Long Term Prospectives of Emerging Energy Technologies

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***Abstract**: Reducing the flow of greenhouse gas emissions to stabilize the stock of greenhouse gases, especially in the context of an expanding global economy, require substantial changes in global energy technology mix. Future technology change will come in form of technologies expected to mature in the near or distant future and technologies not yet known.*

Endogenous technological change has been introduced in strategic energy analysis since about the mid 1990s by implementing so-called energy technology learning rates, which specify the quantitative relationship between the cumulative experience of a given technology and the cost reductions. Emerging technologies typically evolve through several stages of development. A topical question is how technologies pass from one stage of development to another. The possible changes in the cost trends of emerging technologies can be assessed by different but complementary approaches.

In this report, basing on recent empirical data the long time perspectives of emerging energy technology progress will be scrutinized. An analysis of the technical factors was carried out to identify future barriers that can lead to discontinuities in the slope of experience curves. A comparativ analysis was presented at different stages of development including a range of contributing parameters to the learning rate changes. The role of underlying industry characteristics was outlined as well. The cross analysis of the major sources of historical cost reductions for more mature technologies also provides insights to the future cost reduction opportunities.

1 Introduction

Transition from the conventional energy systems used today to one powered by sustainable energy sources is driven by large scale changes such as rapidly increasing energy demands of developing nations, shrinking fossil fuel reserves, concerns over the impact of carbon emissions on global climate change, which could have staggering impacts on the global economy if transition to a secure energy supply is not realized.

The development of the energy infrastructure in use today had its beginnings in the 19th Century. Its development can be described as an evolutionary process not as a designed system project. With the exemption of nuclear fission and hydro power, the energy system of the twentieth century relied upon the combustion of fossil fuels: initially coal and oil and now increasingly natural gas. Planning of the future energy supply mix must be based on the current state and prospects of technology options. The promise of the future technological progress can allow us to envisage energy systems that are capable of realizing climate change mitigation goals. The improved and new technologies will enable:

- to use energy more efficiently, thereby reducing energy consumption and GHG emissions,
- utilize alternative energy carriers that emit less GHG per unit of the final product,
- using systems engineering principles to create alternative means of meeting needs in ways that are less GHG intensive.

This report presents likely progress paths of a couple of energy technologies in different phases of their life cycle considered to be able to tackle the long term challenges. The technologies range from more mature to much less developed options.

Two types of technology performance metrics were investigated:

- future energy technologies potential.
- cost improvement potential.

Energy supply models now use experience curves to endogenate improvements in technology. In the planning and forecasting applications emphasis has shifted away from learning curves based on employee productivity and plant-level analysis, toward experience curves aggregating industries and including all cost components. Despite many shortcomings, a simple experience curve using price data alone can be an effective estimator of future prices for technologies during their growth phases in a competitive international market [1].

The most commonly used single-factor experience curve describes how unit cost decline with cumulative production. While the use of experience curves should not bee seen as a deterministic theory of technological learning, the trend has been observed across many technologies and can provide insight into the future cost perspectives. However, transferring experience curve analyses of historical data to prospective studies must be made very carefully. For the purpose of estimating technology learning rates, a proper level of data aggregation has to be choiced. As this report aims to study global patterns of technology changes, we strive to use aggregate global level data.

The electricity supply system has a pivotal role to play in ensuring environmental and social sustainability of future economic and energy systems due to the size of its contribution to the GHG emissions. Hardly any other sector has such a wide range of emerging and prospective technologies promising to transform the conventional energy systems. It is therefore important to survey the developing electricity technologies and to asses their future development potential. The full picture of technological change should not only consider experience curves for specific technologies but also the effects of spill-over in a cluster of related technologies. For example technologies which utilise CO_2 capture and sequestration in some form will also have many common plant components and will experience spill-over benefits from increasing experience pertaining to any other plant type.

2 Technology Development Life-Cycle

Technology development is conceptualized as a gradual process that involves different stages of progress. There is an ample evidence from the literature that energy technologies have distinct stages of development that correlate to different learning rates. A way to improve the prediction possibilities of experience curve could be to include more information on the stage of development of a specific technology. The future energy technologies exhibit different stage of development and maturity. Several authors identified three phases of development (radical, incremental and mature), others place the technologies in four categories (emerging, evolving, mature and reviving). The distinction between the two classfication is in the identification of the reinvigoration phase.

Emerging technologies have existed for a relatively short time and have almost, no market share, and may never reach any significant commercialization. In the light of existing low levels of installed capacity and presence of market constraints, the emerging technologies are likely to have significant potential for cost improvement. However, for several advanced and complex technologies early cost estimates based on laboratory-scale projects and pilot plans were typically lower than the costs subsequently realized for the early commercial plants. Thus the costs often increase rather than decrease in the early phase of commercial deployment. The liberalisation of the industry has increased the dependence of the emerging technologies on public R & D and promotion schemes.

Incremental / evolving technologies have niche market commercialization and have potential for significant cost reduction. Evolving technologies have faced some market constraints, that limited their growth. Their moderate or low levels of installed capacity suggests that this technologies still prossess scope for significant capacity increases and cost reductions. Incremental development exploits existing technology, focuse on cost or feature improvements, improves competitivness within current markets or industries.

Technologies in the mature category have been developed and utilized over a long period of time and have had a major share of the expansion of the energy industry worldwide. These technologies due to their maistream position and widespread use, have found few market constraints. Mature technologies generally have saturated the market, have well known characteristics and have limited potential for cost reductions. Given the high levels of existing capacity for established technologies, a doubling of capacity and further cost improvements can only take place over a long period of time.

Reviving technologies have been utilised for a long time. The existing high levels of installed capacity for these technologies suggest that they have limited capacity for cost reductions. Besides purely technological developments, myriad factors such as market competition, changes in industry structure, fuel prices and regulations related to health, safety and environment affects the reinvigoration of mature technologies.

A topical question is how technologies pass from one stage of development to another. The possible changes in cost trends of developing technologies can be assessed by different approaches. As installed capacity increases, eventually an emerging technology can become evolutionary and an evolutionary plant can become a conventional one. Therefore, there must be some point defined when technologies are assumed to pass from one vintage to another.

The inflections between vintages are called breakpoints [2]. According to this reference, a revolutionary technology is redefined as an evolutionary technology after three doublings of capacity, and an evolutionary technology is redefined as a convetional technology after five doublings of capacity. Potentially, even a revolutionary technology could become conventional after eight capacity doublings.

However, rather than being a simple linear process, the different stages of technological development are highly interactive. Each stage of development process requires different types of incentives to promote the over all goal of technology change.

3 Development of Low- or No-Carbon Energy Technologies

3.1 Photovoltaics

The cost of photovoltaics (PV) has decreased by a factor of nearly 100 since the early 1950s. Markets for PV are expanding rapidly, recently growing at over 40% per year. However, PV does not compete economically with conventional sources, such as coal and gas, or even with leading renewable sources such as wind and biomass. PV in the evolving phase remains a niche electricity source.

In a 26-year long period from nascent commercialialization (1975-2001.) there was a factor of 20 reduction in the cost of PV modules. Crystalline silicon PV comprised over 90% of production over this period and its share increased in the second half of the period [3]. In explaining cost declines in this time period plant size and cell efficiency were the most important contributors to cost reduction, cost of silicon was moderately important and other factors (e.g. wafer size, poly-crystalline share etc.) were of minor importance. The importance of economies of scale fits with other studies [4]. According to expert assessments the share of material price in the total cost of the module is likely to grow in the upcoming years.

Supposing that the two most important sources of the cost reduction remain the scale and efficiency improvements in the future, the single extension of the historical learning rate and using an 11% anual growth assumption would deliver 1 USD/W modules in about 2030 and 0.10 USD/W modules in about 2090. There are claims that 1 USD/W modules would be too expensive once PV accounts for more than 5-10% of total electricity generation. It is very difficult to predict which of the more innovative developing technologies will break through and when this breakthrough will occur and how its experience curve will look like. Producing electricity on this basis is among the most expensive GHG abatment options. PV should nevertheless be included in long-term energy scenarios.

3.2 Wind Turbines

Wind energy has historically been used to support human activities. Since 1980s wind turbines are considered an important technology mitigating GHG emission, as wind energy is considered clean and safe. Since the early 2000s off-shore wind turbines have been developed and installed. Harnessing wind energy through on-shore and off-shore wind farms has been one of the fastest growing forms of renewable energy in the past decade. Currently, installed world capacity is in the range of 100 GW and second only to hydropower as a source of renewable eleectricity.

Some 60% of cost reductions in the last two decades are estimated to be the result of economies of scale brought about by increased market volume. The remaining 40% of cost reductions can be attributed to technology improvements. However, analyses point out that it appears to be almost impossible to distinquish between reductions due to technological learning and those due to scale effects. The cost reductions presented in different studies varies considerable. Using a large number of price observations, the authors of [4] estimated that the costs for wind turbines have fallen by 12.7% with every doubling of installed capacity.

Technology development and further experience will reduce cost of both on-shore and off-shore wind turbines. As historical cost reductions can be described as a result of incremental technology improvements, the future cost reductions are likely also to rely on incremental improvements. Based on the past experience of incremental improvements, a cost reduction of 10% per every doubling of the installed capacity can be suggested for on-shore as well as off-shore wind turbines.

3.3 Bioenergy Systems

The bioenergy studies reveal large differences to estimate empirical experience curves for investment costs of biomass fuelled power plants. The raison are the varying plant costs due to differences in scale, fuel type, plant lay out, region, etc. The cost of bioenergy will depend on both the bioenergy feedstock and on the conversion techmologies. The biomass systems are complex and comprise many types of combinations of conversion technologies and supply chains. Smaller cost reductions will be expected for well established, mature technologies and larger cost reductions may be achievable for new innovative technologies. For large fluidized bed boiler plants, the total plant costs have fallen by 7-10% with every doubling of installed capacity [5]. The experience curve approach seems to be more efficient when poduction costs of the final energy carrier are analized. Electricity from biofuelled CHP plants yields an 8-9% reduction ef electricity production costs with each cumulative doubling of electricity production. Compared to other technologies- such as wind power or solar PV- significant learning by doing occurs during plant operation and maintenance. For conversion technologies a 5% cost reduction can be estimated for every doublings of installed capacity. This assumption is based on the experince gained with advanced fossil fuel technologies.

3.4 Natural Gas Combined Cycle Power Plants

Natural gas combined cycle power plants (NGCC) feature the best efficiency of all thermal based electricity generation technologies applied nowadays. The efficiency is mainly governed by the efficiency of the gas turbine turbo set. The 60% efficiency barrier can be reached in the near future. However in the long run of the future development the efficiency of natural gas combined cycle power plants will not exceed the 65% barrier. As to the costs of installed capacity gas turbines are the most cost-effective technology for electricity generation. This was not the case four decades ago. The technology could be charecterized as precommercial until the early 1960s, the costs were high. After about 1963 the improvement rate has an average value of 22% per every doubling of the installed capacity. Later in the time period of 1975-1993 the improvement rate declined and it has an average value of 13% per every doubling [6]. The specific investment costs are anticipated to further decline with a learning rate around 5% as higher unit capacity gas turbines are assumed. However, the decline of the specific investment costs is likely level off in long run. Thus, NGCC technology is likely to remain the benchmark technology for some years to come.

3.5 Pulverized Coal-fired Power Plants

Among various fossil fuels, coal is abundant and widely reserved throughout the world, it is one of the most important enery sources.

Pulverized coal-fired power plants have undergone significant technological change over the past century, and are expected to be an important part of future power generation portfolios. Technology improvements in pulverized coal boilers along with other plant components have yielded significant economies of scale and efficiency gains, reliability and environmental performance of the overall power plant. When only the best commercially viable plants were considered, a study found sustained improvements in the overall thermal efficiency of PC plants over 1940-2005 with an average rate of improvement of 3.8% for every doubling of cumulative worldwide capacity [7]. If this trend continues, the projected thermal efficiency of commercial PC plants may reach 46.4% when the estimated worldwide installed coal-fired capacity reach the level of 2000 GW, which is estimated at 2030 [8]. Climate policies and regulatory actions could accelerate the efficiency improvements.

For new PC boilers, the capital cost reduction for every doubling of installed capacity averaged 5.6% over the period of (1942-1999).

3.6 CO_2 Capture and Sequestration

In 2007 the global electricity demand was 18.783 TWh of which 2/3 was generated by fossil fuels. Despite the growing climate change concern, the electricity demand will increase and a major part of the electricity will be generated by fossil-fuelled technologies.

CO_2 capture and sequestration technolgy (CCS) is an important new class of environmental technology with the potential to allow continued use of fossil fuels without significant GHG emissions. CCS is a technology that has the potential to yield dramatic reductions in CO_2 emissions from fossil fuel use by capturing the CO_2 that is currently released to the atmosphere. An important feature of the CCS technologies are thermodynamic effficiencies, which are approximately 10% less than generation technologies without carbon capture and sequestration. Integration of CO_2 capture, transport and geologic sequestration has been demonstrared in several indutrial applications.

Recent studies of CO_2 capture and storage for power plants have focused on currently available technology. Reliance on cost estimates for current technology has the disadvantage of not taking into account the potential for improvements that can affect the overall role of CCS as a climate change mitigation strategy and the log-term competitiveness of CO_2 capture systems in different applications. However, widespread CCS deployment will not occur without a sufficiently strong climate policy driver. Thus, changes in CCS costs over time depend on the policy scenario and its influence on total installed CCs capacity in competition with other carbon mitigation options. In a preliminary modeling study an average learning rate of 12% was used to model the expected rate of capital cost decline for CCS systems in the long run [9].

4 Future Energy Technology Mix

Future energy technology mix can be the response to the long term challenges facing the humanity:

- tackling climate change by reducing carbon dioxide emissions.
- ensuring secure clean and affordable energy supply in face of growing energy needs.

Each technology examined in this study has its own set of characteristics that are valued to more or lesser extents depending on the contextual issues. Research results show that fundamentally different future energy system structure might be developed with similar overall costs [10].

According to this recent energy–systems engineering study, the endogenous technology learning with its uncertainty and spillover effects will have the greatest impact on the emerging energy system structures during the first few decades of the twenty–first century. However, fundamental changes in global energy systems tend to occur slowly. The new technologies can take over the market gradually. The share of the market cotrolled by a new technology plotted against time follow an S-shaped function. In the beginning risk avers firms hesitate to use the new technology. The diffusion rate increases over time as uncertainty is reduced. A change in costs over time also accelerates the spread of new technologies. Long lived capital in the old technology may only be replaced with a new technology as the old phisically depreciates. Thus, the transitional process from the first feasible prototype to the technology diffusion takes time.

Owing to the uncertainty in experience curves, the optimal solution becomes less certain. As a result, there is a broader investment portfolio of technologies with slower diffusion of any particular technology.

Concerning the future fuel mix, energy outlooks tend to agree that the contribution of renewable energy source will increase but no dominate the electricity generation sector in the next decades.

According to a recent projection of the world total electricity generation, conventional fossil-fired technologies, which are primarily coal-based, predominate other forms of generation accounting for 64.5% of total production in 2035 [8]. Limited penetration of wind and solar (4%) with 2.5 and 3 doublings of installed capacity reflects the fact that they are imperfect substitutes for electricity from other generation sources. They are intermittent, and could only penetrate further with investments in storage, redundant capacity or through use of reliable back- up technology. The biomass share in power generation can reach the same level as well.

Table 1

Learning Rates of Energy Technologies

Technology	Period	Classification	Cost reduction/capacity doubling (%)	Reference
PC boilers	1942-1999	Reviving	5,6	7
NGCC	1950-1963	Emerging	n.a.	6
NGCC	1963-1980	Evolving	22	6
NGCC	1975-1993	Mature	13	6
Wind	1991-2003	Evolving	12,7	4
PV	1975-2001	Evolving	23	3
Biomass cofiring	1980-1995	Evolving	15	5
Biomass cofiring	1995-	Mature	7-10	5
CCS	2001-	Emerging	12	9

Conclusions

A critical factor governing future anthropogenic emissions is the rate and magnitude of technological change toward low- or no-carbon technologies. Any successful strategy to significantly reduce GHG emissions will require actions not only to deploy low-emisssions technologies that are available now, but also to foster innovations on new technologies, many of which have not yet been invented, commercialy developed or adopted at a significant commercial scale. A wide range of technologies from more mature to much less developed technologies could reduce GHG emissions. A fundamental lesson learned from the experience curve studies is that low carbon technologies are more costly than the conventional technologies, but the costs of formers can be assumed to decrease with increases of their market share so that at a given moment they will be more attractive choice than the old technology, which is more mature and experiences less cost reduction. The results of the study indicate that there are significant prospects for accelerated development for a range of low-carbon technologies, including wind power, solar PV. However the pace of acceleration differs across the technology mix due to the different stages of development (Table 1).

The uncertainty of long-term technology projections can be reduced by a combination of experience curve analysis and judgemental methodologies, such as interviewing experts, expert panels, etc.

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