OPINION

No quick switch to low-carbon energy

In the first of two pieces on reducing greenhouse-gas emissions, **Gert Jan Kramer** and **Martin Haigh** analyse historic growth in energy systems to explain why deploying alternative technologies will be a long haul.

SUMMARY

- There are physical limits to the rate at which new technologies can be deployed
- Governments need to design policies targeted at specific technologies to accelerate deployment
- More action is required on demand side to increase efficiency and curtail consumption

To combat climate change, the world's entire energy system needs a major overhaul before the middle of the century. But can we build new energy supplies that quickly? Some argue that with the right incentives we can see similar rates of change in the energy system as have been seen in information technology. So most of the debate focuses on how much the transition will cost and who will foot the bill. Here, we argue that cost is less important than the rate at which existing low-carbon energy technologies can be physically deployed. Because the scale of the energy system is so huge, it takes time to build the human and industrial capacity to achieve substantial deployment.

There have been high-profile proposals to 'repower' the world in a decade, loosely based on the way innovative consumer goods such as mobile phones or iPods conquer their markets[1,2]. Unlike with consumer goods, we believe that there are robust empirical 'laws' that limit the build rate of new and existing energy technologies and thereby the potential to deliver much of the hoped-for transformation by 2050 (ref. 3). To accelerate deployment, policy-makers need to tailor their policies to specific technologies in ways that recognize the stage of development.

ROAD TO COPENHAGEN

In the twentieth century, it took 30 years for energy technologies that were available in principle to grow exponentially and become widely available (Fig. 1). This reaching 'materiality' can be defined as delivering about 1% of the world's energy mix. After that, the growth becomes linear until the technology captures its final market share. This pattern is remarkably consistent across energy technologies and the two growth phases can be seen as the 'laws of energy deployment' (see 'The laws of energy-technology deployment'). Policy-makers concerned about carbon dioxide emissions will want to accelerate the first phase, making energy technologies 'material' within one decade instead of three. But we see two fundamental reasons why the exponential growth in the early, pre-material phase will be hard to beat.

First, scale-up means learning by doing, which takes time in the energy industry. Where energy technology relies on conversion processes — as with next-generation nuclear energy, biofuels or carbon capture and storage (CCS) — historically it has taken three years to build a demonstration plant, one year to start it up and two to five years to overcome setbacks and reach satisfactory operability. So it can take a decade to reach the point where one is confident enough to build the first full-scale commercial plant. It can take another decade to build a dozen.

Where energy technology relies on conversion devices — wind energy, for example — scale-up is equally time-consuming. From 1993 to 2007, worldwide electricity from wind grew at more than 25% a year, in agreement with the first law. Almost two-thirds of this growth comes from more-powerful turbines. In the mid-1980s, 50-kilowatt wind turbines delivered an annual total of 1,000 terajoules (TJ). It would have been impossible to deliver 2007 levels of wind energy (about 600,000 TJ globally) with those turbines. To deploy today's powerful turbines (1–5 megawatts) at industrial scale, and at reasonable cost, required a multi-decadal development effort.

Second, industrial capacity is more important than money. In rough terms, it takes US$100 million–200 million to deliver a project at the bottom end of the energy scale (equivalent to 1,000 TJ per year). It takes a few hundred billion to bring the same technology to materiality[4]. When that technology is new, it takes time to build the human and industrial capacity to do that. You cannot just spend $1 trillion overnight in a $30-billion industry, which is where photovoltaics — solar power — is today.

After reaching materiality, growth curves have historically levelled off (Fig. 1). This is our second law. Unlike consumer goods that may become obsolete in a few years, the capital goods of the energy system have a lifetime of 25–50 years. That means only 2–4% of existing technology needs replacing in a given year. These replacement rates are hard to increase because the economic barrier to replacing old technology is extremely high: industry will only consider early retirement of the existing capital stock if the total cost of the new technology (capital and operating costs) falls below the operating cost of the old.

Photovoltaics supply just 0.01% of world energy today. But suppose they supply 10% of the global energy demand by 2050. If solar panels last roughly 20 years, that is a turnover rate close to 5%. As such, the long-term industrial capacity needed to build solar panels and install them will be just 0.5% of world energy demand per year. Together, the replacement rates of old and new stocks explain why the growth curves become linear.

The laws of energy-technology deployment

Law 1
When technologies are new, they go through a few decades of exponential growth, which in the twentieth century was characterized by scale-up at a rate of one order of magnitude a decade (corresponding to 26% annual growth). Exponential growth proceeds until the energy source becomes 'material' — typically around 1% of world energy.

Law 2
After 'materiality', growth changes to linear as the technology settles at a market share. These deployment curves are remarkably similar across different technologies.

Burn out

The sheer scale and inertia of the energy system may explain why some conclude that the energy challenge requires a response comparable to industrial war efforts[5]. Alas, such arguments completely ignore the second law of deployment. In addition, war-scale efforts typically burn out within a decade, leaving a massive bill for posterity.

The empirical laws we describe here are not laws of nature. They are societal laws best explained using a prudent investor perspective — which applies both to private investors and to government financing. Ever since the rise of coal and oil, every major deployment of new energy technology (nuclear, wind, biofuels and even natural gas) has occurred with some

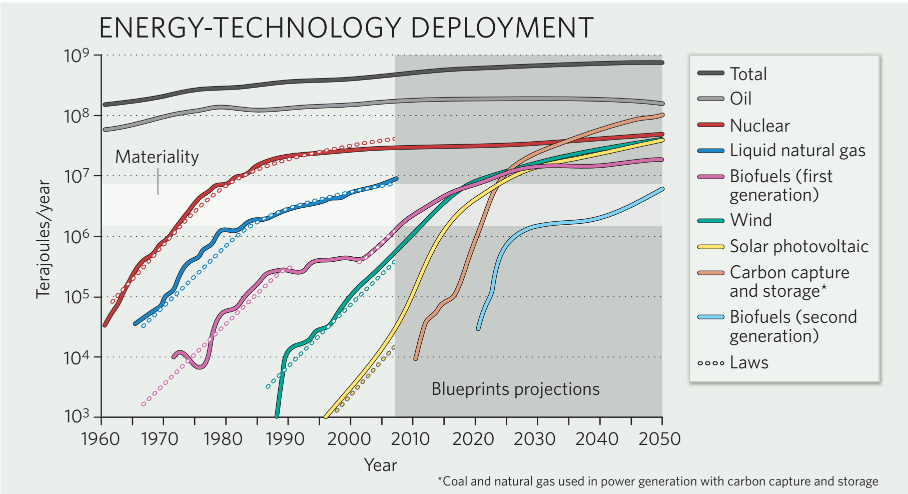

Figure 1 | Global production of primary energy sources. When a technology produces 1,000 terajoules a year (equivalent to 500 barrels of oil a day), the technology is 'available'. It can take 30 years to reach materiality (1% of world energy mix). Projections after 2007 taken from Shell's Blueprints scenario[3].

form of government support. The challenge in the decades ahead is to match, perhaps even outperform, the historic 'laws' by designing energy policies directed at decarbonizing the energy industry.

So what might be possible if policy were aimed at delivering a low-carbon energy supply? Shell tried to answer this question with its 2008 energy scenarios, one of which (Blueprints) has optimistic projections for new energy deployment[3]. In the Blueprints scenario, most new energy types reach materiality by 2030 (photovoltaics by 2020) and their subsequent deployment is on aggregate faster than the historic laws (Fig. 1). CCS is fully available and there is significant carbon pricing and trading. By 2050, total energy demand is one-third lower than business-as-usual projections, mostly through enhanced efficiency and adoption of electric vehicles. Renewable energy supplies one-quarter of the total demand for energy, but none of the individual energy sources exceed 10%.

We believe that the Blueprints scenario is the best we can reasonably hope to achieve for new energy deployment, yet in it, by 2050 two-thirds of the world energy supply still comes from fossil fuels and CO_2 concentrations stabilize at around 550 p.p.m.. At this level, the world is still at considerable risk of dangerous climate change, especially when contributions from other greenhouse gases are taken into account.

How does Blueprints achieve such fast deployment? Partly with a mix of policies that change as a technology moves along the deployment curve. When an energy option is only available in principle, there is little use in subsidizing its deployment through market incentives. Instead, government support for R&D and pilot projects is key. Neither a carbon trading price nor a fuel subsidy will be enough to stimulate commercial investments in demonstration plants for second-generation biofuels or CCS. As technology families they must be picked as winners by the government, even if the market can be left to the job of choosing specific technologies.

Nurturing development

In the case of CCS, governments are hoping to beat the first law by supporting two-dozen pilot projects[6], each at a much larger scale than today's 30-MW project. But CCS will continue to need preferred treatment beyond 2020 to bring it to materiality — through full recognition of CCS in carbon-trading markets and directed government support.

Indeed, as technologies move up the deployment scale, the nature of the support changes from pilot projects to market interventions, such as feed-in tariffs to cover the difference between energy-generation costs and wholesale energy prices. These can be effective, but subsidies need to be technology-specific. Already, feed-in tariffs for photovoltaics and wind differ, allowing photovoltaics to compete with wind. We hope that legislators will treat second-generation biofuels differently from the first generation when the time comes.

Once the threshold of materiality is crossed, the technology costs do become more important. Unit costs will need to fall sufficiently so that any remaining subsidies are small. The real challenge at this stage moves to planning infrastructure and land use.

For example, the dispersed nature of renewable energy means higher land-use requirements, which may act as a significant brake[7]. Another limiting factor is the need for enabling technologies. Utility-scale energy storage, for example, will be needed to smooth the supply from intermittent renewable-energy sources such as wind and solar. Intermittent resources can destabilize an electricity grid if they supply more than 20% of the power unless there is storage available. Similarly, significant CCS deployment will require CO_2 pipelines and storage, eventually at a scale comparable to today's natural-gas infrastructure. Governments must plan for this well in advance, otherwise such factors will limit the later market share of new technologies, and therefore their contribution to a low-carbon world by 2050.

Even with all these policies in place, the CO_2 concentrations achieved in the Blueprints scenario fall short of environmental ambitions. An even tougher goal of stabilizing CO_2 concentrations at 450 p.p.m. — as climate science recommends — would require a largely decarbonized energy sector by 2050. Our best chance of beating the deployment laws requires efforts on multiple fronts, as Blueprints shows, but going beyond those optimistic projections remains an even more significant challenge.

One implication of the deployment laws is that more action is required on the demand side to increase efficiency and curtail consumption. The good news is that demand-side solutions are subject to different laws. In principle, everyone in the developed world could use less energy tomorrow. The bad news is that it has proven exceedingly difficult to restrain our appetite for more energy. No climate actions are easy and none of them is quick. ■

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