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Analysing energy innovation portfolios from a systemic perspective

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ABSTRACT

A systemic perspective on energy innovation is required to design effective portfolios of directed innovation activity. We contribute a standardised set of technology-specific indicators which describe processes throughout the energy technology innovation system, ranging from patents and publications to policy mixes, collaborative activity, and market share. Using these indicators, we then conceptualise and develop benchmark tests for three portfolio design criteria: balance, consistency, and alignment. Portfolio balance refers to the relative emphasis on specific technologies. Portfolio consistency refers to the relative emphasis on related innovation system processes. Portfolio alignment refers to the relative emphasis on innovation system processes for delivering targeted outcomes. We demonstrate the application of these benchmark tests using data for the EU's Strategic Energy Technology (SET) Plan which spans six technology fields. We find the SET Plan portfolio generally performs well particularly in areas over which portfolio managers have direct influence such as RD&D funding. However we also identify potential areas of imbalance, inconsistency, and misalignment which warrant further attention and potential redress by portfolio managers. Overall, we show how energy innovation portfolios can be analysed from a systemic perspective using a replicable, standardised set of measures of diverse innovation system processes.

1. Introduction

Energy innovation outcomes are irreducibly uncertain, dependent on technological progress as well as external developments in markets and institutional environments (Grubler et al., 2012). The scale and scope of energy-system challenges require a correspondingly broad strategy to energy innovation across multiple sectors, applications, conversion-chains, and end-uses. Innovation efforts directed towards public policy goals like decarbonisation can target specific technologies, but the capacity of policymakers to 'pick winners' is fraught with political, informational, and procedural difficulty (Nemet et al., 2017).

Innovation portfolio design has traditionally been concerned with the mix of technologies or investment targets. Portfolio theory was originally developed to identify the optimal mix of financial assets to minimise risk (Markowitz, 1952, 1959). Similar approaches have been applied to energy innovation portfolios exposed to technological, market, and other systemic risks (Fuss and Szolgayová, 2010).

In addition to deciding the composition of technologies in an innovation portfolio, portfolio managers must decide how to allocate their efforts to influence innovation processes and outcomes. A systemic perspective on innovation emphasises the influence of wider institutional, market, and policy conditions on the innovation lifecycle, the coordination and multi-stakeholder governance of innovation processes, and enabling frameworks or conditions to direct innovation activity (OECD, 2015). These and other innovation system processes may be more or less amenable to influence by policymakers seeking to 'direct' innovation efforts (OECD, 2015; Wieczorek and Hekkert, 2012).

Innovation portfolios therefore comprise not just different technologies or investments, but also different innovation system processes. A generalisable insight from the literature on innovation systems is that omissions or weaknesses in specific processes reduce the overall effectiveness of the system (Bergek et al., 2008). Innovation systems which are strongly weighted towards specific processes (e.g., RD&D funding) at the expense of others (e.g., market feedback) are less likely to deliver on desired outcomes (Grubler and Wilson, 2014b). Similarly, a diverse policy mix is more effective than a singular reliance on specific instruments, particularly given the systemic change necessary for energy system transformation (Kern and Howlett, 2009).

In this paper we draw on literature to argue that *balance* across technologies, *consistency* between innovation system proceses, and *alignment* with intended outcomes are three desirable characteristics for energy innovation portfolio design (Table 1). However there are no

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Acronyms

CCS	Carbon capture and storage
RD&D	Research, development and demonstration
SET Plan	Strategic Energy Technology Plan

standardised tests in the innovation systems literature to assess these three normative criteria across any innovation portfolio. The research question we address is: How can energy innovation portfolios be tested for balance, consistency and alignment from a systemic perspective? Our contributions are twofold. First, we develop a comprehensive set of technology-specific indicators characterising the innovation system which can be applied to any innovation portfolio. Second, we develop and apply three simple benchmark tests as indicative diagnostics of whether innovation portfolios are balanced, consistent and aligned. These benchmark tests are not designed to provide definitive assessments, but rather to draw portfolio managers' attention to areas of potential concern worthy of further investigation. We use one of the world's largest energy innovation portfolios - the EU's Strategic Energy Technology (SET) Plan - to show the value of our approach, but emphasise that both the indicators and our simple benchmark tests are designed to be generalisable to any energy innovation portfolio.

The rest of this paper is organized as follows. First, we review relevant literature on innovation portfolios from a systemic perspective and introduce the energy technology innovation system (ETIS) framework. Second, we define a comprehensive set of indicators to measure the different dimensions and processes in the innovation system. Third, we introduce the EU SET Plan as our case study innovation portfolio, and explain our methods for collecting data measuring the indicators for the EU's SET Plan. Fourth, we apply our portfolio design criteria to evaluate the balance, consistency and alignment of the EU's SET Plan and discuss key results. Finally, we explore the policy implications of our analysis for the SET Plan portfolio managers.

2. Literature review

2.1. Analytical frameworks for innovation systems

Analytical frameworks with different emphases have been proposed for evaluating the performance of innovation systems, including those related to energy technologies. The National Innovation System (NIS) framework explains the flow of people and firms within institutions at the national level (Freeman, 1987, 1995; Lundvall, 1992; Nelson, 1993). Using a variant of the NIS framework, the annual Global Innovation Index compiles and analyses quantitative metrics of innovation performance at the country level, capturing a wide range of institutional, human, infrastructural, market, and business factors that influence the efficiency with which countries convert innovation inputs into outputs (Cornell University et al., 2018).

Other innovation system frameworks apply to specific technologies and emphasise either structural elements or functional dynamics (Jacobsson et al., 2017). The Technology Innovation System (TIS) literature analyses the actors, institutions, and networks that comprise structural elements of innovation systems explaining the emergence and development of new technologies (Carlsson and Stankiewicz, 1991; Carlsson and Jacobsson, 1994). TIS scholars have tended to focus on specific technologies within a country (Hudson et al., 2011; Jacobsson and Karltorp, 2013; Hannon et al., 2017). The TIS has also typically been applied to the early formative phase of an innovation system rather than its full lifecycle through growth, maturity and senescence (Markard, 2018).

The Functions of Innovation Systems (FIS) literature shifts the emphasis onto a discrete set of functional characteristics of innovation system performance (Hekkert and Negro, 2009; Bergek et al., 2008). These functions describe how well actors and institutions perform entrepreneurial activities, knowledge development and dissemination, the guidance of search, market formation, resource mobilisation, and the creation of legitimacy (Hekkert et al., 2007). More recent literature has sought to reconcile these structural and functional perspectives, recognising their close inter-dependence (Wieczorek and Hekkert, 2012).

2.2. The Energy Technology Innovation System (ETIS) framework

The TIS and FIS frameworks enable powerful narrative accounts of technology-specific innovation systems emphasising contingencies and context-dependence. However their key elements - whether structural or functional - are hard to measure in a standardised way across technologies and adoption contexts. Consequently empirical studies using TIS and FIS frameworks focus on specific technologies rather than innovation portfolios. Portfolio-based analysis requires an analytical framework which is both technology-specific and generalisable to portfolios of technologies using standardised measures.

Drawing on insights from both the TIS and FIS literature, the energy technology innovation system (ETIS) framework is useful for analysing energy innovation from a systems perspective in a generalisable way (Grubler and Wilson, 2014b). The ETIS framework was originally developed for the Global Energy Assessment (Gallagher et al., 2012; Grubler et al., 2012) based on in-depth analysis of 20 historical case studies of relative success and failure in energy innovation (Grubler and Wilson, 2014b). We summarise the main rationale and explanation for the ETIS framework here and in the appendices, and refer the reader to these source texts for further detail and empirical justification.

The ETIS framework characterises how different elements of the innovation system combine to give rise to successful innovation outcomes (Gallagher et al., 2012; Grubler and Wilson, 2014b). The ETIS framework focuses on observable processes associated empirically with relative success or failure specific to energy technologies. In terms of application, the ETIS framework was designed as a tractable analytical tool for identifying the strengths and weaknesses of any given energy innovation system using a standardised set of dimensions and processes applicable to any technology (Grubler et al., 2012; Grubler and Wilson, 2014b).

Fig. 1 illustrates the four dimensions of the ETIS framework which provide the context for the familiar innovation lifecycle from research and development through to diffusion (Balconi et al., 2010; Grubb

Table 1
Criteria for designing energy innovation portfolios from a systemic perspective.

	Balance	Consistency	Alignment
Rationale	Diversify technology risk	Coordinate innovation system processes	Direct innovation system towards desired outcomes
Cautionary tale	Avoid picking winners	Avoid singular RD&D-led strategies	Avoid *ad hoc* targets and pork-barrel politics
Analytical Approach	Analyse composition of technology portfolio	Analyse omissions, tensions & weaknesses in innovation system	Analyse targets, stated outcomes & innovation outputs
Simple benchmark test [a]	Similar relative shares of technologies across innovation system processes	Similar relative shares of related innovation system processes across technologies	Similar relative shares of outputs and outcomes across technologies

[a] In the absence of clearly-articulated objectives for specific portfolios against which performance can be tested.

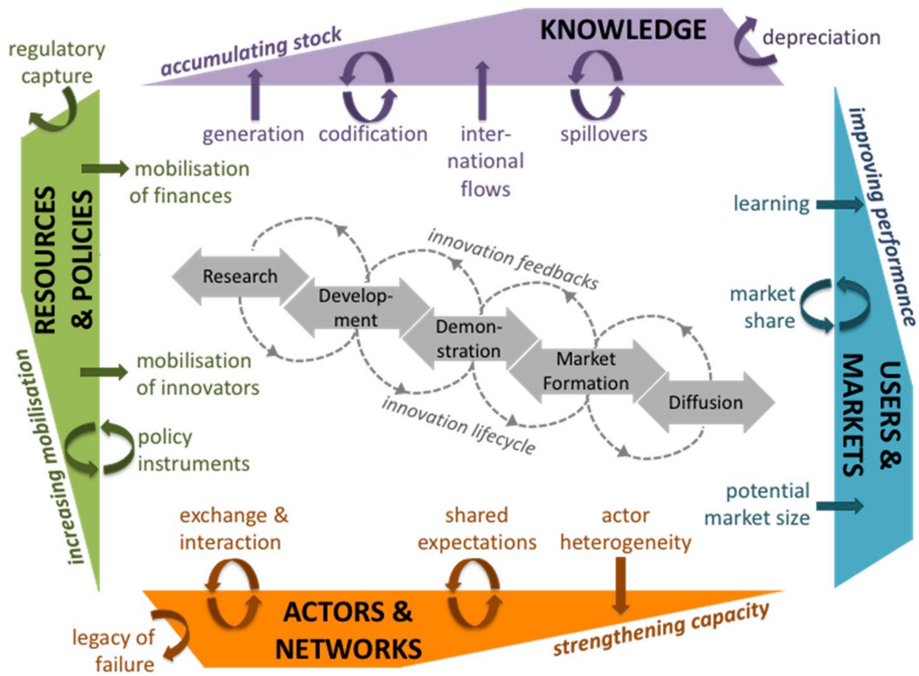

Fig. 1. The energy technology innovation system (ETIS) framework. Adapted from: (Grubler and Wilson, 2014b).

et al., 2017). The knowledge dimension includes processes of knowledge generation, exchange, codification as well as depreciation. The resources & policies dimension emphasises the importance of resource mobilisation in the form of finances, enabling policies, and innovators. The actors & networks dimension includes institutional conditions such as actor networks and heterogeneity. The users & markets dimension is concerned with consumers, market feedback and expectations. Detailed explanations of all these dimensions and innovation system processes are provided in Appendix A.

Compared to other innovation system frameworks, the ETIS framework places greater attention on the role of end users and market adoption, and frames innovation system processes in terms of both accumulating and depreciating capacity to generate and codify knowledge, to mobilise resources and institutional support, to facilitate actor networks and knowledge exchange, and to learn from users in market environments.

Innovation system processes associated with each dimension of the ETIS framework collectively generate successful innovation outcomes (Grubler and Wilson, 2014b). However, the innovation system is a complex, dynamic system characterised by iterative processes and feedbacks. Consequently innovation system frameworks like ETIS - as with the national, technological and functional frameworks (NIS, TIS, FIS) considered above - cannot be represented in a single integrative model explaining deterministically how inputs generate outputs.

First, inputs can not always be clearly distinguished from outputs. As an example, knowledge generated by installing and using innovations (input) causes learning-by-doing and performance improvements (output) which leads to more knowledge generation (input). Consequently we distinguish directed efforts from outcomes rather than inputs from outputs, as our aim is to an unfolding time dimension rather than a specific causal x → y (see also Fig. 2).

Second, whereas discrete causal mechanisms can be isolated, innovation outputs and outcomes are contingent on system conditions as well as exogenous factors. As an example, R&D investments to generate knowledge causes patent filings, but this process is highly uncertain, dependent on the constellation of innovation actors involved, and responds to the wider intellectual property and trade environment.

Third, many innovation system processes are not observable, and can be measured only through proxy indicators often with scarce data. Multivariate quantitative analysis of innovation invariably emphasises R&D, patents, publications and prices as variables for which granular time-dependent databases are readily available. Publications like the Global Innovation Index provide additional country-level data on innovation actors, networks, institutions, policies, and funding, but such data are hard to construct for technology-specific analyses (Wilson and Kim, 2018).

For all these reasons, innovation systems analysis provides insight into specific causal mechanisms within a system which "demonstrates a substantial degree of contingency, heterogeneity, and path-dependence" (Little, 2015, p. 470).

2.3. Designing and managing innovation portfolios from a systemic perspective

As the ETIS framework shows, innovation systems comprise many processes which are more or less amenable to influence by policymakers seeking to 'direct' innovation efforts in response to market, structural and transformational failures (OECD, 2015; Wieczorek and Hekkert, 2012).

Structural and transformational failures in innovation systems provide a strong rationale for strategic intervention, beyond the need to correct for market failures which result in underinvestment in innovation due to its uncertain distant payoffs (Weber and Rohracher, 2012). Structural failures blocking successful innovation outcomes include: institutions creating uncertainty; weak knowledge exchange if interactions are limited; poor capabilities for accessing and learning from new knowledge (Wieczorek and Hekkert, 2012; Woolthuis et al., 2005). Transformational failures include: lack of shared vision and direction; weak market demand and signals from users; lack of policy coordination; lack of monitoring and policy learning (Weber and Rohracher, 2012).

Certain innovation system processes can - in principle - be *directly* managed by policymakers, subject to political and other constraints. Examples include allocation of public research, development & demonstration (RD&D) budgets and regulatory policy instruments. Policymakers have a relatively high degree of control over the relative emphasis placed on such processes within an innovation system. Other innovation system processes can only be *indirectly* shaped, facilitated or incentivised by policymakers but not directly managed. Examples include knowledge spillovers through trade and actor interaction through research collaborations. Policymakers can seek to stimulate (or restrict) such processes, but can not directly determine outcomes. Policymakers have a relatively low degree of control over the relative emphasis placed on such processes within an innovation system. Finally, policymakers can *systemically* influence innovation through strategies, policies, and measures designed to affect overall system conditions (OECD, 2015). Examples include intellectual property protection and training, education and skills development. These broader system conditions may in turn influence many different innovation system processes such as patenting propensity and skilled worker employment. Policymakers have a still lower degree of control over the relative emphasis placed on such processes within an innovation system.

In sum, innovation portfolios comprise not just multiple technologies, but also multiple innovation system processes which policymakers can direct towards targeted outcomes with greater or lesser degree of direct control. The upper panel [a] of Fig. 2 summarises these three axes of an innovation portfolio: across technologies (y-axis in Fig. 2); across innovation system processes (x-axis in Fig. 2); and across time from inputs to outputs and targeted outcomes (z-axis in Fig. 2).

In addition to this descriptive characterisation of the different dimensions to innovation portfolio design, historical analysis of relative success and failures in energy innovation systems supports certain normative criteria: balance, consistency and alignment (Grubler and Wilson, 2014b).

A *balanced* innovation portfolio is diversified across the range of technologies which can contribute to desired outcomes (Wilson et al., 2012). Diversification helps manage risks given that innovation outcomes are highly uncertain. In the absence of clearly-articulated objectives for portfolio composition, a simple benchmark test for portfolio *balance* is a similar emphasis or equal weighting across technology fields (Table 1). For example, one of the key visions of the EU is a diverse portfolio of low-carbon energy technologies for a sustainable green economy (EC, 2007).

A *consistent* innovation portfolio has diverse innovation system processes working in concert (Bergek et al., 2008; Grubler and Wilson, 2014a). Consistency implies a coordinated approach to directed innovation efforts and a policy mix responding to the needs of heterogeneous actors and interests (Kern and Howlett, 2009). For example, a high level of effort to mobilise financial resources in a clear and stable policy environment also requires emphasis on supporting innovation actors and their networks of interaction and knowledge exchange to ensure the necessary human capacity to absorb and effectively use resources. In the absence of technology-specific analysis on innovation system needs and enabling conditions, a simple benchmark test for portfolio *consistency* is a similar emphasis or equal weighting across innovation system processes for any given technology (Table 1).

An *aligned* energy innovation portfolio has inputs directed towards outputs and desired outcomes throughout the stages of the innovation lifecycle, from RD&D to market formation and diffusion. Misalignment creates long-term uncertainty and unclear signals to innovators, can delay or stagnate the development and diffusion of innovations, and can reinforce transitional difficulties in the 'valley of death' between demonstration and commercialisation (Hekkert et al., 2007; Weyant, 2011). A common example of misalignment is between policy efforts to improve energy efficiency (e.g., through performance standards) while simultaneously subsidising the price of retail fuels (Morrow et al., 2010). In the absence of a clearly-differentiated strategy for different technologies in the portfolio, a simple benchmark test for portfolio *alignment* is a similar emphasis or equal weighting on directed efforts and targeted outcomes for any given technology (Table 1).

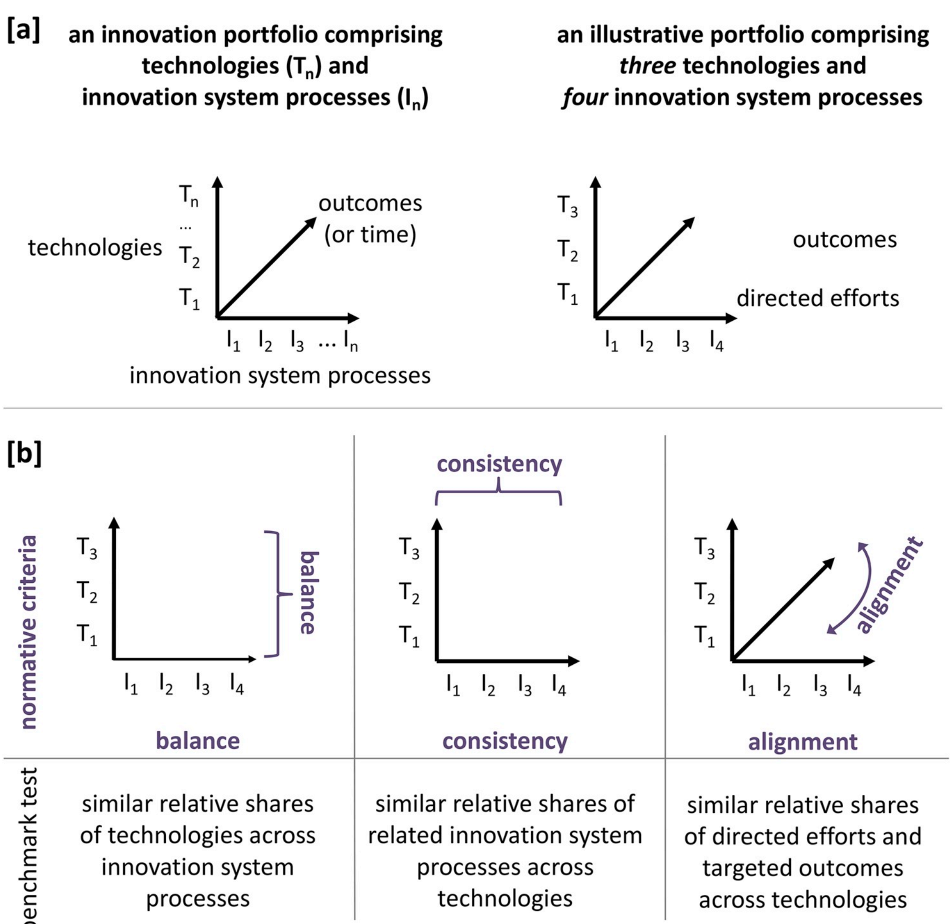

Fig. 2. Innovation portfolios from a systemic perspective. Notes: upper panel [a] illustrates an innovation portfolio comprising multiple technologies, innovation system processes, and time steps towards outcomes; lower panel [b] illustrates three normative design criteria - balance, consistency & alignment - and three simple benchmark tests for each criterion.

3. Methodology

3.1. Indicators

Innovation systems can be tracked and evaluated using indicators as descriptive proxy measures of key processes (IEA, 2011). To measure innovation system processes in the ETIS framework (Fig. 1), we reviewed relevant literature to identify potential indicators (Borup et al., 2008, 2013; Klitkou et al., 2012; Grubler and Wilson, 2014b; Cornell University et al., 2018; Truffer et al., 2012; Speirs et al., 2008; Park et al., 2016; Miremadi et al., 2016). We compiled a comprehensive set of > 100 possible indicators, and then applied two selection criteria: usefulness and availability. Usefulness means indicators should capture specific innovation processes in the ETIS framework, be clearly understandable, and be generalisable across technology fields. Availability means indicators should be measurable from available data sources, drawing either on existing databases or on secondary data sets which allow technology-specific analysis.

The resulting set of indicators as general descriptors of ETIS processes are shown in the left columns of Table 3. Full details of how each indicator is constructed are provided in Appendix A. Collectively these indicators provide a comprehensive account of the ETIS framework represented in Fig. 1. This set of indicators is generalisable to any energy innovation portfolio or technology, subject to data availability. While we cannot capture all of innovation system processes in the TIS, FIS, NIS literature, our indicators capture the main innovation system processes and so support systemic analysis. However, we acknowledge the difficulties caused by data availability and data collection. For example, some indicators in the literature are specific to one technology so cannot be generalised (e.g., capacity factors of power plants). Reliable cost data was also hard to find for all technologies in a standardised form.

3.2. The EU's SET plan

In this paper, we use the EU's SET Plan to demonstrate how the indicators can be used to analyse the design of energy innovation portfolios. The EU's Strategic Energy Technology (SET) Plan sets strategic priorities to support the European Commission's stated "*ambition to achieve … a fundamental transformation of Europe's energy system*" (EC, 2015b). Aligned with the EU's long-term climate, energy security, renewable energy, and energy efficiency goals, the EU's SET Plan was launched in 2008 to provide strategic planning and coordination of energy research and innovation activities within the EU involving a diverse range of innovation actors (Carvalho, 2012). The SET Plan was implemented through European Industrial Initiatives for technologies with near-term market impact, demonstration and commercialisation programmes (e.g., NER 300), monitoring and evaluation (e.g., SETIS), and longer-term research actions (including Horizon, 2020). The Strategic Energy Technologies Information System (SETIS) monitors progress and provides up-to-date information on the SET Plan (Corsatea et al., 2015). The SET Plan Steering Group is the central governance structure of the SET Plan, coordinating extensive stakeholder networks within each action (Joliff-Botrel, 2015). The SET Plan also articulates links to available EU funding mechanisms for energy research and innovation (EC, 2015b).

In 2015 the Commission proposed a revised SET Plan that was more targeted and used a whole systems approach to ensure better integration across sectors and technologies (EC, 2015b). As shown in Table 2, the revised SET Plan set out four priority areas (renewable energy, smart grid, energy efficiency, and sustainable transport) and two additional areas (carbon capture and storage, and nuclear power). These six areas were articulated in a set of ten actions. In this paper, we refer to the six priority and additional areas as 'technology fields' to denote groupings of inter-related technologies in a common field of application.

We choose the EU SET Plan because it is a major pan-national energy innovation portfolio which has been running for over a decade. Unlike other energy innovation portfolios which focus on R&D (such as ARPA-E in the US, or Mission Innovation globally), the SET Plan spans a wide range of innovation processes. Additionally, the SET Plan went through a major revision in 2015 with the specific aim of making it more integrated and systemic (EC, 2015b).

3.3. Data for the EU SET plan

We collected data from diverse sources to measure each of our indicators for each of the six technology fields of the EU's SET Plan. The metrics, as well as the main data source and level of disaggregation (country-level aggregated up to the EU, or EU-level), are shown in the right columns of Table 3. Full details of the data used, database query codes, and other data search protocols are provided in Appendix B. We used data for 2015 as the most recent year for which most data were available. This cross-sectional approach is consistent with our aim of demonstrating how the design of energy innovation portfolios can be evaluated from a systemic perspective.

Following the approach used in Wilson et al. (2012), we collected technology-specific data for each indicator, distinguishing data measuring innovation system processes within the six SET Plan technology fields (e.g., related to renewable energy) from data measuring activity outside the SET Plan portfolio (e.g., liquified natural gas). For data related to the SET Plan, we calculated the relative proportion associated with each of the six technology fields.

3.4. Simple benchmark tests of portfolio design criteria

As noted above, we propose simple benchmark tests for the three normative criteria of balance, consistency and alignment. Each test examines the relative shares of either technologies or innovation system processes in the portfolio, and uses an equally-weighted distribution or

Table 2
Technology Portfolio of the EU's SET Plan. Source: (EC, 2015a). Note: In this paper, we use the term 'technology fields' to refer to the SET Plan's 'priority areas' and 'additional areas'.

SET Plan	Technology Portfolio	Technology-Specific Actions & Targets
priority areas	Renewable Energy (RE)	Performant renewable technologies integrated into the energy system Reduce costs of technologies
	Smart Grid (SG)	New smart technologies & services for consumers Resilience, security & smartness of energy system
	Energy Efficiency (EE)	New materials & technologies for buildings Energy efficiency for industry
	Sustainable Transport (ST)	Competitiveness in batteries & e-mobility Renewable fuels
additional areas	Carbon Capture and Storage (CCS)	Application of carbon capture with storage or use
	Nuclear Power (NP)[a]	High level of safety in nuclear reactors & fuel cycles

[a] The SET Plan emphasises nuclear safety which we interpret broadly to include all nuclear fission-related research and innovation activity.

Table 3
Technology-specific indicators of innovation system processes.

Generalisable indicators		*Application of indicators to the EU SET Plan*		
Innovation system processes in the ETIS framework	Technology-specific indicators of innovation system processes	[Indicator metrics] for EU SET Plan	Level of data	Main data source
KNOWLEDGE				
Generation	Public energy RD&D expenditure	[€m]	national	1
	Demonstration budgets	[€m]	national	1
Codification	Publications	[# articles]	national	2
	Citation-weighted publication counts	[# articles]	national	2
	Patents	[# patents]	national	3
	Citation-weighted patent counts	[# patents]	national	3
International Flows	Publication co-authorships (intra-extra)*	[index] of co-authorships between EU and non-EU actors	national	2
	Patent co-inventions (intra-extra)*	[index] of co-inventions between EU and non-EU actors	national	3
Spillover	Energy technology imports	[€m]	national	4
Depreciation	Volatility in energy RD&D expenditure	[coefficient of variation]	national	1
RESOURCES & POLICIES				
Mobilisation of Finances	Public energy RD&D expenditure as % of GDP	[%]	national	1
	Top 100 clean-tech funds	[€m]	EU	8
Mobilisation of Innovators	Patent activity as % of total patents	[%]	national	3
Policy Density	Policy density (innovation) Policy density (regulatory) Policy density (market-based)	[# instruments] of innovation, regulatory and market-based policies	national	6
Policy Durability	Policy durability (innovation) Policy durability (regulatory) Policy durability (market-based)	[average of cumulative # instruments] of innovation, regulatory and market-based policies	national	6
Policy Mix	Diversity of policy instruments	[Shannon index]	national	6
Policy Stability	Stability of policy instruments	[average of cumulative years of all instruments, adjusted by revisions]	national	6
Regulatory Capture	Public RD&D expenditure on fossil fuels	[€m]	national	1
ACTORS & NETWORKS				
Heterogeneity	Diversity of types of organisation in publication activity	[index]	national	2
	Diversity of types of organisation in patenting activity	[index]	national	3
	Diversity of types of organisation in research collaborations	[Shannon index] for European Energy Research Alliance	national & EU	9
Exchange & Interaction	Publication co-authorships (intra-intra)*	[index] of co-authorships between different EU actors	national	2
	Patent co-inventions (intra-intra)*	[index] of co-inventions between different EU actors	national	3
	Research collaborations (intra-intra)*	[# of activities] involving different EU actors in European Energy Research Alliance	national & EU	9
Shared Expectations	Policy target density	[# instruments] of targets, roadmaps, action plans	national	6
	Policy target durability	[average of cumulative # instruments] of targets, roadmaps, action plans	national	6
Legacy of Failure	Decline in interest following a failure	[exponent of decline function fitted to Google search frequency]	global	7
USERS & MARKETS				
Learning	Learning-by-doing	[learning rate, % cost reduction per doubling of cumulative experience]	global	5
Potential Market Size	Potential market size	[€m] estimated as total # of physical units * € cost per unit	national	5
Market Share	Market share	[%] estimated as actual market size/potential market size	national	5

Table notes.
* Intra and extra refer to patents filed or publications authored from within the innovation region being analysed (intra) or from other regions (extra), hence international knowledge flows include both intra and extra, whereas exchange and interaction include only intra.
Main data sources (see Appendices A & B for full details).
1 International Energy Agency (IEA) energy RD&D statistics [http://wds.iea.org/WDS/Common/Login/login.aspx].
2 Web of Science [https://login.webofknowledge.com/].
3 United States Patent and Trademark Office (USPTO) PatentsViews database [http://www.patentsview.org/web/].
4 Eurostat EU trade statistics [http://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database].
5 Secondary data from peer-reviewed studies.
6 IEA Addressing Climate Change policy database [https://www.iea.org/policiesandmeasures/climatechange/].
7 Google Trends [https://trends.google.com/trends/?geo=].
8 Global Cleantech 100 [https://www.cleantech.com/].
9 European Energy Research Alliance (EERA) [https://www.eera-set.eu/].

similar relative shares as the benchmark or reference point (Table 1). It is important to emphasise that these simple tests are not definitive assessments of portfolio design, but rather serve to draw portfolio managers' attention to areas of possible imbalance, inconsistency, or misalignment in their innovation portfolios. In other words our benchmark tests have a diagnostic rather than an evaluative function. As we discuss further below, there may be good reasons or arguments as to why portfolios perform poorly on these simple tests.

To evaluate balance in the EU's SET Plan, we use stacked bar charts to show the relative share of each indicator across the six technology fields. Balance would see an equally-weighted distribution or similar relative shares for the technology fields on each indicator measuring an innovation system process. This would mean a similar emphasis on each technology in the SET Plan portfolio.

To evaluate consistency, we use box-whisker plots to show the variability in the relative shares of all the indicators within each of the four ETIS dimensions for a given technology field. Consistency would see an equally-weighted distribution or similar relative shares for the innovation system processes, resulting in low variability. This would mean a similar emphasis on each innovation system process in the SET Plan portfolio.

To evaluate alignment, we follow the approach used to evaluate balance. However, in this case, we use stacked bar charts to show the average relative share of indicators in two groups of innovation system process - late stage and market outcomes - across the six technology fields. 'Alignment' would see an equally-weighted distribution or similar average relative shares for the technology fields in each group. This would mean a similar emphasis on late stage directed innovation efforts and targeted market outcomes in the SET Plan portfolio. The two outcomes we analyse are learning and market share. Learning measures cost reductions (or performance improvements) as a function of cumulative deployment experience including knowlege feedback from users. Market share measures the capacity of the new technology to displace incumbents' market dominance.

4. Findings

4.1. Balance across six technology fields in the EU's SET plan portfolio

Fig. 3 shows whether the relative emphasis on each of the six technology fields in the SET Plan portfolio is balanced across the full set of innovation system processes, grouped by the four dimensions of the ETIS framework shown in Fig. 1. Similar relative shares indicate balance in our simple benchmark test. Clear examples in Fig. 3 include knowledge generation by public energy RD&D expenditure and knowledge depreciation measured by volatility in RD&D expenditure. Policy support (density and durability) and policy mix (diversity and stability) are also fairly evenly distributed between the four priority areas of the SET Plan (i.e., excluding nuclear power and CCS). This is an interesting indication of policymaking employing a diverse mix of instruments in all technology fields. These are broadly expected results as policy instruments and RD&D expenditure are directly manageable by policymakers. Innovation system processes measuring actors and networks active within the EU energy innovation system are also mostly balanced across the six technology fields. A core feature of the SET Plan is its bringing together of stakeholders to plan and cooperate around strategic research objectives and technology roadmaps.

Markedly different relative shares indicate imbalance. Clear

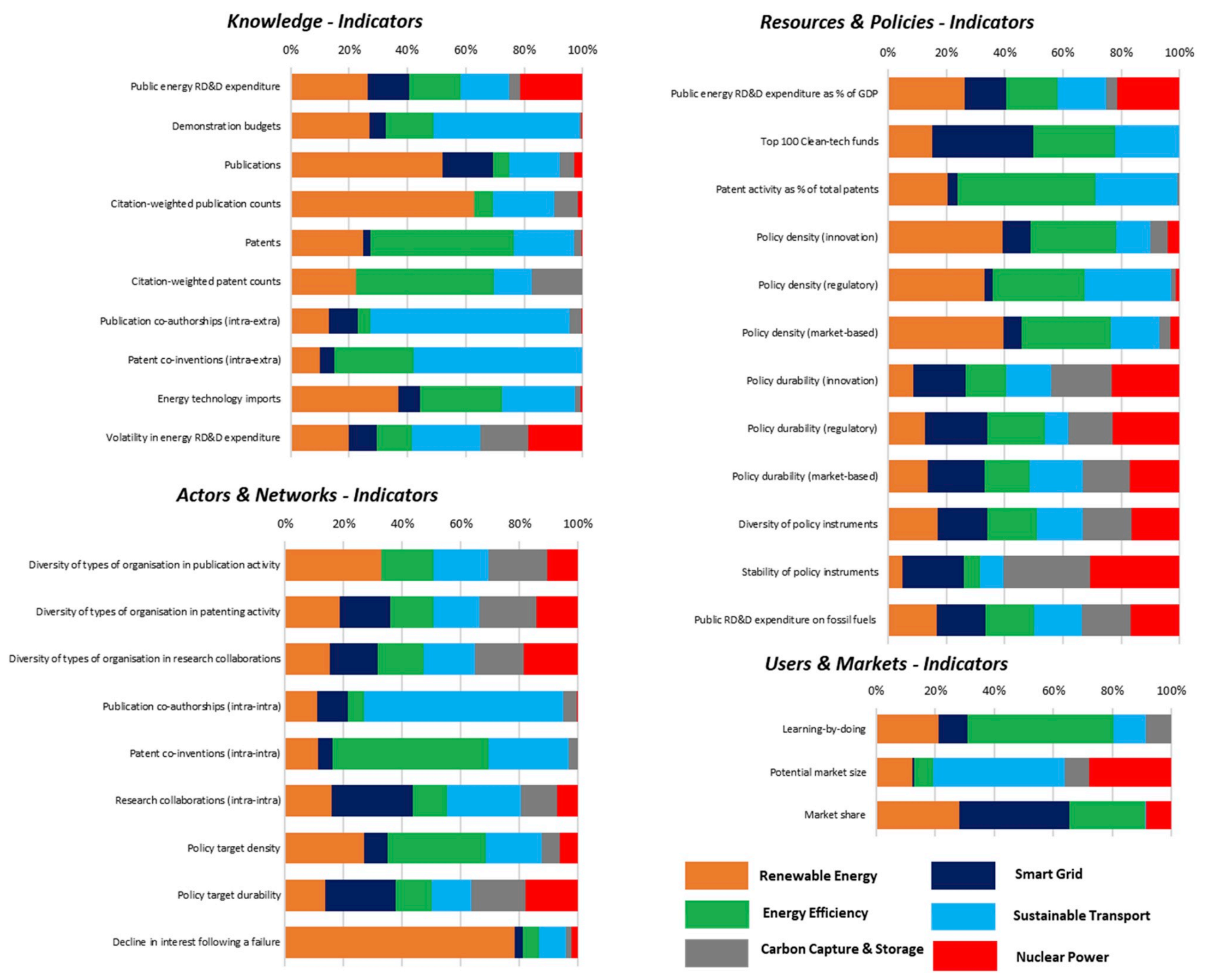

Fig. 3. Relative shares of six technology fields for each innovation system process in the EU SET Plan using 2015 data.

examples in Fig. 3 include knowledge generation measured by demonstration budgets for which sustainable transport accounts for 50% of total activity and renewable energy a further 27%. This is attributable to a recent increase in funding for demonstration activity in the sustainable transport area (Zubaryeva et al., 2015). Knowledge codification measured by patents is also imbalanced, with a high relative share of energy efficiency patent applications. This is likely due to the stable market environment regulated by efficiency standards and backed by long-term targets which incentivise innovators to capture the large remaining potential for efficiency gains (Cullen and Allwood, 2010). Knowledge codification measured by publications is also imbalanced, but in this case skewed towards renewable energy. One interpretation is that the integration of renewable energy into power systems poses challenges for a wide range of research communities from engineering and material science to economics and planning, with this diversity stimulating publication activity. These too are not unsurprising results as patents and publications are not directly manageable by policymakers.

Intra-extra EU collaboration on patents and publications as a measure of international knowledge flows are also strongly imbalanced with sustainable transport accounting for about 60% of the total. One interpretation is that the global automotive industry's concentrated market structure, dominated by Japan and the United States, provides strong incentives for EU innovators to cooperate with non-EU actors. Knowledge spillovers measured by the value of energy technology imports into the EU are also strongly imbalanced with renewable energy accounting for about 30% of the total. This finding is in line with a recent study showing that EU has a negative trade balance in solar photovoltaics (Pasimeni, 2017).

The users & markets dimension of the ETIS framework is characterised by only three indicators in Fig. 3. However, each shows a distinctive imbalance. Learning-by-doing is dominated by energy efficiency, which is broadly expected as it is the most mature and sustained of the SET Plan technology fields with more substantial cumulative experience. Potential market size is dominated by sustainable transport as the vehicle market in € terms is large, with some modelling studies already showing the potential for fully electrifying the vehicle fleet in the medium-to-long term (Connolly et al., 2016). Actual market share is fairly evenly distributed across four technology fields, with sustainable transport and CCS notable by their lack of deployment track record to-date. Despite their market maturity, the current market shares of energy efficiency, renewable energy and nuclear power remain supported by late stage innovation system processes including regulatory and market-based policy instruments.

These areas of imbalance shown clearly in Fig. 3 do not inherently cause for concern. They may have good reason and be defensible. Portfolio managers may also be limited in their capacity to redress the imbalance. The purpose of our benchmark test applied here is to identify areas of imbalance which *potentially* require further attention should they compromise the risk-diversification characteristics of the SET Plan technology portfolio.

In sum, our analysis of balance defined as similar weighting across the six technology fields in the EU SET Plan portfolio shows:

- balance in RD&D expenditures and public policy
- imbalance in knowledge codification, flows and spillover (towards renewable energy, energy efficiency, or sustainable transport depending on the innovation system process)
- more balance for innovation system processes for which policymakers have more direct control or management capacity
- less balance in innovation system processes for which policymakers have less direct control and which are subject to more intervening factors or conditions (e.g., market structure, stability of innovation environment)

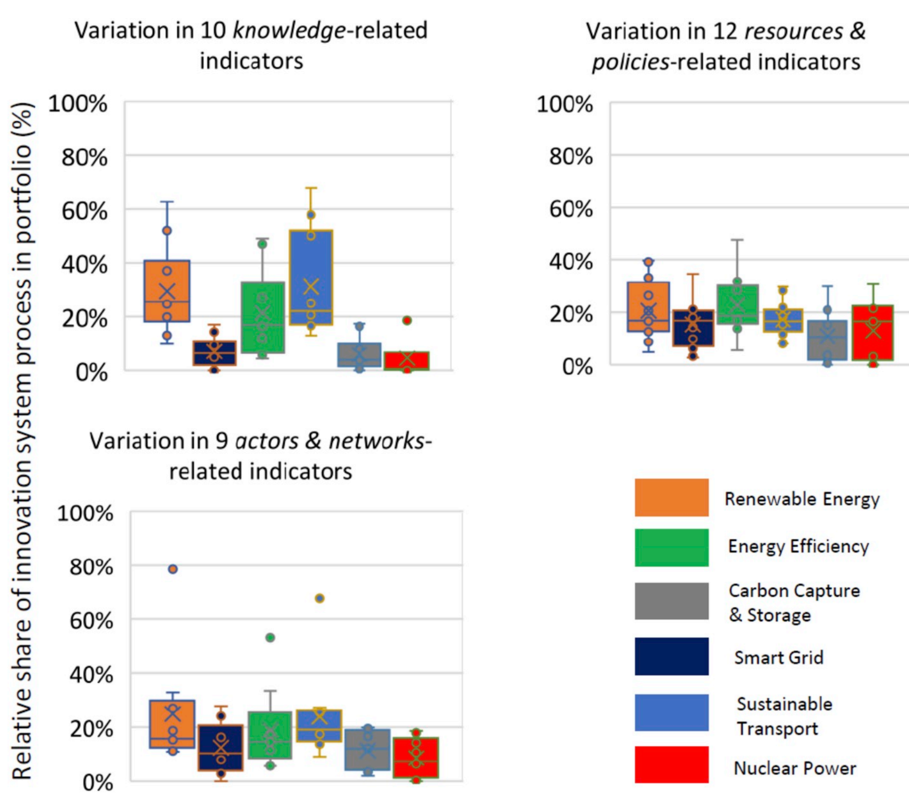

Fig. 4. Relative shares of innovation system processes in each ETIS dimension for the six technology fields in the EU SET Plan using 2015 data. Note: o indicate data points with X as mean, median; box shows second & third quartiles separated by line; whiskers show first & fourth quartiles.

4.2. Consistency across innovation system processes in the EU's SET plan portfolio

Fig. 4 shows whether the relative emphasis on innovation system processes within each of the four ETIS dimensions is consistent for the six technology fields in the SET Plan portfolio. Low variability in relative shares indicates consistency based on our simple benchmark test. As shown in Fig. 4, innovation system processes relating to resources & policies and to actors & networks are noticeably more consistent (lower variability) than those relating to knowledge (Innovation system processes relating to users & markets are not shown due to the small number of indicators).

Inconsistency between knowledge-related innovation system processes is clearest for renewable energy, energy efficiency and sustainable transport. In these technology fields, some knowledge-related processes have dominant shares in the SET Plan portfolio, whereas others have only weak shares. This can be further examined by comparing the specific processes which provide the upper and low bound in each case.

Inconsistency between knowledge-related innovation system processes for renewable energy ranges from citation-weighted publication counts (upper bound, 63% relative share) to patent co-inventions between EU and non-EU actors (lower bound, 10% relative share). This patent co-inventions indicator is a measure of international knowlege flows. One explanation why it may have a low relative share in the SET Plan portfolio is that the EU is a firstmover particularly with respect to renewables deployment. Moreover innovation activity for renewable energy may be concentrated in regions with available resource or with energy security concerns. Indirect evidence for this explanation is provided by the high volume of single authors and single inventors in renewable energy compared to the other technology fields.

Inconsistency between knowledge-related innovation system processes for energy efficiency ranges from patents (upper bound, 49% relative share) to publication co-authorship between EU and non-EU actors (lower bound, 4% relative share). As noted earlier, this high relative share of patenting activity is consistent with clear expectations for returns on innovation investments in energy efficiency due to stable regulatory policy environments including the EU's Energy Efficiency Directive and large market potentials still available. Conversely, the low relative share of international knowledge flows measured by publication co-authorships may be explained by the EU's strong internal competence in this field.

Inconsistency between knowledge-related innovation system processes for sustainable transport ranges from publication co-authorship between EU and non-EU actors (upper bound, 68% relative share) to citation-weighted patent counts (lower bound, 13% relative share). As noted earlier, this high relative share of international knowledge flows may be linked to the EU's need to link with innovation centres on vehicle manufacturing in the US, Japan and elsewhere. The low relative share of citation-weighted patents may reflect the relative immaturity of the electric vehicle field compared to renewables and energy efficiency in which successful patents with higher citations are more established.

A more general explanation for inconsistency within any given ETIS dimension is that it's the result of early stage and late stage innovation system processes being combined. We use 'late stage' to mean directly related to or associated with the materialisation of technology in a market context: e.g., investment in an operational facility. Materialisation is a key late-stage function of innovation systems (Hekkert et al., 2007). Conversely, we use 'early stage' to mean directly related to or associated with pre-commercial or niche technology development: e.g., patents or publications describing new applications of knowledge. Early stage processes are more closely associated with technology development and testing, and technology-push policies such as RD&D incentives. Late stage innovation system processes are more closely associated with market formation and deployment, and market-pull policies such as purchase subsidies.

This is a crude but useful distinction as more mature technologies can capture returns to scale and so benefit from cost reductions (from learning and scale economies) and regulatory alignment. This positive feedback loop creates path dependence as technologies which initially outcompete rivals become entrenched over time.

To test this explanation, we distinguish all innovation system processes as being either early stage or late stage. We treat all RD&D, patent, publication and innovation policy-related processes as early stage. Conversely, we characterise all market-based policy, regulatory

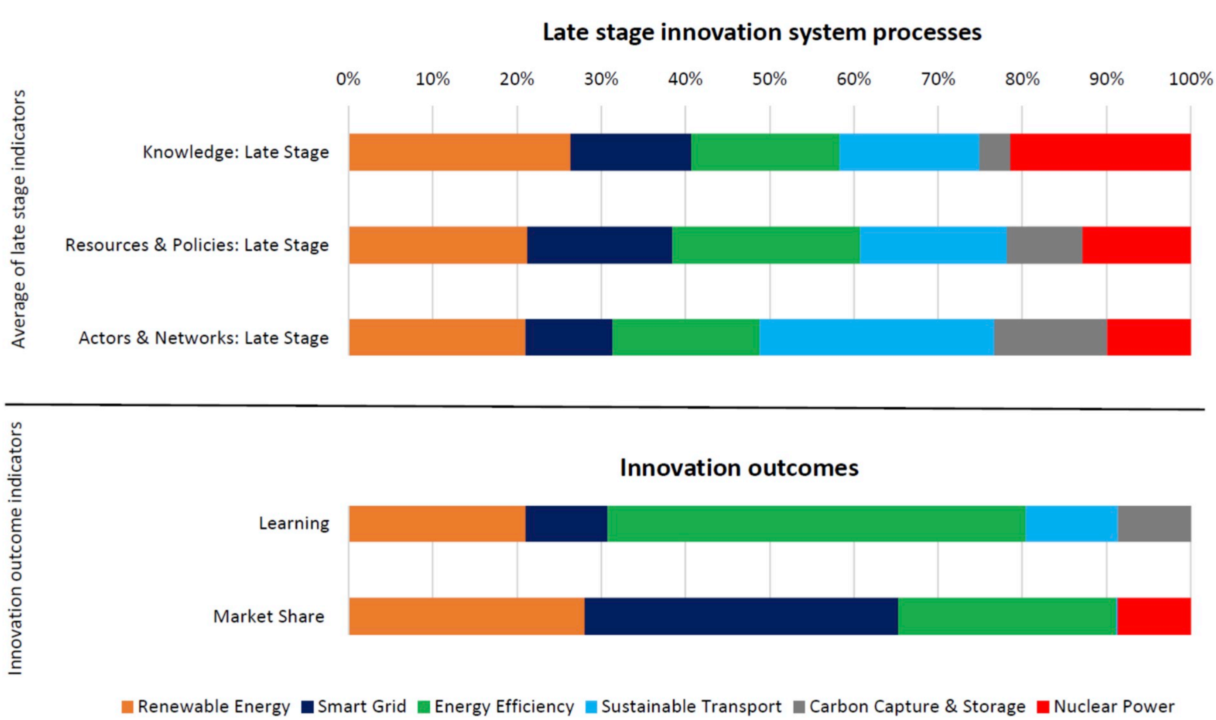

Fig. 5. Relative share of six technology fields between indicators of late stage innovation system processes and two outcomes indicators relating to users & markets.

policy, learning, market size, and trade-related processes as late stage. We characterise research collaborations and strategic policies (e.g., targets, roadmaps) as both early and late stage as they span the full innovation lifecycle. We then reanalyse inconsistency for early and late stage innovation system processes separately. However, we find that this does not explain inconsistency in any of the ETIS dimensions, so we reject this explanation (see Appendix C for full details). However, it should be noted that as we characterised most knowledge-related processes as early stage, this is unlikely to help explain the main inconsistencies observed in Fig. 4.

In sum, our analysis of consistency defined as similar weighting across innovation system processes in the EU SET Plan portfolio shows:

- consistency (similar relative emphasis) for innovation system processes relating to resources & policies and actors & networks across all techology fields
- inconsistency (varying relative emphasis) for innovation system processes relating to knowledge for renewable energy, energy efficiency, and sustainable transport.
- inconsistency is not explained by differing emphases on early and late stage innovation system processes

4.3. Alignment between late-stage innovation system processes and market outcomes in the EU's SET plan portfolio

Fig. 5 shows whether the relative emphases on six technology fields averaged across late stage innovation system processes in three dimensions of the ETIS framework are aligned with learning and market share as desirable innovation outcomes. Similar relative shares across late stage and outcome indicators indicate alignment, based on our simple benchmark test. As shown in Fig. 5, the weighting of emphasis across the EU's SET Plan technology portfolio is evenly distributed for late stage innovation system processes, although knowledge-related processs (energy technology imports) have negligible shares for CCS and nuclear power. Fig. 5 also shows that the relative shares are fairly well aligned between late stage innovation system processes and market outcomes, with two exceptions.

First, learning is skewed towards energy efficiency which, as we noted earlier, is likely associated with the mature and durable policy environment for energy efficiency improvements coupled with the large and relatively low-cost market opportunities remaining for deployment. Second, market share is low or missing for sustainable transport and CCS, but for different reasons. Market incentives for CCS are too weak to support deployment, whereas full or partially electric vehicles are deploying slowly at the margins due to their high relative cost, consumer resistance to different service attributes (such as range), and other socio-technical barriers (such as recharging availability).

The high relative share of energy efficiency on the learning indicator points to the need for more supportive learning conditions in other parts of the SET Plan portfolio, particularly smart grids. The regulated smart meter rollout is effective in driving market share but may not create dynamic incentives for technology improvement. CCS and nuclear power have low relative shares, but learning is more problematic due to their large unit sizes and costs, high barriers to entry, bespoke designs and construction, all of which undermine the repetitive experience necessary for learning-by-doing.

The low relative shares of sustainable transport and CCS on the market share indicator point to an inherent limitation of comparing relative shares in a technology portfolio rather than absolute measures of market uptake (MW, €, €/MW). A given absolute amount of deployment may be high in some fields but low in others. Low relative shares may be due not just to weak innovation system functioning but also to strong performance elsewhere in the portfolio. In the case of CCS, the negligible market share is despite a high potential market size and a mature technology field with applications in enhanced oil recovery dating back decades. The lack of adequate deployment incentives for CCS points to another limitation with policy-related indicators which don't take into account stringency, as the presence or absence of supportive policy is distinct from the extent of support. However, it's also notable that knowledge-related innovation system processes for CCS have generally quite low relative shares in the EU's SET Plan portfolio (Fig. 3) pointing to a more systemic weakness in directed innovation efforts to support CCS development.

In sum, our analysis of alignment across innovation system processes for each of the six technology fields in the EU SET Plan portfolio shows:

- broad alignment (similar relative emphasis) between late stage innovation system processes and learning across all techology fields, with the exception of a high relative share of energy efficiency on learning
- broad alignment (similar relative emphasis) between late stage innovation system processes and market share across all technology fields, with the exception of low relative shares of sustainable transport and CCS on market share
- misalignment is explained by differences in the adoption environments between technology fields: mature and stable for energy efficiency; emerging and very large in size for sustainable transport; concentrated and weakly incentivised for CCS
- misalignment also points to the weaker relevance of innovation system processes for mature technologies deploying in market environments

5. Conclusions and policy implications

Balance, consistency and alignment are all normative criteria for the design of innovation portfolios comprising both multiple technologies and a range of policy interventions through which portfolio managers can exert direct, indirect, or systemic influence over diverse innovation system processes (Fig. 2). All three criteria have a robust basis in the literature and a strong rationale: balance between technologies to diversify risk (Grubler and Riahi, 2010); consistency between innovation system processes to coordinate inter-dependent activity throughout the innovation system (Bergek et al., 2008; Grubler and Wilson, 2014a); alignment between directed innovation efforts and outcomes to ensure innovation systems are oriented towards desired goals (Wilson et al., 2012).

How these criteria should be analysed for any given energy innovation portfolio is less definitive. Portfolio managers may provide transparent rationales for intended portfolio composition, setting *ex ante* conditions for the relative emphasis placed on certain technologies or innovation system processes. Independent analysis may recommend optimal portfolio designs using a range of tools to support decision-making under uncertainty (Anadon et al., 2017).

In our analysis of the EU's SET Plan porfolio, we apply simple benchmark tests of 'similar relative shares' to provide an initial indication of where the portfolio may be imbalanced, inconsistent, or misaligned (Table 1). We emphasise again that these simple tests using relative equal shares as the benchmark serve an initial diagnostic function and should not be overinterpreted. As an example, learning rates would be expected to vary across technologies with different characteristics and maturities, and so non-equal relative shares on this one indicator would not inherently mean an energy innovation portfolio was imbalanced and, by implication, poorly designed. Rather the benchmark test would raise non-equal relative shares as a diagnostic flag warranting further attention. Portfolio managers would therefore seek explicit and clearly justifiable reasons for why learning rates varied strongly across the portfolio. More broadly, our benchmark test for consistency applies across the full spectrum of innovation processes. So in the case of learning rates, the benchmark test would also identify portfolios in which a technology was performing relatively well in terms of learning-related cost reductions, but relatively poorly in terms of other conditions necessary for sustained deployment. This again would raise the area as one warranting further attention by portfolio managers.

In the previous sections, we offered an explanation or interpretation of most such cases in which the benchmark tests point to areas of potential imbalance, inconsistency, or misalignment. Here we focus on those cases which do not have immediately apparent justifications as being areas warranting attention by SET Plan portfolio managers.

Applying our simple benchmark test for balance, we found evidence that the SET Plan portfolio is broadly balanced in its technological emphasis for innovation system processes over which it has direct managerial competence (e.g., public energy RD&D investments). Areas of potential imbalance include knowledge codification, flows and spillovers over which portfolio managers have only indirect influence. In 2015, these were variously skewed towards renewable energy, energy efficiency or sustainable transport. Portfolio managers could use a range of approaches for redressing imbalance in these areas including: introducing tied conditions to research funding (e.g., on requirements for scientific publication); strengthening basic research with higher propensity to generate influential intellectual property (e.g., through ERC programmes); targeting research funding to support single actor research projects with fewer constraints on intellectual property protection (e.g., through Horizon, 2020 programmes); or support for public-private research consortia with higher propensity to engage in open knowlege exchange (e.g., through informal stakeholder networks and formal research frameworks such as the European Industrial Initiatives).

Applying our simple benchmark test for consistency, we found evidence that the SET Plan portfolio is broadly consistent in terms of innovation system processes working in concert in each of the six technology fields, spanning both early state and late stage processes. Areas of potential inconsistency include a skewed emphasis among knowledge-related innovation system processes towards influential (citation-weighted) patents in renewable energy, towards patents in energy efficiency, and towards publication co-authorships in sustainable transport. In each case, portfolio managers can not directly boost activity in under-performing processes to improve consistency. However, there a range of approaches available for stimulating knowledge codification, flows and spillovers including those suggested above in relation to imbalance, as well as stronger incentives for active stakeholder participation in roadmap development.

Applying our simple benchmark test for alignment, we found evidence that late stage innovation processes in the SET Plan portfolio are broadly aligned with learning and market share as targeted innovation outcomes. Areas of potential misalignment include a weak relative emphasis on learning for smart grids and nuclear power, and a weak relative emphasis on market share for sustainable transport and CCS. Nuclear and CCS are exceptional in being large, complex, centralised technologies with relatively closed innovation systems in terms of numbers of actors, actor heterogeneity, and incumbency. EU-level coordination and direction of innovation in these technology fields matches these scale characteristics, but high costs, low funding for demonstration, low and uncertain price support combine to provide inadequate market deployment incentives for innovators (Åhman et al., 2018). Low market share for sustainable transport is the result of relatively slow change at the margins (new vehicle sales) being absorbed into a large stock (all vehicles), reinforcing the importance of strong market-pull incentives in the form of purchase subsidies, differential tax regimes (e.g., feebates to discourage fossil-fuelled vehicles and encourage non-polluting alternatives), and charging or alternative-fuel vehicle charging or refuelling infrastructures (McCollum et al., 2018). Low learning for smart grids is the likely result of regulated smart meter rollout programmes failing to provide dynamic incentives for technology improvement. As with imbalance and inconsistency, these areas of potential misalignment invite redress by SET Plan portfolio managers.

This paper provides a systemic perspective on innovation portfolios using a diverse set of newly-constructed indicators which are applicable to specific energy technologies. Our approach provides a valuable analytical perspective on the design of effective policy environments to stimulate innovation activity that is critical for meeting ambitious energy system transformation goals. This paper is a first effort to bring a wide range of innovation system processes into the realm of comparative, quantitative analysis using a standardised and generalisable set of indicators.

We applied these indicators to analyse three design criteria for innovation portfolios: balance, consistency, alignment. We propose simple benchmark tests for each of these criteria, recognising that in specific cases, portfolio managers have defined robust and transparent conditions for technological diversity (balance), directed innovation efforts (consistency), and targeted outcomes (alignment). Using data for 2015 on the six technology fields in the EU's SET Plan, we show how our approach, criteria and tests can help identify potential areas of concern within the design of current innovation portfolios, inviting further attention from portfolio managers.

Our main findings on the EU's SET Plan portfolio are:

- the SET Plan portfolio is broadly balanced across technologies in terms of RD&D expenditures and public policy instruments, but shows imbalance in knowledge codification, flows and spillover over which portfolio managers do not have direct control
- the SET Plan portfolio is broadly consistent across innovation system processes relating to policies and actors, but shows inconsistency in knowledge-related processes which can not be explained by differences between emerging and more mature technologies
- the SET Plan portfolio is broadly aligned between late stage innovation system processes and market outcomes, but shows imbalance in learning and market share in particular technology fields

In this paper we have applied our benchmark tests for balance, consistency and alignment using historical data for a standardised set of technology-specific indicators. These same indicators could potentially be used to track progress over time in the design of innovation portfolios, just as the annual Global Innovation Index reports track progress in national innovation systems (Cornell University et al., 2018). The general diagnostic nature of the benchmark tests, coupled with uncertainties and contingencies in the energy innovation system, mean indicators for tracking progress should not be overinterpreted (see above). However, a portfolio which was becoming less and less balanced, consistent or aligned over time should raise the attention of portfolio managers to examine reasons why.

We also recognise important limitations with our approach which warrant further research and development. First, research on energy technology innovation indicators provides useful insights on availability and appropriate use (Borup et al., 2013; Klitkou et al., 2012; Hu et al., 2018), but does not systematically and apply a comprehensive set of indicators to compare across technologies. We propose our indicator framework as being generalisable across countries and technology fields (Table 3) but only demonstrate it for six technology fields in an EU context. Its applicability in other contexts needs further data collection efforts and testing.

Second, we demonstrated the applicability of our indicators using only a static cross-sectional perspective. Dynamic time-series analysis of the indicators is necessary for teasing out cause and effect relationships between innovation system processes including targeted outcomes (e.g., successful diffusion). Further research is needed to test time-dependent empirical relationships between innovation system processes. We have applied our benchmark tests for balance, consistency and alignment using historical data for a standardised set of technology-specific indicators. These same indicators could potentially be used to track progress over time in the design of innovation portfolios, just as the annual Global Innovation Index reports track progress in national innovation systems (Cornell University et al., 2018). The general diagnostic nature of the benchmark tests, coupled with uncertainties and contingencies in the energy innovation system, mean indicators for tracking progress should not be overinterpreted. However, a portfolio which was becoming less and less balanced, consistent or aligned over time over time should raise the attention of portfolio managers to examine reasons why.

Third, we used data describing technology-specific innovation system processes at the EU level. These take place within the context of economy-wide conditions (e.g., education, training, trade) which also need to be taken into account. Similarly, data describing member state-level innovation activity within the EU may reveal balance or imbalance at the national level, and the extent to which there is specialisation or harmonisation between the member states in terms of their contribution to SET Plan objectives.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.110942.

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