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Integrated Energy Planning

A Leonardo ENERGY White Paper

Whether it is to reduce CO2 emissions and mitigate climate change, because the reserves of easy accessible fossil fuels are shrinking, or for geopolitical reasons, it looks like the world economy will have to move away from fossil fuels in the coming decades. Given the massive role of fossil fuels today, this is an enormous challenge. Ensuring our future energy supply without fossil fuels will need a radical reorientation.

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WHAT CAN WE LEARN FROM HISTORY?

Today’s energy system has developed over several centuries since the start of industrialisation. There have been many major shifts; water power was replaced by steam power which was in turn replaced by electric power, while wood was replaced by coal as the dominant fuel, supplemented first by oil and gas and then by nuclear energy. These shifts were driven partly by necessity – a price increase or supply shortage of the most commonly used fuel at the time (wood, coal, oil) – and partly by technological innovation. Each of these shifts allowed a further growth in industrialisation and an increase in living standards so that the economy could devour far more energy than before.

Today, many studies about a future without fossil fuels assume that our per capita energy consumption will have to shrink. The paper ‘Searching for a Miracle’, for instance, states that our energy guzzling economy has grown out of a period in the first half of the 20th century when large and extremely accessible oil reserves were exploited. It assumes that only a reduction in energy consumption can ensure a stable energy future. From the above historical perspective, one might get the feeling that such sobering messages are underestimating the power of technological development to increase supply instead. Why wouldn’t we do again what we did before? Why wouldn’t we find new energy sources that have far more potential than those we have today?

On the other hand, it is dangerous to assume that history can *always* repeat itself. Moreover, the changes that occurred in the past were never in the direction of a more sustainable solution - that’s what leaves us holding the baby now. Some thinkers were already aware of the renewability issue very early on. During the wood shortage in England around 1600, Arthur Standish sneered at those who thought that coal could replace wood. Everyone knew, he pointed out, that fuel supplies had to be sustainable, like coppice-wood, while coal mines would be quickly exhausted and could not replace themselves. How could this be a solution to long-term energy needs?

Another key argument is that the energy system has been growing exponentially over the past 250 years. If the energy economy during the shift from wood to coal in the 18th century were represented by a small rowing boat, the economy that has to change direction today is a massive oil tanker.

THE ENERGY SYSTEM OF TODAY

Today’s energy system consists mainly of

1) Electricity as an energy carrier produced by fossil fuel, nuclear, hydro power and other renewables, used in many diverse applications

2) Fossil fuels which are directly used for transport and heating applications.

This system has been growing in a period when demand could be easily met by exploiting large, easily accessible, fossil fuel reserves. This period is approaching its end. Fortunately, electricity has enormous flexibility because it can be generated from almost any fuel, avoiding those which are scarce or expensive.

This flexibility is one of the main reasons why our economy has become increasingly dependent on electricity in the past eighty years. Another reason is that electricity is suitable for control, automation and data processing applications. But not all parts of the economy have yet made this shift. Many energy applications are still directly dependent on fossil fuels and remain deeply rooted in our global economy.

ARE WE ON THE RIGHT TRACK?

During the past decade, change has started. Renewable energy systems have been booming. In pioneering countries like Denmark, Spain and Germany, you cannot drive very far without seeing wind turbines. Electric and hydrogen cars, which were once dismissed as utopian projects, have become hot topics.

Are we on the right track? Reading newspapers, you would think we are. Every day you can find messages like ‘*The new wind farm will supply the equivalent of over 70,000 homes with clean electricity.*’ 70,000 homes, that’s a medium-sized town or city. If wind farms produce that much, how come we are still so far from a fossil-fuel-free society? In his book ‘Sustainable Energy - Without the Hot Air’, David Mc Kay provides the answer: ‘*The “home” annoys me,’* he writes, *‘because I worry that people confuse it with the total energy consumption of the occupants of a home – but the latter is about 24 times bigger.’* Electricity is not only used in homes, but also for the industry, offices, public lighting and public transport that we all share. And most homes do not consume only electricity, but also fossil fuel for heating. All this ‘other’ energy use is about 24 times bigger than the simple residential electricity consumption. As a result, the actual world energy consumption is equivalent to the electricity consumption of about 20 billion UK ‘homes’. This leads us to conclude that 70,000 homes - which seemed such a significant figure at first sight - is actually a drop on a hot plate.

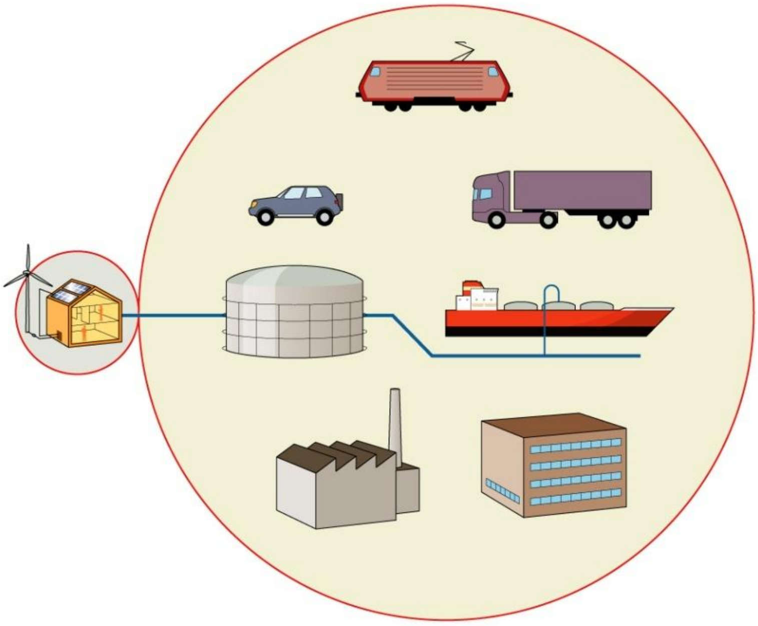


Figure 1: What does 'powering a home with renewable energy' really mean? Residential electricity consumption is 1/25th of the total energy consumption (UK figures).

THE NEED FOR INTEGRATED ENERGY PLANNING

If our goal is to solve the world energy crisis, we cannot hide behind partial solutions. One wind farm doesn't make a summer. Choices will have to be made, many of which are interrelated, making it very difficult to predict their consequences. Each choice has risks and costs. For example, are we going to use farmland for producing biomass or for producing food? How are we going to incorporate a massive deployment of renewable energy generation in actual natural, agrarian, and urban planning? And how can developing countries increase their welfare level, at the same time containing the rise in their carbon emissions?

This clearly demonstrates the urgent need for integrated energy planning. Plans need to address every level (global, regional, national, local), not in the sense of restrictive, top-down plans, but rather as roadmaps that guide actors to focus on a systems perspective and on the big issues. At every level, energy plans need to optimise the system as a whole.

THE COMPLEXITY OF THE PROBLEM

The complexity and diversity of the problem is one of the main barriers to the development of an integrated view; the subject has grown far too big for one head. In order to divide the solution of the problem among the many different parties and sub-parties they need to have a common understanding of the issue.

In particular, there needs to be a common understanding on the following five questions:

WHY ARE WE ACTING – FOR WHAT REASON?

At the start of this whitepaper, we mentioned three main reasons why we should act: climate change mitigation, the shrinking of fossil fuel reserves and geopolitical reasons. Economic development and employment are two others that are often mentioned in this respect. Whether or not these are relevant arguments is often the subject of debate.

Whatever the outcome of this discussion, we must recognise the huge importance of the energy system for today's global economy. Without large quantities of easily available energy, our society would collapse. Imagine, for example, how the sudden loss of electrical power would affect the storage and accessibility of vital information and knowledge. Energy plays such an important role in our contemporary society, that it is no luxury to think about a sustainable energy future.

WHAT TO DO – WHAT GETS PRIORITY?

Should we focus on reducing primary energy use, or on the reduction of greenhouse gas emissions? In a fossil fuel energy economy, both goals are aligned. But for renewable energy systems, the link becomes weaker. It is possible to imagine a situation in which a reduction of primary energy use would increase the emission of greenhouse gasses, for instance when it involves a switch from renewable energy to natural gas. When considering solar power, the amount of primary energy is so abundant that it becomes meaningless as a selection criterion.

The clearest objective is to give priority to the reduction of greenhouse gas emissions. This will naturally promote the development of sustainable energy systems that do not rely on depletable fossil fuels and efforts to maximise energy efficiency. In other words, actions that ensure our energy future.

While the importance of primary energy use is a fallacy, the criterion of land use is a reality to reckon with. Improving the efficiency of solar photovoltaic panels, for instance, is important for this reason.

WHERE TO ACT - AT WHICH LEVEL?

Should we act at a local or global level? Bottom-up or top-down? Should we encourage small initiatives and hope they will eventually grow into one big system that addresses our needs, or should we start from one big global plan to meet our energy needs and then hope it will eventually be implemented in the field? Is it possible to mix both strategies?

Solutions that are specific to communities or regions have the advantage that people understand their relevance and are engaged. On the other hand, renewable resources are not evenly distributed over all regions. If we leave everything to local solutions, in some regions there may be insufficient resources to exploit, while elsewhere all potential resources may not be exploited. Moreover, it can be important that 'efficiencies of scale' are realised which is less likely to happen at a local level.

Another issue is that impact on the local environment, especially in areas of natural beauty, is often diametrically opposed to global environmental interest. How can we deal with this dilemma? Who is the owner of the local environment? Of local renewables? Of the wind? The sun?

In many cases it will be impossible to serve all local and global interests simultaneously, so compromises will be inevitable. Recognising these compromises in a regulatory framework can avoid eternal discussions.

WHEN TO ACT – ACCORDING TO WHICH TIMESCALE?

How fast can the transition towards a low carbon society be implemented? There are two points of view on this subject.

Climate change experts determine what we should do to keep global warming within reasonable limits. According to the Intergovernmental Panel on Climate Change (IPCC), limiting the average global temperature rise to 2 or 3°C would require the stabilisation of greenhouse gas emissions in the atmosphere at 450 to 550 ppm CO_{2eq}. To do so, we should reduce carbon emissions by 60 to 80% by 2050. This means that, by this date, we should already be close to a post-fossil fuel economy.

On the other side, technology specialists estimate the timescale that would be realistic for the introduction and deployment of carbon free technologies. These estimates show that the requirements set for carbon emission reductions will be hard to reach. For an optimal deployment of low-carbon technology, a longer transition period may be needed.

The International Electricity Partnership (IEP) proposed a compromise between those two viewpoints in its *'Roadmap for a Low-Carbon Power Sector by 2050'*. According to the IEP, a massive deployment of low-carbon technologies will only be possible after 2020, unless we are willing to run the risk of high unreliability. The shortfall caused by this delay could then be compensated by a more rapid evolution between 2025 and 2050. (Such a timeframe is at odds with most current political actions, which are concentrated on achieving 2020 emission reduction targets and do not look much further down the timeline.)

The IEP timeframe provides a significant advantage in that we do not have to make all choices at one time. For instance, when choosing electricity as an energy carrier for residential heating and transport vehicles, the choice of the best mix of carbon-free electricity generation technologies can still be made in a later stage. A suitably long planning horizon avoids the locking in of unsuitable or uneconomic technologies, given the long lifetime of power infrastructure (30 — 60 years) and its significant impact on landscape.

Another conclusion is that we need to start with technologies that are available today, otherwise change will come too late. There is no use in trying to start from scratch again. We have many technological options at our disposal that are already on the market or close to market introduction.

HOW TO ACT – WITH WHAT KIND OF MECHANISMS?

What should the driver be for changing the direction of our energy economy? Should change be technology driven, enforced by policies, or induced by market mechanisms? Leaving the initiative to technology experts will ensure that decisions are taken based on accurate technical data, but will not always guarantee cost efficiency and social acceptability. Government policies are typically strong in defending the latter, but do not always give sufficient weight to technological aspects. Finally, market mechanisms will, in most cases, ensure cost efficiency, but cannot always be relied upon to ensure that public interests are served. Probably we need a balanced mix of all three forces.

CONDITIONS FOR THE NEW ENERGY SYSTEM

Based on a common understanding of the above questions, we could draw an outline of the conditions that the future energy system will have to meet. The following four conditions will be essential in any case.

PHYSICAL AND TECHNICAL AVAILABILITY, ON A LARGE SCALE

The technological solutions for our energy future should be available on a large scale. This does not mean that they should be centralised - they can just as well be implemented as a large number of distributed generation units.

Because we are looking for a big solution, we deliberately exclude small-scale solutions from this discussion but we recognise that there are many situations where they make perfect sense in the local environment.

But what is ‘large scale’? Let’s take a look at our energy needs to gain perspective. In 2008, the world average energy consumption was 74 GJ/person/year. The US consumed 325 GJ/person/year, the UK 178 GJ/person/year. Through energy efficient technology and a more efficient organisation of society, the average consumption can be reduced while maintaining current living standards. The papers ‘Searching for a Miracle’ and ‘Sustainable Energy - Without the Hot Air’ both give similar guiding numbers in this respect, being 100 GJ/person/year or 80 kWh/person/day.

How do these figures compare with the renewable energy systems that are already installed today? The following are a few benchmarks to gain insight in the numbers:

- The world’s largest wind park is Horse Hollow in Texas with a maximum capacity of 735 MW. It produces approximately 0.33% of the total energy needs of the state of Texas (capacity factor 30%, 22.5 million inhabitants).

- The total installed wind capacity in the Netherlands is 2229 MW (end 2009). It produces approximately 1.5% of the total energy needs of the country (capacity factor 30%, 16.5 million inhabitants).

- The largest solar photovoltaic (PV) farm in the world is Olmedilla in Spain, with a capacity of 60 MWp and a yearly production of 85 GWh. It produces approximately 0.0006% of the total energy needs of Spain (46 million inhabitants).

- The total installed solar PV capacity in Spain is 2215 MW (end 2008). It produces approximately 0.29% of the energy needs of the country (capacity factor 20%, 46 million inhabitants).

These examples give an idea of what is meant by ‘large scale’; it needs to be very much larger than that achieved so far.

‘Available at large scale’ does also mean ‘available’. Availability might be at risk if, for example, the majority of the energy reserves are concentrated in the hands of a few powerful players – be it countries or companies – that are able to shut-off supply from one day to another.

It also means that the energy is available today and in the future. The longer a technology is expected to be available in the future, the more it is worthwhile to invest in its development today. This means, for instance, that most renewable energy systems are worth large investment. However, a PV panel that makes use of a rare metal is much less so. With this criterion in mind, it is worth considering how much research and development we should invest in Carbon Capture and Storage for coal fired power stations, since the easy accessible coal reserves are expected to disappear in the next 30 to 80 years (see: Searching for a Miracle).

COST-EFFECTIVE

How much will the transition towards a zero-carbon economy cost? And what will be the return on the investment? Those are natural questions to ask, but the answer remains elusive.

A first difficulty is the difference between 'internal costs' and 'externalities'. Externalities are the costs to society that the use of a certain technology causes but that is not paid for by the user. For instance, if a company pollutes without paying any penalties, and the state has to clean up the pollution, the cost of this clean up is an externality. By adding the externalities to the internal costs, the real total cost to society is revealed. This total cost is a good base for comparing the appropriateness of energy technologies. However, externalities are often very difficult to calculate with sufficient accuracy, seriously complicating such comparisons.

And there are other difficulties. Even assuming that it would be feasible to make a fair estimate of the development cost of a new technology, how far into the future should we calculate the return? And how can we calculate the risk and potential consequences of a global economic crisis caused by an energy shortage?

Perhaps the question of cost is, on this occasion, not of primary importance, as indicated in the section 'Why are we acting…'. Developing a sustainable energy future is simply a necessity for our society to survive.

It is more feasible to work in a comparative way and estimate the difference in cost-effectiveness between the various solutions we have at hand. To do so, we can already get a long way with a few common sense rules:

- By starting, as far as possible, from existing systems the costs will be lower than when starting from scratch.
- The Energy Return On Energy Investment (EROEI) should be as high as possible. The EROEI is a key figure for understanding the world energy system (see paper 'Searching for a Miracle'). The EROEI of US produced oil was 100:1 in 1930 but has dropped to only 20:1 today. The high EROEI of oil in the first half of the 20th century was one of the main drivers for the creation of our energy-guzzling economy. It is unlikely that we will find a new energy resource with an EROEI of 100:1 any time soon. The minimum EROEI to sustain a modern industrial society is considered to be 10:1.
- Systems should be as large as possible to enjoy the advantage of scale, and as local as possible to minimise transport losses. These two criteria often work in opposite directions.
- The longer the time over which the costs can be spread, the better.
- Combined technologies, serving multiple purposes with one installation, are to be preferred. Examples include combined heat and power production (where the energy demands are coincident) and solar water desalination combined with power production.

WITH LOW ENVIRONMENTAL IMPACT

The main environmental priority today is the reduction of greenhouse gas emissions. In most cases, the efforts to reduce CO_2 emissions will also reduce other harmful emissions such as SO_2, NO_x and heavy metals. If not, extra focus should be on minimising those other emissions.

Waste should be minimised and in particular toxic waste. One way is by making maximum use of recyclable materials.

Land use is another important environmental criterion, which can be in conflict with emission reduction.

SOCIALLY ACCEPTABLE AND SAFE

The future energy system should not only be sustainable from a technological, financial and environmental point of view, it should also be socially acceptable. This has many aspects:

- The safety of all systems should be high, minimising the risk of accidents involving humans.
- People should feel involved in the energy system. Local, participative projects can be effective to achieve this.
- All countries around the globe should be given the opportunity to grow towards the living standard of the more developed countries.
- Concentrations of energy sources in the hands of a few countries or market players should be avoided.

EVALUATING THREE OPTIONS

THE HYDROGEN ECONOMY

The term Hydrogen Economy was first mentioned by John Bockris during a speech at the General Motors technical centre in 1970. It referred to an energy system using hydrogen for motive power (cars, boats, planes, and industrial motors), the energy needs of buildings and portable electronics. In recent years, the term is often used in a more limited sense, referring to the use of hydrogen for transport vehicles only.

Free hydrogen is rare in nature so it would need to be produced. This requires more energy than is subsequently released when the hydrogen is used as fuel, so hydrogen, just like electricity, is an *energy carrier* and not a primary energy source.

Today, most hydrogen comes from syngas, which is made by steam reforming natural gas or methane, or by gasification of coal. This syngas is then transformed into hydrogen by a shift reaction at 130°C. Since this method requires fossil fuels and releases CO_2, it is not a sustainable option. Another production method is the electrolysis of water, using DC electricity, which can be produced in many ways, including from renewable energy sources.

Some other hydrogen production methods are the subject of research. One is the co-production of hydrogen and electricity in a High Temperature Gas Cooled Nuclear Reactor (HTGR), also called a Generation IV nuclear reactor. Another option is the use of Concentrated Solar Power (CSP) for the thermal decomposition of water at 1200°C. Concepts exist to produce hydrogen in an algae bioreactor.

Hydrogen can be used in two ways: by burning it as fuel in internal combustion engines, or by the use of fuel cells which can have a superior power-to-weight ratio and are much more efficient. If hydrogen is to be used for transport vehicles, road networks will need to be equipped with hydrogen filling stations.

Hydrogen has a high energy density on a mass basis, but a very low energy density by volume. Practical transport and storage therefore requires that it is pressurised or liquefied, both of which are energy intensive processes.

For the transport of hydrogen, former natural gas pipelines could be used if they are coated on the inside to avoid embrittlement of the steel. This assumes that natural gas distribution has ceased so the other option is to install new pipelines. The cost, in both financial and energy terms, of transport can be minimised by producing hydrogen in distributed plants. However, such distributed production will have a lower efficiency, setting off the reduction in transport energy.

ADVANTAGES OF HYDROGEN

- Hydrogen can be produced in many ways, which makes the system flexible. The decision on the best production method can be postponed while development of networks and end-use applications can proceed.
- Storage is fairly easy
- It can be burned in internal combustion engines (using existing technology)

- It can be used for motive power, heating and electric power production.

DISADVANTAGES OF HYDROGEN

- It is an energy carrier, not an energy source.
- There are significant efficiency losses in the conversion steps via both syngas and electricity, reducing the overall EROEI.
- It is produced either from fossil fuels or by electrolysis using electricity. The first is not an option for the future, the second creates one conversion step more compared to the direct use of electricity. Concepts exist to produce hydrogen by nuclear power or Concentrated Solar Power (CSP), but those technologies can more efficiently be used for the production of electricity.
- Because of its low energy density by volume, hydrogen storage and transport requires pressurisation or liquification, which is energy intensive and thus further reducing the total efficiency of the system.
- The production of hydrogen requires large quantities of water.
- When mixed with air, hydrogen is the most explosive of all gasses except for acetylene. Moreover, hydrogen is odourless and pure hydrogen-oxygen flames burn in the ultraviolet colour range nearly invisible to the naked eye.
- Except for the possible reuse of the natural gas network, a completely new infrastructure will have to be created.

CONCLUSION

Because of the second and third disadvantages mentioned above, the hydrogen economy is very unlikely to be a realistic option. In 2003, the Swiss Engineers Ulf Bossel and Baldur Eliasson published the paper ‘The Future of the Hydrogen Economy: Bright or Bleak’ and an updated version was published in 2006. This paper clearly showed the limitations of hydrogen as an energy carrier, and stated that nothing less than the laws of physics will keep the vision of the hydrogen economy from becoming reality. Today, only very few still see an entire hydrogen economy as a serious option.

That said, hydrogen has certainly a role to play in the energy system of the future, although it won’t be the main role. Hydrogen could be useful for long term energy storage, or for other particular applications in the system.

THE BIO-ENERGY ECONOMY

Bio-energy refers to any kind of energy that is based on the carbon cycle. Although burning biomass releases carbon dioxide into the air, the same amount of carbon dioxide had previously been taken out of the air by the plants during growth. The result is that the growing and burning of biomass doesn't produce any net carbon emissions, unlike fossil fuels. Also unlike fossil fuels, biomass is renewable.

Just like fossil fuels, biomass can be an energy source as well as an energy carrier. The 'bio-energy economy' would use biomass as a replacement for fossil fuels in heating and transport.

Biomass can also be used to generate electricity (see 3): The electrical economy) or to produce hydrogen (see 1): The hydrogen economy).

CLASSIFICATIONS OF BIOMASS

Biomass includes a large variety of source products, processing techniques and end-products and can be classified in many ways.

A first classification is that of the end products, which can be

- Solid, such as wood pellets
- Fluid, such as biodiesel (ethanol)
- Gas, including methane and syngas.

A second classification is that between:

- Crops that are especially grown for the production of bio-energy (e.g. rapeseed, corn, switchgrass, jatropha, algae...)
- By-products of agriculture and forestry that would otherwise be wasted (e.g. wood pellets made from forestry waste, bagasse as a by-product from sugar production, straw as by-product from wheat production)
- Organic waste from residential or industrial origin (e.g. residential food residues, residues from food processing industry...).

A third classification is that between:

- First generation biomass. These are produced by fermenting plant-derived sugars to ethanol, making use of food residues or food crops (rapeseed, corn, sugar beet, sugar cane...). The former is limited in scale, the latter is directly competing with food production. Directly burning food or forestry residues can also be called 'first generation biomass'.
- Second generation biomass. These are produced by extracting the sugars that are locked in inside the lignin and cellulose of woody or fibrous biomass. Examples include bagasse (by-product from cane sugar production), switchgrass, and jatropha. Ethanol is produced from the extracted sugar and the remaining lignin is burned in combined heat and power plants. This concept has a much higher EROEI

than first generation biomass, and there is less competition with food production. The problem is that the use of by-products is limited in scale, whereas the crops that are especially grown for cellulose production typically require large quantities of sweet water and they still require large areas of land (although less than food crops).

- Third generation biomass. This is bio-energy produced from algae and solves all of the drawbacks of the first and second generation biomass. Unfortunately, the currently tested systems are highly expensive (high capital cost, high labour cost, and high operational cost).

ADVANTAGES OF BIOMASS

- An energy source and energy carrier in one
- 100% renewable
- Easily stored
- Combustion engines can still be used
- Rural development
- Increase of the global amount of carbon stored in plants (only true for the 2nd generation of biomass)
- Waste reduction.

DISADVANTAGES OF BIOMASS

- Low EROEI (better in the 2nd and 3rd generation, but still low compared to other types of energy)
- Competition with food
    - By using food crops directly (1st generation)
    - By land use (1st and 2nd generation)
- Competition with nature preservation (1 and 2nd generation)
- Water use (especially high for the 2nd generation of biomass, but also for the 1st generation)
- Third generation biomass is highly expensive
- Low value-added jobs in agriculture
- Although it does not produce net emission of CO_2, burning biomass can generate other harmful emissions, such as NO_x and SO_2
- If the crops for bio-energy replace old forest, the global amount of carbon stored in plants decreases.

CONCLUSION

To replace all fossil fuels used in transport and heating, the first and second generation of biomass are not sustainable on a large scale.

The first generation of biomass has a low EROEI and, on a large scale, would compete with food production and nature preservation.

The second generation of biomass has a better EROEI, although still small compared to other renewable energy sources such as wind power or concentrated solar power. On a large scale, agricultural by-products will not suffice and additional cultivation of fibre-rich plants will be necessary, requiring large areas of land. Although these areas might be smaller than those for the first generation of biomass and also include types of land that are not suitable for other crops, some competition with food production and nature preservation will be difficult to avoid. The biggest issue is probably the major need for sweet water.

That said, biomass can sometimes provide a good solution at a local level or in particular cases. A good example is the synergetic production of sugar, biodiesel, electrical power and heat from sugar cane in Brazil. The same can be said about the use of wood pellets from forestry waste in countries like Canada or Finland.

The third generation of biomass, namely algae, overcomes several of the disadvantages of the first two generations. They have a higher EROEI and don't require so much land or sweet water. However, the technology is still in an early stage of its development, and those prototype technologies that exist today are very expensive. Further development may result in a cost-effective technology, but the timescale is uncertain and the need is pressing. Other technologies are already more mature and cost-effective (see 3): The electrical economy).

THE ELECTRICAL ECONOMY

A third option is to adopt electricity as a universal energy carrier. This means that current use would be extended to transport and heating/cooling applications.

In transport, electric vehicles already exist and their introduction on the mass market is expected in the near future following improvements in battery technology. An extensive infrastructure of charging points or battery exchange facilities will need to be constructed along roads and highways.

In heating and cooling, the first step is to ensure that all new buildings are built, and existing buildings upgraded, to passive or very low energy standards. Since improvement of the existing building stock would take many years, it is a prime area for early action. Very low energy buildings can be heated with an electrically driven heat pump, which is a mature and proven technology. In other words, all buildings would eventually be free from direct fossil fuel usage. In Switzerland, this scenario is already close to reality for new buildings.

One of the big advantages of choosing an all-electrical economy is that the vast majority of the infrastructure already exists. A massive introduction of heat pumps and electric vehicles may require selective upgrade of the grid, but the system does not have to be re-built from scratch. Moreover, these technologies could represent an opportunity for establishing a more active role for buildings on the grid; vehicle batteries could be used as distributed short-term storage devices while heat pump operation could be scheduled so as to reduce demand at time of peak load.

Another advantage of electricity is that it can be generated in many different ways. Renewable sources for electricity generation include wind, photovoltaic solar, thermal solar, geothermal, waste, biomass, tidal, hydro, wave, and ocean stream energy. Whether nuclear power and coal-fired power with carbon capture and storage are also sustainable and cost-effective options, is a point of discussion.

Choosing electricity as the energy carrier of choice means that the mix of energy sources can be determined according to which technologies become the preferred choices in terms of efficiency, sustainability and acceptability.

ADVANTAGES OF ELECTRICITY

- Electricity can be produced in many different ways, which allows the electricity mix to vary locally and to evolve over time. It also allows the choice of the best mix of energy sources to be postponed until renewable energy technologies are further developed.
- The electricity network infrastructure already exists, it only needs to be adapted and extended. It is bi-directional, in the sense that energy can be taken out or fed in anywhere on the system.
- Electricity is by nature highly controllable, which makes it the preferred energy carrier for automation.
- Electrical applications have high or very high efficiencies.
- Electricity incorporates the potential to create one single energy system for all applications.

DISADVANTAGES OF ELECTRICITY

- Storage of electrical energy is difficult. Battery technology is rapidly evolving, but still not suitable for large-scale storage. Thermal, compressed air, and pumped hydro storage systems all require conversion steps that entail a loss in efficiency.
- Long-distance transport of electrical energy has a significant impact on the landscape and right-of-way issues slow down the development of new transmission lines.
- Electric vehicles use different drive train technology from those with a combustion engine; houses need to be adapted to be suitable for heat pumps instead of traditional central heating.
- The electrical infrastructure is vulnerable, as one failure can entail a cascade of events that eventually create a black-out for an entire region.

CONCLUSION

The drawbacks of the electrical economy seem less crucial than those of the hydrogen or bio-energy economies. This is also the conclusion of the papers ‘Searching for a Miracle’, ‘Sustainable Energy - Without the Hot Air’, and ‘Roadmap for a Low Carbon Power Sector by 2050’. All three studies suggest an acceleration of the transition towards electrical heating, cooling and transport. This implies that solutions for large scale storage and cost-efficient long distance transport of electricity should be developed.

As already mentioned, choosing electricity as a global energy carrier doesn’t mean that biomass or hydrogen solutions might not be preferred at a local level.

OPTIMISING THE ELECTRICAL SOLUTION

Apart from the main conditions discussed above, several technical criteria should be taken into account when designing the energy system of the future.

A DIVERSE MIX OF ENERGY SOURCES

Expressions like ‘wind is the future’ or ‘without nuclear, the lights will go out’ can often be heard in the media. They suggest that one energy source is key to ensuring our energy future. But that is at the same time unlikely and inexpedient. World energy demand is too great to be met by one or two energy sources, even if they are of very large scale. Without nuclear, the lights will not go out, but the remaining energy sources will have to be fully stretched. Wind is not the future, but it is certainly part of the future. Just like photovoltaic solar power, concentrated solar power, biomass, hydroelectric power, wave energy, tidal energy, waste energy, and geothermal energy could be part of the future energy mix.

Whether nuclear power and coal fired power with Carbon Capture and Storage (CCS) should be included, is part of a heavy debate. Interesting as those debates might be, their outcome does not determine the life and death of the future energy system, but are only part of the complex web of considerations that have to be made.

What are the main technical criteria that we should take into account when evaluating the potential energy sources? The following four are in each case crucial:

- Availability of power (hours/year)
- Variability of power output (how frequently on and off)
- Predictability of availability and variability
- Risk factor = (unit power) x (risk of unpredicted outages)

A perfect energy solution that scores well on all four factors doesn’t exist. For instance, wind power scores poorly on predictability, while a nuclear reactor has a high unit power, increasing its risk factor.

These various deficiencies will have to be overcome at system level. This will require a strong and adapted grid, energy storage systems, and intelligent control. The more diverse the energy mix, the more widely the disadvantages will be spread.

A STRONG AND ADAPTED ELECTRICITY GRID

The existence of a sophisticated and virtually universal grid gives electricity a clear advantage as the energy carrier of the future. This does not mean that the grid will not need to be adapted and reinforced to meet future needs. Examples include power transmission from large-scale renewables at very remote sites, ability to accept a very high degree of distributed generation systems, measures to cope with the intermittency and unpredictability of renewable energy production, and the extra power requirements of electric vehicles and heat pumps. In the following decades, the network concept as we know it will have to adapt to incorporate all these new elements, demanding considerable financial investments.

However, while these new elements bring some problems, they also offer new opportunities. While balancing and frequency regulation are currently organised centrally at grid level, distributed generation and storage facilities can provide those auxiliary services at the local level of a microgrid, improving the protection against black-outs and cascading failures.

It is still hard to predict how the electricity grid of the future will be structured. Perhaps the differences between the 'transmission grid' and the 'distribution grid' will reduce. Innovative energy storage systems are likely to be part of the future grid. The grid may consist of a network of locally controlled 'micro-grids'. It is very likely that Demand Side Management (DSM) will be used to reduce peak demand and help match demand to supply. For example, energy demand for water heating and refrigeration can often be advanced or delayed for a short time and laundry can be scheduled to avoid peaks.

ENERGY BUFFERS AND STORAGE SYSTEMS

In the future, a large and increasing share of electrical energy will be produced by intermittent renewable energy sources connected to the grid, making the amount of power available at any time more unpredictable. At the same time, with the large-scale deployment of electric heating systems such as heat pumps, demand is likely to become greater and more dependent on weather conditions. But the balance between supply and demand must always be maintained; today, that is achieved by the spinning reserve – power generators that are idling and can become active at short notice – but that will not be feasible in a low carbon world. Other techniques for matching supply and demand will be required. An ideal solution would be to store electricity for future use, but, so far, no practical large-scale storage technologies have emerged. The only options are pumped water storage (converting electrical to potential energy and back again) or compressed air storage. The number of suitable sites for these systems is limited.

A breakthrough in storage technology would consequently be very welcome and would ease the transition to an integrated all-electric economy. In the meantime, dispersed small scale storage systems may provide a partial solution. For example, the batteries of electric vehicles could be used for storage whenever they are connected to the grid. The thermal buffers of heat pumps allow significant scope for load shifting, effectively providing virtual storage. Since these distributed storage systems make use of existing equipment, they are likely to be cheaper than dedicated large-scale storage. The price that has to be paid is loss of controllability; distributed storage implies statistical estimations, whereas bulk storage systems can be controlled precisely.

EFFICIENT USE OF ENERGY

As energy is likely to become more scarce than it is today, efficient energy use will gain importance. Today, many energy efficient technologies are readily available, but few are used in daily practice, even though they have, in many cases, the lowest Total Cost of Ownership (TCO). One of the major reasons is what economists call 'the principal-agent problem': the purchaser of the energy using technology is not the same as the purchaser of the energy itself. This does not only happen in business-to-business environments, but also in everyday consumer life. Think, for example, about hotel guests who don't have to pay for their energy consumption, or landlords who buy cheap, inefficient technology because the tenants pay the utility bills.

In the energy economy of the future, we should find ways to bridge this 'efficiency gap'. As solutions with the lowest Life Cycle Cost (LCC) benefit both the economy and the environment, they should always be the preferred option. Ensuring this will require the market to be organised in such a way that those solutions are also the most profitable for the whole value chain.

ON-GOING EVOLUTIONS IN THE ELECTRICAL SYSTEM

Since the change of millennium, the electrical system has entered an era of strong evolution. The change towards a world without fossil fuels has been initiated. What is the state of affairs today, and how do we keep the ball rolling towards its end-goal? What kicks does the ball still need?

CARBON FREE ELECTRICITY GENERATION

During the past ten years we have seen a major breakthrough in carbon free electricity generation. In 2008, wind became the preferred technology for new generating capacity in Europe. Solar PV is still smaller in scale than the wind sector, but growing fast. The past two years we have seen a major breakthrough in Concentrated Solar Power (CSP) with many projects in development in Spain and California.

Despite this growth, the share of renewables in total energy consumption remains small compared to fossil fuels. If we are to reach some figure between 50 and 100% of carbon free electricity generation by 2050, the biggest effort is still ahead of us. To achieve it, development in wind energy, particularly off-shore, should continue, the deployment of solar energy should accelerate and wave and tidal energy, so far limited to occasional pilot installations, should be developed to reach market maturity.

Recently, the Transgreen project, under the custody of the French power producer EDF, revealed a plan for CSP power stations in the North-African desert. A similar plan has already been suggested by DESERTEC. These projects have the potential to grow to the kind of scale that is required to make the energy system shift. According to the estimations of David McKay ('Sustainable Energy - Without the Hot Air'), solar power in the Sahara desert could supply up to one quarter of all European energy consumption.

Nuclear energy and CCS-equipped coal fired power stations are two other technologies that have the potential to make large scale contributions to carbon free electricity production. Whether these are sustainable options, is a point of debate.

CCS is currently the subject of several R&D projects. The technology consists of three elements. The first is Ultra Super Critical coal fired power plants, which operate at the higher temperatures (700°C) and pressures (300 bar)needed to compensate for the efficiency loss that CCS incurs. Such power plants are currently in the development phase. The other elements are carbon capture, for which technologies are in test phase, and carbon storage, which is still far from commercial realisation.

The first generation III nuclear reactors, which boast evolutionary improvements in safety and efficiency, are currently under construction. Generation IV nuclear reactors are still in the research phase. Concerning nuclear fusion, a research reactor is being constructed by ITER in Cadarache, France. The first nuclear fusion reactor is predicted to be ready in 2040, but considering the many barriers that have to be overcome, this is no more than a good guess.

THE ADAPTATION OF THE ELECTRICITY GRID

'The grid of the future' has become an active research topic but it is expected that it will be some years before the results could lead to conceptual changes in the field.

Nevertheless, some hands-on grid improvements are already being undertaken, mainly in the form of organisational improvements (e.g. brokering of cross-border power transport), and technical solutions to maximise the usage of the existing infrastructure (e.g. phase-shift transformers). Useful as those actions may be, if we are heading towards an all-electrical economy, they will not be sufficient to meet future needs. Large-scale grid infrastructure works will be necessary over the next few decades.

DESERTEC and TransGreen investment plans for developing CSP in the North-African desert include the construction of high capacity transmission lines between North-Africa and Europe.

ELECTRIFICATION OF TRANSPORT

The electrification of transport is slowly taking off. The introduction of vehicles with hybrid drive trains and regenerative breaking, like the Toyota Prius, is a small first step in this evolution. However, the introduction of a mass-market plug-in hybrid vehicle seems to be eternally two years ahead. The recent economic crisis provides both a barrier and an opportunity. On one hand it forces the companies to focus on short-term profit but on the other, it makes them realise that a paradigm shift towards electrical vehicles provides a new opportunity for this commodity market. Government support programmes for the car manufacturing industry are sometimes coupled with the development of electric vehicles. However, evolution towards electric vehicles is such a huge shift that it is expected to happen slowly. The cape of 50% of all new vehicles sold is not likely to be rounded in the coming ten years.

In public transport, the share of electrically driven systems is growing slowly but steadily. Ever more railway lines are electrified around the world, and trams and metros are gaining ground in city transport.

ELECTRIFICATION OF HEATING AND COOLING

In some countries (Switzerland, Sweden, the Netherlands), passive houses, low energy houses and heat pumps are the prevailing concepts for new houses and buildings. All three concepts include in most cases an 'electrical booster' in the form of an electrical resistance heating element for use when the outside temperature is below a certain limit. Since a heat pump compressor is also electrically driven, relying on those three concepts implies that building heating is going all electrical.

But change is happening slowly and most other countries are far behind the trend-setters. Moreover, houses and their heating systems have a long life span. So if only new houses are equipped with these new heating systems, it will take several decades, if not a century, before the shift is completed. To accelerate the change, new heating concepts need to be part of renovation projects, even though it is more difficult and more costly than in a newly built construction. Accelerating the shift in this way would also require a high renovation rate of buildings.

THE EFFICIENCY OF ELECTRICITY

The major concern about energy efficiency goes back to the oil crisis in the 1970s. Since then, efficiency labels, standards and incentives have influenced the market towards a more efficient end-use of electricity. Without those efforts, our energy situation would be even more precarious than it is today. Improved efficiency has, to a large extent, compensated for the high increase in energy services that the world has seen in the past 40 years, so avoiding an exponential growth in energy consumption.

The measures that are being taken are, however, only a fraction of the global potential. Despite energy efficiency improvements being economically profitable, the potential is still largely untapped. As Science Magazine wrote in their article on ‘the efficiency gap’, it is ‘not even low-hanging fruit, but fruit laying on the ground’. Organisational changes and the availability of initial investment capital will be the key to exploitation of this potential.

Efficiency improvements are not only possible in electricity end-use, but also in generation and transport. Compared to other energy systems, electricity transport and distribution is highly efficient, but there is still a range of possible improvements. These include high efficiency power transformers, busbars and power cables specified for high efficiency, and intelligent devices for optimal network use.

CONCLUSION: IN WHICH TECHNOLOGIES SHOULD WE INVEST?

In which technologies should governments, companies and institutions invest? That is the question. This paper contains some initial thought exercises that can lead towards an answer.

The transition towards a non-fossil fuel economy has started, but is still in its infancy. We have only achieved a small part of the shift so far, and we are in acute need of an integrated vision of how to proceed.

It is important to recognise the urgency of the matter. It requires solutions that, as far as possible, build on existing systems and technologies, while taking care not to lock-in costly and ultimately unsuitable solutions.

Since a clear vision on the energy systems of the future is still lacking, it would be good if we could start the change without having to take all decisions right away.

Taking all these elements into account, the only serious option we have today is to go for the 'electrical society' as sketched above. It is a system that is already up and running, but needs to be adapted to meet the additional needs of transport and heating, and cope with the renewable and carbon free energy sources. This is where we should invest the majority of our resources.

There are very few alternatives to this vision. A lot of enthusiasm is being expressed for various parts of the energy system, but very few comprehensive solutions for the energy society as a whole are being presented.

This doesn't mean that electricity is the only domain that should receive support. Proportional parts of the cake could go to other technologies that are useful as alternatives on a local level or in specific applications.

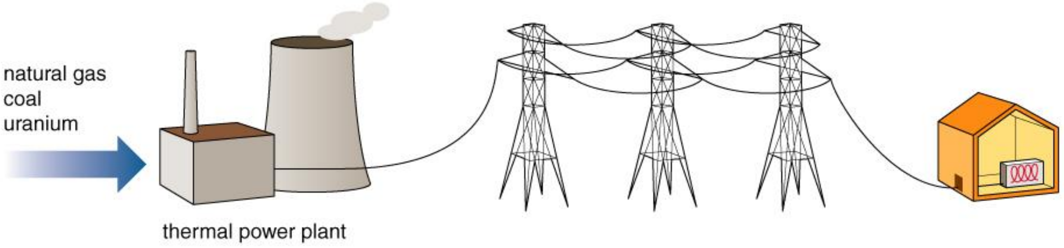
A smaller share of the resources could also go to research on technologies that might offer new solutions in the longer term, such as algae, energy from space or nuclear fusion.

A FEW AFTERTHOUGHTS

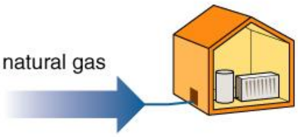
IS ELECTRIC HEATING INEFFICIENT?

There is a long tradition of opposition to electrical heating, mainly by environmental groups, because of its assumed poor energy efficiency. It might sound contradictory that we present electric heating as the most efficient and environmentally friendly option for the future.

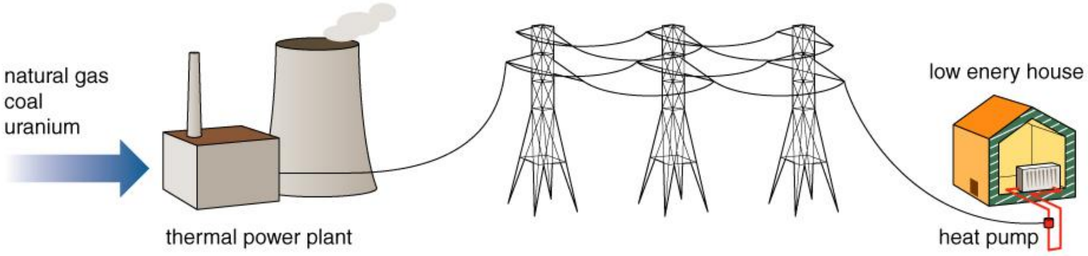
To understand this contradiction, one should go back to the origin of the opposition. The reasoning behind it was that the use of natural gas in a power plant introduced unnecessary additional steps in the energy chain:



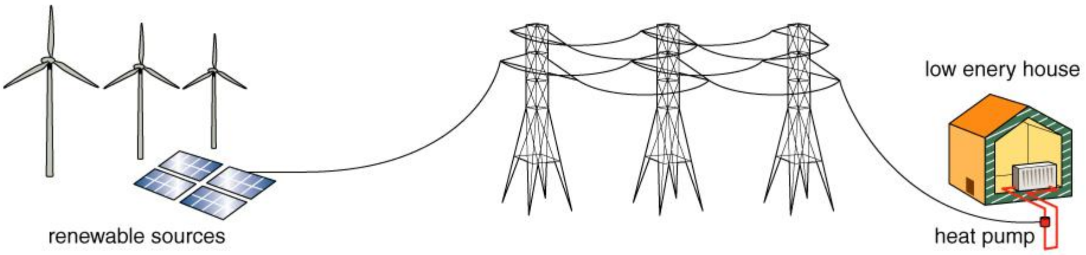
Making direct use of natural gas at the place of consumption removes those steps, and will always be more efficient:



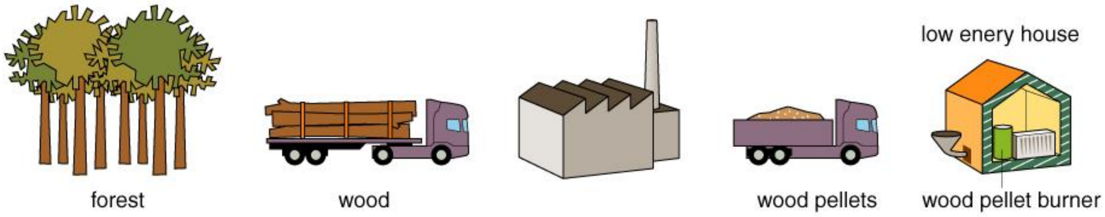
Always? But what if the electric heating device has an efficiency of 400%, like a heat pump? A heat pump delivers low temperature heat, requiring the house to be well insulated:



And what if the electricity is not produced by fossil fuel, but by renewable energy sources? The electricity generation mix is predicted to be 50 to 100% zero carbon by 2050, while a natural gas boiler will never be zero carbon. And, after all, buildings and their heating systems are constructed for at least 30 years.



Now the picture looks entirely different than it used to be. The choice today is no longer between a natural gas boiler or an electrical resistance heating system. The choice is rather between a heat pump driven by electricity from renewable sources, or the burning of biomass at the place of consumption:



It would require a detailed Life Cycle Assessment to determine which of those options has the lowest ecological footprint.

But who says a heating system is required at all? Very low energy houses or passive houses are so well insulated that they only need additional heating on the coldest days of the year. If that is the case, it doesn't make sense to invest in a high peak power central heating system; a few electrical heating elements will be the preferred solution.

IS THE ELECTRIC VEHICLE ONLY DISPLACING POLLUTION?

An argument that can sometimes be heard is that the electric vehicle is no more environmentally friendly than a traditional gasoline vehicle since 'the pollution is only displaced from the exhaust pipe of the car to the stack of the power plant'. Since electricity is only an energy carrier (just like hydrogen), it is true that its ecological footprint depends entirely on the energy sources that are used to produce the power. But even when the electricity is entirely produced by coal fired power stations, and even when the transmission and distribution losses of electricity are taken into account, the electric vehicle still has a smaller ecological footprint than a traditional gasoline car.

Taking the hypothetical case of electricity produced solely from coal, the electric vehicle has 'well-to-wheel' emissions of 950 to 1200 g CO_2/kWh. This has to be compared with the emissions of a traditional gasoline car, which amount to approximately 1800 g CO_2/kWh (source: ‘Green power of electric cars’). The difference can be explained by the fact that electrical power stations have an advantage of scale compared to a car’s internal combustion motor. Producing high power at high temperatures, their overall efficiency is much higher.

Moreover, the electric vehicle is developed for the electricity mix of the future. The EU is aiming for 20% renewable electricity by 2020, and for 50 to 100% by 2050. This means that the ecological footprint of electric vehicles can be expected to become several times smaller than it is today.

ARE ELECTRICITY TRANSMISSION AND DISTRIBUTION LOSSES HIGH?

The energy losses in transmission and distribution of electricity are often thought to be high. Many people are surprised if they are provided with the actual figures. In Europe and North America, network losses are typically around 7%. One reason for the common misjudgement is that energy conversion losses (from primary energy to electrical energy) and network losses are often combined in one figure, giving a misleading picture of the situation.

That said, because of the continuous and high amounts of energy that flow through transmission and distribution lines, it is worth making the effort to minimise the losses. There is certainly a potential left for improvement, for instance through the use of high efficiency power transformers and Ultra High Voltage (UHV) lines.

ON ENERGY SOURCES, ENERGY CARRIERS, AND END-USE ENERGY

In discussions on the electrical system, there is often confusion about the meaning of the terms *energy source*, *energy carrier*, and *energy end-use*.

Fossil fuels are *energy sources*, just like biomass, sun radiation, wind, and water power. They can be found in a usable form in nature.

This is not the case for electricity and hydrogen. These are merely *energy carriers* since they do not exist in a usable form in nature and need to be produced from energy sources, a process that always costs more energy than can ever be taken out again. The advantage of the energy carrier is that it is transportable, which is not always the case for energy sources. Energy carriers transport energy, made using local natural energy sources, and to the place of use. It also allows the centralisation of the conversion of primary energy to usable energy in highly efficient large-scale power stations. Another advantage is that some energy carriers are very practical for certain forms of energy end use (e.g. electricity for motion power, light, and electronics). Fossil fuels and biomass are at the same time energy source and energy carrier.

Energy end-use is the final functional use of energy, e.g. to produce heat, cold, light, and motive power.

LINKS

- ‘Sustainable Energy - Without Hot Air’ http://www.withouthotair.com/
- ‘Searching for a Miracle’ http://www.ifg.org/pdf/Searching%20for%20a%20Miracle_web10nov09.pdf
- ‘Roadmap for 2050’ http://www.fepc.or.jp/about_us/pr/oshirase/__icsFiles/afieldfile/2009/12/18/IEP121809_E_1.pdf
- Science Magazine: ‘Leaping the Efficiency Gap’ http://www.sciencemag.org/cgi/content/short/325/5942/804
- DESERTEC http://www.desertec.org/
- ‘Green Power of Electric Cars’ by University of Delft http://www.greenpeace.org/belgium/nl/press/reports/greenpower