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Up-scaling, formative phases, and learning in the historical diffusion of energy technologies

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HIGHLIGHTS

- Comparative analysis of energy technology diffusion.
- Consistent pattern of sequential formative, up-scaling, and growth phases.
- Evidence for conflation of industry level learning effects with unit level up-scaling.
- Implications for experience curve analyses and technology policy.

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ABSTRACT

The 20th century has witnessed wholesale transformation in the energy system marked by the pervasive diffusion of both energy supply and end-use technologies. Just as whole industries have grown, so too have unit sizes or capacities. Analysed in combination, these unit level and industry level growth patterns reveal some consistencies across very different energy technologies. First, the up-scaling or increase in unit size of an energy technology comes after an often prolonged period of experimentation with many smaller-scale units. Second, the peak growth phase of an industry can lag these increases in unit size by up to 20 years. Third, the rate and timing of up-scaling at the unit level is subject to countervailing influences of scale economies and heterogeneous market demand. These observed patterns have important implications for experience curve analyses based on time series data covering the up-scaling phases of energy technologies, as these are likely to conflate industry level learning effects with unit level scale effects. The historical diffusion of energy technologies also suggests that low carbon technology policies pushing for significant jumps in unit size before a 'formative phase' of experimentation with smaller-scale units are risky.

1. Introduction

Energy systems have witnessed transformative growth over the last 100 years. Global primary energy consumption increased 16-fold in the 20th century, as did GDP, compared to a 4-fold increase in population (Smil, 2000). Nested within this centennial trend are periods of rapid and pervasive technological diffusion. In the 1960s, roughly one coal-fired steam turbine unit averaging 125 MW in capacity was installed every other day, and around 3 in 4 of these were in OECD countries alone. In the 1990s, Boeing and Airbus' combined production was about three commercial jet aircraft every other day carrying the equivalent of around 150 MW of power plant. The ever-expanding capacity of the energy system to convert primary energy into energy carriers into useful services (and on into human welfare) is the result of increasing numbers of energy technologies, but also increasing sizes: more coal power plants and jet aircraft; larger capacity coal power plants and jet aircraft.

Technological change in the energy system is typically characterised at the industry level. As a current example, frequent reference is made to the double digit growth rates of the wind or solar photovoltaic industries (IEA, 2008). This industry level growth is characterised by falling units costs associated with increasing experience, a relationship described by learning phenomena.

Alongside learning, scaling is another widespread characteristics of technological diffusion in the energy system. Many energy technologies have increased in size and energy conversion capacity over the past 100 years (see Smil (2008) for many examples and graphics). In the early 20th century, the first mass produced car, Ransom Old's Curved Dash, carried around 10 horsepower, and the model-T Ford double that. Over the next 50 years, this increased seven-fold: by 1975, the average new

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vehicle in the US packed close to 140 horsepower. More commonly associated with energy supply technologies, a salient current example of 'up-scaling' is the steady march of wind turbine rated capacities and tower heights from the tens of kilowatts with 20–30 m towers in the early 1980s up to 2–5 MW with hub heights well over 100 m today. The urgency of decarbonisation objectives mean near-term policy and engineering expectations are for rapid up-scaling or increases in the capacities of other low carbon technologies including carbon capture and storage (Haszeldine, 2009) and concentrating solar power (Shinnar and Citro, 2008).

By capturing available scale economies, up-scaling can also lead to reductions in average unit costs. If these are concurrent with increasing production, then scale effects at the unit level may be conflated with learning effects at the industry level. So: what role does the up-scaling of energy technologies play in industry level growth? And by extension, how likely are the potential confounding effects of up-scaling on cost reductions attributed to learning from cumulative experience?

To address these questions, we investigate how rapidly and how pervasively energy technologies have diffused historically, distinguishing the timing of different phases within this overall diffusion process and the 'up-scaling' phase in particular. We also assess the factors that have enabled (or constrained) up-scaling at the unit level within the overall industry level growth. We find consistent evidence for a sequence of formative, up-scaling, and growth phases in our sample of energy technologies, and a trade-off between unit scale economies and heterogeneous market demand in determining the rate and timing of up-scaling. We conclude that up-scaling is likely to be conflated with learning effects in particular for centralised energy supply technologies. We also draw some general implications for technology policy.

2. Energy technology diffusion: learning and up-scaling

2.1. The lifecycle and diffusion of energy technologies

The pattern of diffusion over time for energy technologies has been characterised by logistic substitution models (Marchetti and Nakicenovic, 1979). Logistic growth describes an initial period of gradual diffusion as a technology is introduced as a new commercial application, moving then through a rapid, exponential growth phase, before slowing and eventually saturating (Grubler et al., 1999). The substitution of incumbent technologies by new competitors leads to subsequent decline and eventual obsolescence.

Early on in their lifecycle, new technologies are crude, imperfect, and expensive (Rosenberg, 1994). New energy technologies are attractive for their ability to perform a particular task or deliver a new or improved energy service (Fouquet, 2010). This is often circumscribed by a particular set of needs in a particular context: a market 'niche'. End-users in niche markets are generally less sensitive to the effective price of the energy service provided or have a higher willingness to pay for its performance advantages (Fouquet, 2010). Thus initially, performance dominates cost competitiveness (Wilson and Grubler, 2011). Market niches afford some protection from competitive pressures, allowing technologies to be tested and improved in applied settings, reducing uncertainties with performance or market demand (Kemp et al., 1998). Costs may only fall substantively after an extended period of commercial experimentation, concurrent with the establishment of an industrial base and characteristic moves towards standardisation and mass production (Grubler, 1998). The influence of accumulating production experience on costs is captured by the concept of learning.

2.2. Learning, and experience curves

Learning is a descriptive label for a multi-faceted process of knowledge generation, application and exchange. Learning may lead to product design improvements, material efficiencies, labour productivity, process refinements, lower contingencies or conservatism as perceived risks are reduced, better system integration, and so on (Argote and Epple, 1990). Originally associated with the experience of 'doing' (Arrow, 1962), learning effects have also been attributed to using, operating, implementing, copying, searching and building (Sagar and van der Zwaan, 2006).

Cost reductions associated with learning processes are described by industry-level experience curves which express unit costs as a function of cumulative production experience (Yeh and Rubin, 2012).[1] The learning rate measures the cost reduction for each successive doubling of cumulative production. Historical learning rates have been extensively characterised for energy technologies. Weiss et al., 2010a compiled data on over 200 learning rates for both energy supply and energy end-use technologies, finding means of $16 \pm 9\%$ and $18 \pm 9\%$ respectively.

Expectations of future learning rates, particularly for low carbon energy technologies, are widely used to inform or rationalise technology policies (Wene, 2000; Nemet, 2009) and to model the diffusion of technologies under different scenario assumptions (Clarke et al., 2008). Although preferable to forecasting either constant costs or declining costs over time (Alberth, 2008), the use of prospective learning rates is contentious.

First, learning rates even for the same technologies are subject to considerable uncertainties (Weiss et al., 2010a). Both data and learning processes are sensitive to the context of analysis, including the temporal and geographic system boundaries (Nemet, 2009) and other social and political factors (Yeh and Rubin, 2012). The price of production inputs, as well as profit margins (if price is used in lieu of cost as the performance measure) may change over time (Ferioli et al., 2009). Changes in product designs and the qualitative characteristics of the energy service provided need to be accounted for in standardising the cumulative production data (Coulomb and Neuhoff, 2006; Weiss et al., 2010b).

Second, learning is not a deterministic outcome of increasing production, but rather is contingent on a host of firm and industry-level innovation processes and efforts (Grubler, 2010). Two-factor experience curves, for example, explicitly represent the influence of cumulative R&D expenditure and the resulting R&D-based knowledge stock on unit cost reductions (Söderholm and Klaassen, 2007; Ek and Soderholm, 2010). But other omitted variables may still introduce biases. Examples include autonomous technological improvement, input price volatility, and knowledge spillovers (Nemet, 2006; Nordhaus, 2009).

Scale effects at the industry level realised through manufacturing and other scale economies are recognised as important drivers of the cost reductions described by experience curves (Argote and Epple, 1990). In their early synthesis, Dutton and Thomas (1984) find that "sometimes much of what is attributed to experience is due to scale". In the case of solar photovoltaic modules in the US, manufacturing scale economies explained 43% of observed cost reductions ($/Wpeak) between 1980 and 2001 (Nemet, 2006). Qiu and Anadon (2012) found economies of scale at the wind farm level in China explained roughly twice as much of the observed cost reductions as learning-by-doing, though the effects of both were dwarfed by the domestication of wind turbine manufacturing to exploit lower labour and material costs. Differing potentials for manufacturing scale economies in the

[1] Learning curves are a similar concept but apply to specific manufacturing plants or processes and focus on labour productivity (Dutton and Thomas, 1984).

component supply chains and assembly plants of cold versus wet household appliances was one factor that helped explain differences in observed learning rates (Weiss et al., 2010a).

The emphasis of this paper, however, is on up-scaling at the unit level and its potential conflation with industry level processes in explaining observed reductions in the unit costs of energy technologies.

2.3. Up-scaling

'Scaling up' or 'up-scaling' are terms used to describe the increase in size or performance capacity of a technology (Luiten and Blok, 2003). Economies of scale associated with up-scaling also lead to reductions in average unit costs.[2] Wind turbines are a useful example. The power output of a turbine is proportional to the swept area of its blades, so a doubling of rotor diameter quadruples power output (Burton et al., 2001). Longer blades need taller towers, so scale economies are further improved by the stronger and more laminar wind speeds further from the ground. But capturing returns to scale is not without trade-offs. Longer blades are also heavier (notwithstanding design and materials innovations), imposing additional stresses on the generating equipment and other nascelle components (Coulomb and Neuhoff, 2006). Ultimately, this defines a unit scale frontier above which diseconomies of scale impose additional costs.[3]

Nelson and Winter (1977) argued that up-scaling was routed in the natural development trajectories of technologies. Using the DC3 aircraft in the 1930s as an example, they argue: "Engineers had some strong notions regarding the potential of [metal skin, low wing, piston powered planes]. For more than two decades innovation in aircraft design essentially involved better exploitation of this potential; improving the engines, *enlargening the planes*, making them more efficient" (our italics, Nelson and Winter, 1977, p. 57). Indeed, the progressive exploitation of scale economies is one of two features common to a wide range of technologies' trajectories (the other is mechanisation).

Winter (2008) argues that for many types of durable equipment, scaling is a powerful heuristic or "constant background condition" of production. Drawing on the concept of technological paradigms which guide the design process (Dosi, 1982), up-scaling can be seen as an embedded part of the process of normal engineering. Seeking ways to exploit the potential for up-scaling is how technologists, designers and engineers think.

Frenken and Leydesdorff (2000) found that up-scaling occurs during a period in the technology lifecycle when a radical innovation becomes embedded as the dominant design. Proposed originally by Abernathy and Utterback (1978), a dominant design is one which appeals to a wide number of users (beyond particular niches), and settles core design concepts in both components and their integration in a complex assembled product (Murmann and Frenken, 2006). This leads competitors to imitate and production to move from bespoke to standardised manufacturing. Whereas a radical innovation may introduce a wholly new set of trade-offs between a product's technical and service attributes, subsequent incremental innovations holds this trade-off constant while varying scale so as to adapt the dominant design to particular market segments (Frenken and Leydesdorff, 2000). The scaling heuristic does not always imply up-scaling. In the case of mobile phones, scaling trajectories balance demands for longer battery lives and increased functionality with the ergonomic need for handsets of appropriate weight and size (Windrum et al., 2009).

Developed originally by Saviotti and Metcalfe (1984), this conceptualisation of the relationship between technical and service characteristics as a way of mapping technological trajectories has been applied to a range of energy technologies. In the case of propeller aircraft, up-scaling to increase take-off weight left unaltered the basic relationships between technical characteristics such as wing loading, and performance or service characteristics such as speed and passenger capacity. Up-scaling was thus part of a service-oriented adaptation of the dominant design (Sahal, 1985). Similar patterns have been found in the technological evolution of tractors and computers (Sahal, 1985), helicopters (Saviotti and Trickett, 1992), and tanks (Castaldi et al., 2009).

In sum, up-scaling to capture unit scale economies is therefore driven by the potential for cost reductions but constrained by the market demand for larger scale technologies, and by engineering and design limits. Sahal (1985) argued that overcoming the structural constraints to up-scaling to produce designs of different scales was a major spur for innovation and learning processes.

2.4. Conflation of learning effects and up-scaling

Isolating the relative contribution of unit level up-scaling and industry level learning processes to cost reductions over time requires econometric or bottom-up engineering models that disaggregate and control for concurrent influences. These are the exception rather than the rule in conventional experience curve analyses (Weiss et al., 2010a).

Examples of these exceptions include two studies of coal power plants built in the US from 1960 to 1980. Joskow and Rose (1985) found that a doubling of unit scale (in MW terms) reduced the cost per unit capacity by 12%, controlling for learning effects as well as compliance with environmental regulation and changes in productivity and input prices. McCabe (1996) extended the analysis to include steam turbine units in nuclear power plants from 1967 to 1988 and similarly found unit scale economies to be significant, controlling for other factors. In the case of coal power, a doubling of unit capacity reduced unit costs by 20–24%, and in the case of nuclear power by 15–19% (although with higher uncertainty) (McCabe, 1996). It is worth noting that the time period over which these models were fitted describes the period of rapid up-scaling during which unit scale economies might be expected to be most evident. In contrast, McNerney et al. (2011) use a decomposition model of the cost of coal-fired electricity generation in the US over the long-run from 1902 to 1970. They find that reductions in capital costs ($/MW) associated with scale economies explained 12% of the observed cost decline, compared with 55% attributed to improved plant efficiency and 26% to higher capacity factors (McNerney et al., 2011).

Coulomb and Neuhoff (2006) distinguish learning effects from component-specific scale effects in an engineering-based decomposition study of the price of wind turbines in Germany from 1991 to 2003. The learning rate increased from 11% to 13% after controlling for unit scale effects, pointing to diseconomies of scale associated with up-scaling (Coulomb and Neuhoff, 2006). Ek and Soderholm (2010) similarly find that up-scaling in wind turbines results in cost increases, although not significantly so, after controlling for learning effects and R&D expenditures. Again, this multi-factor approach is the exception rather than the rule. In a meta-analysis of 113 learning rates estimated for onshore wind power by 35 studies, Lindman and Soderholm (2012) found only 14% controlled for unit scale effects. Whereas the inclusion of

[2] For analysis of the benefits and challenges of up-scaling energy technologies: in the case of nuclear power, see Grubler (2010); for centralised electricity generation plant, see Victor (2002); for cars, see Raff (1991); for wind power, see Heymann (1998).

[3] Although up-scaling is associated with unit scale diseconomies for turbines above 0.4–0.5 MW, the optimal turbine size for project developers is much larger as the fixed cost of balance of plant components including the grid interconnect can be spread over a larger capacity (i.e., plant or windfarm scale economies) (Coulomb and Neuhoff, 2006).

knowledge spillovers, turbine-specific costs, and public R&D expenditures had a statistically significant effect on estimated learning rates, up-scaling did not (Lindman and Soderholm, 2012).

3. Method

3.1. Aims of study

This study aims to: (i) assess the importance of up-scaling or unit level growth in energy technologies; (ii) characterise the timing of up-scaling relative to industry level learning processes; and (iii) evaluate the potential for conflating learning effects and unit level scale economies on observed or expected cost reductions. The analysis therefore focuses on the distinction between unit level growth ('up-scaling') and industry level growth (cumulative production) for a range of different energy technologies.

3.2. Data

To ensure the generalisability of findings, we sampled from a range of energy technologies, including both centralised, capital intensive energy supply technologies as well as distributed, low cost technologies directly providing useful services to end users. For energy supply technologies, we selected refineries, large scale power plants (coal, natural gas, nuclear), and small to medium scale power plants (wind, solar PV or photovoltaic). For end-use technologies, we selected jet aircraft, helicopters, cars, compact fluorescent light bulbs (CFLs), and mobile phones. In each case, technologies were selected based on their significant role or contribution to the accumulation of energy conversion capacity within the energy system.

The time series data compiled are summarised in Table 1, with technologies ordered from high to low unit capacity. Data for energy supply technologies mainly describe installation and use; data for end-use technologies mainly describe production or sales. From this sample, we were unable to use data on solar PV, helicopters, and mobile phones, due to their relative youth in technology lifecycle terms, data limitations, or difficulties of constructing meaningful energy-related metrics. Our final sample of energy technologies therefore had five energy supply and three energy end-use technologies. The small size of the sample means findings are illustrative only.

To account for the spatial diffusion of technologies from their initial market of first commercial application ('core') through to subsequent ('rim') and then final markets ('periphery'), we disaggregated global data into regions defined for each technology

Table 1
Technology diffusion time series data.*Notes*: Of the eleven technologies shown, eight were include in the final analysis. Solar PV, helicopters and mobile phones were excluded. See text for details.

Technology	Data & units	Time series			Notes	Main sources[a]
		Unit level capacity	Unit numbers	Industry level capacity		
Supply-side technologies						
Oil refineries	Total capacity (bpd)	1940–2000 (average only)	Not available	1940–2007	*Industry level*—installed not cumulative capacity *Unit level*—US only (fluid catalytic cracking units)	Oil & Gas Journal, BP, Enos
Power—coal	Capacity additions (#, MW)	1908–2000 (max. & average)	1908–2000	1908–2000	*Industry level*—cumulative capacity (includes all substituted/retired capacity).	Platts
Power—nuclear	Capacity additions (#, MW)	1956–2000 (max. & average)	1956–2000	1956–2000		Platts
Power—natural gas	Capacity additions (#, MW)	1903–2000 (max. & average)	1903–2000	1903–2000		Platts
Power—wind	Capacity additions (#, MW)	1977–2008 (average only)	1977–2008	1977–2008		DEA, BTM Consult
Power—solar photovoltaic (PV)	Cumulative capacity (MW)	Not available	Not available	1975–2007		Maycock, EPIA
End use technologies						
Passenger Jet Aircraft	Aircraft delivered (#, model) & engine thrust (kN)	1958–2007 (max. & average)	1958–2007	1958–2007	Boeing, McDonnell–Douglas, Airbus only[b]	Jane's, aircraft databases
Helicopters	Helicopters introduced (model)	1940–1986	Not available	Not available	*Unit level*—different measures of capacity	Saviotti & Trickett
Passenger cars	Cars produced (#) & engine capacity (hp)	1910–1960, 1960–2005	1900–2005	Calculated from unit data	*Unit level*—US only to 1960; numbers from all motor vehicle data	AAMA, US NHTSA, ACEA
Compact fluorescent light bulbs (CFLs)	Light bulb sales (#)	Estimated	1990–2003	Estimated from unit data	*Unit level*—capacity assumed constant	IEA
Mobile phones	Mobile Phone Subscribers (#)	Not available	1982–2008	Not available	Unit level—capacity data not meaningful for service provision	OECD, ITU

[a] Main sources described in detail in Wilson (2009): *Refineries*—OGJ (1999, 2000), Enos (2002) and BP (2008); *Coal, nuclear, natural gas power*—Platts (2005); *Wind power*—BTM_Consult (2002), Danish_Energy_Agency (2008); *Solar photovoltaics*—Maycock (2002); *Passenger jet aircraft*—Jane's (1998) with supplementary data from online sources including www.airliners.net, www.flightglobal.com, www.boeing.com, www.airbus.com; *Helicopters*—Saviotti and Trickett (1992); *Passenger Cars*—AAMA (1980, 1995, 1997) with supplementary data from online sources including US National Highways Traffic Safety Agency (www.nhtsa.dot.gov) and European Automobile Manufacturers' Association (www.acea.be); *Compact fluorescent light bulbs*—IEA (2006); Mobile phones—OECD (2007, 2009) with supplementary data from International Telecommunications Union (www.itu.int/ITU-D/ict/statistics/index.html).

[b] We estimate that these three manufacturers have accounted for over 2/3 of total cumulative sales of large commercial jet aircraft (and currently account for over 90% of annual sales). Historically, the other main manufacturers were from the former Soviet Union (e.g., Tupolev, Ilyushin) but available data are incomplete. See Wilson (2009) for full discussion.

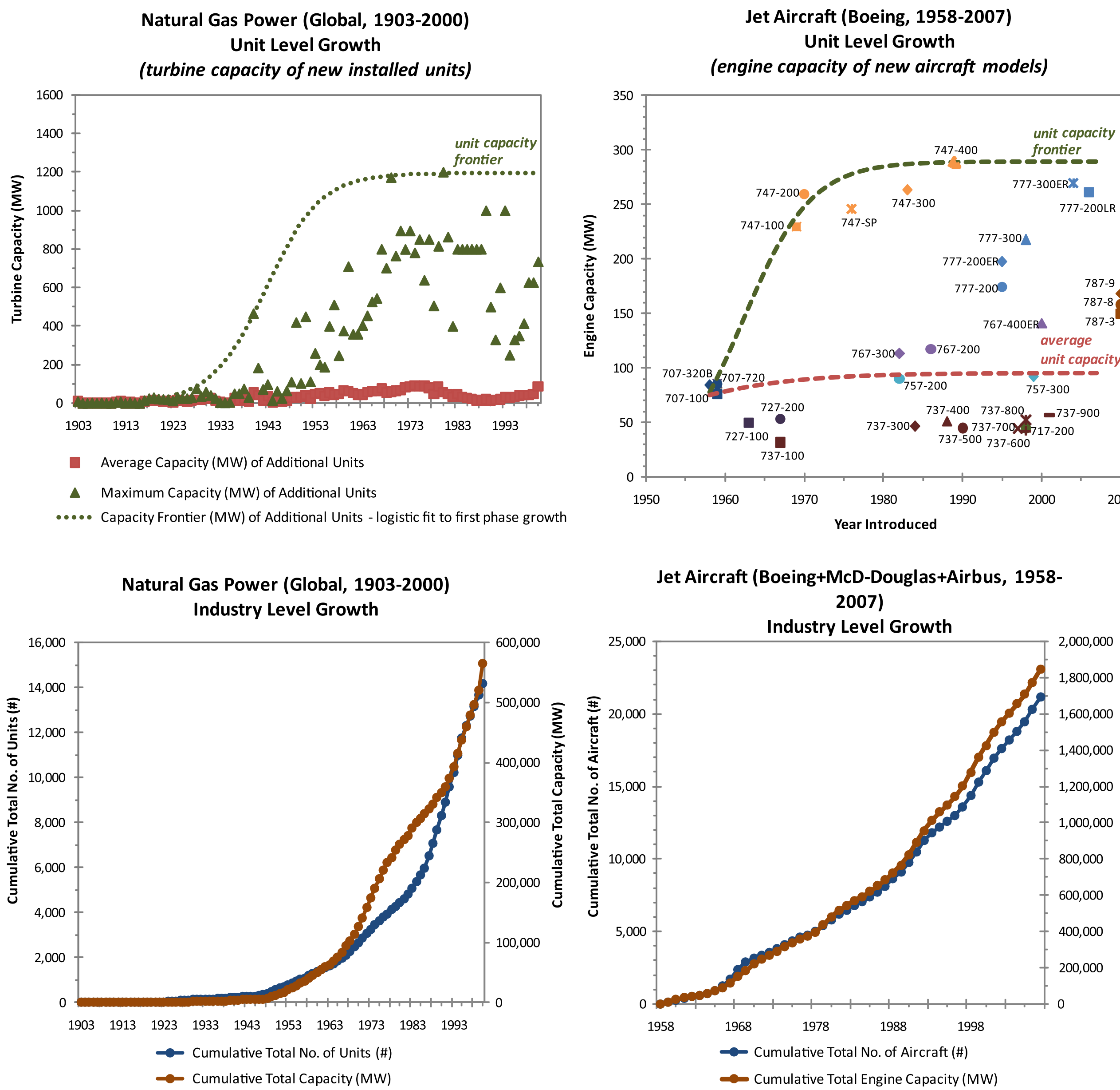

Fig. 1. Unit level growth (upper panels) and industry level growth (lower panels) in natural gas power (left panels) and jet aircraft (right panels) globally. *Data*: see Table 1 for details.

by the sequence of spatial diffusion in the data (following Grubler, 1998). Thus, for example, Denmark is the core region for wind power; the US is the core region for cars; the OECD is the core region for natural gas power. Further details on the method and data are provided in Wilson (2009); all data are also freely available online.[4]

3.3. Metrics and Definitions

We used energy conversion capacity in MW as a common metric of both unit and industry level growth. Capacity data are widely used in experience curve studies as a proxy for production experience. Capacity measures the energy conversion potential of different technologies and so what Winter (2008) calls a "productively-relevant feature" to which the scaling heuristic applies. For all the technologies in our sample, capacity is also meaningful to the energy service provided: the horsepower of cars and the thrust of jet engines is related to the mobility service provided; the wattage of light bulbs is related to the illumination service provided; and so on.

We expressed unit level growth in terms of: (i) average capacity (or size) of additional units; (ii) maximum capacity of additional units; and (iii) unit capacity frontier. We expressed industry level growth in terms of: (i) cumulative total capacity of all units and (ii) cumulative total number of all units.

We drew on the concept of an operational principle in defining the unit level as a technological system purchasable by final consumers in order to provide a useful service (Murmann and Frenken, 2006). In the case of aircraft, for example, we selected as units the jet engine rather than the turbine (which is a component or sub-system) or the aircraft itself (which is a hierarchy of systems).

As examples of the unit level data analysed, the top two panels of Fig. 1 show the maximum and average capacities of steam

[4] Please cite this paper if using the data or graphics made available online at: http://www.iiasa.ac.at/Research/TNT/WEB/Publications/Scaling_Dynamics_of_Energy_Technologies/.

turbine units installed in natural gas-fired power plants since 1903, and the engine capacity of Boeing jet aircraft since 1958 (see Table 1 for details of data and sources). These two technologies are inter-related by the application of aeroengines in the power sector for use as gas turbines in a combined cycle configuration with conventional steam turbines (Lee, 1987). As examples of the industry level data analysed, the lower two panels of Fig. 1 show the corresponding growth of cumulative total unit numbers (left-hand y-axis) and cumulative total capacity (right-hand side y-axis) for natural gas-fired power plants and jet aircraft over their respective lifecycles.

3.4. Growth functions

We used logistic growth functions to describe the time series data subject to criteria of accuracy (minimum $R^2=95\%$) and reliability (minimum % of estimated asymptote reached by data=60%).[5] Growth function parameters then allowed inter-technology comparisons over the whole period of diffusion from initial commercialisation to saturation. Three parameters in particular were of interest:

- K=the saturation level or asymptote, used as a measure of the *extent* of growth;
- Δt (delta t)=the time period taken to grow from 10% to 90% of K, used as a measure of the *duration* of growth (and inversely related to the *rate* of growth);
- t_0=the point of maximum growth, used as a measure of the *timing* of growth.

For industry level growth, we fitted logistic functions to the full data period except for technologies with distinct, sequential phases of growth (e.g., refineries). In these cases, logistic functions were fitted to the 1st phase of growth to the extent that it evidenced a clear plateau. For unit level growth, we fitted logistic functions to data describing maximum unit capacities or the unit scale frontier. We also used logistic functions to describe the change in average unit capacities over a technology's lifecycle, although only indicatively as average capacities around the asymptote tend to be highly variable (see Fig. 1) and so breach the accuracy criterion. For full details of the logistic function fitting, and its rationale, see (Wilson, 2009).

4. Results

We report findings that are broadly consistent across the sample of eight energy technologies analysed. We organise our findings in four sections. First, we characterise sequential phases in unit level and industry level growth (Section 4.1) emphasising the importance of an initial formative phase (Section 4.2). Second, we explore the up-scaling phase and its timing (Section 4.3). Third, we situate these unit level growth processes within the overall pattern of industry level growth (Section 4.4). We were particularly interested in the timing and duration of up-scaling at the unit level in relation to the expansion of production in industry level growth, as this could indicate the confounding of cost reductions attributed to learning effects with those attributable to unit scale economies.

Throughout, we present data and figures either globally or from the core region (market of first commercial introduction); however, all the findings discussed are consistent across different regions. For full details, see footnote 4 and (Wilson 2009).

4.1. Sequential formative, up-scaling and growth phases

The upper panels of Fig. 2 show unit level and industry level data for coal power through the 20th century. The left-hand graph shows the number of steam turbine units built each year, along with their average and maximum unit capacities. The right-hand graph shows the total capacity added each year as well as the cumulative total. Over the first 50 years of diffusion, slow growth in cumulative total capacity was driven by unit numbers. Unit capacities remained low, with maximum unit capacities typically in the 10–50 MW range. During the next 20 years, continued growth in cumulative total capacity was increasingly driven by a concentrated period of up-scaling at the unit level, though unit numbers also increased. Maximum unit capacities increased to around 1000 MW; average unit capacities to around 250 MW. For the next 30 years, unit capacities fluctuated around these levels, but sustained growth in cumulative total capacity was again driven by unit numbers.

This sequence within the overall diffusion pattern of coal power through the 20th century can be summarised as:

(i) a 'formative phase' of many smaller-scale units with only small increases in unit capacity;
(ii) an 'up-scaling phase' of large increases in unit capacities, particularly at the scale frontier, concurrent with an increase in numbers of units;
(iii) a 'growth phase' of large numbers of units at larger unit capacities.

The lower panel of Fig. 2 clarifies this sequence by plotting unit level and industry level growth on the same graph using logistic functions (lines) fitted to the data (markers), with both indexed to their corresponding saturation levels (shown in the box). This indexing means that the timing and steepness (growth rate) of the logistic functions are only meaningful relative to one another. However, the timing of up-scaling between the formative and growth phases is made very clear. Moreover, this basic sequence is found in each of the energy technologies analysed, although the timing and distinctiveness of the up-scaling phase varies.

The up-scaling phase of nuclear power, for example, occurred closer to the beginning of commercial diffusion if compared to the sequence for coal power shown in Fig. 2. The unique issues associated with managing nuclear fuel cycles coupled with the need to reduce capital costs drove rapid up-scaling from the mid-1960s to mid-1970s following a relative short formative phase. The build out of large capacity units continued until the late 1980s after which growth saturated.

Natural gas follows a similar pattern to coal, with units at the scale frontier rising markedly in capacity in the 1950s and 1960s, although in this case the growth in unit numbers was subsequent to, rather than concurrent with, this up-scaling phase.

Up-scaling in US refineries was concentrated during the several decades following World War II which is concurrent with the growth phase of the industry in total capacity terms. Increases in unit scale were largely saturated by the 1970s; industry-led growth similarly plateaus following the oil shocks.

For jet aircraft, the unit scale frontier was largely saturated by the introduction of the Boeing 747-100 in 1969 (see Fig. 1). This

[5] The 3-parameter logistic function takes the form: $y=K/(1+e^{-b(t-t_0)})$ with K=asymptote, b=rate, t_0=inflection point of maximum growth at $K/2$ about which the logistic function is symmetrical. (We also tested the Gompertz, Sharif–Kabir and Floyd functions which relax the symmetry requirement of logistic growth, but these were poorer fits to the data, see Wilson (2009) for details). The derived Δt (delta t)=$\log 81/b$ which is the time period over which y grows from 10% to 90% of K (or from 1% to 50% or 50% to 99% of K). For further details, see Marchetti and Nakicenovic (1979).

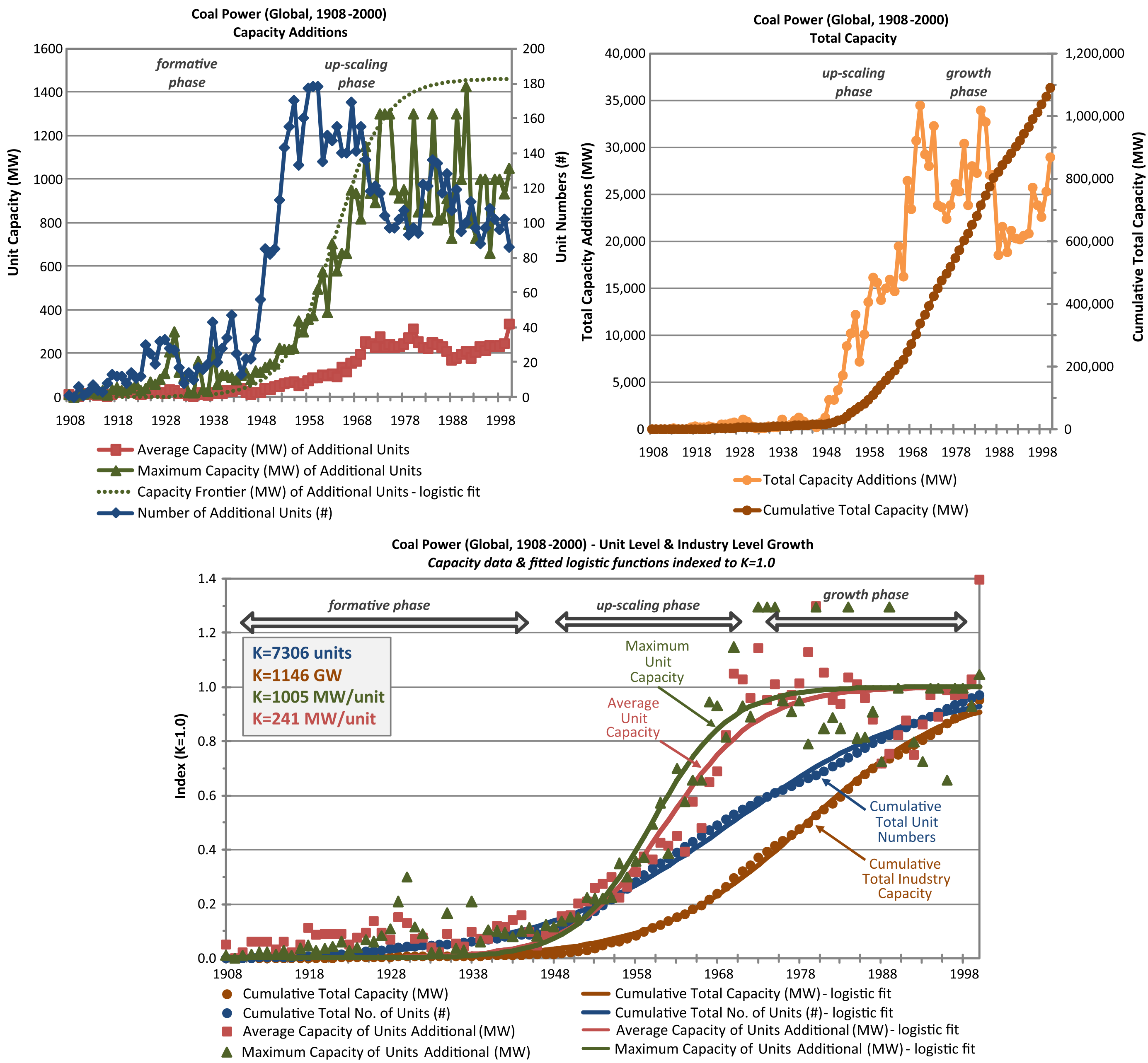

Fig. 2. Unit level and industry level growth in coal power globally. *Notes*: Upper left panel shows unit level growth in terms of the maximum capacity (green), average capacity (red), and numbers (blue) of additional units each year. Upper right panel shows industry level growth in terms of additional capacity each year (orange) and cumulative total capacity (brown). Lower panel shows logistic functions fitted to these data and also cumulative numbers of units (blue). Each logistic function is indexed to its respective asymptote; absolute asymptote values are shown in the box. Data from: Platts (2005); see Wilson (2009) for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

took place during the first 10 years of a 50-year period of continual growth in unit numbers.

By comparison, the successful commercialisation of modular end-use technologies in the 20th century (represented by cars and light bulbs in the sample analysed) has been associated with mass production rather than up-scaling or unit level growth. The average unit capacity of new cars grew from 7 kW to 140 kW over the last 100 years; the average unit capacity of new compact fluorescent light bulbs (CFLs) has held roughly constant at 15 W (IEA, 2006). The initial emphasis on unit numbers as the main driver of diffusion during the formative phase is therefore less remarkable. The subsequent up-scaling phase during which unit capacity increases (if at all) is less distinctive and more drawn out.

4.2. The formative phase: experimentation with many small-scale units

In the sequence through formative, up-scaling, and growth phases, wind power is an interesting case in that it combines clear up-scaling at the unit level with the modularity more characteristic of end-use technologies.

Fig. 3 compares unit level and industry level growth for wind power in Denmark, its 'core' region of first commercial application. The commercial history of new turbine models developed by Vestas, the leading Danish (and global) manufacturer, is used as an approximation of the unit scale frontier. The resulting up-scaling of turbines is still far from saturation, particularly in the

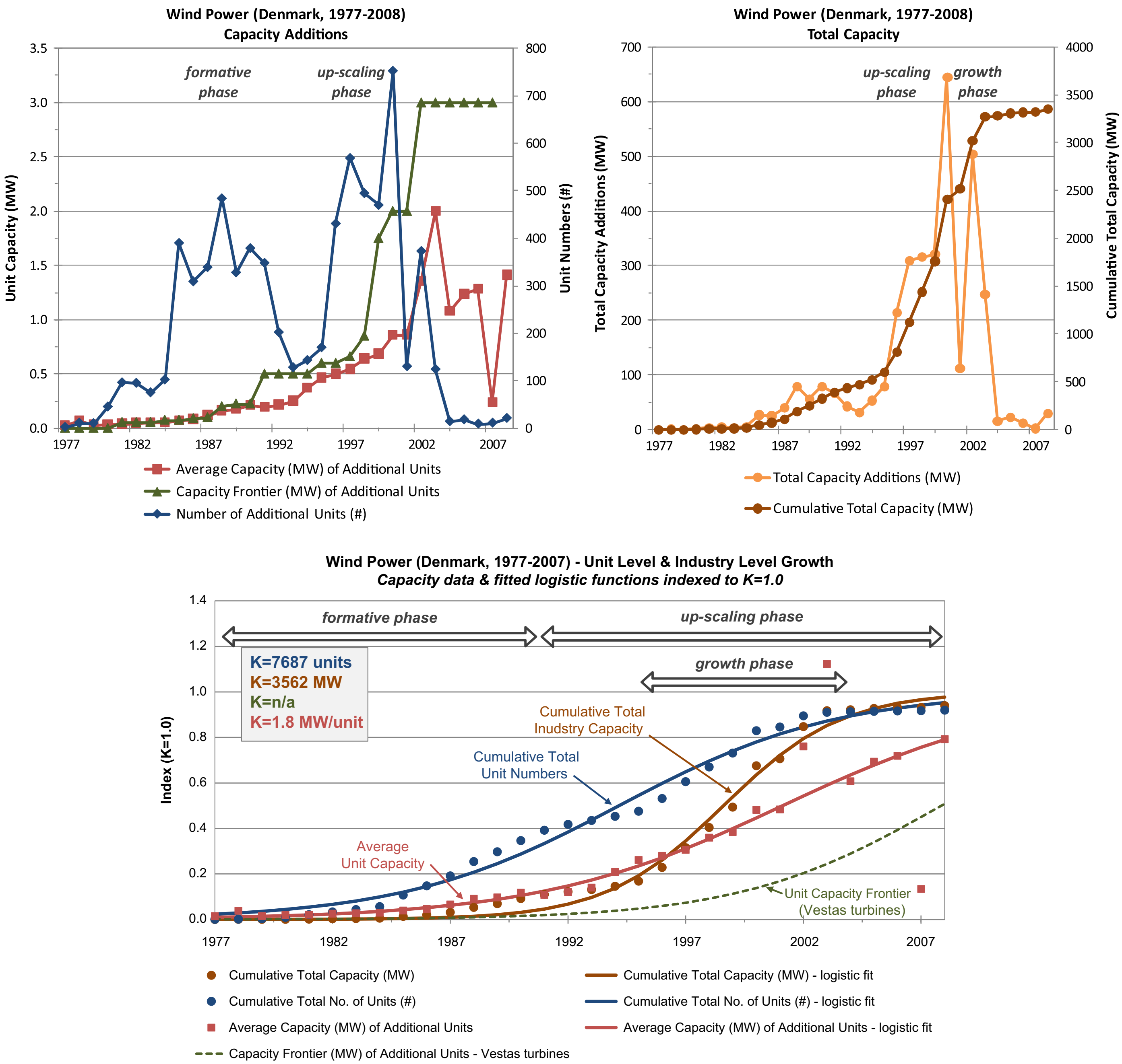

Fig. 3. Unit level and industry level growth in wind power in Denmark. *Notes*: Upper left panel shows unit level growth in terms of the maximum capacity (green), average capacity (red), and numbers (blue) of additional units each year. Upper right panel shows industry level growth in terms of additional capacity each year (orange) and cumulative total capacity (brown). Lower panel shows logistic functions fitted to these data and also cumulative numbers of units (blue). Each logistic function is indexed to its respective asymptote; absolute asymptote values are shown in the box. Data from: Danish_Energy_Agency (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

offshore segment for which 5 MW and larger unit capacities are envisaged (GWEC, 2008).

Notable in Fig. 3 is the lengthy formative phase which precedes the up-scaling phase. In the Danish wind case, this was a period of experimentation and learning from the build out of many units of a relatively small and fairly constant unit size from the late 1970s to the early 1990s, a period extending well into the full commercial application of the technology (Heymann, 1998). Importantly, learning was facilitated by relationships between industry actors supported by public investments in, for example, testing infrastructure which meant experiences fed back into subsequent designs (Garud and Karnoe, 2003). In contrast, countries like Germany, Sweden, and Netherlands placed early emphasis on rapidly increasing turbine capacities to capture unit economies of scale. In Sweden, for example, early government R&D emphasised up-scaling turbines to the 2–3 MW range in a context of uncertain market demand (Astrand and Neij, 2006). This premature move to the up-scaling phase failed to build an enduring industry (relative to the Danish case) (Meyer, 2007).

The importance of the formative phase as a precursor of efforts to up-scale unit capacities is further illustrated in Table 2 which compiles data for the five energy supply technologies in their core regions (which vary geographically and in size). The right-hand column shows the length and number of units built during a

Table 2
Formative phases of energy supply technologies. Formative phase runs from first commercial application to the point at which new units reach 10% of the eventual maximum unit scale.

Technology	Initial market	First commercial units installed	10% of Eventual maximum unit scale reached	Formative phase: number of years & number of units
Natural gas power	OECD	1900s	1948	50 years, >400 units
Coal power	OECD	1900s	1950	50 years, >775 units
Nuclear power	OECD	1950s (1940s)[a]	1963	10 years, 25 units
Wind power	Denmark	1970s (1880s)[a]	1987	15–100 years, >1400 units
Refineries[b]	US	1860s–1870s	(1948—average capacity only)	(80–90 years, >500 units?)[b]

[a] First nuclear installations on submarines date to 1940s; first wind power generators date to 1880s, but from 1970s in their modern form.
[b] Refineries data are indicative only. Maximum unit scale approximated by average capacity additions; number of units are rough estimate.

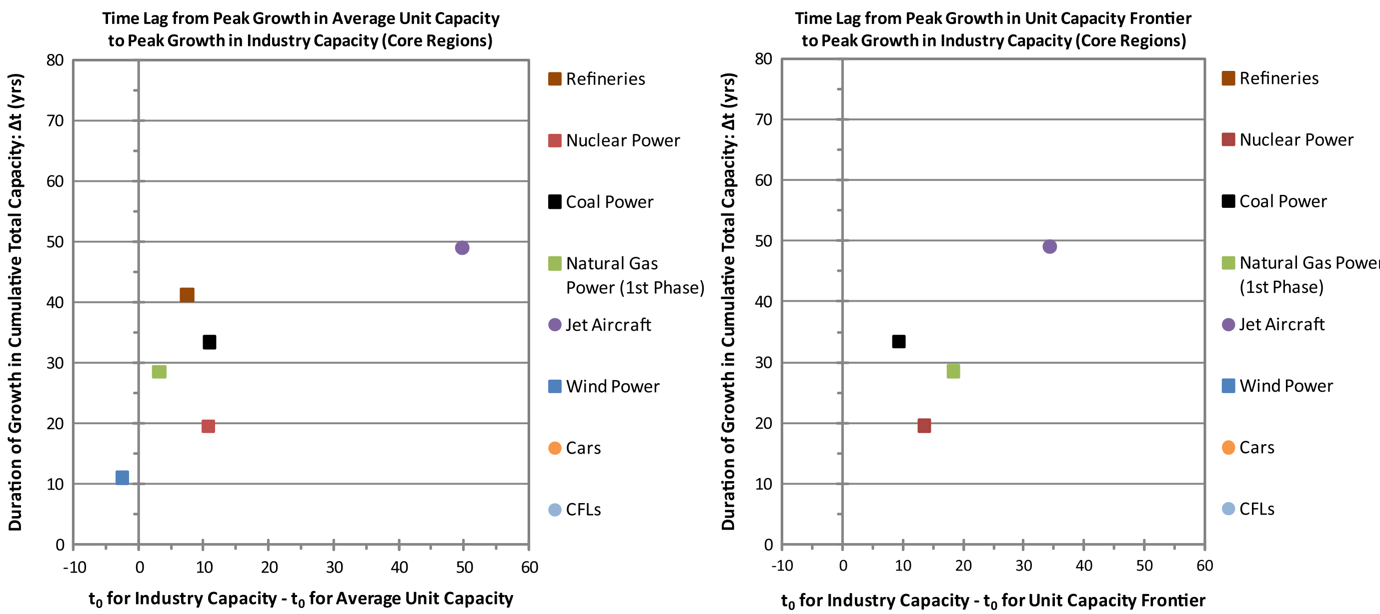

Fig. 4. Timing of unit level growth or up-scaling relative to industry level growth for different technologies in their core regions using available data. *x*-axes show period between year of peak growth (t_0) in unit capacity and year of peak growth in industry capacity. Left-hand graph shows average unit capacity; right-hand graph shows maximum unit capacity. *y*-axes show duration of industry level growth.

formative phase which runs from first commercial application to the point at which new units reach 10% of the eventual maximum unit scale. This formative phase lasts decades, and sees the build out of hundreds of units.

Nuclear power is the outlier with a relatively short formative phase and relatively few numbers of units built prior to up-scaling. The unit scale frontier of nuclear power increased five-fold in the decade that followed commissioning of the first 50 MW commercial reactor in 1956. Ultimately, these rapid increases in unit scale were a contributing factor to the rising complexity that created diseconomies of scale and constrained further growth of the industry in the late 1970s (Lovins et al., 2003; Grubler, 2010).

The initial formative phase of industry level growth shown in Table 2 describes the building out of large numbers of units over an often extended period. During the formative phase, technologies are repeatedly and iteratively tested, modified, refined, and adapted to market demands (Jacobsson and Bergek, 2004). This process may begin with demonstration plants or projects which are an "extension of the prototyping process into the next phases of development" (Hendry et al., 2010) and are widely used to prove the viability of scaling up small scale lab applications into commercial technologies (Sagar and Gallagher, 2004). Current and recent historical examples include carbon capture and storage (de Coninck et al., 2009), wind power (Harborne and Hendry, 2009), and solar photovoltaics (Hendry et al., 2010). Market niches with either price insensitive user preferences or support from public policy then provide a subsequent testing ground, protected from full commercial pressures.

But the length of formative phases shown in Table 2 suggests that experimentation extends well into the commercial diffusion phase of the technology's lifecycle, and contributes to the knowledge, technical skills, and institutional developments which underpin subsequent increases in the unit scale of a technology. Historical evidence suggests therefore that the formative phase is a necessary precursor to the up-scaling phase.

4.3. *The up-scaling phase: the timing of unit level growth relative to industry growth*

Fig. 4 compares the relative timing of up-scaling or unit level growth within the overall industry level growth for all technologies for which data were available and described by logistic functions (the figure legend shows the full sample). The left-hand graph uses average unit capacities as a measure of unit level growth; the right-hand graph shows maximum unit capacities. Data points further to the right describe technologies for which

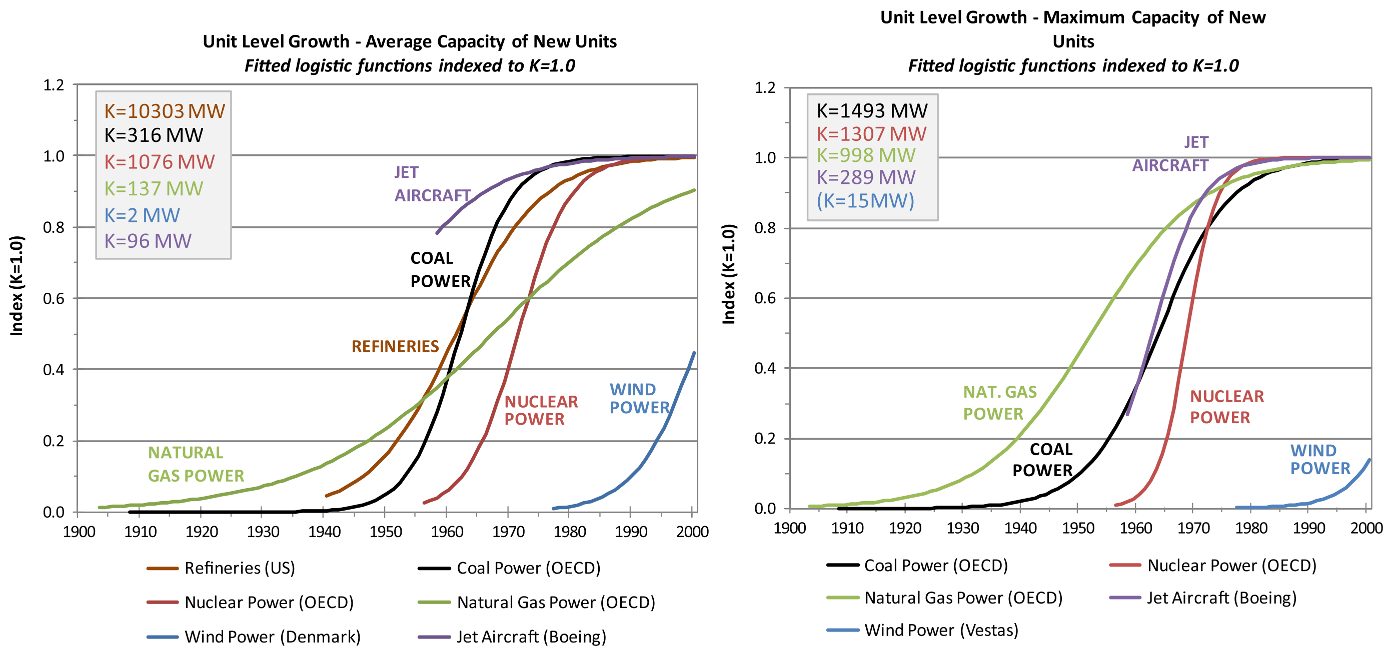

Fig. 5. Unit level growth or up-scaling in energy technologies in their core regions. Logistic functions fitted to data on average unit capacities (left-hand graph) and maximum unit capacities (right-hand graph). Each logistic function indexed to its respective asymptote; absolute asymptote values are shown in the box. For details, see Wilson (2009).

the rate of unit level growth peaks earlier than the rate of industry level growth (e.g., jet aircraft); data points further to the left describe technologies for which unit level growth peaks concurrently with, or after the peak rate of industry level growth (e.g., wind power). The y-axis plots the duration of that industry level growth from relatively rapid diffusion with low Δt's (e.g., nuclear power) to relatively slow diffusion with high Δt's (e.g., refineries).

The number of data points in Fig. 4 are limited, and jet aircraft is the only end-use technology represented (and an outlier on the left-hand graph). With these caveats in mind, two general patterns are observed. First, up-scaling peaks up to 20 years before industry growth peaks (data points to the right of the $x=0$ vertical axis). Second, up-scaling occurs earlier for technologies with longer diffusion times (data points slope upwards from left to right).

Fig. 5 shows logistic functions fitted to the time series data of unit level growth in terms of both average unit capacity (left-hand graph) and maximum unit capacity (right-hand graph). This allows easier comparison between the timing and rate of up-scaling between different technologies. As before, each logistic function is indexed to its respective asymptote with absolute values shown in the box. Average unit capacities in particular vary widely around these saturation levels (see Fig. 1).

Immediately evident in Fig. 5 is the slow rate of unit level growth for natural gas power. Jet aircraft and, to a lesser extent, wind power, also grow relatively slowly at the unit level compared to coal and nuclear power.

The up-scaling patterns shown in Figs. 4 and 5 are descriptive. They do not directly indicate the mechanisms or drivers of up-scaling. Yet the commonalities and differences between technologies allow certain inferences to be drawn in line with the existing literature (reviewed earlier).

First, the up-scaling phase preceding the main industry growth phase is consistent with the innovation literature on dominant designs. The dominant design of a technology settles on a particular set of key design concepts (Murmann and Frenken, 2006) and ensures the appeal of a technology beyond its initial niche markets (Abernathy and Utterback, 1978). Changes in unit scale become part of what Frenken and Nuvolari (2004) describe in evolutionary terms as a “growing variety and differentiation into distinct design species” (p. 420). This emphasises the important influence of different market segments or “application domains” on the evolution of the technology. Diffusion throughout these segments then comprises the main phase of industry level growth measured in terms of cumulative total capacity as in the analysis presented here.

Second, differences in the rates (and durations) of unit level growth can be attributed to the push and pull of economies of scale and market heterogeneity. Nelson and Winter (1977) noted that the pursuit of economies of scale was a natural element in many technologies' development trajectories, with up-scaling a common heuristic guiding innovation in the production of durable equipment (Winter, 2008). Using civil aircraft as an empirical case, Frenken and Leydesdorff (2000) found that up-scaling to exploit unit level scale economies occurred once the fundamental design issues had been settled, and a technology could then be adapted to the needs of particular market segments. ‘Technology-push’ drivers to drive down costs are thus tempered by and situated within ‘market-pull’ drivers demanding technologies at different, and potentially, larger unit scales. Slow growth in terms of average unit capacity (left-hand graph, Fig. 5) indicates technologies with heterogeneous applications in diverse market segments. Rapid up-scaling in terms of maximum unit capacity (right-hand graph) indicates technologies with strong unit scale economies. In other words, the larger the difference between rates of up-scaling described by maximum unit capacities (right-hand graph) and average unit capacities (left-hand graph), the stronger the countervailing influence of demand heterogeneity on scale economies at the unit level.

The potential tension between these two drivers are played out in the case of wind power as discussed above in the Danish context, but more clearly with natural gas power for which scale independence in terms of technical efficiency has meant its use in applications spanning distributed units in the kW range up to centralised combined cycle configurations in the 100s of MW or even GW range (Lee, 1987). Natural gas power up-scales much more rapidly in terms of maximum capacity ($\Delta t=29$ years) than average capacity (Δt=64 years), i.e., economies of scale but heterogeneous applications. At the other extreme, nuclear power up-scales rapidly in terms of both maximum (Δt=11 years) and average unit capacity (Δt=18 years), i.e., strong economies of scale with homogeneous applications.

An end-use technology like cars up-scales slowly in terms of both maximum and average capacity, i.e., weak economies of scale at the unit level and heterogeneous applications. The demand context for each technology determines the appropriateness of different unit scales and in general, market segments are more heterogeneous for distributed end-use technologies than for centralised energy supply technologies producing homogeneous energy carriers (e.g., electricity, liquid fuel).

4.4. The growth phase: industry level growth and substitute technologies

Fig. 6 compares the duration (Δt) of industry level growth between technologies in terms of both cumulative total capacity and cumulative total numbers of units. Technologies are ordered from top to bottom by increasing average unit capacity.

Two patterns are evident from Fig. 6. First, the duration of industry level growth is shorter in terms of cumulative total capacity than cumulative total unit numbers. This again points to the formative phase of early commercialisation during which unit numbers are built out before unit capacities are up-scaled, so extending the duration of diffusion in terms of unit numbers.

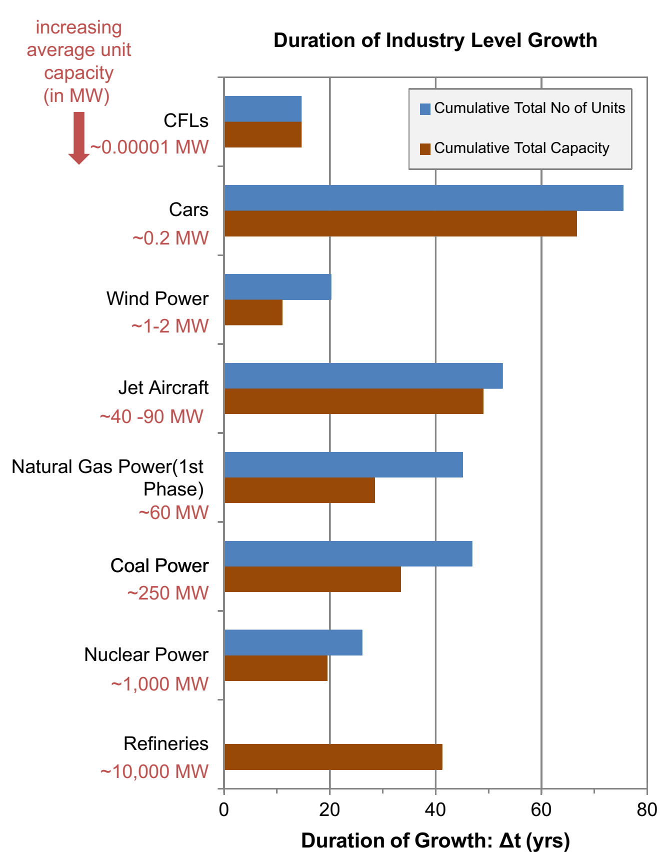

Fig. 6. Duration of industry level growth for eight energy technologies in their core regions. Duration of growth (Δt) in terms of cumulative total numbers of units (blue bars) and cumulative total capacity (brown bars). Technologies are ordered from top to bottom by increasing average unit capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Second, the duration of industry level growth tends to be shorter as technologies increase in unit capacity (bars get shorter from top to bottom). Compact fluorescent light bulbs and wind power are clear exceptions to this pattern, with relatively short duration growth despite relatively small unit capacities. There are various possible explanations. They are both less capital intensive in $ per unit terms (not $ per MW), and have more recent introduction dates into more globalised markets, potentially accelerating knowledge transfer ('spillover') effects and driving a faster increase in manufacturing capacity and market development. A more probable explanation, however, is also the simplest: compact fluorescent light bulbs and wind power are both direct substitutes for incumbent technologies (Grubler et al., 1999). As a result, the diffusion of these technologies required less concurrent change in associated infrastructures and institutions (Rip and Kemp, 1998). This ready substitution is markedly different from the early coal, gas, and hydro-driven expansion of the electricity system earlier in the 20th century.

5. Discussion

5.1. Implications for experience curve analyses

The timing of the up-scaling phase following the formative phase and preceding the industry level growth phase supports the argument that learning rates are sensitive to time periods analysed (Nemet, 2006; Lindman and Soderholm, 2012). Experience curve analyses may be preferable on time series data covering first commercial introduction through to maturity (McNerney et al., 2011), though this is rarely the case. Experience curve analyses which model the relationship between cumulative production and cost during the up-scaling phase but not the subsequent growth phase are more likely to overstate industry level learning rates.

The conflation of production experience with up-scaling effects as the source of observed unit cost reductions is more likely for technologies with clear economies of scale at the unit level and technologies servicing homogenous market demands. Such technologies are characteristic of energy supply and conversion, and particularly centralised electricity generation of an almost perfectly substitutable product (Kalkuhl et al., 2012). Centralised energy supply technologies (including nuclear power, coal power, and refineries in the sample analysed) up-scale rapidly in terms of both maximum and average unit capacities earlier on in the overall growth of the industry, so at a time when production experience and learning effects are also salient. Due to the mismatch between large scale supply and distributed end user demand, up-scaling or unit level growth is dependent on, and has been enabled by, the concurrent scaling up of distribution infrastructure (e.g., pipelines, tankers, grids) and associated institutions (e.g., wholesale and retail markets) (Grubler, 1990).

By comparison, modular end-use technologies service diverse market demands and user preferences. Up-scaling of the unit size of technologies is less marked, more drawn out, and less conflated with the learning effects and scale economies associated with production or manufacturing (including cars and CFLs in the sample analysed).

5.2. Limitations

The findings of this analysis are first order. Their inherent generality and the limited sample size means their application to selected energy technologies, past or future, should be treated with caution.

5.2.1. Limited sample size of selected technologies

Findings could be interpreted with greater confidence if more data points are found to fit the observed patterns. Time series data for eight technologies were analysed from an initial sample of 11 (see Table 1). Technologies were selected based on: (i) significant contribution to energy conversion and/or end-use service provision; (ii) maturity of observed growth to allow reliable logistic function fitting; and (iii) available data. A combination of (i) and (ii) meant the eight technologies sampled had made a significant observed contribution to the energy system historically through their widespread diffusion. This should not, however, be interpreted as underwriting their future success. Further data collection should extend the scope of energy technologies analysed, particularly end-use technologies. Examples include piston aircraft, steamships, rolling stock, industrial motors, and any number of household appliances (e.g., fridges, microwaves, TVs). Inclusion of biofuel production (e.g., ethanol, biodiesel) would extend the set of non-power energy supply technologies.

Using capacity as a metric of scale fails to control for key technology characteristics which vary between technologies. These include capital stock turnover, conversion efficiencies, and load factors. Further analysis should examine the effects of a technology's lifetime and efficiency on the timing and extent of the up-scaling phase, relative to other technologies.

5.2.2. Generality

The eight technologies analysed moved through their respective formative, up-scaling, and industry growth phases at different times, over different geographies, and in different institutional contexts. The findings presented and inferences drawn are therefore inherently general. Innovation studies make clear that the drivers and mechanisms of – in this case – up-scaling will vary as a function of institutional, infrastructural, and other differences between innovation systems at different scales (Edquist and Johnson, 1997; Jacobsson and Lauber, 2006). Local knowledge and institutions are needed to develop, manufacture (or import), adapt, install, and above all, use a new energy technology effectively (Grubler et al., 2012).

At best, therefore, the inferences drawn offer an interpretation of observed generalisable patterns whose interest lies precisely in the commonalities found among very different energy technologies. This is particularly marked spatially. The time series data presented describe the growth patterns of energy technologies either globally or in each technology's respective 'core' region of first commercial application. For the eight technologies analysed this includes: the OECD (coal, nuclear, gas power), Denmark (wind power), the US (refineries, cars), North American and Western Europe (aircraft, CFLs). The findings presented also held for each technologies' respective 'rim' and 'periphery' region, ranging from the former Soviet Union to current day Africa.

6. Conclusions and policy implications

6.1. Summary of findings

Table 3 summarises the key findings of this analysis of unit level and industry level growth on a sample of eight energy technologies ranging from 10 GW-eq. oil refineries to 15 W compact fluorescent light bulbs. In particular, an up-scaling phase in which technologies increase rapidly in scale at the unit level is found to follow an often extended formative phase and precede the main growth phase of an industry. This has an important implication for experience curve analyses which may conflate unit scale effects with learning effects in the attribution of observed unit cost reductions over time. The coincidence in time of the up-scaling phase with learning processes is likely to be particularly acute for centralised energy supply technologies with clear economies of scale in homogeneous market segments. Examples in the sample of technologies analysed include large-scale power plants and refineries.

6.2. Implications for technology policy: a conceptual framework of unit level and industry level growth

The commonalities shown in Table 3 for a range of energy technologies also offer some insights for policies aiming to support the diffusion of low carbon energy technologies.

Fig. 7 draws together the various factors found to have enabled or influenced unit level growth in the context of industry level growth. Each factor is illustrated by technologies both historically as covered in the analysis (grey) and also suggestively in the future in low carbon scenarios (grey italics).

These unit level enabling factors are broadly of two types:

- *Characteristics specific to the technology*: Returns to scale, 'retrofitable', modularity, and flexibility.
- *Characteristics specific to the market or system into which the technology diffuses*: Expanding production, and complementary technologies and institutions.

Table 3
Summary of findings on unit level and industry level growth in a sample of eight energy technologies.

Theme	Section	Empirical finding	Example technology
Sequential phases in unit level and industry level growth	**4.1**	Industry scaling in capacity terms is driven first by unit numbers, then by unit scaling, then again by unit numbers. This is described by the sequence through a 'formative phase', an 'up-scaling phase' and a 'growth phase'	Coal power
	4.2	The formative phase lasts several decades, involving experimentation with many small-scale units as a precursor to up-scaling	Wind power
	4.3	The midpoint of the up-scaling phase can occur up to 20 years before the midpoint of the growth phase	Jet aircraft
Up-scaling	**4.3**	Rates of up-scaling are a trade-off between economies of scale and demand heterogeneity across different market segments	Natural gas power
Industry growth	**4.4**	Rates of industry level growth are more rapid for technologies with larger unit capacities, and technologies that are ready substitutes for incumbents	Nuclear power, CFLs

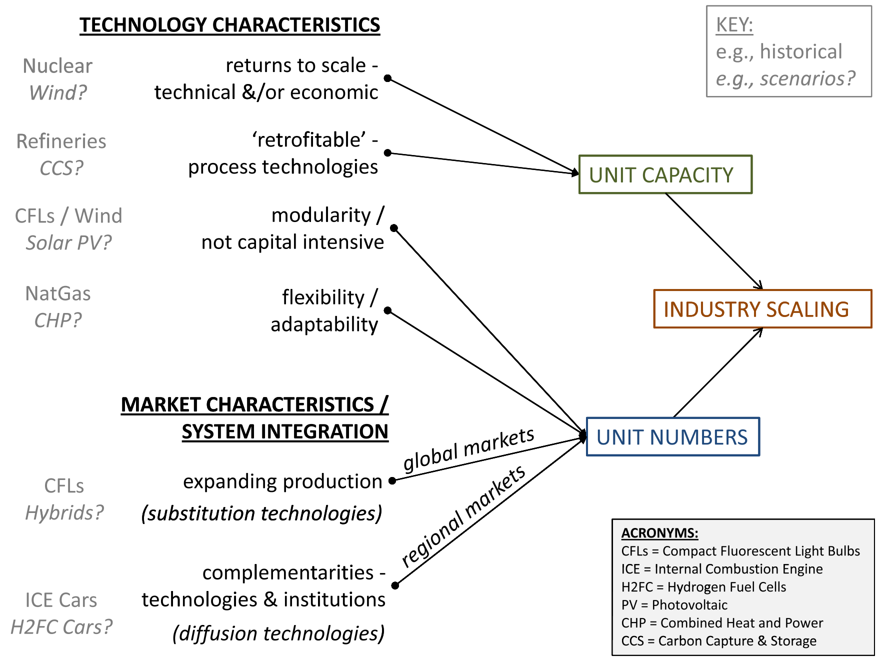

Fig. 7. Unit level enabling factors for industry level growth. Illustrative technologies are shown for each enabling factor both historically (grey) and prospectively (grey italics).

All these have been discussed in earlier sections with the exception of 'retrofitable'. This describes up-scaling through the retrofitting of existing units rather than the building of new units, and is a distinctive characteristic of process technologies such as refineries.

Interpreted as potential levers for technology policy to exploit, the enabling factors outlined in Fig. 7 comprise different 'routes' to the industry level growth of low carbon energy supply or efficient end-use technologies. Depending on the characteristics of the technology in question, policies can target unit numbers or unit capacities. Policies to support scaling of unit numbers might protect diverse market niches for small-scale distributed applications, or might diversify R&D investments for a technology across multiple sectors and operating environments. Policies to support scaling of unit capacity might co-fund demonstration projects and field trials testing large-scale infrastructure, or might streamline the licensing process for up-scaling retrofits.

Timing, however, is important. Up-scaling without sufficient numbers of commercial 'experiments' (or small-scale applications) risks being premature, as in the Danish success in wind power compared to other countries' relative failures. This strikes a cautionary note for policies acting too early in a technology's commercial lifecycle to support up-scaling, and similarly for policies which presume rather than support the discovery of returns to scale.

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