the use of joint probability density functions is insufficient (Huld et al. 2010). As a result, the following factors and equations are used for calculation (see Table 3.1 and Figure 3.3).

Table 3.1

All relevant factors used to calculate the total potential solar energy output

	Measure used	*Source*
Cell efficiency (C)	19%	(de Hart, 2016; Huld et al., 2010; *Jinko Solar-Tiger Neo*, n.d.; Martz-Oberlander, 2017)
Degradation rate per year (D)	0.4%	(Chen et al., 2022)
Performance ratio (PR)	0.78	(Chen et al., 2022; Ito et al., 2010)
Packing factor (PF)	0.86	(Chen et al., 2022)
Lifespan (L)	25 years	(Chen et al., 2022)

Figure 3.3

Formulae for calculation of final solar energy output

1. To calculate the average solar cell efficiency with a linear degradation rate over 24 years after the first year:

$$AC = C(D)(L-1)$$

Where:
AC = Average cell efficiency over total lifespan;
C = Cell efficiency;
D = Degradation rate per year, and;
L = Lifespan in years

2. To calculate solar radiation in Wh/m2 with the average cell efficiency over 25 years, taking into account the performance ratio and packing factor:

$$Total\ energy\ output = Average\ solar\ radiation \cdot AC \cdot PR \cdot PF \cdot (L)$$

Where:
AC = Average cell efficiency over lifespan;
PR = Performance ratio of the entire electrical system;
PF = Packing factor on the station rooftop, and;
L = Lifespan in years.

However, rather than analysing both the possibility of integration of solar PVs with the railway infrastructure as well as the placement of solar arrays along the track, as done by Chen et al. (2022), this analysis focuses strictly on the railway station shelter roofs and does not perform a financial analysis of any implementation of renewable energy. There are three reasons for this. Firstly, the placement of solar panels on plots of land alongside the railway cannot be considered to be spatial integration, as the placement of solar arrays on land uses such as croplands, grasslands for livestock, etc. would come, to some degree, at the expense of those land uses. This is not the case with a railway station roof, which can function both as a shelter and as a renewable energy generation site simultaneously. Secondly, because these railway shelters are owned by NS Stations (with some tunnels, etc. owned by ProRail), it allows for easier development of these assets for renewable energy generation without having to incentivise development (ProRail & NS Stations, n.d.; Spijkerboer et al., 2019). This, combined with the highly political nature of using non-government and particularly agricultural land in the Netherlands for renewable energy generation, makes this narrowing of scope desirable. Thirdly, a financial analysis is not done in this study because the financial return on any solar investment is seen as secondary to the environmental benefits gained and not related overtly to any of the three aspects of systems outlined by Geels (2004). However, this financial aspect is a vital part of environmental planning, which future studies should take into account.

To accomplish the analysis of stations rooftops, measurements were taken using Google Earth to calculate the available area of each of the stations on the line available for energy generation. This data was then used to calculate an estimated solar energy output, given a number of assumptions. As mentioned previously, although no train stations are technically situated "on" the HSL-Zuid, a number of stations are included in this analysis to aid in comparability to the Beijing-Shanghai case study. Whether the stations are on the HSL-Zuid or not, they are owned by NS Stations and could be used for energy generation. This demonstrates the possible utility of train station rooftops, whether the energy generated feeds back into the adjacent railway or not. Nine railway stations are located on the HSL-Zuid, only two of which (Amsterdam Schiphol Airport and Rotterdam Central) have platforms available for high-speed traffic. The other seven stations: Hoofddorp, Rotterdam Blaak, Rotterdam Zuid, Rotterdam Stadion, Rotterdam Lombardijen, Barendrecht, and Lage Zwaluwe, are all on the route between Schiphol and the Belgian border heading towards Antwerp, but high-speed traffic does not stop at these stations on routine travel. Not all of these nine stations are analysed in this study. Three of the nine stations on the railway line between Amsterdam Schiphol and Antwerp Central are not considered for analysis, each for distinct reasons.

Firstly, Amsterdam Schiphol train station is not considered. This is because the train station itself is situated underground, beneath Schiphol Airport, making rooftop installation impossible without installation on the airport roof. Because NS Stations and ProRail own all of the stations and shelters on the railway network and do not own the airport roof, any implementation of renewable energy generation could not be achieved at Schiphol Airport. Secondly, Rotterdam Central station is not considered because it already has a large area of solar panels on its roof. Although it is possible that the remainder of the Rotterdam Central roof space could be used for solar energy generation, this possibility is omitted from the analysis, as the renovation which included the solar array was completed 10 years ago with the intent to allow for natural light to illuminate the interior of the station through the remaining glass roof. Thirdly, Rotterdam Blaak station is also not considered because the station is underground and the limited rooftop area it does have is not suitable for the placement of solar panels. The roof is made of glass and has metalwork above it which, although potentially available for solar panel placement, may obstruct light from entering the station below. Implementation of renewable energy generation in each of these cases would call for much more technical work (Rotterdam Blaak), institutional work (Amsterdam Schiphol airport), or the redevelopment of a station whose renovation was finished just 10 years ago (Rotterdam Central). As such, only six of the nine stations were considered for this quantitative geospatial analysis. These were Hoofddorp, Rotterdam Zuid, Rotterdam Stadion, Rotterdam Lombardijen, Barendrecht, and Lage Zwaluwe, the available rooftop areas of which are illustrated via aerial photography in Figure 3.4 on the next page.

Figure 3.4

Six stations under study and the rooftop areas considered

Note. Source of World Imagery basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community. The areas shaded in light pink/red are those rooftop areas which are used to calculate the solar output of each station for the quantitative portion of this study.

Results

Quantitative findings

As previously outlined, the quantitative analysis portion of this research involves the spatial analysis of the physical feasibility of the integration of solar photovoltaics with the existing railway infrastructure of the HSL-Zuid. Drawing on insights from the analysis done by Chen et al. (2022), the quantitative analysis applied in this study uses an altered version of their model to demonstrate the possible use of railway infrastructure for solar energy generation; this is done to answer the research question: "What is the technical potential of using solar PVs for renewable energy generation on station rooftops along the Hogesnelheidslijn-Zuid (HSL-Zuid)?".

The use of the methods of data collection and analysis as outlined in the previous section led to results in the form of total energy outputs. These total energy outputs were calculated for each of the six stations along the HSL-Zuid. These six stations were those which did not already have rooftop solar installations and had suitable rooftops available for development. As mentioned in the 'Methods and methodology' section, Schiphol Airport station, Rotterdam Central station, and Rotterdam Blaak station were omitted from the analysis. Below you can see a table showing the most important statistics and findings about each of the six stations considered, as well as a theoretical total energy output per year and over a 25-year lifespan.

Table 4.1

Results of the quantitative analysis

Stations:	Station type	Total roof surface area considered (m^2)	Solar irradiance per metre squared per annum[a] (Wh/m^2)	Energy output per annum[b] (MWh)	Total energy output over a 25 year lifespan (MWh)
Hoofddorp	Plus	2272.59	654,432.7122	198.8470	4,971.1741
Rotterdam Zuid	Basic	788.8	661,670.4474	69.7817	1,744.5424
Rotterdam Stadion	Stop	157.15	541,111.3601	11.3693	284.2326
Rotterdam Lombardijen	Basic	2 966.34	785,942.7657	311.7057	7,792.6421
Barendrecht	Basic	11210.8	847,667.3410	1,270.5797	31,764.4915
Lage Zwaluwe	Stop	171	770,903.8589	17.6250	440.6251
Total/average (x̄) for all 6 stations		17,566.68	710,288.0809 (x̄)[c]	**1,879.9083**	**46,997.7077**

Note. [a]Calculated based on the estimates for the year 2023. [b]Calculated based on the 25 year average module efficiency using solar modules of manufactured 23.3% efficiency at a 0.4% per year degradation rate, a packing rate of 86% and a performance ratio of 85.92% (NREL, n.d.; Chen et al., 2022). [c]Average amount of solar radiation (Wh/m^2/year) over the entire available station rooftop area, where all other fields in the final row represent totals.

The table above indicates that Barendrecht makes up the majority of the available station rooftop space on the HSL-Zuid. Along with its mostly flat roof, it also has the most available solar assets of any of the stations analysed. This, combined with the fact that the rooftops are solid and opaque, provides ample opportunity for the integration of solar panels. It also opens up possibilities for multiple different methods of technical integration. One possibility is the integration of solar PVs into the roofing of station shelters, examples of which can be seen at Rotterdam Central and Delft Campus stations. This could be done at stations which currently have slightly curved rooftops, such as Hoofddorp and Rotterdam Lombardijen. The use of optimally-tilted solar panel arrays on otherwise mostly flat or angled roofs is another possibility, which can be seen at stations like Eindhoven Central. Rotterdam Zuid, Rotterdam Stadion, Barendrecht, and Lage Zwaluwe are all stations that could incorporate solar panels at optimal tilt or mounted on the existing angles of the rooftops. While Rotterdam Stadion, Barendrecht, and Lage Zwaluwe all have flat roofs, Rotterdam Zuid has angled roofs which were used as available areas in this analysis. In both cases, mounted PV is likely the most suitable and affordable option. In the case of Barendrecht, which is by far the most cost-effective site for renewable energy generation according to this analysis, the use of mounted solar panels at optimum tilt is likely the most effective option due to its flat roof.

Although both of these options are possibilities and have been deployed on other station roofs in the Netherlands, this analysis does not account (mathematically) for the difference of each of these methods of integration because of the widely varying circumstances at each of the stations in question. This analysis does not assume the placement of optimally-tilted arrays as used in the model by Chen et al. (2022). This is due to the prevalence of roof-integrated PVs rather than mounted panels in the renewal of other nearby stations (such as Rotterdam Central and Delft Campus), as mentioned previously. Indeed, the method of technical integration would affect any possible energy output from such arrays at the stations analysed, but is not directly tackled in this analysis. Details such as the size, shape, tilt, orientation, etc. of the integrated solar panels are excluded from consideration, unlike in the analysis done by Chen et al. (2022). These details were excluded due to the variation in station rooftops under study and the relative difficulty with which mounted, optimally-tilted solar panels could be used on sloping shelters (such as those at Hoofddorp and Rotterdam Lombardijen). The nature of the Area Solar Radiation tool in ArcGIS Pro is such that it accounts for the slope of the rooftop area under study. As such, although the formula used to come to the final energy output of the solar arrays for each station is dependent on a number of assumptions across all of the stations, the tool does account for the variation in slope of the individual roofs. Before the implementation of any solar energy generation, more in-depth analysis would have to be done as part of each renovation project to examine which of these two methods would suit best for the context: mounted or integrated.

The utility of what might be perceived as small-scale renewable energy integration can be quite large. Although stations with very little rooftop space such as Rotterdam Stadion and Lage Zwaluwe may be perceived as too small for worthwhile use, Barendrecht is an example of where the integration of energy landscapes might be worthwhile. It is in an urban area, and on a train line used multiple times a day. The placement of solar panels at Barendrecht would give options regarding how the energy generated could be used: either being fed into the grid or used locally at the station. This station would likely be the most cost-effective of these chosen locations for solar energy generation and provides further evidence of the utility of the integration of energy landscapes. This quantitative analysis shows not just the technical feasibility of using train station rooftop space for solar PVs, which has already been demonstrated in the Netherlands before, but also an estimate of the amount of energy that could be expected to be produced from each of the stations under study.

Qualitative findings

From the interviews conducted, a number of insights were gathered about the 'rules' and 'play of the game', the institutions associated with the railway, energy, and planning systems as well as the interpretations of these institutions. Tables outlining the complete list of findings can be found in Appendix A, showing the role of each of the interviewees (Table 4.2), as well as the 'rules' (Table 4.3) and 'play of the game' (Table 4.4), split up into the seven variables outlined by Ostrom (2005). As detailed before, the codes highlight the latent content of the transcripts from each of the interviews and are categorised according to the seven variables. Certain codes are combined due to similarity of content, such as code S51, which comes from the interviews with staff members from ProRail and Rijkswaterstaat, representing an aspect of the ambitions of the two organisations. The insights shown in the tables below are only those which were corroborated by more than one interviewee or those highlighted by one interviewee that are backed up by the findings of Spijkerboer et al. (2019). The tables show the institutions which were mentioned by interviewees as well as interviewees' interpretations of those institutions, addressing those situations where actors dealt with a lack of rules and where institutions were challenged by actors in their 'play of the game' (Spijkerboer et al., 2019).

A changing action situation

Since 2019, a number of key developments have taken place that affect the manner in which renewable energy infrastructure is developed in the Netherlands. Firstly, the 2019 Dutch Climate Agreement (Klimaatakkoord) outlined a number of key ambitions which the Dutch state as well as other parties have agreed to (S4). In particular, the goal of 50% local ownership of renewable energy on land was mentioned as a key condition of the agreement (Climate Agreement, 2019, p. 172) and should not only be pursued but also made legal, as opposed to the current 'voluntary agreement' nature of the Climate Agreement (Ic50). Secondly, the establishment of Regional Energy Strategies (RES) for the realisation of 35TWh of renewable energy on land by 2023 and 50TWh by 2050 has addressed some of the previous institutional ambiguity as to who was responsible for actioning the energy transition by creating "problem-owners'' of the provinces, municipalities, water boards, and other regional organisations, actors responsible for actioning the energy transition (Spijkerboer et al., 2019). Thirdly, the commissioning and beginning of the OER programme at the end of 2020 has enabled government institutions (such as Rijkswaterstaat, ProRail, etc.) to offer their land assets to the newly created RES regions in order to realise energy targets (A51). This has given a clearer direction for development through an assignment from the Ministry of Economic Affairs and Climate to the other government (and government-owned) authorities. It has also allowed for joint map-making, cooperative strategizing, a more structured assessment of assets, and created a platform for communication. In doing so, it has made renewable energy generation a more primary task of these organisations than used to be the case by combatting fragmentation at the highest level. These are all aspects of the 'play of the game' mentioned by Spijkerboer et al. (2019). These three developments, combined with the shift in Ministerial responsibilities, have changed the methods by which renewable energy is implemented and exploited.

Beyond the establishment of a new set of "problem-owners" in the RES, the OER programme is one of the most influential of these developments. It has enabled cross-organisational and cross-sectoral cooperation and knowledge-sharing in order to maximise the renewable energy returns from government assets. All four of the interviewees regarded OER as a step in the right direction, with one thinking more change was needed regarding the interaction between the OER programme and the ambition to "localise" or decentralise the energy system through local ownership. This '*local turn*' in the energy transition was highlighted by both interviewees from the Province of Zuid-Holland, and addresses the currently spatially detached energy system. The agreement to work towards 50% local ownership of renewable energy projects in the Netherlands is seen by multiple parties as a way to tackle many of the problems posed during the planning of the energy transition. Attention being given to area-based planning, local participation, and energy citizenship are aspects of this *local turn*, which local ownership might stimulate. In a spatial sense, closely linking the production and consumption of energy could work to alleviate pressure on the electricity grid. This is beneficial due to ongoing grid congestion which currently prevents many new grid connections for newly-built renewable energy projects (C52).

The necessity for internal harmonisation, as well as cross-sectoral and cross-organisational harmonisation (Spijkerboer et al., 2019), is validated by the shortcomings of the OER programme highlighted by interviewees. Particularly, the adaption of the business culture (to allow for the role of ProRail as an organisation which has an active role in renewable energy generation and the energy transition) is necessary to break siloed actions situations and enable cross-sectoral integration (Ip5). The OER programme allows for government and government-owned organisations, whose primary focus and objective is not the realisation of renewable energy, to offer their assets for use in the generation of renewable energy. The renewable energy objectives of existing governmental authorities has not been significantly altered with the introduction of the RES regions and the OER programme; however, the OER programme has meant that some government authorities have been assigned to offer their available assets to the RES regions. Interviewees mentioned the need for a change in business culture (Ip5), as well as the seeming reliance of outcomes on individual persuasion power or having the right people in the right situations in order to realise progress (Ia5).

Among these insights lie more complexities of the energy transition in the Netherlands which hamper progress. One primary point of insight from the interviews related to the localisation and decentralisation of planning related to renewable energy which started with the RES. This *local turn* in renewable energy planning has been spurred on by goals, agreements, and ambitions to reach climate neutrality (in the case of many government and government-owned organisations), and to generate large amounts of renewable energy (in the case of the RES regions).

Discussion and conclusion

Using the findings from the two complementary lines of inquiry, a complex and deeply context-dependent scenario within which infrastructure planning takes place, is revealed. In the past few years, there has been rapid development of national, international, provincial, and local coordination in action to limit GHG emissions and reduce the impact of key societal systems on the planet's ecological processes. In the Netherlands, this has involved the decentralisation of national targets to reach CO_2 reduction and carbon neutrality, as well as the establishment of key programmes to enable government and government-owned organisations to help limit national climate impact. In the electrical energy sector in particular, there is a need for drastic change. We are discovering our limits not only in terms of what the planet can put up with, but also with what our systems can withstand. Grid congestion in the Netherlands has been an issue in many parts of the country for a number of years and threatens to remain one for years to come. In response, decentralisation – not only of responsibilities, but also of systems – can act as a key to limiting the need for further infrastructure expansion which is already affecting the landscape. Hundreds of local energy initiatives and cooperatives have sprung up throughout the Netherlands over the last decade in response to this and other calls to action, such as rising energy prices due to reliance on foreign energy sources.

These factors have combined to create a phase of accelerating action in response to climate change and system changes required to effectively reduce our impact on the planet. Sectors such as energy, transport, and agriculture are just some of the sectors which will have to undergo substantial changes. Transport, especially transport that relies on fossil fuels, is one of the sectors that most significantly affects the planet. The more widespread use of public transport is a good start for reducing climate impact. However, even in the Netherlands, where the Dutch national railway company, Nederlandse Spoorwegen, is completely powered by wind energy, there remains further potential for limiting climate impact. The Netherlands, like other densely populated parts of the world, is running out of space to use for renewable energy generation in this acceleration phase of transition. To address this, integrating renewable energy with other uses of space is seen as a possible way forward. Looking at the railway network in particular, this can involve the use of station rooftops for solar energy generation, as has already been seen at stations in the Netherlands. This seems an optimal use of space since land uses such as agriculture and the built environment are less suitable for renewable energy generation.

Looking at a case study of the only high-speed railway line in the Netherlands, this paper aimed to discover how much further renewable energy integration in the infrastructure of the railway network can be taken by looking at the technical and socio-institutional barriers which prevent it. On the technical side, despite abundant exploitable solar resources, there remain challenges to the more rapid implementation of renewable energy. Renewable energies, due to their intermittency and reliance on favourable atmospheric conditions, conflict with the always-on-demand nature of the energy system of today. This is exacerbated by the congestion of the Dutch electricity grid which stands as an obstacle, encouraging creative ways to reduce the necessity for grid connection. More local usage of energy seems to offer a possible solution to this problem. This requires a transition from the second-generation, spatial detached, and footloose energy system which runs the Netherlands today to a more decentralised system reliant on local renewable energy sources. Such a transition requires not only technical changes to the energy system, but also changes in responsibilities as well as markets, actors, and institutions, as the participation of citizens in the provision of the energy which sustains them becomes critical.

On the socio-institutional side, there remain numerous barriers which prevent the integration of renewable energies with space such as that used by train stations along the HSL-Zuid. While ambitions are set for rapid and comprehensive societal decarbonisation by 2050, the manner in which such ambitions are to be achieved remains institutionally ambiguous. While national authorities urge for action, local and regional authorities are scrambling to find any available space to use for renewable energy generation. This has been aided by the creation of the Regional Energy Strategies and the implementation of the 'Generation of Energy on Government Real Estate' programme. Nonetheless, ambiguity persists regarding how the increasing prevalence and power of local energy cooperatives will interact with the urges of national governments to get something done now. The necessity for rapid action makes learning from past projects difficult and begs questions about whether government organisations should focus on realising a few large energy projects or on many small-scale projects which, combined, will contribute to decarbonisation. Current siloed business cultures and institutional action situations are being slowly challenged and altered, but not overturned. This has led to the realisation of some very integrative projects, where windows of opportunity presented by renovation or renewal have been used for the implementation of renewable energy generation and/or climate adaptation. However, there remains lots of untapped potential, especially in light of the rapidly closing window in which humanity must act to prevent average global warming above 1.5 or 2°C.

For the HSL-Zuid in particular, a window of opportunity remains open. While the track is currently maintained by a private company, ProRail and NS Stations can still use their assets on the line for renewable energy generation, whether as a part of the OER programme or not. Barendrecht in particular, the station with the largest available rooftop area has the potential to generate on average 1155MWh of renewable electricity per year. This electricity could either be used for station and/or nearby railway functions such as monitoring, switching, and signalling, or could be used by the local energy cooperative, De Groene Stroom, to power local homes and businesses, thereby relieving pressure on the electrical distribution system. These options are also available for the train stations in Hoofddorp and Rotterdam Lombardijen, which offer cost-effective implementation of renewable energy generation and possibility for local involvement via the relevant local initiatives. Such developments could be bundled with projects designed to renovate or renew these stations, which would provide a window of opportunity for concurrent development. Although waiting for the renewal of train stations in order to develop renewable energy generation at these locations conflicts with the need to see urgent action now, ProRail and NS Stations have been renovating stations throughout the country over the past number of years, including Almere Centrum, Eindhoven Central, Groningen, and Delft Campus (ProRail, n.d.). Each of these stations has seen (or will see) the introduction of solar power generation in their renewed designs, which demonstrates the existing ability and willingness of actors (such as ProRail and NS Stations) to use renovation as an opportunity to generate renewable energy going forward. There is increasing regime-level change resulting from institutional work done by individuals and organisations offering to help reduce emissions.

The methods used in this paper demonstrate the need for mixed methods approaches to research in order to tackle complex phenomena, such as the integration of renewable energy with railway infrastructure. Quantitative models for calculation and prediction such as that used by Chen et al. (2022) (and replicated here) illustrate the utility of cross-contextual comparison. In particular, while Chen et al. (2022) conclude that the Beijing-Shanghai High-Speed Railway line could (theoretically) be powered by solar power integration on station rooftops and on plots of land along the route, such a development is highly unlikely in the Netherlands. The lack of available space, combined with the highly political nature of using agricultural land for renewable energy generation, the smaller footprint of station rooftops, as well as the smaller amount of available solar resources and less favourable climatic conditions, makes a solar-powered high-speed railway line less viable in the Dutch context. While there remains potential and feasibility for the integration of solar power into the infrastructure of the railway network, it is unlikely to solve many of the problems currently being experienced because of or alongside climate change.

This study has applied the institutional analysis approach developed by Spijkerboer et al. (2019) to a new sector, in an updated Dutch context. This adds to the literature on institutional settings and their effect on outcomes relating to the energy system, and answers Spijkerboer et al.'s (2019) call for the application of the analysis approach to other sectors. This method of data collection and analysis, combined with a quantitative analysis of technical feasibility, has garnered thorough and intriguing results about the transition of complex socio-technical systems in society towards sustainability using insights from a highly relevant case study. Future research should aim to further examine the politics surrounding the energy transition that can often be discussed as rather apolitical planning procedures. The influence of having actors in the right positions who believe in the need for change and transition should also not go unstudied. Updated methods for analysing the development of national, as well as international and regional policy regarding the energy transition, should be pursued. Knowledge about how policies are currently failing to address (or addressing too slowly) the need for systemic transformation should inform future action required to overcome obstacles in realising social change.

Reflection and limitations of the study

While acknowledging the thoroughness and validity of the findings presented in this paper, there are improvements which could have been made to the analyses, which will be discussed briefly below. These improvements are broken into three categories: the theoretical/methodological, the quantitative, and the qualitative. Theoretically, despite the focus of this paper being on the energy transition, humanity is faced with many wicked problems in the world today. There needs to be a balance of ambitions to realise the energy transition with other needs brought on by climate change, biodiversity loss, etc. Additionally, although the need for more renewable energy capacity is evident, some suggest that the production of more renewable energy is more of an *addition* rather than transition (York & Bell, 2019). York and Bell (2019) argue that the energy "transition" isn't a transition at all, but an addition of renewable energy sources to the energy mix, without substantially reducing dependence on fossil fuels and thus not curbing the onset of climate change. They argue that characterising the energy transition as a transition could "inhibit the implementation of meaningful policies aimed at reducing fossil fuel use" (York & Bell, 2019, p.40).

Solar and renewable energies have gained an increasing share of the electricity supply, but have taken much longer outside of the electricity sector, where, overall, the Netherlands' total energy supply is much more reliant on fossil fuels. Expanding renewable energy production in the electricity sector alone has its limits and only helps one part of the complex puzzle of decarbonising key sectors. Despite this, integrated developments (such as the one analysed in this paper) are essential if Dutch authorities are hoped to meet their targets and mitigate GHG emissions. Moreover, in attempting to deal with the many aspects of the energy transition and the many systems which need to undergo change to realise it, this study may have failed to analyse each aspect deeply enough. This could lead to a less thorough understanding than could have been achieved had only one of the two methods of inquiry been used. Having said this, tackling both the technical and socio-institutional aspects of the energy transition has given a more comprehensive picture of the many complicating factors which affect action in mitigating climate change. Future research hoping to tackle complex issues, given more resources, should involve multidisciplinary teams of researchers to give a more balanced outlook on the object of study. As pointed out by one of this study's interviewees, having many people with different insights, specialities, and perspectives makes knowledge and ideally action more comprehensive.

On the quantitative side, while solar technology continues to improve, the relevance and accuracy of this analysis will continue to decline. This may already be true given the use of figures from a two-year-old study which are likely outperformed by the abilities of new integrated solar technology developed in the interim. In addition, many nuances and intricacies regarding the physical layout of each of the station's rooftops are unaccounted for in this analysis. This, combined with a lack of consideration for other technical details such as the angle of incidence of the potential solar arrays at each of the stations and the other mathematical assumptions, makes for a lack of analytical depth in a technical sense. To account for this, rather conservative estimates of cell efficiency, system performance, and lifespan are used. The only more liberal metric is that of the packing factor, which would also likely change depending on the physical circumstances of each station. Every mathematical assumption of the quantitative calculation is open to change and there are large discrepancies in the literature regarding cell efficiency and the effect of different atmospheric conditions and soiling (de Hart. 2016; Martz-Oberlander, 2017). Such detailed factors would need to be accounted for on a case-by-case basis for more accurate calculations.

Qualitatively, the number of interviewees that were used for this paper's analysis restricts much of the analytical power of the study. As outlined by Saunders & Townsend (2016) in their meta-analysis of 798 organisation and workplace studies, the norm in the number of interviews conducted ranged from 15 to 60, with 23.4% of studies not acknowledging the number of participants interviewed. This paper hopes to remedy the latter by being transparent about the number of research participants, and to explain the lack of total number of participants given the time and resource constraints (both of the researcher as well as the many organisations involved in the systems under study). Unlike the example set by Spijkerboer et al. (2019), in which 16 in-depth interviews were used to come to conclusions, this paper has only 4 interviews with which to come to conclusions. It leaves much to be desired in terms of analytical power and the insights which can be drawn from this portion of the study. In addition, the omission of the municipal governments from the interview process and analysis may lead to a biased understanding of the challenges experienced by actors in the planning system. However, it still allows for "standing on the shoulders of giants", as the insights gained from the interviews conducted in this study were able to add directly to the findings of Spijkerboer et al.'s (2019) analysis, who also omitted municipalities from their analysis. This research therefore lends credence to a number of their findings about the integration of solar PVs with the highway network, which seems to have significant overlap with development in the railway network. This paper also gives a more recent account of the Dutch infrastructure planning context, adding to a growing body of research on integrative planning in the Netherlands (such as Warbroek et al.'s (2023) paper from earlier this year).

Developments such as the integration of solar energy generation with railway networks are unlikely to be the most important steps which governments need to take in order to limit the negative impacts of climate change. Moreover, climate change is not the only wicked problem which faces humanity in what some have referred to as the sixth mass extinction (Ceballos et al., 2017). It will take much more to relieve the world's ecological and socio-ecological systems than the spatial integration of solar energy with railway infrastructure. Indeed, as discovered through interviews with participants in this research, the need for emphasis on other, non-energy-based issues is evident, such as the preservation of natural habitats, etc. However, much like the needed transition in the human use of energy, there must be a much wider societal shift in the way we interact with the world around us, lest we squander it.

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Appendix

Appendix A

Results of the qualitative analysis

Table 4.2

Interviews and the associated codes.

Code	**Interview participant**
I1	Staff member from ProRail
I2	Staff member from Province of Zuid-Holland
I3	Staff member from Rijkswaterstaat
I4	Staff member from Province of Zuid-Holland

Note.

Table 4.3

All the results regarding 'rules of the game' found by Spijkerboer et al. (2019) corroborated by the findings of this institutional analysis combined with additional findings.

Code	**Boundary rules** define who may enter or leave positions	Sources
B1	*Location*: Ownership, governance or management of land or infrastructure assets within a specified area determines which actors are involved (e.g. province, municipality, grid operator, and regional department of Rijkswaterstaat).	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
B3	*Project*: Based on the specific project, additional parties may enter or leave the arena (e.g. advisory bureaus, experts from national departments of Rijkswaterstaat, or market parties).	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
Code	**Position rules** define the positions held by actors	Sources
P3	*Organisations*: ● ProRail is the government-owned organisation responsible for the construction, maintenance, management and, if necessary, expansion of the Dutch railway network.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*

	● A private company (Infraspeed) is responsible for the day-to-day management of the HSL-Zuid. ● Rijkswaterstaat is the executive organisation of the Ministry of Infrastructure and the Environment and responsible for design, construction and maintenance of the main infrastructure networks in the Netherlands for the purpose of safety, accessibility and livability, which is laid down in assignments set by the Ministry.	
P4	*Developer*: A market party or citizen initiative is allowed to develop and exploit renewable energy on government assets. ProRail is not allowed to hold this position, unless the energy produced is used locally for internal organisational functions.	*Spijkerboer et al. (2019)*; *I1*; *I3*
P5	*Licensing authorities*: Municipalities or provinces are the licensing authority for the environmental permit.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
P7	*Grid operator*: The grid operator is responsible for realising the grid connection.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
P50	*Offers*: The Regional Energy Strategies (RES) are the result of an offer from the provinces, municipalities, and water boards to realise a sustainable Netherlands by generating 35TWh of renewable energy by 2050 and 50TWh by 2050.	*I1*; *I2*; *I3*; *I4*

Code	**Choice rules** specify what actors in certain positions may, must, or must not do at certain points	Sources
C6	*Apply for permits*: The developer must apply to the municipality or the province for an environmental permit.	*Spijkerboer et al. (2019)*; *I1,*
C7	*Set permit conditions*: Provinces and municipalities may set conditions connected to the environmental permit, only to ensure the spatial quality of their territory.	*Spijkerboer et al. (2019)*; *I1*
C10	*Apply for subsidies*: After winning the auction, the developer may apply for SDE ++ subsidy with the Netherlands Enterprise Organization. Government organisations are not eligible for SDE ++ subsidies.	*Spijkerboer et al. (2019);*
C11	*Involve citizens*: A developer may include citizen participation in the project.	*Spijkerboer et al. (2019)*; *I3*
C50	*RE near large-scale infrastructure*: RES partners often look to develop renewable energy generation near infrastructure, given that much of the area near to large-scale infrastructure can't be used for other purposes such as housing or agriculture.	*I1*; *I2*; *I3*; *I4*
C51	*HSL-Zuid*: Not much is being done with the HSL-Zuid regarding renewable energy, and it is not the site of any projects which are a part of the OER programme.	*I1*; *I3*
C52	*Grid congestion*: The current congestion of the grid in the Netherlands prevents many new renewable energy projects from being implemented and connected.	*I1*; *I2*; *I3*; *I4*

Code	**Aggregation rules** determine how actors jointly affect decisions regarding proposed actions and activities and in what manner.	Sources
A2	*Subsidies*: The Ministry of Economic Affairs and Climate must decide whether to appoint subsidies to developers after they have won the bid and have the necessary permits.	*Spijkerboer et al. (2019)*; *I1*

A50	*Landowner*: The landowner gives guidelines, criteria, and demands in the tendering process, within which the developer has freedom for implementation.	*I1*; *I2*; *I4*
A51	*OER*: The OER programme is an assignment from the Ministry of Economic Affairs and Climate to help the RES regions and combine the knowledge and assets of government organisations such as the Ministry of Defence, The Central Government Real Estate Agency, Netherlands Enterprise Agency, Rijkswaterstaat, ProRail, and Staatsbosbeheer to speed up the energy transition.	*I1*; *I2*; *I3*
A52	*Cooperation with developers*: Primary objectives regarding safety and maintainability of the railway, as well as risk associated with development close to railways makes cooperation of developers with ProRail less desirable.	*I1*; *I3*
Code	**Scope rules** determine which outcomes may occur.	Sources
S1	*Asset reservation*: Solar panels may not be realised on grounds reserved for other government initiatives.	*Spijkerboer et al. (2019); I1*; *I3*; *I4*
S2	*Safety*: Solar panels must not compromise the safety of the infrastructure networks.	*Spijkerboer et al. (2019)*; *I1*; *I3*
S3	*Maintenance*: Panels must be accessible to maintenance, and must not hinder maintenance of networks.	*Spijkerboer et al. (2019)*; *I1*; *I3*
S4	*General agreements*: Goals set in the Dutch Climate Accord (Klimaatakkoord), such as the objective of 50% local ownership of energy projects, etc.	Spijkerboer et al. (2019); *I1*; *I2*; *I3*; *I4*
S5	*Target*: Target stating that ProRail (and Rijkswaterstaat) must become energy neutral by 2030.	Spijkerboer et al. (2019); *I1*; *I3*
S50	*Competing targets*: Energy and climate neutrality is just one goal among many important ones such as climate adaptation, nature preservation, etc.	*I1*; *I2*; *I3*
S51	*Organisational aspirations*: ProRail, like Rijkswaterstaat, is not an energy company and has no aspiration to become an energy company.	*I1*; *I3*
Code	**Payoff rules** assign costs and benefits to actors.	Sources
Y3	*Subsidies*: ProRail is not eligible for SDE ++ subsidies.	*Spijkerboer et al. (2019)*; *I1*; *I3*
Y6	*Highest bid*: Rijkswaterstaat land is granted to the party issuing the highest bid.	*Spijkerboer et al. (2019)*; *I1*; *I3*

Note. Many of the codes and concept titles are taken from Spijkerboer et al. (2019). Additions and alterations have been made to fit the updated institutional arrangements and different objects of study. See Spijkerboer et al. (2019) for a complete table of their findings. Added are also those findings of the interview analysis of this paper. Only codes from Spijkerboer et al. which are corroborated by this analysis are included and for which the same code is used. Codes with a number below 12 are the same as those used by Spijkerboer et al., with codes above 50 taken only from the findings of this analysis. Where possible, findings have been combined.

Table 4.4

All the results regarding 'play of the game' found by Spijkerboer et al. (2019) corroborated by the findings of this institutional analysis and combined with additional findings.

Code	Ideas related to **boundary rules**	Sources
Ib1	*Early involvement*: Partners (neighbours and municipalities) should be involved early to create more certainty regarding permits and grid connection.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
Ib2	*Citizen involvement*: Citizen initiatives, local energy cooperatives, and municipalities should compete in auctions but they are bound to one location and often perceived as lacking knowledge, competency, and experience.	*Spijkerboer et al. (2019)*; *I2*; *I3*; *I4*
Code	Ideas related to **position rules**	Sources
Ip2	*Contradictory positions within government organisations*: Citizen involvement should be a point of attention in PV projects, because the ambition of government organisations to contract the most financially viable bid is at odds with the importance of citizen involvement in infrastructure projects where quality criteria are always required in bids.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I3*; *I4*
Ip5	*Adapt organisational culture*: ProRail should adapt the culture of the organisation so employees are aware of the fact that they can have a role in PV projects even if it is not the primary objective of the organisation (contrary to the current culture where you are solely responsible for railway management).	*Spijkerboer et al. (2019)*; *I1*; *I3*
Code	Ideas related to **choice rules**	Sources
c50/	*Local ownership*: Energy projects should be required to have at least 50% local ownership in national legislation to bypass the problems posed by long-distance electricity transmission and grid congestion	*I2*; *I4*
Code	Ideas related to **aggregation rules**	Sources
Ia5/	*Individual persuasion power:* The success of initiatives should be less dependent on the right people at the right level pulling their weight, thereby making initiatives less ad hoc.	*Spijkerboer et al. (2019)*; *I2*
Code	Ideas related to **information rules**	*Sources*
Ii2/	*Learning*: Structures should be installed that stimulate learning from initiatives and past projects.	*Spijkerboer et al. (2019)*; *I3*
Ii50/	*Defining local*: The national government should clarify what constitutes "local" in reaching the goal of 50% local ownership and give a clearer vision of the role local ownership plays in the energy transition more generally.	*I2*; *I4*
Code	Ideas related to **scope rules**	Sources
Is4	*Operationalization*: ProRail and Rijkswaterstaat should realise a few large-scale projects or many smaller projects.	*Spijkerboer et al. (2019)*; *I1*; *I3*
Is6	*Place-based assessment*: The provinces want to assess per project, in the context of the location, what fits the landscape for solar projects, so exceptions from the rule may be possible but have to be assessed on a case-by-case basis.	*Spijkerboer et al. (2019)*; *I1*; *I2*; *I4*

Is7/	*Spatial quality and participation*: Provinces want to safeguard spatial quality and participation in the energy transition through local ownership.	*Spijkerboer et al. (2019)*; *I2*; *I4*
Is50	*Transition speed*: The Ministry of Economic Affairs and Climate should not be too hasty in trying to realise the energy transition, which may reduce time to learn from projects and cause negative side effects in areas other than energy.	*I2*; *I3*
Code	Ideas related to **payoff rules**	Sources
Iy5	*Include quality criteria in the bid*: Quality criteria regarding e.g. citizen involvement and 50% local ownership should be part of the bid to enable developers to use experiences with citizen participation, reduce possible resistance, and reduce energy prices and the need for long-distance electricity transmission	*Spijkerboer et al. (2019)*; *I2*; *I3*; *I4*
Iy50	*Complexity of small-scale integration*: The integration of solar cells with small-scale infrastructure such as noise barriers is not that effective, increases complexity, and has a relatively high cost, but should be pursued nonetheless.	*I1*; *I3*

Note. Many of the codes and concept titles are taken from Spijkerboer et al. (2019). Additions and alterations have been made to fit the updated institutional arrangements and different objects of study. For further details, see note of previous table, which also applies here.