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Electricity intensity backstop level to meet sustainable backstop supply technologies ☆

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Abstract

The concept of a backstop level of electricity intensity[1] is introduced and illustrated for the highest income economies of the world. The backstop level corresponds with the intensity that would be triggered by applying end-use electricity prices equal to the cost price of a fully sustainable electricity supply.

Section 1 of the paper discusses the issue of electricity (also energy) intensity of economies. It is argued that identifying a "demand for electricity intensity" bridges the gap between the high willingness to pay for electricity services on the one hand and the disinterested attitude of consumers regarding the invisible and impalpable product electricity on the other hand. Assessment of the demand curve for electricity intensity in a cross section of high income OECD countries comes to a long-run price elasticity of almost −1.

Section 2 revives Nordhaus' concept of backstop supply technologies for weighing three power sources (fossil, nuclear, and renewable sources) in meeting today's criteria of sustainable backstop technology. Only renewable sources meet the main sustainability criteria, but the economic cost of a fully sustainable electricity supply will be elevated.

The closing question of Section 3, that is, whether the countries can afford the high cost of backstop electricity supplies, is answered by indicating what reductions in intensity are required to keep the electricity bills stable. The targeted intensity level is called the backstop level, and provides a fixed point for electricity efficiency policies. The analysis supports the call for comprehensive and enduring tax reform policies.

Keywords: Electricity intensity; Price elasticity; Sustainable energy supply

0. Introduction

The futures of hydrogen and of electricity have a lot in common. Both energy modes are secondary, i.e. they are conversions of primary energy sources. So far, the primary sources generating hydrogen and electricity worldwide are mainly fossil fuels (Rifkin, 2003).

Today large-scale hydrogen supplies are a by-product of ammonium plants or purposely converted from fossil fuels (natural gas being the most productive source). Direct extraction of hydrogen from water by electrolysis consumes about 4.5 kW h electricity/m^3. Hydrogen as a long-term future energy mode cannot depend largely on the conversion of fossil fuels but needs the input of sustainable electricity supplies.

The supplies of electricity and of hydrogen will be intimately intertwined. One produces hydrogen from electricity (electrolysis) and one generates electricity from hydrogen (fuel cells or combustion in internal combustion engines, etc.). Because the manufacturing and handling of hydrogen is more cumbersome and expensive than the ones of electricity, it is expected that bulk electricity will serve as a source for producing hydrogen that after distribution

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[1]Intensity (kWh/GDP) and efficiency (kWh/activity) are related by the identity "Intensity = Structure × Efficiency" with structure being activity/GDP. Intensity can be observed statistically, but efficiency is difficult to observe and to measure. For a cross-section of wealthy OECD nations, Verbruggen and Couder (2004) show that most of the variability in electricity intensity is explained by a varying degree in implementing efficient solutions. This article focuses on "intensity", but most of the results are valid for "efficiency" too.

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may be reconverted into power. The future of hydrogen is, to a large degree, dependent on the future of the supply of electricity (European Commission, 2003b, p. 11). Because the latter energy mode has been developing since the end of the nineteenth century and is still rising in volume and in market share, the study of electricity supplies in a sustainable future is very instructive to assess the perspectives for hydrogen. Analysing the role of electricity in our societies and predicting its future can be based on more observations, studies, models and forums than there are available about hydrogen directly. This explains why this article is centred on the supply and the use of electricity.

The article is organised in three parts. Section 1 deals with the question of electricity intensity of economies. First, the IEA forecasts are discussed. Then some of the literature is discussed. Data of electricity intensities in a sample of high income countries are shown. Next, a regression of intensity on price is proposed and it is argued why people maintain a "demand for electricity intensity". Section 2 is a brief discussion of the electricity supply options with an argument that only renewable electricity generation can be labelled sustainable, and can be considered the backstop supply options. In Section 3, demand and supply are brought together to derive the electricity intensity backstop level that economies should realise to keep their electricity bill at the present level when the kilowatt hour is priced at the full cost of the backstop sustainable electricity supplies offered by renewable sources. A brief policy discussion rounds up the article.

1. Electricity intensity of economies

The relationship between electricity demand and economic wealth is significant, and the study of the ratio between both variables is instructive and became common practice. We discuss a few references and offer some complementary results.

1.1. The IEA prognosis of the world electricity intensity

Fig. 1 shows an almost linear relationship between aggregate world GDP and electricity consumption over the period 1971–2001 (Birol, 2003). The slope of the shown line is about constant and represents the average electricity intensity of the world economy, amounting to ~320 kW h/1000 $-95GDP. The box in Fig. 1 mentions expected yearly growth rates of electricity demand for the 30 years, from 2001 to 2030, i.e. 1.5%/year for the OECD, 4.1%/year in developing countries and 2.4% for the world on average. Because the growth in world GDP is forecasted at 3.1%/year, the electric intensity is expected to decrease. The average intensity would fall from the nearly constant ~320 to ~210 kW h/1000 $-95GDP in the period 2001–2030, and when a smooth logarithmic pattern for the change is supposed (because a sudden kink in the intensity curve is less likely), the intensity would have dropped in 2030 to ~190 kW h/1000 $-95GDP.

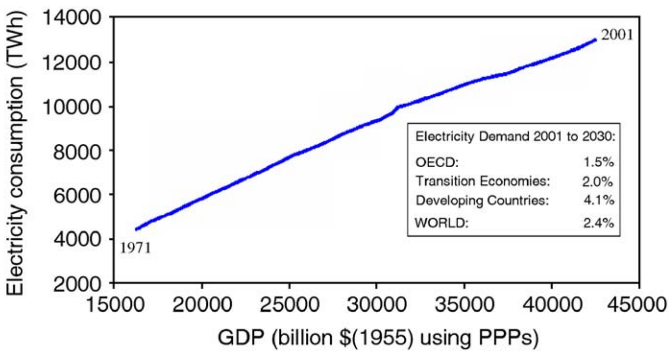

Fig. 1. World electricity consumption vs. GDP 1971–2001. *Source*: copy from Birol (2003).

1.2. Diversity in energy/electricity intensities

In a longitudinal analysis of end-use *energy* demand, Medlock and Soligo (2001) investigate the impact of development (expressed as increasing GDP/capita) on energy intensity (energy/GDP). Next to income (GDP/capita), they include price as an explanatory variable, mainly to avoid specification errors and to obtain unbiased income elasticities. Due to the goal of their research and the constraints accepted, their "panel data consists of 28 countries from all levels of development" in order to "construct a 'map' of energy use by sector during the course of economic development" (Medlock and Soligo, 2001, pp. 77–78).

They show that the shifting structure of economies from agricultural over industrial to tertiary activities along growth in GDP/capita is paired by nonlinear shifts in energy use/capita in the main sectors (industrial and other, residential and commercial, transportation). Structure is shown to be very important in explaining shifting energy intensities over time.

Medlock and Soligo use their econometric model results to construct energy intensity curves as a function of real GDP per capita for a hypothetical *average* country. By intention, they waive the differences in energy intensity that exist between nations of equal income.

Their article is convincing in showing decreasing average energy intensity with higher average income of countries. At the highest income levels, the decline is flattening out. The authors provide no separate information on *electricity* intensity.

Variances in energy and electricity intensities at the sector level have been investigated and documented extensively by Schipper et al. (1992, 2001). In the 2001 article, they argue that intensity is a too broad variable: "One of the most widespread indicators—the ratio of energy use to GDP—does not measure much. Little can be said, on the basis of that ratio, about why energy use for any sector has reached a certain level, how efficient that use is, or why use varies so much between otherwise similar countries" (p. 50). The authors' finding that an aggregate indicator does not reveal changes in its components is trivially true, but the question of interest here is at the end of the quote: *why energy use varies so much between otherwise similar countries*?

For Schipper et al., "measuring the impact of 'structural' changes is crucial to understanding how the ratio of energy use to GDP changes *over time*" (2001, p. 54), which agrees with the findings of Medlock and Soligo. They therefore step down from the aggregate level and define energy intensity at the sector or activity level, adding that "intensities reflect behaviour, choice, capacity or system utilisation, and other factors besides just process efficiencies" (p. 55). They, however, face a lot of data problems to assess the more detailed models, e.g. "observations of actual end-uses are difficult to develop, but surveys can be combined with regression techniques to estimate the relative importance of each end-use …" (p. 60). After applying adjustments to make the intensities comparable among a small (due to data shortcomings) sample of developed OECD nations, they conclude that "there are still wide variations across countries. These variations indicate that the levels of sub-sector intensities differ from country to country." (p. 65). It is noted that "prices play a strong role", but they conclude that the (detailed) "indicators approach offers the only way to explain large differences in aggregate energy use, energy to GDP ratios (…)" (p. 76).

1.3. Observed diversity in electricity intensities in high income OECD countries

While Fig. 1 shows a quasi constant world average electricity intensity, Fig. 2 shows the evolution over 1995–1999 of quite different electricity intensities (kWh end-use per 1000 US$-1995PPP GDP) of 14 high income (the 1995 GDP per capita exceeds 15,000 $) OECD countries. Sweden and Finland at ~700 kW h, New Zealand at ~550 kW h and USA and Australia mark above the others, whose intensities range between 250 and 350 kW h. Given that the intensity in the last three decades was almost constant and that the world average intensity is forecasted to fall below 200 kW h in 2030 (Section 1.1) and given that intensities are the lowest in highly developed economies (Section 1.2), significant efficiency improvements are necessary to make the forecast come true.

The electricity intensity by country shifts only slowly over time. On the one hand, this is an expected pattern because most of the technological stock that uses electricity has an average lifetime of several years. On the other hand, the stability can result from a rather stable evolution of the main economic determinants that influence intensity. The significant variance in electricity intensities in otherwise similar countries raises the question of which economic variable could explain the differences.

1.4. Electricity intensity in high income OECD countries regressed on electricity price

The sample shown in Fig. 2 is limited to *similar high income* OECD nations. In this sample, there is no correlation between GDP/capita as an indicator of income and electricity intensity. In addition, all countries have an equal *access* to electrical technologies, but the different intensities show that they make different use of this access, i.e. the *adoption and implementation* of the various electrical technologies differs; which is for a minor part, due to structural differences and for the major part, reveals differences in end-use efficiencies (Verbruggen and Couder, 2004). Because next to income and technology, price is the third main determinant of demand and production optimisation, the electricity intensities of 14 OECD countries are regressed on the average end-use prices (year 1997). A hyperbolic function $\mathrm{EI} = \alpha . P^{\beta}$ (EI = electricity intensity; P = price) has been estimated, leaving 12 degrees of freedom. Results of the regression are as follows:

Elasticity β		Constant α		R^2	Sum squares of regression
Estimate	Standard error	Estimate	Standard error		
−1.04	0.15	3.41	0.37	80	1.28

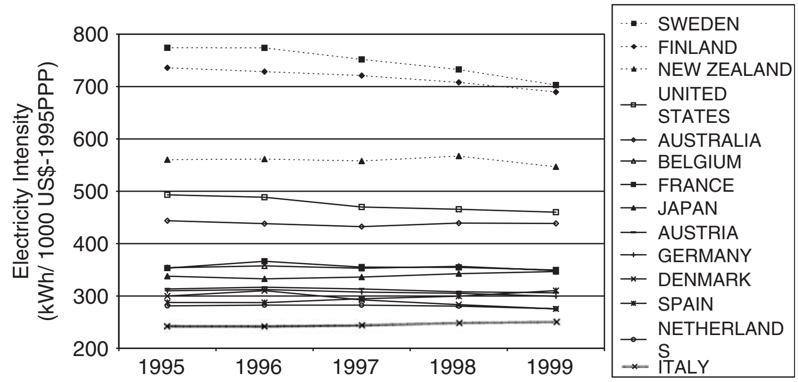

Fig. 2. Yearly electricity-use intensities over the period 1995–2000 in 14 OECD countries. *Source*: OECD/IEA.

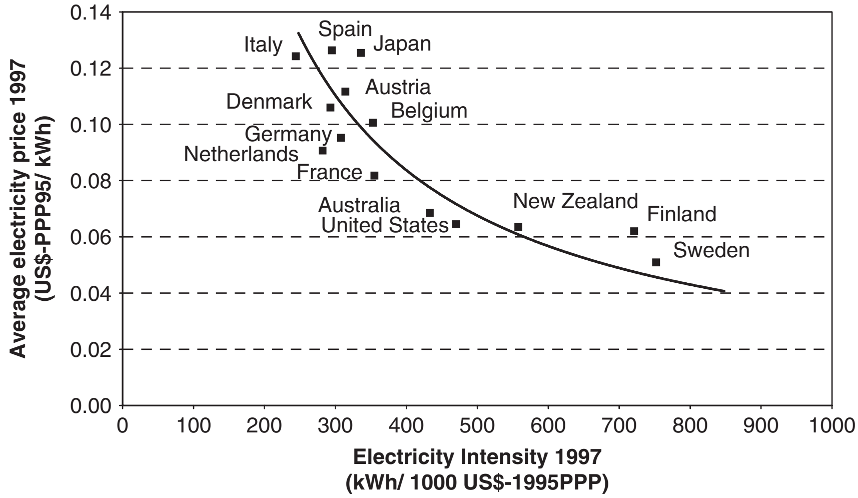

Fig. 3. The 1997 demand curve for electricity intensity (wealthy OECD countries).

Fig. 3 shows the 1997 observed market equilibriums (squares) in the 14 countries and the fitted curve (solid black line). The statistical results indicate that the assumed hyperbolic relationship between electricity intensity of an economy and the end-use electricity price fits the observed data points well, and that it approaches the form of an orthogonal hyperbole, given that the value of the parameter β is close to -1.

Given the exclusion of income and of access to technology as explanatory variables, the specification $\mathrm{EI} = \alpha.P^{\beta}$ can be interpreted as a *demand curve* where β equals the price elasticity of electricity intensity, and the percentage share of the GDP that is spent on the electricity bill is given by $\alpha.P^{\beta+1}$. In particular, when $\beta \sim -1$, this ‘‘budget share’’ is independent of the height of the price and given by the α parameter. With a unitary elasticity, countries spend in the long run[2] about equal shares of their GDP on electricity use, whatever end-use price levels are adopted.

Analysing electricity intensity as a ‘‘demanded good’’ is an unusual way of explaining people’s real behaviour, although this unusual way bridges the gap between, on the one hand, an inelastic demand for electricity services (light, cooling, entertainment, etc.) and, on the other hand, obvious indifference of people regarding the physical product kilowatt hour (voltage, current, frequency). While we observe a very inelastic demand for the services providing wealth and comfort, there is no personal interest by people to bother about how many kilowatt hours are consumed by the services (the reality is that the overwhelming majority of the population has not the faintest idea of how much electricity a particular service consumes; even experts do not know well). While there is no interest in the quantity of kilowatt hours, companies and households are sensible for the height of their electricity bill at the end of the month or of the year. When the bill exceeds expected levels, they take measures to lower their consumption of kilowatt hours by becoming more efficient. When the bill is low or decreasing, they do not care about efficiency because being efficient requires attention, learning, understanding, time and often some specific change in behaviour or investment. Mostly the latter efforts and investments are paid back by a decreased electricity bill and several other spill-over benefits (e.g. safer and healthier living climate). The length of the payback period of every efficiency effort depends on the price of the electricity saved, and therefore the demanded intensity depends on this price too. Intensity as a ‘‘demanded good’’ reflects the preference of rational consumers and producers not to bother about efficiency or spillage. Indeed, electricity intensity is a truly neutral variable without passion or personal commitment for the overwhelming majority of people. Here, rational behaviour prevails and the electricity price balances the rational choice of people between efficiency effort and paying the power supplier.

The rather tight relationship between intensity and price teaches that countries (i.e. their households and companies) will only reach low intensity (high efficiency) if and only if the end-use prices are set at a high level.[3]

2. Sustainable electricity supply

Electricity being a ‘‘secondary energy carrier’’, every kilowatt hour generated needs a womb where it is created. The three main sources of energy supply, fossil fuels (coal, oil, natural gas), nuclear processes and renewable sources

[2]Regression results based on a cross-section sample show long-run effects, i.e. effects after countries have had full time to adapt to the impact of the driving variables.

[3]This conforms to the basic economic theory, as e.g. Becker states ‘‘Perhaps the most fundamental finding in economics is the ‘law’ of the negatively sloped demand curve’’ (Becker, 1971, p. 11).

(hydro, wind, solar, biomass, tidal and other), are also the sources of power generation.

2.1. Overview of the main sources of electricity

The history of the electricity sector since World War II offers a dynamic picture, where sources and solutions compete in ever changing positions and conditions. The dominance of coal at the beginning of the period has ended, but coal remains a significant source in the generation of power. Although the public, financial and policy support for nuclear energy has been overwhelming up to 1979 (Three Miles Island)/1986 (Chernobyl), nuclear energy has not succeeded in taking over from coal, except in a few countries (e.g. France). Oil and gas cover important shares in power generation, notwithstanding their exhaustible and premium fuel character. Distributed generation by on-site combined heat and power units and by renewable energy has not taken over from centralised systems. They struggle with financial return requirements and with barriers imposed by incumbent central generators.

The future will witness a continuing fierce competition between the three main power sources: fossil fuels, nuclear and renewable energy. Every source scores differently on a set of main characteristics as summarised in Table 1.

From Table 1, it becomes evident why fossil fuels have conquered such a large market share in overall energy supplies and also in the power sector. One may expect fossil fuels being enough resilient to keep strong positions in a low carbon emission future. Natural gas is too valuable to be given up, as are premium oil resources, while coal presumably will concentrate on bulk technologies to sequester the CO_2 in the emissions. All forecast studies foresee an important place for fossil fuels in the coming decades, e.g. the European Commission's "World energy, technology and climate policy outlook" (European Commission, 2003a; IEA, 2003).

But is it wise to continue to follow the easiest path, and endanger future supply security and climate stability in particular? A more voluntary approach proposes to bring down the role of fossil fuels earlier and further[4] and to develop alternative pathways such as the hydrogen one (European Commission, 2003b). The discussion opens with whether we should opt for nuclear or for renewable energy, or for both as the alternative. A useful concept in this discussion is the one of a "backstop" supply technology.

Table 1
Characteristics of three main future energy options

	Options		
Characteristic	Fossil fuels	Nuclear	Renewable sources
Energy density	Dense	Very dense	Mostly diffuse[a]
Scale	Divisible	Centralised	Distributed
Control (modulation)	At command	Inflexible	Intermittent, partly unpredictable
Cost price	Cheap	Expensive	Very expensive
Acute risks	Manageable, although severe accidents can happen (mines, tankers)	High (nuclear accidents; radioactive releases)	Mostly tiny but major risks from large scale hydro dams
Chronic pressures	CO_2 emissions; air pollution; leakages to soils and aquifers	Minor emissions; nuclear waste	Landscape impact
Sustainability	Exhaustion of premium sources	Critical	Global and eternal

Sources: Twidell and Weir (1997).
[a]Renewable sources concentrated by nature such as rainfall in mountainous areas (hydro) or such as biomass are unevenly distributed and limited in sustainable supply.

2.2. Backstop supply technologies

In the high days of the first oil crisis, Nordhaus (1973) introduced the concept of a "backstop" supply technology. By definition, a backstop supply technology can deliver an unlimited amount of energy at a given (high or very high) cost. In the 1973 debate, all focus was on energy exhaustibility, sustainability being at that time the concern of academic and societal minority groups. Nordhaus (1973) describes nuclear power with breeders, followed up by fusion, at that time as the evident backstop candidate.

Because today the exhaustibility issue is complemented by the discussion about a sustainable development including democratic, environmental and social concerns (WCED, 1987), one adds "globally accessible", "environmental benign" and "low-risk and affordable" to the "unlimited" property of backstop supply solutions.

Today, nuclear power fails on the criteria to pass the test as a reliable backstop technology, as commented in Table 2.

Renewable electricity sources are arguably the only candidate for passing most of the criteria of the sustainable backstop supply technology, except perhaps for the aspect of financial affordability when compared to the present low prices of fossil and nuclear power. For example, photovoltaic power is unlimited as long as the earth circles the sun but expensive to collect, convert and store, as several other renewable power resources are (wave, tidal, wind, small hydro, biomass).

In weighing nuclear against renewable energy sources as the long term backstop technology, one has a difficult case in being the nuclear advocate. As a corollary, a vast majority accepts the role of renewable sources as the long term backstop. Some people argue for nuclear as a transient source to meet the Kyoto targets and/or as the large scale centralised partner in complementing the distributed renewable sources.

[4]As the stone age did not end by lack of stones, the oil age does not have to end by lack of oil (Yamani, former minister of oil resources of Saudi Arabia).

The two crucial questions of a long-term policy to bring the renewable backstop technology in the forefront are:

(1) What are the costs of the backstop renewable energy supplies?
(2) What policies are necessary to realise the transition successfully?

On both questions, the available literature is very extensive, but has not yet lead to a consensus about the answers. This article cannot overview the literature, nor come up with definite answers. For the question about costs is accepted that the present day cost of unlimited renewable energy will also be the long-term backstop cost. Let us assume that the cost price of the kilowatt hour from the renewable backstop technology equals $0.40/kW h in 1995 prices (UNDP 2000, p. 16).[5] This conservative position is the outcome of the interaction of opposite forces. On the one hand, *technological progress* will increase the performance and lower the investments in renewable energy appliances (wind turbines, PV cells, hydro stations, etc.). On the other hand, the *full phasing out of cheaply priced fossil fuels* will raise the costs to provide goods and services in the economy, also the costs of constructing, placing and operating renewable energy installations. When, in addition, renewable sources must also take care of ancillary services in a continuous supply of power, the cost of the average kilowatt hour delivered by a full renewable system will remain at the higher end. The renewable and hydrogen economy will be clean but not cheap, although some studies suggest more optimistic futures (Hoogwijk, 2004).

The question about necessary policies is discussed in Section 3 of the article.

3. Electric intensity backstop level

In this third part, the results of the two preceding parts are combined to find out about the intensity backstop level. Next, caveats and policy considerations are added.

3.1. Assessing the backstop intensity level

Fig. 4 brings the results of the preceding two parts together. First, the statistical demand curve for electricity intensity reveals the long-run behaviour of companies and households in high-income countries. It shows the likely intensity attained after these had the time to adapt to a given electricity price height.

Secondly, at the 0.40 $-95/kW h ordinate, the constant long-run cost price of a fully renewable electricity supply is shown by the horizontal bar. When this price, well above

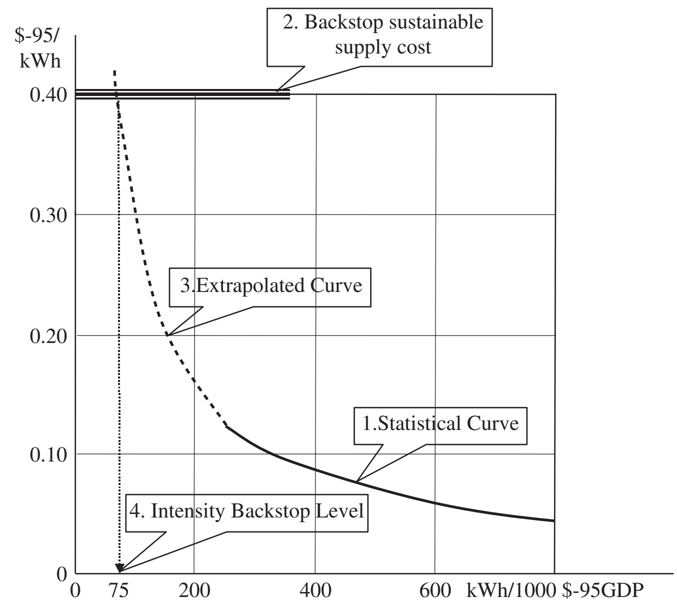

Fig. 4. Backstop end-use intensity level at given backstop supply price.

the market prices we are accustomed to since decades, would be established without ample time for the economies to adapt, the share of their GDP spending on electricity would more than triple for all economies. This is why at present there is a strong argument against renewable supplies as being economically not affordable. It can also be seen as an argument that our economies are too electricity intensive and that the efficiency in using electricity should be increased. However, Fig. 3 shows that intensity only comes down (or efficiency goes up) when the end-use price stimulates the numerous decision makers—households and companies—to change decisions and behaviour.

By stretching the results from Section 1.4, the statistical curve is extrapolated (step 3 in Fig. 4). One must refer to the literature to see whether such extrapolation is acceptable. Bottom-up electricity efficiency specialists (Krause, 1993; Lovins et al., 2002) argue that the necessary efficiency performance of such extrapolation is feasible, also given the technological development expected. Innovation specialists, however, also point to the diminishing returns to research in a given field (Popp, 2002). In addition, the lingering performance of the best practice countries (see Fig. 2) gives weight to arguments that some technical ceiling could be hit; i.e. the demand curve cannot be extrapolated because it could house a kink, before the backstop level is attained.

We suggest here to combine the analysis and conclusions of the bottom-up experts with the prevailing view and observations of the top-down studies on rational decision-makers that safeguard their financial interests. Bottom-up experts argue that opportunities of commercially available technology permit a fourfold reduction in intensity and top-down experts underpin the evidence that consumers

[5] A capacity cost of $5000/kW is annualised with a 6% annuity, covered by an average annual production of 750 kW h/kW installed. The assumed constant marginal cost of the non-exhaustible renewable supplies does not entail that there are no large quantities of renewable power available at a lower cost.

will react on higher prices by implementing such opportunities. This makes the case stronger that extrapolation may be warranted. This results in the crossing point of the demand curve for electricity intensity with the horizontal supply curve of the sustainable renewable electricity sources. From this crossing point, one assesses the intensity level triggered by the electricity end-use price of 0.40 $-95/kW h at about 75 kW h per 1000$-95GDP (step 4 in Fig. 4).

A major question remains as to what attaining the backstop end-use efficiency level costs to the economies of the OECD member states. Will the present situation of countries, companies and households using electricity efficiently not facing (significantly) higher investment costs than the spilling ones endure into the future? That is, will technological progress bring timely rescue? Many will argue "yes, if 50% of the R&D efforts are directed towards efficiency technologies and solutions" (Jochem et al., 2002). For such redirection to happen, an enduring and stepping-up price signal is necessary, one can learn from Popp's analysis (2002).

When the demand curve cannot be extrapolated but is kinked somewhere in the 75–250 kW h intensity interval, society will face higher electricity budget shares and must transcend the purely technical efficiency discourse. This also means that the energy conservation[6] question is addressed for electricity bills ceiling at a constant share of GDP. Physical limits on intensity reduction lift the discussion about energy use to non-energy policies (redirecting social activities and consumption patterns). However, when societies bring up the flexibility to adapt and the technological focus is redirected to efficiency and to the development of environmental benign, low-risk and unlimited supplies, energy and climate doomsday can be removed from the agenda.

3.2. Policy considerations

Policy has to make choices in the face of climate change, nuclear technology risks and the irreversible combustion of finite premium fuels (Hennicke, 2004). Policy making for the long term needs clear buoys such as backstop supply technologies. Weighing nuclear and renewable sources confirms the common expert and laymen judgement that renewable sources are the only long-term sustainable option. A renewable energy future will be sustainable and clean but never as cheap as the oil and gas era, living upon an immense bequest of resources, has accustomed us to.

Renewable electricity and a hydrogen economy as backstop technologies are affordable[7] in industrial economies when electricity is used much more efficiently as done today. However, why and when should the numerous households and companies bother more about being efficient when spillage is easier. The cross-section regression of electricity intensity on price shows that in the long run, intensity mainly depends on the level of the end-use electricity price. The results from the data analysis confirm basic economic wisdom and observed experience in the energy field that prices do matter and that widespread and continuous efficiency improvement requires backing by the financial self-interest of the end-users. The analysis shows that lower *overall* intensity cannot be reached and maintained without a sufficiently high end-use price level. However, the analysis also reveals that such higher price levels are not destructive for economic well being. Because of more and better implementation of efficient solutions, practices and technologies, high-price countries pay about equal electricity bills as low-price countries do (elasticity around -1).

If governments prepare the transition to a sustainable electricity future, the electricity intensity of their country's economies has to come down. If not, such a sustainable future will not be accepted as affordable by households and industry. For raising the overall electricity efficiency of a country, one cannot bypass the increase in electricity end-use prices.[8] This result is fully in conflict with the main agenda of the electricity sector liberalisation that aims at increasing the efficiency of power supply and at lowering electricity end-use prices. A comprehensive tax reform (including the elimination of subsidies to non-sustainable supplies and the internalisation of externalities as Bleischwitz (2005) emphasises) policy can spur power suppliers to more efficiency and set out a path to increase end-use prices towards the backstop supply cost that must be attained when renewable sources have to take over. The German parliamentary commission on sustainable energy supply also highlights tax reform as a national instrument (Hennicke, 2004).

[6]Energy or electricity conservation affects the way end-use goods and services are delivered or consumed. Conservation eventually requires the reduction of some services. Conservation is not neutral as efficiency is.

[7]Affordability is measured by the GDP share a country spends to obtain the electric current for powering the wanted services. An affordable share is one that does not diverge a lot from the reference one, amounting to about 3.4% in high-income OECD countries (see Section 1 of this article).

[8]A metaphor referring to the basic laws of energy physics may help in showing the interaction of the top-down approach (prices, taxes as instruments) and the bottom-up approach (efficient technology promotion) in improving the energy efficiency of economic activities. Thermodynamic conversion of heat into power is limited in efficiency by Carnot's formula as $\eta < 1 - T_{\mathrm{cold}}/T_{\mathrm{hot}}$, with the latter ratio being the ratio of the temperatures of the cold and of the hot heat sources. Because the practical cold source is the ambient environment, the limits of the conversion efficiency are determined by the temperature (and correlated pressure) of the hot source. The actual technical efficiency of a conversion depends on the lay-out and performance of the machinery installed between the hot and the cold sources for extracting work from the heat flow. It happens that bad machinery wastes the opportunities for delivering work that are available in the heat flow. However, when the temperature (pressure) gap between hot and cold sources is small, even the uttermost performing apparatus cannot deliver high conversion efficiencies.

Similarly, when the energy end-use prices are low, there is not enough financial pressure to extract enduring and generalised results from the energy flows independent of how good the applied technologies. But performing technology is a condition "sine qua non" for approaching the efficiency ceilings imposed by the pressure level. Top-down and bottom-up approaches are not conflicting but natural allies.

The plans that countries must develop for a step-by-step increase of their end-use electricity prices to prepare for a sustainable energy future will be different depending on the present price levels they start from. Their distance to the target intensity backstop level is also quite different (Figs. 2 and 3). The latter observation may lead to a questioning of the actual practice of burden sharing in the climate change policy process.[9] In the EU, this is mainly based on ''grandfathering'' allocation principles with adjustments for structural factors. For future assignments, one may question more the attained intensity levels triggered by particular pricing (and taxing) policies. It is possible to ''normalise'' the intensity levels of the various countries to found a more equitable basis of burden sharing.

This article confirms the irresistible power of the most fundamental law in economics (Becker, 1971). As energy engineers must obey the laws of energy physics, we argue that energy policy makers must live upon the economic laws. The robustness of the negatively sloped curve of the demand for electricity intensity (efficiency) challenges all endeavours and instruments (such as tradable permits distributed for free) to keep the end-use prices of energy low. High end-use prices are a prerequisite for low intensities, and the latter are a necessity to make sustainable electricity supplies affordable. All pieces of the policy puzzle match well together, but the policy process has to be triggered by a comprehensive and enduring tax reform.

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[9] Bo Kjellén, the former Swedish Ambassador for the Environment, suggested on the ECOSPHERE Forum at the European Parliament (February 16, 2005) to think of ''targets to cut emissions relative to energy intensity or to economic growth'' (ENDS Daily, February 18, 2005).