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On the resilience of innovation systems

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ABSTRACT
Mission-oriented innovation policies address urgent societal challenges, often through rapid technological upscaling. However, upscaling may endanger the resilience of an innovation system by limiting variety. A resilient innovation system is ambitious in scaling up while intelligently fostering variety. To assess resilience, a country's technology portfolio needs to be contextualised against global trends. We introduce *contextualised variety* to uncover threats, windows of opportunity and poorly allocated resources and evaluate the maturing Dutch offshore renewable energy innovation system based on 236 R&D projects 12,000 industry contracts and 34 interviews. Our results indicate that the Netherlands invests in variety for its installation sector, bolstering resilience, while it neglects its foundations sector, indicating a threat. The Netherlands further supports a non-existent traditional wind turbine sector, suggesting poor resource allocation. However, it backs disruptive wind turbines, a window of opportunity contingent on upon concerted innovation policy. This framework demonstrates how to evaluate the resilience of any innovation system.

KEYWORDS
Mission-oriented innovation policy; technological innovation systems; resilience; variety; offshore wind

JEL CLASSIFICATION
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1. Introduction

As the world barrels towards the two-degree threshold laid out in the Paris Agreement to mitigate the most devastating impacts of climate change, governments around the globe have embarked on myriad programmes to address the crisis (Geels et al. 2017; Rosenbloom, Haley, and Meadowcroft 2018). Accordingly, innovation policies have shifted attention towards the rapid development and diffusion of low carbon technologies, such as renewable energy or the electrification of transport (Diercks, Larsen, and Steward 2019; Mazzucato 2015, 2018; Ministry of Economic Affairs and Climate 2019; Robinson and Mazzucato 2019; Wanzenböck et al. 2020). These so-called mission-oriented innovation policies (MIP) exert technology selection, fostering the rapid upscaling and diffusion of specific technologies driven by a shared sense of urgency. Upscaling and rapid diffusion occur when products reach a certain degree of technological maturity and achieve a dominant design, supply chains move to rapid production, distribution becomes more efficient and research and development (R&D) shifts to

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incremental and process innovation (Christensen 1997; Wilson 2012). MIPs have gained popularity around the world, such as in Germany, Japan, the Netherlands, Norway and Sweden and the European Union (Larrue 2021a, 2021b; Ministry of Economic Affairs and Climate 2019).

Innovation systems arose as a heuristic to grasp the dynamics affecting the generation and diffusion of technology (Bergek et al. 2008; Edquist 1997; Hekkert et al. 2007; Jacobsson and Bergek 2004). Successful innovation systems foster the development of national industries that can compete on a global scale (Nelson and Rosenberg 1993). Technological innovation systems (TIS), for their part, address the emergence of specific technologies (Carlsson and Stankiewicz 1991). As a TIS exits the nascent emergence phase where products generally have weaker performance characteristics, rapid upscaling and diffusion may potentially lead to lock-in.

Hence, the increasing popularity of MIP may lead to unforeseen consequences on such innovation systems if they are remit of appropriately embedded oversight and built-in corrective measures. One potential pitfall is that tailored research and development (R&D) programmes designed to encourage rapid upscaling and cost reduction may lead to a reduction in the variety of solutions to address these very challenges in the long run (Hekkert et al. 2020). This may create lock-in, leading to vulnerability and an inability to respond to disruption. Disruptoins occurs when new products or services emerge based on fundamentally different principles that threaten the existing dominant products and services. Disruptive innovation contrasts with sustaining and incremental innovation, which targets small improvements to the dominant technology and market, such as enhanced product performance or more efficient production and distribution practices. Indeed, evidence shows that demand side policies lead to a strengthening of mature technologies at the expense of less mature technologies (Lee, Jun, and Lee 2022). While rapid diffusion and upscaling may be essential in the short-term, the system may be less capable of dealing with uncertainty and disruption; this means that the system itself may not be resilient in the long-term due to unforeseen shocks. Furthermore, rapid upscaling may be blind to negative spill-over effects and environmental problem shifting, such as an increase in e-waste heading to tertiary countries (Hansen, Nygaard, and Dal Maso 2021). Indeed, what may seem promising now may turn out to be unsustainable in the long-run (Biggi and Giuliani 2021); this means that systems need to be resilient and able to adapt to uncertainty while also rapidly scaling up to address urgent grand societal challenges.

While technological variety – i.e. the number of technologies and the extent these are related to each other – has long been regarded as a hedging strategy for unforeseen economic development by geographers (Attaran 1986; Frenken, Van Oort, and Verburg 2007), we argue that equating the variety within an innovation system with the resilience of an innovation system is too simplistic. First, variety always comes at a cost; innovation policies, therefore, must be selective to some degree. Second, the strategic value of certain technologies present in a geographically bounded innovation system (e.g. national) should be assessed against emerging trends at the global level. These emerging trends can be disruptive but can also provide windows of opportunity. We argue that a resilient nationally bound innovation system is one that is strategic in scaling up well-functioning and proven technologies while also fostering variety in relevant disruptive technologies.

Essentially, we provide a roadmap to avoid system level lock-in rather than at the singular product or company level.

To do so, we introduce the notion of *contextualised variety*, which reasons from the opportunities and threats that the global innovation system (Binz and Truffer 2017) poses to a nationally embedded innovation system given the specific markets and technologies in which it is active. Countries active in a global innovation system are likely to provide some, but not all, of the products and services required to support that innovation system, such as solar or wind energy, electric vehicles, etc. This means that different countries will have different exposure in the event of disruption depending on where their contributions lie, for example if they produce wind turbine blades or electric vehicle batteries. It follows that disruptions to the global innovation system can be threatening or non-threatening to a national technological innovation system. Contextualising variety provides a means to evaluate national innovation policies regarding the coherence between targeted innovation activities and existing market capture for certain products and services.

This research is a first attempt to address how variety is influenced by mission-oriented innovation policies that affect a technological innovation system's ability to respond to an uncertain future. We apply our framework to the offshore renewable energy technological innovation system in the Netherlands, which includes classic offshore wind, disruptive offshore wind and adjacent maritime renewable energy technologies, such as wave, tidal and kite energy. This currently well performing TIS is heavily influenced by an ambitious mission-oriented innovation programme to fully decarbonise the electricity sector by 2050; indeed, an estimated two-thirds of final energy consumption in the Netherlands will stem from offshore renewable energy by 2050, with over 20 gigawatts of offshore wind installed by 2030 and over 70 gigawatts by 2050 (Secretariaat Klimaatakkoord 2019; TKI Wind op Zee 2019a; Van der Loos et al. 2021; Van der Loos, Negro, and Hekkert 2020a).

We use the notion of contextualised variety to evaluate the resilience of this TIS and how it is affected by a strongly guided MIP. Based upon a database of 236 government sponsored offshore renewable energy R&D projects, over 12,000 industry contracts and 34 expert interviews, we evaluate the resilience of a maturing technological innovation system. Subsequently, we provide a framework to evaluate the resilience of any maturing innovation system.

2. Theory

2.1. National and global technological innovation systems

Innovation systems' thinking arose out of a discontent for traditional linear models of innovation processes, claiming that feedback loops and a multiplicity of actors beyond companies play a strong role in innovation and diffusion (Lundvall et al. 2002). The Technological Innovation System (TIS) framework, for its part, provides a means to address barriers hindering the generation and diffusion of specific technologies (Bergek et al. 2008; Hekkert et al. 2007; Jacobsson and Bergek 2004). Generally, TIS studies emphasise the historical development and shifts in functional performance of emerging technologies and the underlying structure of their supportive innovation systems (De

Oliveira and Negro 2019; Reichardt et al. 2016). However, little reflection has been paid to what happens when a technological innovation system enters a more mature phase to ensure its long-term success (Dewald and Truffer 2011). Indeed, most TIS studies stop once a system has successfully fulfilled its functions with little attention given to its newfound regime status, decline, life-cycle or resilience (Markard 2020; Suurs 2009; Suurs et al. 2010).

Furthermore, TIS are not confined to the boundaries of a nation-state but are rather embedded in global production and consumption systems, known as global innovation systems (Binz and Truffer 2017). This means that the products, services and system dynamics needed for a specific technology to succeed are spread across numerous nationally delineated innovation systems (Wieczorek et al. 2015). Different countries will produce different components and will seek to further embed their expertise while at times hoping to broaden their range of offerings (Van der Loos et al. 2022). A nationally bound technological innovation system can perform well even if it does not fulfil every innovation system function or produce every component and service (Wieczorek et al. 2013). Changes in the global innovation system therefore influence the national technological innovation system. The effect on the geographically bound innovation system is dependent on the degree of disruption and its market share of a given component.

2.2. Threatening and non-threatening disruption and variety

An uncertain future indicates many plausible pathways that may threaten a mature technological innovation system, particularly in the event of disruption (Castrejon-Campos, Aye, and Hui 2020). We understand disruption as a "Radical change in one or more of the elements of a stabilised technological system, causing pressure to alter the system more than incrementally" (Johnstone et al. 2020, 1). Disruptions to stable technological systems often lie in major technological shifts dominated by incumbent actors, often brought about by actors outside the current system (Bergek et al. 2013; Christensen 1997; Kivimaa et al. 2021; Utterback 1994). Examples include shifts from fossil fuel power to renewable energy technologies, traditional internal combustion engine cars to electric mobility or analogue to digital media formats.

Major disruptions to industries in a global innovation system – within which a nationally delineated TIS is nested – will have differentiated effects depending on the products and services the country offers to that very global innovation system. A TIS therefore needs to be contextualised within global trends. While some countries will see their current knowledge base and industrial activity decline due to disruption, windows of opportunity may arise for other countries to enter a particular market. This leads to two major potential effects on the nationally delineated innovation system relative to the global innovation system in question: *non-threatening* and *threatening disruptions.*

(1) *Non-threatening disruptions* replace components and services in which an innovation system does not participate. It indicates a no-risk opportunity because there is not much to lose, whilst potentially creating a chance to capture new value. For example, a country that produces tyres for cars but does not produce cars itself will not be disrupted by the rise of the electric car since they both require tyres. However, as electric cars are disruptive for the automobile global innovation

system, there may be windows of opportunity for a new nationally delineated innovation system to enter this emerging market. One could consider Chinese electric car manufacturers attempting to enter Western markets an example of this phenomenon.

(2) *Threatening disruptions* replace existing components and services in which the delineated innovation system actively participates. There is high risk because there is a lot to lose. Such technological changes may have severe consequences for the competitiveness of firms. Firms may rapidly lose market share to either domestic or foreign competitors due to disruption (Tushman and Anderson 1986). Indeed, disruption often occurs at the physical component level (e.g. aircraft engine) or the service level (e.g. installation services for solar panels). Disruptions to a product's architecture can also prove detrimental to the companies that produce it without fundamentally altering the product's components (Henderson and Clark 1990). While individual companies may be severely affected by disruptions, this is not necessarily the case at the technological innovation system level. For example, the rise of Tesla may force some traditional American car companies out of business, but it is a zero-sum game at the national level because the American automobile technological innovation system as whole remains strong. However, if an automobile producing nation (like Germany) is unable to make the switch to electric cars, then they are disrupted from the outside, leading to enormous ripple effects.

2.3. Resilience through contextualized variety

For policy makers, particularly when engaging with mission-oriented innovation policies, scaling up a small set of well-performing technologies in a short period of time may lead to lock-in and deviate attention away from potential disruptions. The tension between addressing urgent societal challenges and avoiding technological lock-in resonates with theoretical work in evolutionary economics (Arthur 1989; David 1985; Unruh 2000). Most technologies – as well as institutions – benefit from strong increasing returns of adoption, meaning that the value of adopting a particular technology (or institution) increases over time as each adoption generates positive externalities for future adopters. Such externalities can stem from learning-by-doing, learning-by-using, lowering risks, increasing legitimacy and social embedding (Arthur 1989). The policy challenge then is often framed as one of variety, which comes down to a matter of timing (Foray 1997; van den Bergh 2008): early sponsoring of one particular technology may lead to lock-in of an ultimately sub-optimal technology, while waiting for too long as to continue learning about all technological options may be wasteful as positive externalities remain minimal.

Innovation policies may aim not only to stimulate existing and well-defined technological trajectories, but also to increase the number of distinct technologies, components and services through radical innovation. This reflects a need for a balance between 'exploitation' – i.e. improving existing competencies and leveraging positive externalities – and 'exploration' – i.e. pursuing as many options as possible to prepare for any eventual outcome (March 1991; van den Bergh 2008). Expanding variety can help a country prepare for disruption, while it also allows for more potential recombinations between components and services, thus enlarging the sheer scope of future innovation (van den Bergh 2008). The value of variety in the face of disruption speaks to the distinction between related and unrelated variety introduced in the field of regional studies; here, variety does not refer to variety across technologies, products and services within a technological innovation system, but across sectors within a regional economy (Frenken, Van Oort, and Verburg 2007). Related variety spurs recombinant innovation across technologically related sectors by developing new businesses in times of crises, while unrelated variety bolsters regional resilience against sudden sector-specific shocks (Boschma 2015). Broadly speaking, the higher the degree of relatedness, the better the odds of being able to adapt to both shocks and long-term shifts; nonetheless, unrelated variety may also help deal with shocks as the recombination of unrelated technologies may prove extremely valuable, which might not have otherwise emerged (Castaldi, Frenken, and Los 2015; Steijn et al. 2023). Naturally, it is not a one-size-fits-all model (Pike, Dawley, and Tomaney 2010): the effect of resilience also depends on the degree of relatedness, the timing of the shock and innovation crisis response strategies (Cainelli, Ganau, and Modica 2019; Esposito 2023; Lien and Timmermans 2023): for example, a high degree of relatedness may help underpin resilience in the immediate aftermath of disruption, but may be poorly suited to long-term trends, particularly when they expand beyond purely technological changes, such as market shifts.

Acknowledging the nested nature of nationally delineated technological innovation systems within a global innovation system, fostering variety per se is effectively blind regarding the specific technologies in the portfolio of an innovation system. Equating the *variety* within an innovation system with the *resilience* of an innovation system is thus too simplistic. First, fostering more variety comes at a higher cost. Hence innovation policies, by definition, must be selective at least to some degree (van den Bergh 2008). Second, more fundamentally, the strategic value of certain components or services present in an innovation system at the national level must be assessed against emerging trends at the global level, as global trends can be disruptive but may also provide windows of opportunities. Hence, building in variety intelligently that strategically incorporates the national context of a given global innovation system is fundamental. This leads us to the notion of contextualised variety.

Contextualised variety zooms into the specifics of a nationally delineated technological innovation system and the specific technological expertise and specialisations a TIS generates relative to its global innovation system. As large-scale technologies are generated from component technologies and services sourced from different locations throughout the world, a TIS can be contextualised in reference to the global system by its market capture of various components and services. The policy question then becomes in which components and services to invest given their current presence in the portfolio and the potential for disruption in the global innovation system. Therefore, policy should direct attention towards developing, producing and diffusing particular components and services with reference to the state of the national innovation system at hand given global trends (Sagar and van der Zwaan 2006). The nuances of contextualised variety elucidate what falls within and outside of the existing expertise, what existing technologies may be under threat and what new technologies are good candidates for new technology development. To contextualise variety in a TIS, one can thus look at sustaining versus disruptive innovation (at the global innovation system level) for dominant and marginal components and services (at the national innovation system level) Figure 1.

1) Block 1 'Business as Usual': Sustaining innovations are those that incrementally improve the technological performance of a product – such as improved product efficiency – or optimised production and processing techniques – such as more efficient supply-chains, better logistics or enhanced labour productivity. Sustaining innovations for dominant components or services of the innovation system are generally the purvey of the companies already present in the industry, meaning that government support has more limited additionality. Classic incumbent dynamics suggest that dominant companies will pursue incremental product and process innovation to maintain their market share (Christensen 1997). For example, car engine manufacturers in a country with a strong technological innovation system in internal combustion engine vehicles will focus on incremental R&D to sustain their global market position. Government support can nevertheless be beneficial for start-ups seeking to provide improved components or services to these larger companies, or for SMEs with more limited R&D resources. However, there is minimal additionality in supporting already well-performing industries.

2) Block 2 'No-go area': Sustaining innovations for marginal components or services of the innovation system are highly unlikely to help domestic companies enter globally well-established, but nationally underdeveloped, segments. Dominant foreign firms with large R&D portfolios supported by their own domestic technological innovation systems are unlikely to lose the sustaining innovation race. That is to say that new entrants are highly unlikely to enter a market by offering a component or service similar to ones readily available globally. For example, a Dutch company entering the market for internal combustion engines stands little chance. An exception may occur in the event of high demand for a product with few suppliers in times of rapid growth. A sub-supplier may also succeed at offering an improved product or service to a large company. Support by the government here may indicate poorly allocated resources.

3) Block 3 'Prepare for disruption': As mentioned above, disruptive innovations radically alter certain elements of the technological system. These can be either entire systems – such as the forlorn physical video-rental industry involving VHS or DVD manufacturers, distributors, retail outlets and others – or disruptive components within this system, such as DVDs disrupting VHS tapes without disrupting the larger innovation system.

Targeting disruptive innovations for dominant components and services of the innovation system are the most fundamental to help avoid external disruption. A country dominant in a specific component or service of a global innovation system has a lot to lose in the event of disruption. Disruptive technologies, by definition, initially underperform relative to existing technologies, which means that government stimulation has the highest additionality. An example is electric car production in the United States disrupting the entire global automobile innovation system. Fundamentally, disruption from within a country ensures that the nationally-bound TIS maintains its strong market share and is a zero-sum game, while external disruption results in devastating ripple effects and enormous losses. Hypothetically, an automobile producing nation, such as Japan, that fails to make the transition to electric vehicles would face extraordinary hardship.

4) Block 4 'Window of opportunity': Marginal components and services mean that a country has a minimal contribution to a global innovation system. Attempting to ride a wave of global disruption with minimal repercussions in the event of failure can be an opportunity to expand a country's offerings. For example, a country with no traditional automobile industry may seek to develop electric vehicle battery production capacity to enter the electric vehicle global value chai. Hypothetically, if Norway were to become an electric vehicle battery producer, it would enter the electric vehicle global innovation system despite not having any traditional auto manufacturers. Success, however, is contingent on substantial resource commitments, suggesting that it may be wiser to first address threatening disruptions before seeking to disrupt. However, the additionality potential is very high, as domestic firms are unlikely to master a new disruptive technology without government support. These opportunities may be more likely to succeed if the disruption at the global level is related to technologies already produced in the country in question, fostering a process of 'related diversification' (Boschma et al. 2017).

Figure 1, below, depicts our four building blocks according to dominant or marginal components or services captured by the nationally bound innovation system and whether an innovation is globally sustaining or disruptive. We analyse each of these four blocks to measure the resilience of the Dutch offshore renewable energy innovation system according to contextualised variety.

	SUSTAINING INNOVATION	DISRUPTIVE INNOVATION
DOMINANT SECTORS	**Block 1 'Business as Usual'** • High threat • Low government additionality • Responsibility of industry incumbents • Policy helpful for firms with few R&D resources • Ex: German traditional car manufacturing	**Block 3 'Prepare for Disruption'** • High threat • High government additionality • Disruption from within ensures resilience • Policy pivotal to maintain market share • Ex: American electric vehicle disruption
MARGINAL SECTORS	**Block 2 'No Go Area'** • Low threat • Low government additionality • High entry barriers • Policy unlikely to foster new market share • Ex: Dutch internal combustion engine	**Block 4 'Window of Opportunity'** • Low threat • High government additionality • Technological relatedness supports entry • Policy opportunity to capture new market share • Ex: Norwegian electric vehicle batteries

Figure 1. Sustaining vs. disruptive innovation and high vs. low market capture.

Contextualised variety strategically assesses potential threats to the nationally bound innovation system and can identify if and where resources are lacking or overly generous. It can be considered as a geographically bound specification of the relevant technological variety embedded within a global innovation system. It offers a means to identify weaknesses by considering industrial capacity, institutional frameworks and future prospects. Essentially, it is first imperative to grasp the specific contribution of a country to any given global innovation system to ascertain its strengths and hence what would be affected if disruption were to occur. For example, to what extent does a country substantially produce car tyres, engines, sensors, seats, etc. for the global automobile innovation system? Mapping the structure and trends in the global innovation system showcases the dominant components and services and where disruptions may arise.

To subsequently determine whether a country is resilient in the face of changes to the global innovation system, attention shifts to the type of variety a country dedicates to this innovation system. In the case of the car, does a country producing car engines also invest in electric vehicle motors? If there is only minimal attention directed towards these disruptive technologies, it may ultimately succumb to external disruption. The model therefore helps to identify where a country may unevenly pursue an existing competency, chase a technology too distant from its core competencies – leading to an inefficient use of time and energy – or fail to invest in potentially disruptive innovation, thereby putting the entire innovation system at risk. Hence, contextualised variety takes previous notions of ambidextrous variety as a proxy for resilience and specifies them to a unique country context as embedded in a given global innovation system.

3. Methods

Our purpose is to investigate the resilience of a maturing TIS through the notion of contextualised variety. We take several steps and combine multiple data sources in a mixed-methods approach to evaluate the resilience of the Dutch offshore renewable energy innovation system: we do so by measuring the activity level for different products and services in the Netherlands, which products and services it invests its resources and whether there is sufficient and coherent attention paid to potential disruption.

3.1. Data

Our data comes from four primary sources: the first is a database of 236 government-sponsored R&D projects from 2010–2020. The database is an aggregation of publicly available data compiled by the Netherlands Enterprise Agency (RVO) and the Dutch Research Council (NWO). It contains R&D projects on offshore renewable energies that have been awarded through various Dutch funding programme lines, such as the NWO, DEI+, HER and TSE. Information includes the funding mechanism, project title, project description, project number, start date, end date, technology readiness level, project partners and project value in Euros (excluding NWO projects).

Second, the 4C Offshore Wind database provides a highly detailed classification of all offshore wind projects, including all involved stakeholders, their respective roles in the individual projects, company headquarters, and for which windfarm the contract is awarded. Stakeholder roles include categories such as ‘foundation manufacturer’, ‘installer’ or ‘turbine supplier’. There are over 12,000 awarded contracts for operational and under construction offshore windfarms in Europe (4C Offshore, 2019).

Third, we conducted 34 expert interviews with incumbent firms, established small and medium enterprises (SMEs), start-ups and young enterprises, government experts, incubators, accelerators and networking organisations. These interviews provide highly detailed insights into the dynamics behind the support and choices made for sustaining and disruptive innovations. All interviewees gave prior informed consent, and any direct quotes were anonymised and verified prior to publication. A list of the interviews can be found in Appendix 1.

Finally, we use industry reports (i.e. DNV, NORWEP and the International Energy Agency (IEA), industry news (i.e. 4C Offshore Wind and OffshoreWindBiz), company reports (i.e. publicity statements, financial reporting, strategic agendas, etc.) – and government reports and white papers. This mixed-methods approach combining a medium-*N* R&D project database, a large-*N* contractor database, 34 highly detailed semi-structured interviews and a wide range of industry and government reports provides both a macro and micro level picture of the innovation system and allows us to contextualise its variety and thereby its resilience.

3.2. Setting the stage: establishing the global innovation system

Before analysing the technology portfolio within a country, we lay out the broader confines of the global innovation system. Core criteria include 1) total installed capacity of the technologies; 2) the dominant design of these technologies; 3) the dominant design of the components and the services needed to produce them; 4) the predominant sustaining and disruptive innovations to the technologies, their subcomponents or services; 5) critical geographic specifications, such as key markets and producers. Engaging primarily with industry reports, industry news, government reports and publicity statements, we determine the dominant technologies, markets and trends in the global innovation system.

3.3. Dominant versus marginal sectors

The next step to assess contextualised variety is to determine the activity level of components and services in the country in question (the Netherlands) for the global offshore renewable energy innovation system. This provides a means to assess the country's specific strengths and weaknesses. Since offshore wind is the only commercial-scale offshore renewable energy, this data is primarily derived from the 4C Offshore Wind database. Participation is measured through Dutch contracts awarded for the construction or operation of windfarms in different countries. The contracts are coded into roles, such as 'foundation supplier' or 'wind turbine manufacturer'. To evaluate production share per component market, we calculate the share of contracts won by Dutch companies out of all contracts per component or service. There are a total of 12,329 contracts, of which 1,815 are awarded to Dutch companies (~15%). Appendix 2 shows the full breakdown per stakeholder category and respective Dutch market penetration across Europe. We use our interviews, industry reports and news to evaluate access to new markets and determine whether the Dutch enter via dominant components or services or if they seek new opportunities. By evaluating market penetration, we gain a first insight into what would be the most affected if disruption were to occur at the global level. The higher the market share, the higher the risk of threatening disruption whereas the lower the market share, the lower the risk of disruption. Efforts to capture new products and services indicates a window of opportunity.

3.4. Sustaining versus disruption innovations

Subsequently, we map government resource allocation guiding technology selection, which will allow us to cross-reference the Dutch contribution to the global innovation system with the attention given to various components and services for both sustaining and disruptive innovations. We first classify each project in the R&D database as either sustaining or disruptive. These projects are coded in reference to the global innovation system for offshore renewable energy, regardless of how active Dutch companies are. Sustaining innovations include making monopiles bigger, wind turbines more powerful, production lines more efficient, optimising wind farm layouts or improving weather forecasting; it can also encompass highly modified components that improve the current system and technological paradigm, such as hydrogen powered vessels or quieter monopile hammers (C. M. Christensen 1997; Dedecca, Hakvoort, and Ortt 2016; Lacerda 2019; Tack et al., 2016). Disruptive innovations are based on new engineering principles, thus providing opportunities for new entrants in existing or new markets. Examples include floating foundations, disruptive turbines, blue energy or float-and-sink foundations (DNV GL 2020; IRENA 2016; NORWEP 2019). Appendix 3 lists the breakdown of R&D projects by category. Projects in the database are pre-classified along the technology readiness level scale from 1–9, which we cluster into ‘Discovery’ (TRLs 1–3), ‘Development’ (TRLs 4–6) or ‘Demonstration’ (TRLs 7–9) (TKI Wind op Zee 2019b).

Finally, we break these innovation projects into their specific categories, such as ‘installations’, thereby mapping which component segment the project targets, whether it is disruptive or sustaining and its degree of technological readiness. Projects are coded on three dimensions: ‘category’; ‘sustaining or disruptive’; ‘TRL’. For example, a project can be coded as ‘installations, sustaining, demonstration’ or ‘foundations, disruptive, discovery’.

3.5. Assessing resilience

We assess resilience by analysing the contextualised variety of the offshore renewable energy innovation system. To do so, we map the alignment and discrepancies between 1) market capture of one country and the global innovation system; 2) trends in sustaining and disruptive innovations at the global level; 3) directionality of R&D at the national level. We thus apply our four analytical blocks to determine resilience. Importantly, resilience is not dichotomous in nature, but rather a spectrum, meaning that an extensive, mixed methods approach is essential to capturing the full complexity of the system in question.

An innovation system *increases its resilience* for a component or service that enjoys a strong market share as it increases both sustaining and disruptive innovation for that component or service. Sustaining innovations fall into the ‘business as usual’ block while disruptive innovations fall into the ‘prepare for disruption block’. An innovation system *loses resilience* if it enjoys a strong global market share for a component or service but insufficiently stimulates both sustaining and disruptive innovation. This indicates that it fails to adequately invest in the 'business as usual' and 'prepare for disruption' blocks. '*Windows of opportunity*' occur for investments in disruptive innovations for segments in which the country is not substantially active. This indicates an attempt to break into a new component or service within the global innovation system by disrupting incumbent actors embedded in other countries. Contextualised variety also unearths incoherent investments in sustaining innovations for marginal contributions to the innovation system; this indicates poorly allocated resources that may be better directed towards addressing threatening disruptions or pushing to capture windows of opportunity. This is considered the '*no-go zone*'.

Crucially, these effects are measured not only by comparing numbers across the respective databases, but also by elucidating key strategies, challenges, goals and ambitions highlighted by our in-depth interviews. The R&D Projects and 4C Offshore Wind Contracts databases highlight the dominant and marginal sectors of the national contribution to the global innovation system and government-oriented directionality. The interviews and reports highlight plans, strategies and investments that are not captured by the databases. The empirical results provide a means to evaluate contextualised variety via our four analytical blocks: 1) Sustaining innovation for strong sectors; 2) Sustaining innovation for marginal sectors; 3) Disruptive innovation for strong sectors; 4) Disruptive innovation for marginal sectors.

4. Results

A resilient Dutch offshore renewable energy TIS presumes that it will remain strong post-2030 when the current pipeline of projects comes to an end. The expansion of Dutch offshore wind may become complicated as issues related to space limitations, power offtake, intermittency, political uncertainty, technological disruption or new markets that have their own unique context conditions arise (The Carbon Trust 2008; IRENA 2019; Offshore WIND 2019). Disruptive technologies may threaten the current dominant design and incumbent actors, thus necessitating adaptability to new and changing playing fields (Köhler et al. 2019; Van der Loos, Negro, and Hekkert 2020b). In this light, we assess resilience according to our notion of contextualised variety.

4.1. Setting the stage: establishing the offshore renewable energy global innovation system

The offshore renewable energy innovation system is composed of classic offshore wind and alternative maritime renewable energy technologies. These technologies are encapsulated within the same innovation system as they engage in overlapping industrial skill sets, policy frameworks, knowledge development and knowledge infrastructure (Hillman and Sandén 2008; Sandén and Hillman 2011).

The offshore wind dominant design entails three-bladed upwind turbines installed on fixed-bottom monopile foundations using self-lifting jack-up vessels and high-impact monopile hammers (Dedecca, Hakvoort, and Ortt 2016; Van der Loos, Negro, and Hekkert 2020b). Turbine towers and foundations are connected by bolted transition-pieces. Expensive bubble curtains mitigate the noise generated by the monopile hammers, which disrupt marine ecosystems (NORWEP 2019). Inter-array cables connect the turbines to a substation, which steps up the alternating current voltage and distributes the energy to the onshore grid via a high voltage transmission line (TKI Wind op Zee 2019a; WindEurope 2019). Figure 2, below, shows the typical layout of an offshore windfarm.

Offshore wind has witnessed tremendous growth over the past decade, reaching 2.5 GW of installed capacity and another 4 GW under construction in the Netherlands alone (RVO 2015). A further 22 GW are expected by 2030 and 38–72 GW by 2050 (Cleijne et al. 2020). Excellent knowledge institutes – such as the Delft University Wind Energy Institute (DUWIND) and the Marin Research Centre – and networking organisations strongly spur the innovation system; further, there is a high level of public and private sector legitimacy (Cleijne et al. 2020; Ministry of Economic Affairs and Climate 2018; Van der Loos et al. 2021; Van der Loos, Negro, and Hekkert 2020a; Vos 2011). This well-functioning system was achieved after many years of hurdles, snafus, setbacks and resistance (Agterbosch, Vermeulen, and Glasbergen 2004; Loyens and Loeff 2016; Ministry of Economic Affairs and Climate 2002; RVO 2015; Verhees et al. 2015). Further, offshore wind has reached over 20 gigawatts of installed capacity across Europe, providing electricity to roughly 40 million people, rising to over 560 gigawatts by 2040 (IEA 2019; The Renewables Consulting Group 2020).

Disruptive offshore renewable energy can be split between disruptions within offshore wind and disruption from adjacent offshore renewable energy technologies. Disruptions within offshore wind are broken into wind turbines, foundations and installation. The ‘slip-joint’ is a conical addition to the top of a monopile foundation that replaces the need for an expensive and cumbersome connecting ‘transition-piece’ between the foundation and the turbine tower. Floating offshore wind retains its own category since no dominant design has emerged yet (DNV GL 2020; IRENA 2016). Other maritime renewable energy technologies include wave and tidal energy, airborne kite systems, blue energy (harnessing the osmotic difference between saline and fresh water) and floating solar photovoltaic. Please see Appendix 4 for a detailed description.

4.2. Dominant versus marginal sectors: assessing component market share

The Netherlands participates very strongly in the offshore wind industry: 15% of all offshore wind contracts in Europe and 25% of value goes to Dutch companies (4 C Offshore Ltd 2019a; Rijksoverheid 2021). Figure 3, below, shows that the Dutch have a very high market share in ‘transition-pieces’ (46%), ‘Engineering, Procurement, Construction and Installation (EPCI)’ (40%), ‘vessels – heavy lift’ (28%), ‘ports’ (27%)

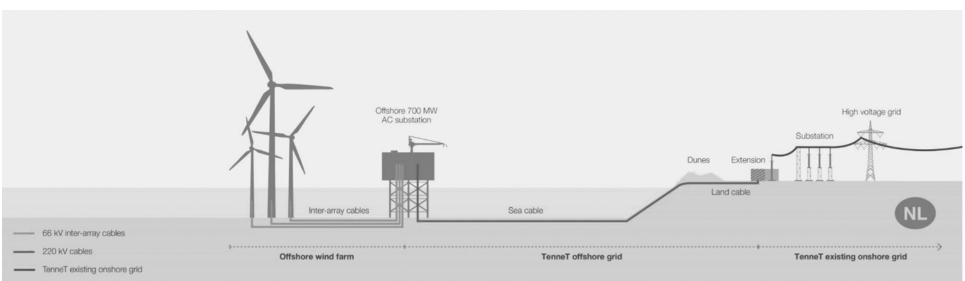

Figure 2. Typical offshore windfarm and grid connection. Source: Jaarsma (2018).

'installations' (26%) and 'foundations' (26%). There is medium penetration in 'substations', 'vessels – smaller', 'design', 'suppliers' and 'other activities'. There is very minimal penetration in 'wind turbines', 'cables', 'developer', 'consultancy' and 'ownership'.

Disruption to one of the dominant segments, such as transition-pieces or monopile foundations, would have the largest impact on the innovation system. Disruption to wind turbines or cables would have a minimal impact.

4.3. Sustaining versus disruption innovations: assessing R&D directionality

4.3.1. Sustaining innovation

Figure 4, below, shows the number of sustaining and disruptive innovations per market category. 'Design and planning' accounts for nearly 20% of all projects, which is directly linked to the optimisation of windfarms to improve the planning, construction and physical layout of the windfarm. 'Installations' and 'operations and maintenance' also receive considerable sustaining R&D support. They enhance current offshore wind practices and ties into the 'cost-reduction' subsidy instrument programme line (TKI Wind op Zee 2019a). More recently, the government awarded 5.8 million Euros for two monopile installation projects in 2021, indicating huge investments in sustaining innovations for the dominant installation and foundation segments (Buljan 2021; Skopljak 2021b). In reference to incremental innovations, one Dutch incumbent states,

> We have central R&D and some topics that are worked out within the company ... within the business units. So, we've also got a team who's working constantly on improving products and [...] equipment ... We're also looking at start-ups, and we see if we can use it and if we can do something together.

One start-up asserts,

> [They] decided a thousand years ago to become a niche monopolist in the monopile offshore wind farm business. So, they're not interested in a product like [ours]. They're only

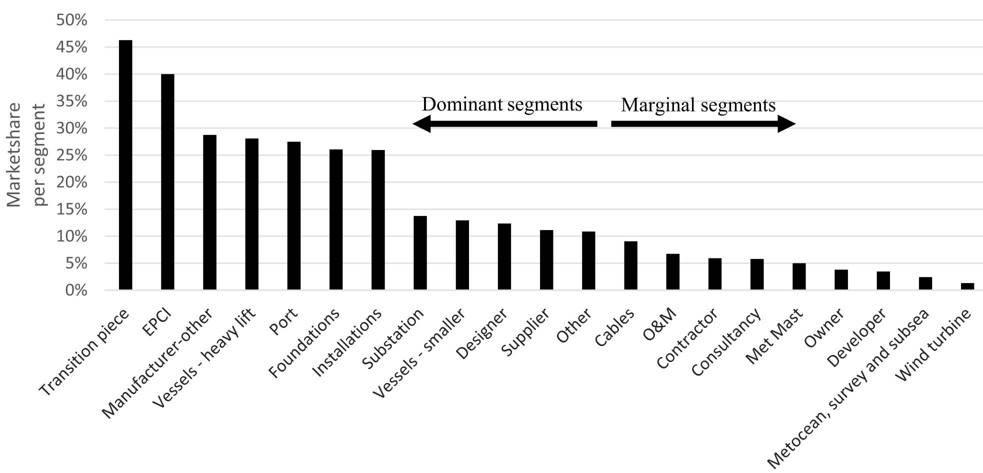

Figure 3. Dutch production share in Europe by component.

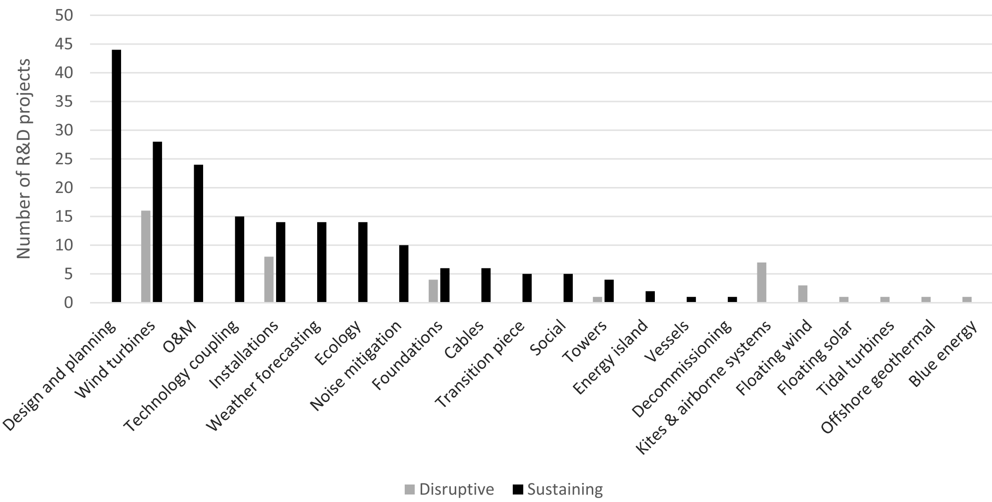

Figure 4. Sustaining and disruptive innovation across all TRLs.

> interested in a type of foundation which involves their vessels. They will actively try to keep everybody out. Even though they're big and they can afford it, they stick to their own R&D, which is incremental in order to stick to that market.

'Weather forecasting' also receives significant support and meets the program line criteria for 'optimisation' (cost reduction), also leading to sustaining innovation. 'Noise mitigation' from quieter monopile hammers or alternative pile-driving techniques is a final category that strongly benefits from R&D subsidies and helps the incumbent system reduce traditional noise mitigation costs. These examples highlight that the government and industry are highly coordinated to ensure that the Dutch remain dominant through investments in sustaining innovations and are part of 'block 1 business as usual'.

'Wind turbines' receive the second most projects for sustaining innovation (and highest for disruptive innovation, as discussed below). The government substantially invests in R&D to develop and improve classic wind turbines and has several world-renowned institutes and research centres, such as the Delft University Wind Energy Institute (DUWIND) and the MARIN Research Centre (TU DELFT 2015). However, wind turbines make up a negligible share of the Dutch offshore wind industry. Wind turbines hence fit into 'block 2 no go area'.

4.3.2. Disruptive innovation

Wind turbines also receive the most disruptive innovation support. Several Dutch start-ups are involved in disruptive wind turbines, including the hydraulically operated Delft Offshore Turbine, the donut shaped Monobase Wind or the 2-B Energy downwind two-bladed turbine (Haans et al. 2015; Monobase Wind 2014; Offshore WIND 2018a). The 'installation' category also receives disruptive support with an exclusive focus on dynamic-positioning, also known as active motion compensation. For example, the Dutch incumbent Heerema developed a dynamically-positioned crane to instal turbines using floating vessels, thereby eliminating the need for expensive self-lifting jack-up vessels (Skopljak 2019).

There are five disruptive innovation projects for the transition-piece, all of which target the conical slip-joint. Given its substantial market share, there is a high level of exposure. Investing in the slip-joint helps ensure resilience, as discussed in the analysis, below; importantly, all five of these projects focus on the slip-joint, meaning limited variety within disruptive transition-piece innovations.

'Disruptive fixed-bottom foundations' receive tepid support. The two high-TRL demonstration projects, out of only four in total, were co-financed by incumbents and tested in the United Kingdom and Denmark. Suction-bucket foundations – a disruptive foundation based upon oil and gas experience – receive moderate industrial attention: Dutch oil and gas suction-bucket specialist SPT Offshore was contracted to design and support installation on the Aberdeen Offshore Windfarm in the United Kingdom (Offshore WIND 2017; SPT Offshore 2018). They also designed and built suction-bucket foundations for two Chinese offshore windfarms, a rare example of European access to the Chinese dominated Chinese offshore wind market (4 C Offshore Ltd 2019b; Skopljak 2020, 2021a).

In another example, Dutch incumbent Royal BAM won a contract by EDF (France) to construct five gravity-based float-and-sink foundations that were installed at the British Blyth Offshore Demonstrator in 2017 (Royal BAM 2017).

There is nearly no R&D focus on floating offshore wind, particularly at the demonstration level of the foundation itself. According to one Dutch government official:

> **[Interviewee]** So, I think for Dutch companies who want to stay in the market, floating will be a very important point they have to invest in because otherwise they are dependent on the North western European markets, but the rest of the world, they don't have any business. **[Interviewer]** Is there a risk for Dutch companies then that are very focused on the shallow sandy bottom monopile approach, in terms of the future? That there's a risk for them in terms of staying alive after these years? **[Interviewee]** The next 10 years, that's okay. But I think especially the rollout in a longer run on the global scale, I think, they need to diversify to stay in business. Yeah.

Few Dutch start-ups are present in floating offshore wind. Some large incumbents have participated on international full-scale demonstration projects. For example, Royal Boskalis – a major Dutch dredging, cabling and offshore wind installation incumbent – transported and installed the foundations and pre-installed turbines on the Scottish Kincardine floating offshore windfarm and the Port of Rotterdam acted as the marshalling port (Durakovic 2020). However, the major added value, the foundation itself, was designed by an American start-up (Principle Power) and constructed in Portugal as part of the Portuguese-led WindFloat Atlantic floating innovation project (DNV GL 2020; GWEC 2020, 2022).

We can therefore derive that several existing Dutch companies with origins in oil and gas, maritime and/or construction are able to partially participate in disruptive fixed-bottom foundations and floating wind if there is external impetus. Effectively, these innovations are the purvey of existing private companies and receive minimal support from the government.

Finally, alternative maritime technologies have seen several scattered projects and the presence of a few start-ups, such as the tidal turbine company Tocardo (Unen 2020). Due to the low energy potential of maritime renewable energies in the Dutch corner of the North Sea, funding is scarce and legitimacy is weak (Scheijgrond and Raventos 2015). According to one start-up, 'Maritime renewable energy is just not on the government agenda'. Another mentions, 'At this moment, we get very few subsidies from the Netherlands.' Airborne kite systems have received attention, particularly at the discovery and development level, but not (yet) for full-scale demonstration.

Neither floating offshore wind nor maritime renewable energy will likely play a large role in the Dutch energy transition in terms of the share of total renewables, these innovations have struggled to gain a foothold. Indeed, they may only provide a small share of predictable energy output. One exception may be floating solar, which, when integrated into an offshore windfarm, could provide sufficient energy output to warrant use in Dutch waters. For example, the 760-megawatt Hollandse Kust Noord offshore windfarm will feature a 500-kilowatt floating solar demonstration project by 2025 (Buljan 2020). Figure 5, below, breaks down disruptive innovation per segment and technology readiness level according to the R&D database. Figure 6 summarises the attention given to potentially disruptive subcomponents or services. For example, within 'wind turbines', there are multiple potentially disruptive design-types, such as two-bladed or vertical axes turbines. Green indicates substantial investment and attention for each of these design types, orange indicates a moderate but positive level of attention, yellow a medium but negative level of attention while red indicates nearly no attention. For example, the Netherlands directs nearly no attention towards floating offshore wind and limited attention to disruptive foundations. In the analysis, below, we discuss the implications of these choices on the resilience of the nationally delineated innovation system.

5. Analysis: resilience

In evaluating the resilience of a nationally bound technological innovation system, we refer back to our four theoretical blocks, which are dependent upon the amount of

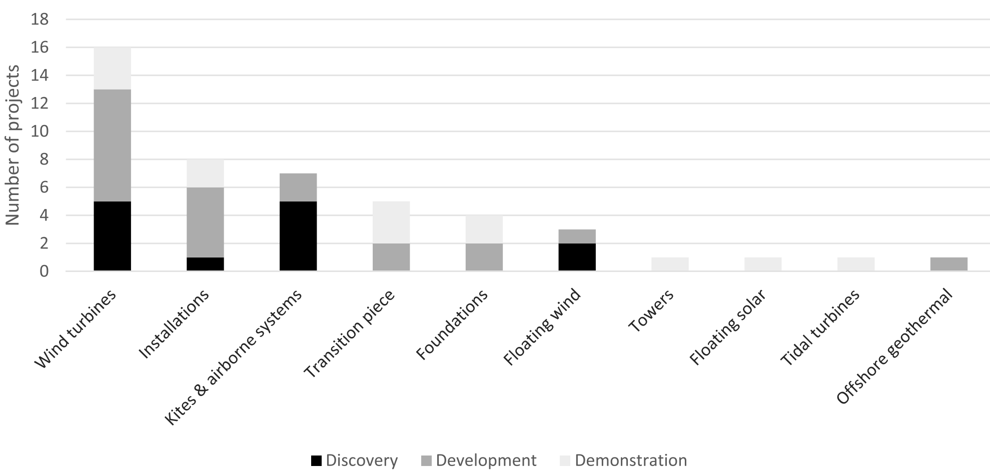

Figure 5. Disruptive innovation by TRL. (Derived from the R&D database).

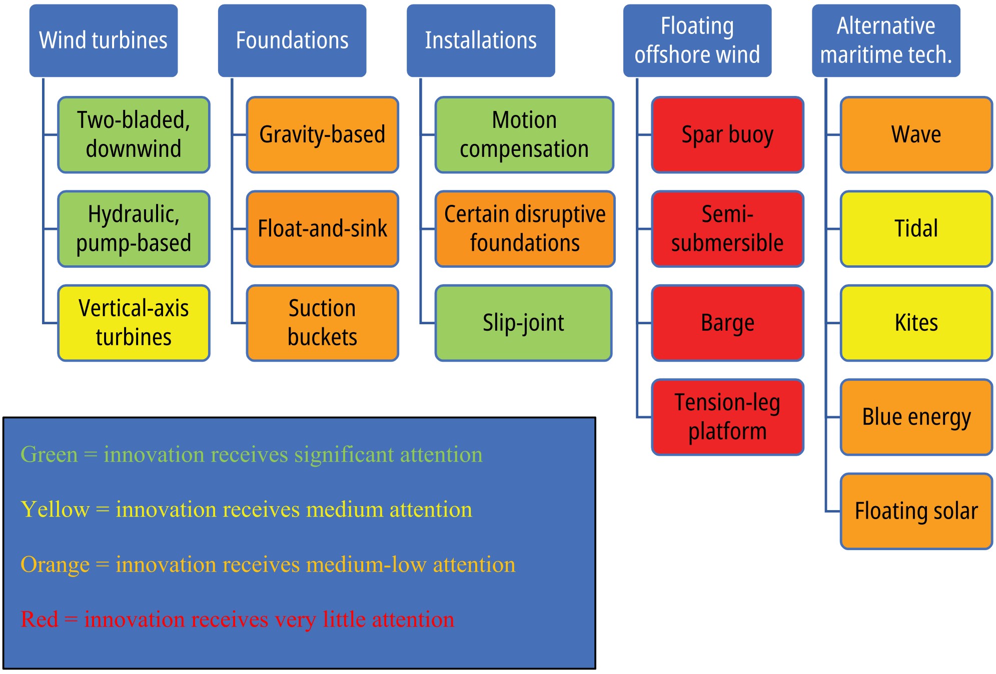

Figure 6. Attention given to potentially disruptive technologies.

	SUSTAINING INNOVATION	DISRUPTIVE INNOVATION
DOMINANT SECTORS	**Block 1 'Business as Usual'** • Monopile manufacturing (+) • Transition-piece manufacturing (+) • Installations (+) • Operations & maintenance (+) • Ports (+)	**Block 3 'Prepare for Disruption'** • Foundations (-) • Installations (+/-) • Transition-pieces (+/-) • EPCI (+/-)
MARGINAL SECTORS	**Block 2 'No Go Area'** • Classic wind turbines (+)	**Block 4 'Window of Opportunity'** • Disruptive wind turbines (+) • Alternative maritime renewables (+/-) • Floating wind (-)

Figure 7. Summary of sustaining vs. disruptive innovation and high vs. low market capture. B.: (+) indicates strong innovation activity; (±) indicates medium or inconsistent innovation activity; (-) indicates poor innovation activity.

disruptive versus sustaining R&D support received for dominant versus marginal component products or services: 1) 'Business as usual': Sustaining innovation for strong component sectors; 2) 'No-go area': Sustaining innovation for marginal component sectors; 3) 'Prepare for disruption': Disruptive innovation for strong component sectors; 4) 'Window of opportunity': Disruptive innovation for marginal component sectors. Below, we analyse each of these four blocks to measure the evaluate of the Dutch offshore renewable energy innovation system.

5.1. Business as usual: sustaining innovations in dominant sectors

Sustaining innovations for dominant components and services are generally the responsibility of the private companies and industries that are involved in their production. The government can contribute through co-financing innovation projects and setting guidelines. R&D investments are essential from across the industry and government to remain resilient; failure to do so would be considered poor business practice. Smaller, under-resourced companies or sub-suppliers benefit from government support.

Sustaining innovations for 'design and planning', 'operations and maintenance' and 'installations' are highly related to existing competencies, namely the dominant 'EPCI', 'installation' and 'port' categories. Monopiles receive extensive incremental support. Both businesses and the government demonstrate a strong willingness to invest in the sectors in which the Dutch are already dominant. As the first piece of the resilience puzzle, the Dutch are stimulating the areas in which they are dominant. Such a system level aggregation is analogous to incumbent actors funding their R&D departments to retain their dominant position.

5.2. No-go area: sustaining innovations in marginal segments

Investing in sustaining innovation in non-dominant components and services indicates a poor allocation of resources, particularly in countries with high labour costs. It is unlikely that a new entrant will be able to compete with existing actors for a slightly improved version of the same product. Exceptions could occur if demand for a product outstrips production capacity, or a country can compete on lower labour costs.

Wind turbines are the most glaring incoherence in this study. The Dutch have tried and failed to create a wind turbine manufacturing industry for decades (Agterbosch, Vermeulen, and Glasbergen 2004; Eecen 2011; Kamp, Smits, and Andriesse 2004). Companies such as Lagerwey or Darwind either went bankrupt multiple times and/or were acquired by foreign turbine manufacturers (Kamp 2002). The DUWIND institute at the Delft University of Technology is one of the leading wind energy institutes and engages in fundamental research often dedicated to wind turbine aerodynamics (TU DELFT 2015). One can therefore question the value of resource allocation. Nonetheless, a small sub-component sector and other Dutch firms, such as installation companies, can benefit from enriched wind turbine knowledge for their own operations (Haans et al. 2015; Roy, Reynolds, and Clayton 2014; Vos 2011). Furthermore, the increased knowledge supports the innovation system at the European level, in principle helping to improve competitiveness against (non-European) competitors. Nonetheless, R&D investments in wind turbines are an example of attempted diversification into a field that is controlled by a handful of incumbents – namely Siemens-Gamesa Renewable Energy (German-Spanish) and Vestas (Danish) – in possession of vast R&D departments and embedded in well-developed innovation systems. It is highly unlikely that the Dutch will ever become a global traditional three-bladed wind turbine manufacturer.

5.3. Prepare for disruption: disruptive innovations in dominant sectors

Investing in disruptive innovations in dominant segments is fundamental to resilience. Governments and industries need to be extremely attentive to help ensure that, if disruption occurs, it occurs from within the confines of the nationally-delineated innovation system. Failure to do so puts the entire system at risk due to spill-over effects.

As the 'Innovator's Dilemma' suggests that companies need to be aware of potential disruptions to their businesses and take proactive measures, so does the innovation system (C. M. Christensen 1997). Hence, contextualised variety strategically focuses on this innovation block. The government has particular influence here via a large pot of funding, ability to set visions and power to guide innovation. An excellent example of resilience is dynamic positioning for installations, which may supplant the dominant and expensive self-lifting installation jack-up vessels. Disruption could potentially come from within the Dutch innovation system, hence retaining dominance in the installation segment. Similarly, slip-joints may replace traditional transition-pieces and disrupt from within the Dutch innovation system, indicating system-level resilience for this segment. Notably, the Dutch are placing all of their disruptive installation eggs in the dynamic-positioning and slip-joint baskets, respectively.

Disruptive foundations are the least resilient and most vulnerable product in the Dutch innovation system: it has the widest discrepancy between market dominance, targeted innovation and potential disruption, indicating a high threat level. Disruption to foundations may also disrupt the installation industry, thus causing major spill-over effects. For example, the lack of major investments or vision into 'gravity-based float-and-sink' or 'suction-bucket' foundations indicates that the Dutch industry and government are locked into the monopile foundation dominant design. If a disruptive fixed-bottom design were to emerge outside of the Netherlands and successfully supplant the major monopile foundation manufacturers, the effects could be devastating. Regulatory shifts may have an equally devastating effect. For example, more stringent noise regulations during the monopile installation process may effectively render the monopile obsolete. The industry may respond with improved noise-mitigation measures, which we indeed already see, but these response mechanisms usually fail to prevent looming disruptions in the long run (Offshore WIND 2018b; Utterback 1994).

5.4. Window of opportunity: disruptive innovations in marginal segments

Stimulating disruptive innovation in non-dominant segments leverages no-risk opportunities. Failure indicates a loss of resources while success means disrupting global actors and capturing new markets. Given the non-existent industry, success is dependent on substantial resource investments. The Dutch heavily invest in disruptive wind turbines, falling into the category of a 'non-threatening disruption'. If a disruption were to occur externally, there is no threat to the innovation system because there are no Dutch turbine manufacturers. Turbine production is an extremely complex and expensive endeavour that has witnessed massive consolidation over the past decades, suggesting that there are high entry barriers for new actors (IRENA 2019; REN21 2020). The onshore wind industry underwent a series of designs before converging on the three-bladed upwind turbine, which was subsequently adapted for offshore wind (Dedecca, Hakvoort, and Ortt 2016). Therefore, disruptive wind turbines need to be tailored to, and designed for, offshore conditions to be successful. Such a strong R&D agenda should, strategically speaking, be coupled with a vision for disrupting the wind turbine market, rather than a piecemeal, *ad hoc* approach.

Other maritime renewable energies, such as tidal and wave, receive some attention from Dutch R&D funding programmes, but remain one-off projects rather than as part of a concerted agenda. This is partly due to the weaker wave and tidal energy conditions in the Netherlands. There could be an opportunity to help mitigate intermittency through predictable and stable energy flows create a new export industry to countries where geological and political conditions are more favourable.

Floating foundations may not serve the shallow Dutch North Sea due to minimum draught requirements but will dominate as soon as water depths permit, generally beyond 60 metres. This could be an area worth targeting given the extraordinary global potential (DNV GL 2020; IRENA 2016). While floating wind is unlikely to supplant fixed-bottom foundations in the coming 30 years due to the vast near-shore potential, there may be missed opportunities for potential diversifiers; Dutch start-ups that try to enter the technological design race may also stand a chance because no dominant design has emerged yet. If space constraints or regulations prohibit new fixed-bottom wind farms, countries may be forced to go to the wider expanses of the open ocean. Figure 7, below, summarizes our findings four our four blocks.

6. Discussion & conclusion

6.1. Theoretical implications

This research departs from traditional technological innovation system studies engaged with emerging technologies and system functions and widens the scope towards the resilience of maturing innovation systems. While innovation systems are global in nature, national governments have a vested interest in supporting the components and services in which it excels (Alkemade and Hekkert 2010; Jänicke 2012). Mission-oriented innovation policies direct attention towards rapid upscaling of one or a few technological solutions, their components and services, which can lead to system-wide lock-in. Such concerted efforts limit variety and can undermine the system's resilience. Contextualised variety, therefore, becomes essential for the long-term competitiveness of the innovation system and its firms.

We propose a strategic framework grounded in the notion of contextualised variety to assess the resilience of maturing technological innovation systems, which zooms in on the specificities of a given nationally bound technological innovation system in the context of its global innovation system; it subsequently maps the specific innovation activities with reference to disruptive threats and opportunities. We use four analytical blocks to evaluate the coherence between sustaining and disruptive innovation and dominant versus marginal components and services: 1) 'Business as usual' means stimulating sustaining innovation for already dominant sectors; 2) 'No-go area' means stimulating innovation for marginal sectors and is considered unlikely to succeed; 3) 'Prepare for disruption' means stimulating disruptive innovation for dominant sectors and is essential to resilience; 4) 'Window of opportunity' means stimulating disruptive innovation for marginal sectors, potentially leading to new market capture. Importantly, while governments can guide directionality and provide resources, individual companies and innovators need to take up these challenges, meaning that strong synergies need to be found between public and private actors.

Using our framework, one can map the current strengths of the industry to identify potential threats and windows of opportunity and then identify whether innovations in the global innovation system are sustaining or disruptive in nature. Innovation policies for sustaining innovations in marginal components or services are likely a futile undertaking, while policies for sustaining innovations in dominant sectors are important but have limited additionality as industry incumbents have their own R&D resources. Stimulating disruption in dominant sectors may help retain global market capture and avert external disruptive forces by ensuring a sufficient degree of explorative variety. Disrupting from within the nationally delineated innovation system, while potentially devastating for individual companies, leads to no nefarious effects on the innovation system. Finally, policy support for disruptive innovation in marginal sectors may disrupt foreign firms as domestic firms capture new markets, further diversifying a technological innovation system. Benefiting from such windows of opportunity is more likely to occur in related sectors (Afewerki et al. 2019; Steen and Weaver 2017). However, non-technological shifts, such as changing markets, may favour unrelated variety.

6.2. Practical implications

Empirically, we use the case of the Dutch offshore renewable energy technological innovation system. Dutch firms are dominant players in the installation, vessel, monopile and transition-piece sectors, while weaker in cables and wind turbines. Sustaining innovations in the dominant segments are performing extremely well, indicating a first level of resilience, for example dynamic positioning for installations or slip-joints for transition-pieces. If successful, these disruptions would occur from within. Disruptive foundation innovations, on the other hand, receive the least support relative to the large monopile foundation market share, indicating a high threat level. External disruptions to the monopile foundation industry would be devastating.

Interestingly, sustaining and disruptive innovations in wind turbines – a marginal component – receive vast R&D support. It is highly unlikely to lead to new market capture since companies would have to scale up and compete against well-established foreign incumbents in possession of large R&D programmes. This may indicate poorly allocated resources. However, strong investments in disruptive wind turbines have the potential to disrupt foreign incumbents, thereby offering a window of opportunity. The ability to disrupt would thus require enormous time, effort and finances.

6.3. Limitations, generalizability and future research

One limitation of this study is that only government sponsored R&D projects are included in the R&D data; private in-house R&D is not disclosed by companies, so it may be that some companies are working on disruptive technologies that would improve the resilience of the innovation system but are not captured by this research. However, large government funded R&D programmes directed towards specific technologies indicates technology selection and trend setting. Furthermore, our interviews provide insights into the strategies within the private sector.

Since the innovation system is in the acceleration phase, there are many instances of attempted disruption. We suggest that the contours of our framework could be applied to any maturing or mature innovation system. However, generalisability is likely more limited in the case of nascent or very young innovation systems that have yet to establish a substantial market share and independent supply chain. Furthermore, we have concentrated our framework on the national delineation of a global innovation system, as policies, regulations and public & private actors are often nationally embedded. There is the potential to apply this framework to the regional level; to do so, the system may need to be adapted to capture unique regional characteristics, such as NIMBY issues, regional capacity, relative autonomy, regional assets, etc. For example, assessing the regional resilience of a small province in the Netherlands will demonstrate far different characteristics and conditions than a large state in the United States, such as California.

6.4. Policy implications

Our results shed light on the broader implications for innovation policy in the present-day context. Many countries have moved from generic support for corporate R&D and university-industry-government collaboration to a focus on mission-oriented innovation policies that help tackle societal challenges, including global warming, biodiversity loss, healthcare, geopolitical tensions and transport (Diercks, Larsen, and Steward 2019; Mazzucato 2018; Wanzenböck et al. 2020). In many countries, mission-oriented innovation policies go hand in hand with industrial policies to support domestic industries, despite warnings not to use an industrial policy logic in the context of mission-oriented innovation policy due to industry lobbying practices (Mazzucato 2018).

Our study speaks to this ongoing debate by linking mission-oriented innovation policies to technological innovation systems. Notably, our framework highlights that mission-oriented innovation policies may create vulnerabilities for established technological innovation systems in the event of disruption, as such policies may be drawn towards supporting a small network of companies that focus on one dominant design. Here, there is an imbalance between the energy spent on improving existing competencies and exploring new and potentially disruptive options. Mission-oriented innovation policies directed to scaling up and reducing costs to diffuse singular technologies or components with predefined dominant designs to tackle societal challenges, while effective in the short-run, may ultimately lead to a loss of competitiveness and negative unanticipated consequences (Hansen, Nygaard, and Dal Maso 2021).

Within mission-oriented innovation policies, there is a strong rationale to devote resources to policies to increase variety and 'unlock' a technological innovation system, also touched upon in the 'failures' framework by (Weber and Rohracher 2012) deriving rationales for transformative change more generally. It may be imperative to complement upscaling and cost reduction strategies with programmes that help increase variety for both existing competencies and disruptive innovation. A resilient technological innovation system strategically supports both the upscaling of existing competencies and the nascent innovations that may contribute to the innovation system of the future. These policies may be especially directed towards supporting start-ups or incumbents from related sectors that engage in disruptive innovations for components and services in which the target country is already strong or components and services in which the target country sees opportunity in which to diversity. In assessing contextualised variety and looking at global trends of disruptions and the possible consequences for existing firms, countries can ascertain which components and services should be stimulated and supported through, for example, R&D funding programmes, networking organisations, innovation competitions, protected niche spaces and demonstration zones.

Logically, resilience requires significant human and financial investments, indicating that it is not possible to support every imaginable outcome, but rather to ensure that there is a balanced portfolio of potential solutions at varying phases of development according to the bespoke needs and contributions of a given technological innovation system (van den Bergh 2008). Therefore, our notion of contextualised variety is strategically important in the face of limited government resources and interdependencies within the global innovation system. There is, however, no 'magic formula' as each innovation system needs to assess its resilience, competencies, industrial diversity and background, and thereby adapt its policies accordingly. This research highlights the need for a qualitative and contextualised framing to unearth the resilience of geographically-delineated technological innovation systems as embedded within broader global innovation systems. The theoretical foundations and qualitative metrics used in this research provide the contours of a new framework to evaluate the resilience of innovation systems.

Disclosure statement

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

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Appendix 1. List of interviews

Actor type	Date	Interviewee's role
Incumbent	30.5.18	Head sale's manager
Incumbent	5.6.18	R&D manager
Incumbent	19.6.18	Commercial manager
Incumbent	9.7.18	Business development and acquisition manager
Incumbent	12.7.18	Head of business development
Incumbent	5.12.18	Head of offshore wind business unit
Incumbent	11.12.18	Business developer
Incumbent	27.3.19	Chief commercial officer
Incumbent	27.5.19	Former CEO
Incumbent	29.6.18	Business manager
Incumbent	18.7.18	Manager of renewables
Incumbent	25.7.18	Commercial general manager of wind
Incumbent	15.11.18	Managing director
Young SME	16.7.18	CEO & founder
Young SME	19.7.18	CEO & founder
Young SME	24.7.18	Project leader
Young SME	23.11.18	Head of offshore wind business unit
Young SME	30.11.18	CEO
Young SME	27.3.19	Co-founder
Start-up	16.7.18	General director
Start-up	17.7.18	CEO & founder
Start-up	26.7.18	CEO & founder
Start-up	29.11.18	Head of technical development
Start-up	6.12.18	Project developer
Networking organisation	7.6.18	Coordinator
Networking organisation	25.6.18	Manager/coordinator
Networking organisation	20.12.18	Director
Networking organisation	20.12.18	Former director
Government agency	24.6.19	Senior advisor
Government agency	4.9.19	Offshore wind project leader
Ministry	11.9.19	Senior advisor for offshore wind
Start-up	11.26.20	Project leader
Start-up	7.12.20	Co-founder
Accelerator	13.1.21	Coordinator

Appendix 2. Offshore wind stakeholder type and breakdown

Stakeholder type	Totals	Dutch stakeholder totals	Market share in Europe	Share of Dutch industry
Consultancy	760	44	6%	2.4%
Contractor	506	30	6%	1.7%
Designer	356	44	12%	2.4%
Developer	202	7	3%	0.4%
Other	184	20	11%	1.1%
Installations – cables	456	109	24%	6.0%
Installations – foundations	264	86	33%	4.7%
Installations – other	101	24	24%	1.3%
Installations – substation	81	39	48%	2.1%
Installations – topside	316	58	18%	3.2%
Cables	309	28	9%	1.5%
EPCI	30	12	40%	0.7%
Substation	291	40	14%	2.2%
Foundations	445	116	26%	6.4%
Met Mast	60	3	5%	0.2%
Wind turbine	226	3	1%	0.2%

(*Continued*)

Stakeholder type	Totals	Dutch stakeholder totals	Market share in Europe	Share of Dutch industry
O&M	415	28	7%	1.5%
Manufacturer-other	80	23	29%	1.3%
Transition piece	216	100	46%	5.5%
Owner	368	14	4%	0.8%
Port	131	36	27%	2.0%
Supplier	718	80	11%	4.4%
Metocean, survey and subsea	409	10	2%	0.6%
Vessels – foundation	241	87	36%	4.8%
Vessels – other	675	219	32%	12.1%
Vessels – personnel	2629	213	8%	11.7%
Vessels – cables	491	121	25%	6.7%
Vessels – seabed	63	10	16%	0.6%
Vessels – O&M	405	16	4%	0.9%
Vessels – substation	64	35	55%	1.9%
Vessels – surveying	565	103	18%	5.7%
Vessels – TP Installation	125	43	34%	2.4%
Vessels – turbine Installation	147	14	10%	0.8%
Totals	**12329**	**1815**	**14.7% (avg.)**	**100%**

Appendix 3. Full R&D breakdown by category

Unique Categories	Sustaining	Disruptive	Totals
Design and planning	44	0	**44**
Wind turbines	28	16	**44**
O&M	24	0	**24**
Technology coupling	15	0	**15**
Installations	14	8	**22**
Weather forecasting	14	0	**14**
Ecology	14	0	**14**
Noise mitigation	10	0	**10**
Foundations	6	4	**10**
Cables	6	0	**6**
Transition piece	0	5	**5**
Social	5	0	**5**
Towers	4	1	**5**
Energy island	2	0	**2**
Vessels	1	0	**1**
Decommissioning	1	0	**1**
Kites & airborne systems	1	6	**7**
Floating wind	0	3	**3**
Floating solar	0	1	**1**
Tidal turbines	0	1	**1**
Offshore geothermal	0	1	**1**
Blue energy	1	0	**1**
Totals	**195**	**41**	**236**

Appendix 4. Description of disruptive offshore renewable energy technologies

Disruptive offshore renewable energy can be split between disruptions within offshore wind and disruption from alternative offshore renewable energy technologies. Disruptions within offshore wind are often broken into the wind turbine, foundation and installation; floating offshore wind retains its own category. Other maritime renewable energy technologies include wave and tidal energy or airborne kite systems.

Disruptive wind turbines may feature two blades instead of three blades, a vertical axis rotation in place of a horizontal axis or a hydraulic, pump-based system rather than a classic magnetically driven electric motor in the nacelle. Current foundations are typically pile-driven monopiles or pin-pile driven jacket foundations. Disruptive foundations may include suction-buckets, which place a cylinder at the bottom of the foundations after which the air is pumped out, creating a vacuum and thereby forcing the foundation into the seabed (Skopljak 2020). This is a very quiet alternative that eliminates the need for loud monopile hammers. Classic gravity-based foundations, while not new in design, and yet still potentially disruptive, use large concrete blocks that rest on the seabed, thus also avoiding the need for pile-driving (Leanwind 2017). Expensive self-stabilising jack-up vessels are still required. Gravity-based float-and-sink foundations are floated out to the site location and then lowered onto the seabed where they rest, like classic gravity-based foundations (Monobase Wind 2014). The advantage is that the turbine can be pre-installed at the dock and the entire structure is towed out using classic and widely available tugboats. This technology would also disrupt the installation sector.

In addition, dynamic position – also known as motion-compensation – may disrupt the installation sector by digitally and mechanically compensating wave movements during the installation process, which would allow for the use of classic barges and floating installation vessels, rather than expensive jack-up vessels.

Floating offshore wind is essential a disruptive foundation category whereby the foundation and turbine float, rather than being fixed into the seabed. They are then anchored to the seabed via mooring cables, chains, etc. There are many different designs, and all require water depths of at least 50 metres, with some (such as a 'spar buoy') requiring much deeper water depths.

Floating solar has also received some attention and consists of classic solar photovoltaic panels placed on top of innovative floating structures. These floating solar farms may be integrated into offshore wind projects and connected to the offshore wind substation (Buljan 2020).

Kites and other airborne systems are generally lightweight devices attached via a spooling cable to a motor and base that is anchored to the seabed via mooring cables. As the wind carries the kite higher into the air, the cable extends; at its apex, gravity brings the kite down and the cable reels in, thereby spinning the motor and producing electricity (Andersson, Hellsmark, and Sandén 2018; IRENA 2019).

Ocean thermal energy acts similarly to traditional geothermal energy extraction, but rather than relying on temperature differences in the ground, it relies on temperature differences between surface water, which is relatively warm, and deep ocean water, which is much colder.

Finally, blue energy uses the osmotic difference between salt and fresh water to produce electricity. This can occur in places where there is a regular interaction between salt and fresh water (IPCC 2012).