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Marginalization of end-use technologies in energy innovation for climate protection

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Mitigating climate change requires directed innovation efforts to develop and deploy energy technologies. Innovation activities are directed towards the outcome of climate protection by public institutions, policies and resources that in turn shape market behaviour. We analyse diverse indicators of activity throughout the innovation system to assess these efforts. We find efficient end-use technologies contribute large potential emission reductions and provide higher social returns on investment than energy-supply technologies. Yet public institutions, policies and financial resources pervasively privilege energy-supply technologies. Directed innovation efforts are strikingly misaligned with the needs of an emissions-constrained world. Significantly greater effort is needed to develop the full potential of efficient end-use technologies.

A recent review of US energy research and development identified a persistent under-investment in building, industrial and vehicle end-use efficiency compared with investment in a clean electricity supply[1]. This emphasis on innovation of energy-supply technologies is not peculiar to the US. The EU and the major developing countries, as well as the US, allocate around two thirds of public R&D budgets to energy-supply technologies[1–3].

Directed innovation efforts for climate change mitigation are not limited to public R&D investments. They involve broader processes of knowledge generation and exchange; are guided by strategic plans, technology roadmaps, and research collaborations; are dependent on leveraged private sector resources; and they are reinforced by experiences with technologies once commercialized. Directed innovation efforts thus permeate the entire system of innovation for energy technologies.

The aim of this Perspective is to assess the balance between energy supply and end-use technologies for directed innovation efforts in response to the challenge of climate change mitigation. First, we develop an analytical framework that integrates the key elements of the innovation system. Second, we apply this analytical framework to energy technologies using a broad set of indicators that characterize a diverse range of innovation processes. In particular, we assess whether inputs into the innovation system are aligned with observed outputs. We also consider required innovation outcomes in an emissions-constrained world, drawing on large-scale modelling studies that find efficient end-use technologies may contribute the majority of cumulative emission reductions to 2100[4]. Third, we offer a viewpoint on the reasons for our central empirical finding: energy end-use technologies are pervasively marginalized in directed innovation efforts.

The distinction between energy-supply and end-use technologies is widely used in energy systems analysis, management and policy[5]. Energy-supply technologies are used to extract, process, transport and convert energy resources into a form useful to end-users. The emphasis of innovation efforts for reducing emissions from the energy supply is to develop and deploy low or zero carbon-supply options[6–8]. End-use technologies are used to convert energy into a useful final service like heating, mobility or communication. The emphasis of innovation efforts for reducing emissions in end-use is twofold: to improve the energy efficiency of devices and applications; and to substitute for energy-intensive forms of service provision[9,10]. Fuel-efficient vehicles and mode-shifting from car to public transport are examples, respectively. We use this simple dichotomy between energy-supply and end-use technologies to characterize and assess directed innovation efforts.

Key elements of the innovation system

A comprehensive review of the literature on energy innovation was recently completed as part of the *Global Energy Assessment*[11], and concluded that a systemic perspective on innovation was necessary to account for the complex interdependencies between different innovation stages, processes and drivers (Fig. 1).

The review also found that innovation analyses and policies are often partial, focusing only on selected elements of the innovation system. For analyses, this can mean biased or decontextualized findings, and for policies guiding broader innovation efforts, partiality can lead to unintended or adverse consequences.

The early years of the wind-power industry in the 1970s and 80s is a useful case in point. In countries like Sweden, the Netherlands and Germany, public R&D programmes pushed for step-change advances in large-scale, high-efficiency turbines[12,13], but limited attention was paid to stimulating market demand, and the energy utilities proved reluctant adopters of these unproven innovations[14]. In Denmark, by comparison, R&D programmes emphasized smaller-scale reliable turbines whose commercial adoption was supported by investment and production subsidies. Developers and landowners became actively engaged in the process of commercial deployment alongside the manufacturers[15]. Institutions like the national testing and certification station at Risø provided a means of exchanging knowledge and user experiences within the innovation system[16].

Denmark's systemic approach to wind-power innovation led to its world-leading position in manufacturing and market growth. The selective and partial focus of its early rivals on pushing novel technologies from R&D labs into the market failed to integrate potential adopters and failed to direct broader processes of knowledge generation and exchange. In the *Global Energy Assessment*[11], many other cases of innovation success are covered, such as the Brazilian ethanol

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and flex-fuel car industry[17], as are cases of innovation failure, such as the US 'synfuels' programme to develop liquid or gaseous substitutes for petroleum[18]. In each case, the successes are distinguished by the systemic characteristic of directed innovation efforts.

To assess directed innovation efforts for climate change mitigation, we developed an analytical framework integrating key elements of the innovation system as applied to energy technologies (Fig. 1). At the centre of this analytical framework are the stages of innovation during a technology's lifecycle from R&D, through demonstration projects and niche markets, to diffusion and ultimate phase-out. Innovation processes link these stages. Once considered unidirectional, with innovation driven strongly by basic research[19], these innovation processes are now understood to include feedbacks as well as flows[20,21]. As an example, knowledge generated through R&D activities flows through into the design of commercial prototypes, which are tested in niche markets protected from full commercial pressures[22]. The experiences of technology users then feed back into the iterative process of technology development and improvement.

The innovation lifecycle is driven by forces of both supply and demand. 'Technology-push' drivers reduce the costs of innovation through, for example, education and research; 'market-pull' drivers increase the pay-offs from innovation, for example, by improving the relative advantage of new technologies in the market place[23]. The stages and drivers of the innovation lifecycle for a particular technology play out within a broader innovation system.

Of the elements shown in Fig. 1, knowledge is the most fundamental[24], and includes processes of generation and learning[25]. These, in turn, involve many actors and institutions. Actors are diverse, from entrepreneurs and established firms to research organizations, governments and end-users. Innovation is thus a collective activity, supported by many institutions. The institutions emphasized in our analytical framework are twofold: the propensity of entrepreneurs to invest in risky innovation activities with uncertain pay-offs; and shared expectations around an innovation's future trajectory[26–28]. Other important and related institutions include law, markets and public policy. Public resources are invested directly into specific innovation stages, or are used to leverage private sector resources through regulatory or market incentives structured by public policy[29,30].

Knowledge, actors and institutions, and resources encapsulate the key elements of the innovation system (see Fig. 1). These elements emphasize necessary inputs into the innovation system to ensure its successful functioning. The ultimate measure of success for a particular technology is its widespread adoption and use. This output of the innovation system is also the means towards broader outcomes of interest such as climate change mitigation. New technologies successfully diffuse as a function of their relative advantage over incumbent technologies[31]. For energy technologies, this can be measured by the difference in cost and performance of energy service provision in terms of quality, versatility, environmental impact and so on[32]. Many of these attributes of relative advantage can be shaped by public policy as well as the other elements of the innovation system.

Innovation systems research has typically paid less attention to the diffusion and use of technology[33]. Yet the needs and preferences of technology adopters distinguish innovation successes from failures[34]. Technology adoption and use are also strongly interdependent with the knowledge, actors and institutions, and resources of the innovation system[27,30].

Indicators of directed innovation efforts

To assess directed innovation efforts in response to climate change mitigation needs, we compiled a set of indicators describing all the key elements of our analytical framework for the innovation system. The different stages, processes and drivers of innovation represented in Fig. 1 thus provide the sample space for our indicators. Table 1 shows how our categories of indicators map onto these elements. For the indicators in each of these categories, we contrast the proportion of effort directed at energy-supply and energy end-use technologies.

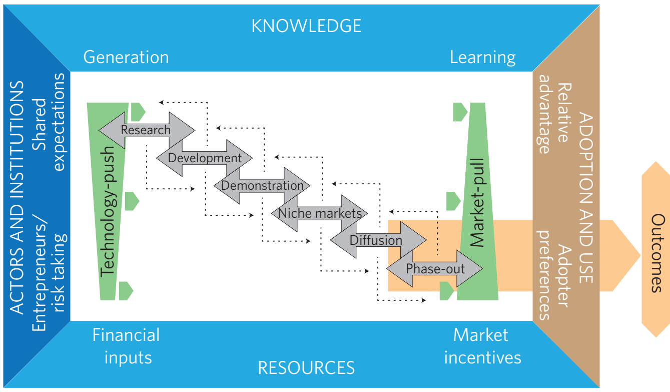

Figure 1 | An analytical framework of the innovation system for energy technologies. This stylistic representation of the innovation system includes the following key elements: innovation stages (grey double-headed arrows, illustrating the importance of feedbacks between stages); innovation drivers (green rhombi and block arrows); and innovation processes (blue and brown frame). Drivers and processes more characteristic of innovation inputs (blue frame) are distinguished from those more characteristic of innovation outputs (brown frame). Innovation outcomes are also shown (orange arrow).

Inputs to the innovation system

To characterize inputs to the innovation system, we use indicators of: analysis and modelling; technology roadmaps, collaborations, portfolios and programmes; public research, development and demonstration (RD&D) investments; and niche market investments (Table 2). The correspondence between these indicators and our analytical framework is shown in Table 1.

Analysis and modelling are knowledge-generation activities that underpin our evolving understanding of the potential contribution of technological change to mitigating climate change (see indicators I1.1–1.6 in Table 2). Technology roadmaps (I2.1–2.4), collaborative research ventures (I3.1–3.4), and technology portfolios, programmes and training (I4.1–4.4) are all influential public institutions that frame and direct innovation efforts. They also help build shared expectations and support entrepreneurial risk-taking "by crystallising the vision of all stakeholders around the common objectives constituted by the roadmaps"[2]. Public resource inputs to the innovation system change over the innovation lifecycle from directly investing in research and development activities (I5.1–5.8) to structuring incentives in specific market niches to attract private capital. We capture the leveraging of private resources by these directed efforts through additional indicators of niche market investments (I6.1–6.3).

Almost without exception, the indicators of innovation system inputs in Table 2 are strongly weighted towards energy-supply technologies (see column 'End-use as % of total'). This finding is most robust for the public RD&D investment indicators that we consider to offer good coverage both spatially and in terms of sample space (see Methods for details). Figure 2 extends the indicators I5–I6 by summarizing available data on direct public expenditures as well as the leveraging effect of public policy and expenditures on private investments in niche markets. Energy-supply technologies are disaggregated to distinguish resource extraction from conversion (for example, electricity generation), and renewable from fossil-fuel technologies.

Table 1 | Indicators of Directed Innovation Efforts.

		Analytical framework: Key elements of the innovation system								
		Stages			Drivers		Processes			
Categories of indicator (distinguishing innovation system inputs and outputs)		RD&D stages	Niche market stage	Diffusion & phase-out stages	Technology-push drivers	Market-pull drivers	Knowledge	Actors & institutions	Resources	Technology adoption & use
Inputs										
I1	Analysis & Modelling	*	*	**	**	*	**	*		*
I2	Technology Roadmaps	**	*		**		*	**	*	*
I3	Technology Collaborations	**	*		**		*	**	*	*
I4	Portfolios & Programmes	**	*		**		*	**	*	*
I5	RD&D Investments	**			**		*	*	**	
I6	Niche Market Investments		**		*	**	*	*	**	*
Outputs										
O1	Market Diffusion			**		**	*	*	**	*
O2	Learning Rates	*	*	**	*	**	**	*		*
O3	Social Returns on Investment			**		**	*	*		**
O4	Mitigation Potentials†			**		**	*	*		**

Columns show the analytical framework of key elements of the innovation system (see Fig. 1). Rows show categories of indicator sampled to characterize the innovation system. Cells containing stars denote elements of analytical framework covered by each category of indicator. The number of stars indicates the strength of coverage of each indicator. †The broader outcome of interest, or the end for which the innovation outputs are the means.

Although Fig. 2 is a partial snapshot of directed innovation expenditure, it usefully illustrates two further points. First, the magnitude of subsidy for fossil-fuel consumption, estimated to approach $500 billion[35], dwarfs innovation investments of some $160 billion in a post-fossil-fuel energy supply. Second, renewable electricity supply (predominantly wind and solar PV) and 'smart' grid technologies dominate public support in the early RD&D and niche market stages of the innovation lifecycle. Directed innovation efforts are therefore 'pushing' energy-supply technologies to mitigate climate change into a market occupied by heavily subsidized incumbents. Efficient end-use technologies are marginalized throughout.

Outputs & outcomes of the innovation system

Table 2 and Fig. 2 illustrate the pervasiveness of privilege accorded to energy-supply technologies in directed innovation efforts. An innovation system with knowledge, institutional and resource inputs heavily weighted towards energy-supply technologies might be expected to produce similarly weighted outputs. To characterize outputs of the innovation system, we use indicators of market diffusion, learning and social returns on investment. We include a fourth set of indicators for the broader outcome of interest: mitigation potentials of energy technologies across a range of climate stabilization scenarios.

Table 3 summarizes the indicators. The correspondence between these indicators and our analytical framework is shown in Table 1. Widespread commercial application of energy technologies contributes directly to mitigation. End-use technologies dominate market diffusion in terms of both capital invested in the energy system (see indicators O1.1–1.3 in Table 3) and energy conversion capacity (O1.4–1.5).

Diffusion is driven by improving performance and decreasing costs associated with learning processes (O2.1–2.2). The effects of learning are often measured by the percentage unit cost reduction per successive doubling of cumulative capacity or production as a proxy for experience[36,37]. Mean learning rates in a sample of mass-produced energy end-use technologies such as refrigerators or automobiles are twice as high as for large-scale energy-supply technologies such as nuclear reactors or gas turbines. Moreover, learning rates for large-scale energy-supply technologies reported in the literature confound learning effects with scale economies, which also reduce unit costs as technologies mature and increase in size. Actual learning rates for energy-supply technologies are therefore likely to be over-estimated.

Learning rates describe technology-specific consequences of innovation system processes. Social returns on investment capture broader economic, environmental and energy security benefits, among others. Estimating social returns is methodologically complex[38] and so is often not attempted[39]. Two landmark studies in the US did, however, estimate the social benefits of federal energy RD&D expenditure[40,41]. The ratio of all realized benefits to total programme costs from 1978–2000 was 83:1 for efficient end-use technologies compared with 7:1 for fossil-fuel energy-supply technologies (see indicators O3.1–3.2 in Table 3)[40]. Not only did end-use efficiency programmes dominate the top rankings of benefit:cost ratios (O3.3), they were also the least costly in the event of unsuccessful commercialization[42]. A subsequent study estimated the expected future benefit:cost ratios for ongoing technology programmes at 10:1 for end-use efficiency and 4:1 for fossil-fuel energy supply[41]. Under assumptions of future carbon pricing, the benefit:cost ratio for efficient end-use technologies improved further to 12:1 (O3.4–3.5).

Almost without exception, the indicators of innovation system outputs in Table 3 are strongly weighted towards end-use technologies (see column 'End-use as % of total'). This finding is most robust for the learning and social returns categories, which we consider to offer good coverage of the sample space.

Table 3 also includes indicators of future mitigation potentials based on scenario analyses (O4.1–4.3). The respective contribution of any technology to climate change mitigation is inherently uncertain. Salient uncertainties include baseline growth in energy demand, climate targets, and mitigation technologies and costs. Of these, baseline uncertainties are the most important[4,43]. As mitigation analysis is by definition relative to a baseline or reference scenario, assumptions embedded in that baseline are inevitably influential. Yet baselines are rarely consistent in their treatment of energy-supply and end-use technologies. Although the trend of improving end-use efficiency is invariably extended into the future, the trend of decreasing carbon intensity is not (for example, Fig. 3 in ref. 44). The apparent contribution of end-use technologies to

Table 2 | Indicators of Innovation System Inputs.

	Indicator	Units	Supply	End-Use	Other	End-use as % of total	Spatial scale	Spatial coverage	Sample coverage
I1	Analysis & Modelling							M	L/M
I1.1	Technological resolution of 11 IAMs in 3 climate stabilization studies[43–45]	# IAMs	11	3	n/a	21%	Gbl	H	M
I1.2	Technological resolution of 6 modelling studies of energy system transitions[78]	# studies	6	4	n/a	40%	Gbl	H	L
I1.3	Restricted technology portfolio analysis in 4 climate stabilization studies[43,44,79,80]	# scenarios	21	2	1	8%	Gbl	H	M
I1.4	Restricted technology portfolio analysis in UK transition pathways[81]	# analyses	4	1	0	20%	UK	L	L
I1.5	Technological focus of energy research published over 10 years in 3 specialist energy journals[55]	% of articles (total >100%)	84	31	59	18%	Gbl*	H	M
I1.6	Focus of 245 learning rate estimates in 2 review studies[36,82]	# learning rates	171	86	0	33%	Gbl*	H	H
I2	Technology Roadmaps							L	L
I2.1	EU SET-Plan strategic technologies[83]	# technologies	12	4	5	19%	EU	M	L
I2.2	EU SET-Plan R&D review of priority technologies[84]	# technologies	7	0	2	0%	EU	M	L
I2.3	European Industrial Initiatives[83]	# initiatives	5	1	1	14%	EU	M	L
I2.4	US DoE Quadrennial Technology Review technology roadmaps[85]	# roadmaps	8	5	4	29%	US	L	L
I3	Technology Collaborations							M	L/M
I3.1	US Energy Innovation Hubs, established & proposed[86]	# hubs	3	1	2	17%	US	L	L
I3.2	US-China Clean Energy Research Centre work plans[87]	# plans	1	2	0	67%	US-China	M	L/u
I3.3	IEA Implementing Agreements[88]	# agreements	24	11	7	26%	Gbl	H	M
I3.4	cf. I3.3 but country participation[88]	# countries	267	149	94	29%	Gbl	H	M
I4	Technology Portfolios & Programmes							L	L/u
I4.1	EU FP7 energy research programme activities[1]	# activities	5	1	4	10%	EU	M	L/u
I4.2	EU FP7 energy research themes in 2011[1]	# themes	13	3	6	14%	EU	M	L/u
I4.3	US ARPA-E research projects[89]	# projects	66	36	79	20%	US	L	L
I4.4	UK energy research doctoral training centres[90]	# centres	7	1	4	8%	UK	L	L/u
I5	Public RD&D Investments							H	H
I5.1	EU FP7 energy research budget in 2011[1]	€ million	161	35	72	13%	EU	M	L/M
I5.2	EU FP6 energy research budget in 2002-6[84]	€ billion	1.8	0.1	0.2	5%	EU	M	L/M
I5.3	European Industrial Initiatives funding[39]	€ million	47	10	2	17%	EU	M	L/u
I5.4	UK energy research programme funding as of 2011[90]	£ million	200	100	89	26%	UK	L	L
I5.5	US ARPA-E research project funding[89]	$ million	211	101	209	19%	US	L	L
I5.6	IEA public RD&D investments in 2008[66]	$ billion	7.9	1.7	3.1	13%	Dev-d	M	H
I5.7	BRIMCS public RD&D investments in 2008[3]	$ billion	8.3	0.2	5.3	1%	Dev-d	M	M
I5.8	cf. I5.6 but cumulative 1974-2007[66]	$ billion	315	38	65	9%	Dev-d	M	H
I6	Niche Market Investments							H	u
I6.1	Global asset finance investment in energy niche markets in 2008[91]	$ billion	17	2	92	2%	Gbl	H	u
I6.2	Global venture capital investment in energy niche markets in 2008[91]	$ billion	4.6	2.8	7.6	19%	Gbl	H	u
I6.3	cf. I6.2 but cumulative 2002-2008[91]	$ billion	13	8	22	19%	Gbl	H	u

Subjective assessments of spatial coverage globally, regionally and nationally, and sample coverage of full potential set of indicators: high (H), medium (M), low (L) coverage, or unknown (u) if insufficient data exist to assess coverage. See Methods section and Supplementary Information for details and additional input indicators. Gbl = Global. Gbl* = Global with English-speaking language bias[77]. Dev-d = Developed countries, typically IEA members. Dev-g = Developing countries. Advanced Research Projects Agency - Energy (ARPA-E); Brazil, Russia, India, Mexico, China, South Africa (BRIMCS); Department of Energy (DoE); Framework Programme (FP); Integrated Assessment Models (IAMs); International Energy Agency (IEA); Research, development & demonstration (RD&D); Strategic Energy Technology Plan (SET-Plan).

reported mitigation potentials is therefore reduced, as the baseline already includes substantial efficiency gains (for example, Fig. 5 in ref. 45).

The exclusion of end-use efficiency from mitigation analyses due to its inclusion in baseline assumptions is not just a characteristic of modelling studies. For similar reasons, the influential work on climate 'stabilization wedges' only included a limited subset of end-use technologies (relating to cars and buildings) despite recognizing that efficiency improvements offered the greatest potential source of emission reductions[46].

To compare potential contributions to mitigation of energy-supply and end-use technologies on a like-for-like basis, the baseline

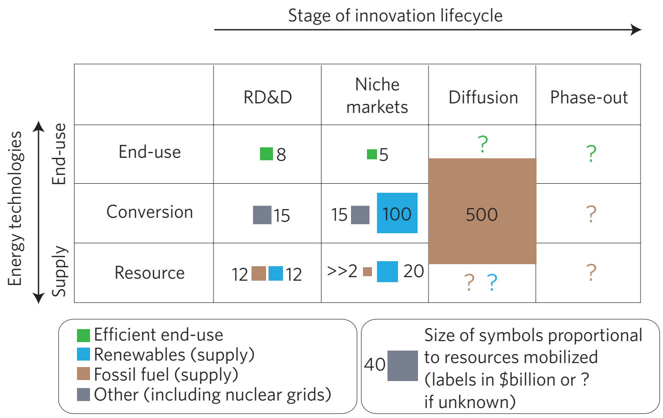

Figure 2 | Global mobilization of financial resources for energy technologies. Energy efficiency improvements in end-use technologies (green).Energy resource extraction and conversion disaggregated into fossil-fuel (brown), renewable (blue), and nuclear, network and storage (grey) technologies (see Supplementary Information for details). The phase-out stage of the innovation lifecycle is included to highlight its importance for capital stock retirement and replacement (that allows for growth of post-fossil-fuel alternatives); however, insufficient data exist to populate its cells.

needs to hold end-use efficiency constant at current levels[4,47]. One large-scale modelling study that made this adjustment found efficient end-use technologies accounted for 58–75% of cumulative emission reductions to 2100, with an average of around 60% (ref. 4). These provide the outcome indicators (O4.1–4.3) shown in Table 3.

Even studies that do not correct for the over-estimation of energy-supply contributions still find efficient end-use technologies constitute an important, if not the dominant, mitigation option[44]. A review of mitigation scenarios to 2050 in six countries found end-use efficiency contributed 42–89% of emission reductions with a mean of 63% (see Table 3.8 in ref. 48). Moreover, the relative importance of end-use technologies increased both in nearer-term scenarios and under less stringent stabilization targets[43,49].

Input–output asymmetries in the innovation system

Taken together, the indicators summarized in Tables 2 and 3 characterize the different stages, processes and drivers of innovation in the energy system. Figure 3 compares representative indicators of innovation inputs (Fig. 3a) with outputs and outcomes (Fig. 3b). Directed innovation efforts clearly privilege energy-supply technologies (indicators I1-6). Yet end-use technologies dominate innovation system outputs (indicators O1-3) and the required outcomes for climate change mitigation (indicators O4).

End-use technologies dominate system outputs for various reasons. End-use efficiency is economically attractive as it reduces lifecycle costs and so improves productivity[50,51]. It also offers 'co-benefits' ranging from reduced import dependence and reduced price volatility to reduced air pollution and better-quality energy services[52].

These generic advantages of end-use efficiency are complemented by technology-specific potentials. In the context of learning, each technological unit invested in and adopted can be seen as an experiment: the more experiments that take place, the higher the potential for learning (all else held constant). This favours dispersed, small-scale end-use technologies as a source of potential cost reduction to drive widespread diffusion. End-use technologies are also the final link in an energy-conversion chain whose purpose is to provide useful services to end-users. Many end-use technologies are produced, marketed and sold in consumer goods markets characterized by non-directed private activity (in comparison to the regulated energy-supply sector). The relative advantage of end-use innovations has proved central to changes in the energy system observed over time[32].

In summary, efficient end-use technologies occupy a greater share of energy system investments and capacity, engage higher levels of private-sector activity, offer higher potential cost reductions, return larger social benefits and promise greater future mitigation of climate change.

Why Are Energy End-Use Technologies Marginalized?

In this section, we offer our perspective on the reasons for the privileging within directed innovation efforts of energy-supply technologies over efficient end-use technologies. We emphasize from the outset that this is our interpretation of the data rather than a finding substantiated by the data. Our perspective is also necessarily general and does not distinguish the institutional and political differences between innovation systems at different scales for different technologies[29].

These caveats notwithstanding, we consider four possible arguments to explain why end-use technologies may be marginalized in directed innovation efforts: analytical intractability; invisibility and dispersion; weak political economic influence; and bounded innovation heuristics.

First, end-use technologies are smaller in scale, orders of magnitude larger in number, more dispersed, and highly heterogeneous compared with the pits, pipelines and power plants of the energy supply. Data are correspondingly patchy or unavailable (see p437 in ref. 53). Many end-use technologies are also consumer goods with a variety of attributes over which end-user preferences vary. Efficiency may be traded-off against style, speed and safety[54]. With engineering as the dominant disciplinary approach to energy research[55], these 'behavioural' characteristics of end-use technology adoption pose greater problems for modellers and analysts. Most widely used integrated assessment models do not resolve end-use technologies. Energy assessments can exclude them all together[56].

Second, the scale and visibility of statuesque wind turbines or monumental engineering constructions engender achievement and capture attention[57]. China's vast new coal-to-liquids facility is a recent case in point[58]. Renewables, nuclear and carbon capture hog the headlines of a low-carbon future. The Greenpeace-funded scenario that sparked controversy in the Intergovernmental Panel on Climate Change *Special Report on Renewable Energy Sources and Climate Change Mitigation* depicted 77% of global energy needs in 2050 being supplied by renewables[59,60]. Yet among the 160+ scenarios reviewed, it was an outlier not for its assumptions about renewable technology deployment but for its assumptions about end-use efficiency and energy demand[61,62]. This went unnoticed. The end use of energy is largely invisible, and incremental efficiency improvements dispersed over many hundreds of end-use innovations are somehow "less tangible"[46].

Third, the fossil-fuel-dominated energy supply has been described as a 'techno-institutional complex' that has become locked in[63]. As interrelated technological and social systems evolve, they develop increasing institutional rigidity and resistance to change[64]. Established infrastructures and rules create barriers to entry. Vested interests exert political and market pressure to preserve the dominant position of incumbent technologies. Energy-supply companies are among the largest, most capitalized corporate interests in the world. In contrast, end-use technologies lack coherent influence in the political economy. There are no simple metrics to substantiate this contention, but it is indicative that fossil-fuel industry revenues are on the order of $5 trillion annually, whereas the largest energy end-use technology industry — automobiles — has revenues of $1.5 trillion (ref. 65).

Table 3 | Indicators of Innovation System Outputs and Outcomes.

	Indicator	Units	Supply	End-Use	Other	End-use as % of total	Spatial scale	Spatial coverage	Sample coverage
O1	**Market Diffusion**							**H**	**M**
O1.1	Global capital investments in 2005, central estimates [92–4]	$ trillion	0.8	1.7	n/a	68%	Gbl	H	M
O1.2	cf. O1.1 but with low estimate for end-use [92–4]	$ trillion	0.8	1.0	n/a	55%	Gbl	H	M
O1.3	cf. O1.1 but with high estimate for end-use [92–4]	$ trillion	0.8	3.5	n/a	82%	Gbl	H	M
O1.4	US installed energy conversion capacity in 2000 [95]	TW	3.4	30	n/a	90%	US	L	M
O1.5	cf. O1.4 but excluding cars [96]	TW	3.4	5.5	n/a	62%	US	L	M
O2	**Learning Rates**							**H**	**H**
O2.1	Average learning rates for mass produced end-use technologies (n=14) & large-scale energy supply technologies (n=14) [11,17,36,96–107]	% learning rate	8	20	n/a	71%	Gbl*	H	H
O2.2	cf O2.1 but excluding nuclear power [11,17,36,96–107]	% learning rate	12	20	n/a	62%	Gbl*	H	H
O3	**Social Returns on Investment**							**L**	**M**
O3.1	Realised economic benefits & costs of US federal RD&D in 28 technologies from 1978-2000 [40]	share of benefits / share of costs †	0.3	21	n/a	99%	US	L	L
O3.2	cf. O3.1 but including environmental and security benefits as well as economic benefits [40]	share of benefits / share of costs †	0.7	9.1	n/a	93%	US	L	M
O3.3	Benefit:cost ratios of US federal RD&D in 16 commercialised technologies from 1978-2000 [42]	share of top 5 B:C ratios / share of all ratios	0.3	2.1	n/a	87%	US	L	M
O3.4	Expected economic benefits & costs of US federal RD&D in 5 technologies from 2006-2050 [41]	share of benefits / share of costs †	0.7	1.8	n/a	73%	US	L	M
O3.5	cf. O3.4 but in carbon constrained scenario [41]	share of benefits / share of costs †	0.5	1.7	n/a	77%	US	L	M
O4	**Mitigation Potentials**							**H**	**L**
O4.1	Cumulative emission reductions from 2000-2100 relative to constant year 2000 baseline [4,47]	1,000 GtC	0.9	1.7	0.2	59%	Gbl	H	L
O4.2	cf. O4.1 but minimum emission reductions [4,47]	1,000 GtC	0.1	0.7	0.1	75%	Gbl	H	L
O4.3	cf. O4.1 but maximum emission reductions [4,47]	1,000 GtC	1.8	3.0	0.4	59%	Gbl	H	L

Subjective assessments of spatial coverage globally, regionally and nationally, and sample coverage of full potential set of indicators: high (H), medium (M), low (L) coverage, or unknown (?) if insufficient data exist to assess coverage. See Supplementary Information for all data and explanations, as well as additional output indicators . †For each category of technology (supply, end-use, other), the indicators describe the proportion of all benefits generated by that category of technology divided by the proportion of all costs incurred by that category of technology so that proportional benefits are normalised to proportional costs. Gbl = Global. Gbl* = Global with English-speaking language bias[77] .Benefit:cost ratio (B:C ratio). .

Fourth, directed innovation efforts in the energy system until now have cumulatively reinforced the dominant influence of the energy-supply industry over its end-use counterparts. Since the late-nineteenth century, for every $1 in US federal subsidies to efficient end-use technologies, $35 have gone to energy-supply technologies[66]. Since 1974, more public resources in developed countries have been invested into RD&D of nuclear fusion than on all efficient end-use technologies combined[47,67]. The search for solutions in evolving innovation systems becomes limited by prevailing practices, ways of thinking, and expectations, conceptualized as a 'technological trajectory'[68]. For energy innovation, this trajectory points firmly towards the energy supply. Proponents of a R&D-led mitigation strategy conclude "there should be no need to pick 'winners' or to get locked into inferior technologies"[69] before citing six 'neutral' technology options worthy of R&D support; five of the six relate to the energy supply. Silver bullets of radical innovation for single-handedly tackling climate change are similarly sought only in low cost, limitless, zero carbon supply or geo-engineering technologies[7]. Analogous silver 'buckshot' strategies distributing solutions across many heterogenous end-use technologies are considered less applicable, with greater perceived difficulties in scaling a breakthrough to make a large contribution to emissions reduction via private sector investment.

The Importance of Assessing Innovation Systems

Our analysis reveals a pronounced and pervasive asymmetry in the innovation system for energy technologies seen through the lens of climate change mitigation. Whereas the outputs of innovation emphasize the importance of efficient end-use technologies, inputs privilege energy-supply technologies. Directed innovation efforts are misaligned with their required outcomes. Our conclusion is that significantly greater effort is needed to develop the full potential of efficient end-use technologies.

The allocation of public resources to innovation is ultimately political[70]. A diversified portfolio of mitigation options preserves option value and insures against the risk of particular innovation failures[71]. But concentrating scarce resources in a more narrowly focused investment strategy can harness the benefits of scale through a virtuous cycle of learning, cost reduction, standardization, network expansion, further scaling, and so on[72]. The merits of diversification and concentration in portfolio design should be argued openly for energy-supply and end-use technologies with clear criteria.

Our analytical framework provides such criteria and ensures efforts are matched to requirements, or directed inputs to resulting outputs and outcomes. The Department of Energy's *Quadrennial Technology Review* of energy innovation in the US used a similarly comprehensive and transparent approach[1]. It concluded that the US federal portfolio needed "rebalancing" in large part towards

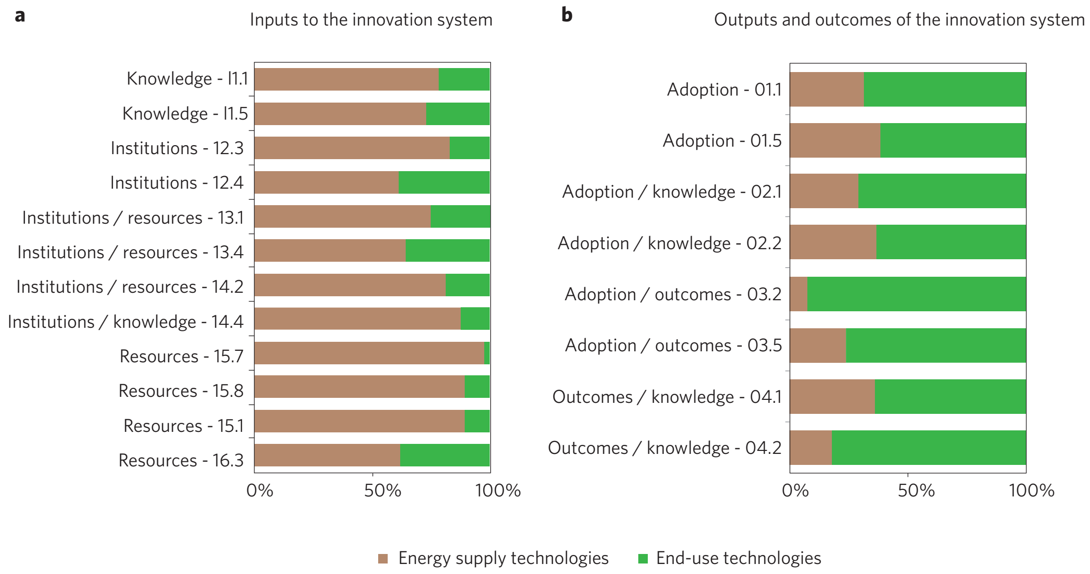

Figure 3 | Technological emphasis of directed innovation efforts. a, Inputs to the innovation system, for details of indicators see Table 2. **b**, Outputs and outcomes of the innovation system, for details see Table 3. Bars show two representatives for each category of indicator. Labels link indicators to elements of the analytical framework shown in Fig. 1 and summarized in Table 1. 'Other' technologies are not shown.

end-use efficiency. We draw the same conclusion about the relative underinvestment throughout the innovation system in end-use technologies, in the US, the EU, and elsewhere.

Although we have focused on the supply–end-use dichotomy, there are other potential tensions within directed innovation efforts. These include: radical versus incremental innovation[7,46], centralized versus distributed generation[73], near-term versus long-term outcomes[71] and technology-push versus market-pull drivers[23]. Climate change mitigation is also not the only objective for technological change in the energy system. Energy security and universal access to modern, clean energy are other important global scale issues[52]. Inevitably, trade-offs have to be made, but the analytical framework we have set out supports comprehensive, consistent and aligned innovation efforts[11].

A failure to tackle innovation systemically can lead to unintended or even adverse outcomes. The magnitude of the innovation challenge for climate change mitigation also means narrowly focused or partial responses are wholly inadequate. Efficient end-use technologies should take their rightful place at the centre of directed innovation efforts and public resource allocations.

Methods

We compiled a set of indicators describing all the key elements of our analytical framework for the innovation system (see Fig. 1). Using indicators to characterize innovation systems is well established, for example, to distinguish innovation inputs from outputs[3,74] or to map changes over time in key innovation system functions[75,76].

For each indicator, we contrast the proportion of effort directed at energy-supply and energy end-use technologies, in each case distinguishing innovation system inputs from outputs (following ref. 74). To minimize categorization bias, we include a third 'other' category for technologies that link supply with end-use. 'Other' technologies include grid and network infrastructure, electricity storage and distributed forms of electricity and heat generation. (All data and explanations for the indicators are provided in the Supplementary Information).

Our selection of the categories of indicator and the indicators themselves was designed to cover: all the elements of the innovation system represented in our analytical framework; the principal types of indicator referenced in the literature on energy innovation; and different spatial scales, from national to global.

For each category of indicator, we provide a subjective assessment of the extent to which we sample from the full 'indicator space', that is, the set of all possible indicators for the corresponding element of the innovation system. Our assessment distinguishes high, medium, low coverage and also unknown if insufficient data exist to assess coverage. We assess spatial coverage as well as sample coverage.

As examples, we assess our 'public RD&D investments' category of indicator to have high spatial coverage as indicators are global, regional, national and include new data on the major developing economies (see Table 2). We also assess this category of indicator to have high sample coverage as the indicators describe all public RD&D activities with no major omissions (but subject to data availability, see below).

In contrast, we assess our 'analysis & modelling' category of indicator to have medium spatial coverage as indicators are principally global with only selected national data (see Table 2). We also assess this category of indicator to have low sample coverage as findings from less cited studies are omitted, particularly those outside the peer-reviewed literature.

We similarly provide a subjective assessment of both spatial coverage and sample coverage for all of the indicators within each category. The indicators, as well as these subjective assessments of coverage, are summarized in Tables 2 and 3, with full details provided in the Supplementary Information

Our selection of indicators was heavily constrained by data availability, particularly for developing countries. As a result, some categories of indicator are biased towards developed countries, particular the US and the EU. These biases are reflected in our assessments of spatial coverage. Global scale indicators describe both developed and developing countries, although energy-related innovation data for smaller developing countries are incomplete so may introduce an under-reporting error.

Collectively, our indicators provide a comprehensive and representative account of directed innovation efforts. However, we do not assume our indicators are directly commensurable, so we do not provide an aggregated descriptor. Rather, we present each of the indicators in their original units as their purpose is to describe succinctly particular elements of the innovation system. Insufficient understanding of the inter-dependencies between these elements and their relative importance, compounded by data limitations, prevents a quantitative rendering of the innovation system as a whole.

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Author Contributions

All authors contributed to the intellectual content. C.W. and A.G. led the data collection and drafting of the text with contributions from K.S.G. and G.N. All authors reviewed and edited the text.

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The authors have no competing financial interests.