Transition to a Post-Fossil Fuel Future - Contributions from Space

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Fundamental energy choices have changed almost every aspect of society, economy and even politics during the last 200 years. While energy supply security, access and cost have been the main decision parameters so far, with the now confirmed effects on the global climate, environmental aspects have now become an additional important element. This paper analyses the main current global energy system trends and choices and addresses the question how space applications and space technology can contribute to accelerating and easing the transition to a more sustainable and environmentally benign post-fossil fuel energy future.

Key Words: space, energy, fossil fuels, energy efficiency, solar power

1. Introduction

"*At present we derive the energy which drives the wheels of industry from coal and oil. Both these substances are won from nature at the expense of much money and vast stores of muscular energy, nor are their supplies inexhaustible. [...] This problem will be solved before 2030. [...] For the first time in his history man will be armed with sufficient power to undertake operations on a cosmic scale. It will be open to him radically to alter the geography or the climate of the world.*" This is a quote from "The world in 2030", a book written in 1930 by Frederick Smith, the 1st Earth of Birkenhead, who tried to imagine what the world would look like in 2030.[1)] While being a lawyer and politician by training and profession, he correctly had already identified energy as being one of the key parameters determining the course of the next 100 years. While the details of our energy system are quite different from the one of the 1930s, this paper argues that the key questions have not changed: energy security, abundance, controllability/access and generation cost are still at the core of our energy strategies. Not envisaged in 1930, environmental sustainability has completed these factors.

The present paper discusses how space can contribute to one of the key challenges faced by humanity: a fast and smooth transition to a post-fossil fuel energy system.

2. Starting Point – Current Energy Situation

Any energy discussion is fundamentally along one of the three main strategic pillars:

1. Energy Security
   control over and timely access to supply;
2. Energy Supply and Competitiveness (including the suitability of the stored form of energy)
   the availability of energy should not be a limiting factor for social, economic, military or social policies; energy should be competitively priced since cheap energy has proven to be one of the key drivers of industrial growth
3. Environment and Climate:
   Energy system (power generation, energy conversion and storage) have impacts on the environment; environmental secondary costs are increasingly factored into the overall tradeoff.

The respective relative importance of these three key requirements change over time and between regions, countries and societies, due to economic, historical, geographical (e.g. natural resources) differences. This has led to different energy mixes and strongly varying high-level energy strategies. It is therefore unlikely to find any one-fits-it-all solution.

Europe has been largely energy sufficient until the end of the coal-dominated energy area. With the gradual shift from coal to oil and gas, this situation has changed substantially. Energy produced within the EU represents 46% of the total consumed.

In a communication of the European Commission from October 2010, the situation is described as follows: "*Today, in the EU, our primary energy supply is 80% dependent on fossil fuels. Networks and supply chains have been optimised over decades to deliver energy from these sources to our society. Economic growth and prosperity has been built on oil, coal and gas. But, they have also made us vulnerable to energy supply disruptions from outside the EU, to volatility in energy prices and to climate change.*" [2)]

At present, imports comprise 61% of EU gas gross inland consumption. 42% of these imports come from Russia, 24% from Norway, 18% from Algeria, and 16% from other countries, the latter mostly in the form of LNG. By 2020, as EU indigenous production continues to decline, the percentage of gas imports is expected to increase to 73% from 61% today.

Before the 20-20-20 initiative, this was set to fall to 36% by 2020. Implementation of the new Energy Policy would keep it at around 44% of EU consumption.

The development of renewable energy such as wind, solar, hydro, biomass energy and marine resources has to be seen as the EU's greatest potential source of indigenous energy. Today it accounts for around 9% of final EU energy consumption, the objective of a 20% contribution by 2020 has been agreed in principle. In the words of the European Union: "*Reinventing our energy system on a low carbon model is one of the critical challenges of the 21st Century.*" [2)]

3. Main Energy Trends

"*Oil is the world's vital source of energy and will remain so for many years to come, even under the most optimistic of assumptions about the pace of development and deployment of alternative technology*."[3)]

The transport sector accounts for 97% of the average 1% annual increase in oil use until 2030. Conventional oil production in countries not belonging to OPEC peaks around 2010.

OECD countries as a group are projected to spend on average close to 2% of their GDP on oil and gas imports to 2030 (500 B$/yr in case of EU, 400 B$/yr in case of US) - up from 1% average during last 30 years. Interestingly, while projecting the exact contrary, there is also large consensus on the needs for substantial change. In the words of the OECD/IEA: "*Preventing catastrophic and irreversible damage to the global climate ultimately requires a major decarbonisation of the world energy sources.*" "*Securing energy supplies and speeding up the transition to a low-carbon energy system both call for radical action by governments — at national and local levels, and through participation in co-ordinated international mechanisms*." [3)]

Even under the most optimistic green scenarios, fossil fuels will remain the worlds vital source of energy - in the most likely scenario of the IEA/OECD, all three are expected to increase until 2030, mainly due to the needs in developing countries.[3-5)]

In a business-as-usual scenario, world primary energy demand will grow by 1.5% per year on average in 2007-2030, from 12000 Mtoe to 16800 Mtoe. China and India are expected to account for just over half of this increase, while in total, non-OECD countries account for 87% of the increase. Well reflecting the shift in economic power, their share of world primary energy demand rises from 51% to 62%.

While being the most carbon intensive and thus without large-scale carbon sequestration the most ecologically contested, world demand for coal is expected to advance by 2% a year on average until 2030, even rising its share in global energy demand from 26% in 2006 to 29% in 2030. 85% of the increase in global coal consumption is expected to come from the power sectors of China and India.

While modern renewable energy sources (wind, solar, tidal, etc) are growing most rapidly, their low current share will only increase to a total of 8.6% in 2030 in a business following current policies. The share of non-hydro renewable energy sources in the total power output rises substantially from 2.5% in 2007 to 8.6% in 2030, with wind power expected to seeing the biggest absolute increase.

According to the 2009 edition of the World Energy Outlook, fossil fuels will account for 77% of the increase in world primary energy demand from 2007 to 2030.[5)]

Out of all the electricity generation capacity currently under construction worldwide, a total of 613 GW, more than 200 GW are coal plants, and about 150 GW generation capacity is added in form of new gas plants. Two third of this additional capacity is constructed in non-OECD countries.[5)]

These increases don't come for free, but are associated with already planned heavy investments into the energy sector. Only for the business as usual scenario, on average more than 1100 Billion dollars per year, or 1.4% of the global GDP are foreseen. Investment required for meeting projected energy demand through to 2030 in the OECD Reference Scenario amounts to $26 trillion (in year-2008 dollars). More than 50% of it will be invested in the power sector.

Due to the recession, 2009 has been the first year since almost 30 years that has seen a decreasing energy demand and thus also decreasing energy investments. While some expect this to be an indication for a long-term reversal of a very solid trend, it is widely expected to be of temporary nature only. The decreasing global energy demand and the financial crisis have also led to a decrease of private energy investments: especially global upstream oil and gas investment budgets for 2009 have been cut by around 19% compared with 2008 (reduction of over $90 billion). At the same time, investment in renewable energy sources and their technologies have fallen about 20% in 2009 compared to 2008.

3.1. Energy Investment Repartition

About 52% of the total investment foreseen until 2030, or $13.6 trillion, are expected to be spent in the fastest growing energy sector: the electricity sector to generate power. About half of this investment will be for the generation and the other half for its transmission and distribution. This represents average annual investments until 2030 of $590 million in just the power sector.[5)]

Oil and gas take up the majority of the other 48%, or $6.3 trillion, with most of the investments being spent in the exploration and development aspects of both sources. A notable difference is the substantially larger part required to transport and distribute gas: while investments in the transmission and distribution of oil are expected to require a cumulated $250 million until 2030, funding for transmission and distribution of gas will need $1.7 billion over the same time period.

It is interesting to note that total public sector budgets for energy RD&D have declined in real terms over the last 35 years and until 2008 and that pre-stimulus nominal levels in 2008 were only slightly above amounts budgeted in 1976. Furthermore, the relative share of energy in total RD&D has declined significantly, from 12% in 1981 to 4% in 2008, and only since 1997, government RD&D budgets have steadily increased.

Including the stimulus spending, annual IEA member country spending is about $23 billion; $16 billion without stimulus spending. This stimulus-related increase nearly doubles IEA member country spending from 2008 levels.

4. Environmental Trends Related to Energy

These energy policies not only don't come for free economically, they also have their own substantial ecologic burden: Most expectations count with a continued rapid rise in energy-related CO_2 emissions through to 2030, after having already increased from 20.9 Gt in 1990 to 28.8 Gt in 2007, CO_2 emissions are projected to reach 34.5 Gt in 2020 and 40.2 Gt in 2030, an average rate of growth of 1.5% per year.

It is interesting to note that non-OECD countries account for practically all of the projected growth in energy-related CO_2 emissions to 2030:

- 3/4 of the 11-Gt increase comes from China (emissions rise by 6 Gt), India (2 Gt) and the Middle East (1 Gt).
- OECD emissions are projected to fall slightly, due to a slowdown in energy demand and the increased reliance on nuclear power and renewable power sources.

Non-OECD countries today account for 52% of the world's annual emissions of energy-related CO_2, they are responsible for only 42% of the world's cumulative emissions since 1890.

The CO_2 concentration of the business as planned scenario (OECD) would result in the global average temperature rising by up to 6°C. "*This would lead almost certainly to massive climatic change and irreparable damage to the planet*."[5)]

Of the total spending of $520 billion in 2009, approximately $23 billion is spent by governments for RD&D for LCETs. The United States has the largest amount ($12 billion) of RD&D in its stimulus packages, followed by the European Union ($6 billion).

5. European Situation – Energy Policy

Given the challenges, the EU has endorsed an energy strategy, called the Strategic Energy Technology Plan, SET-Plan.[2), 6-10)] The SET plan is essentially a vehicle to accelerate the development and large-scale deployment of low carbon technologies.

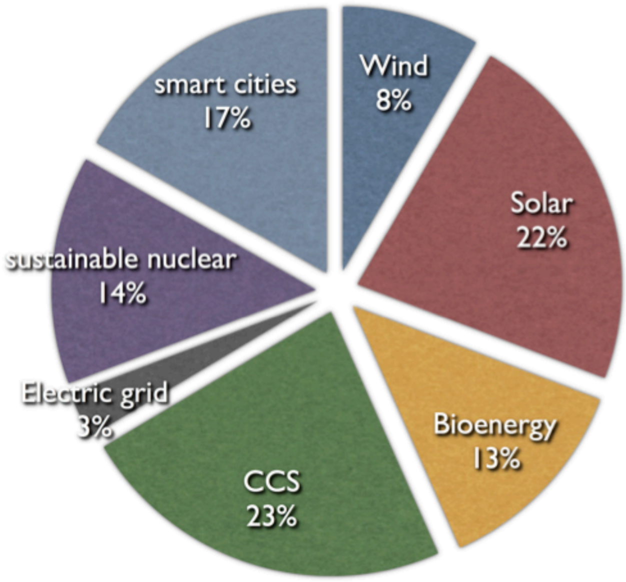

Fig. 0. Relative repartition of investments proposed within the EU SET-Plan. (Graph generated from data obtained from [11)])

According to the analysis of the European Commission, already before the adoption of the SET-Plan, the aggregated R&D spending towards most non-nuclear SET-Plan priority technologies amounted to €2.38 billion in 2006/7.[2)]

These €2.38 billion are composed of €1.66 billion, or 69%, from corporate R&D investments, €0.57 billion, or 24%, from public national R&D budgets in EU Member States in 2007 and €0.16 billion, or 7%, financed via the 6th European Research Framework Programme in 2006. [2)] Comparing the investment areas, the largest share combining public and private R&D investments went into hydrogen and fuel cell research (€616 million), followed by roughly equal amounts spent on photovolatics (€384 million), wind (€383 million) and biofules (€347 million). The rest is shared by investments into smart grid, carbon capture and storage and concentrating solar power technologies.

To get the to the total SET-plan low-carbon energy related R&D funding in Europe of about €3.3 billion in the same time period, this non-nuclear funding needs to be completed by the nuclear R&D budget, which include research on reactor technologies (including next generation reactors such as Gen IV) but also research on environmental protection, waste storage, nuclear safety and fusion research.

With the European SET-Plan, the European Union tries to transform the challenge of growth in a carbon-constrained world into an opportunity for European industry to take leadership worldwide in clean and efficient green energy technologies. The basis of this strategy is the assessment that "*technology mastery will increasingly determine prosperity and competitiveness*".[11)] The EU policy framework that has been put in place, including the European Industrial Initiatives, focus the effort on key challenges and bottlenecks for the period 2010- 2020.

It proposes to invest €58-71 billion over 10 years towards the realization of the 20-20-20 vision. This investment is planned to be shared between industry and public funding (Member States and the European Commission). While R&D programmes are likely to have a prominent public investment component, the demonstration programmes are expected to have a strong industrial component, which would be accompanied by public support. The close to market part of the investment are expected to have a dominant participation from industry.

As part of the proposed roadmap, seven detailed energy technology roadmaps are elaborated, which contain concrete action plans for each of these. The general vision is that by 2020 the European energy system will be on a solid path towards a low carbon economy and that by 2050, all of these technologies will substantially contribute to an essentially carbon-neutral system.[11] The main targets set forward in 2009 are:

- Wind energy will contribute up to 20% of the EU electricity by 2020.
- Solar energy will contribute up to 15% of the EU electricity by 2020. In case the 'desertec vision' were achieved, the contribution of solar energy would be even higher, especially in the longer term.[12]
- The development of smart electric grids will enable the European grid to integrate up to 35% renewable electricity by 2020.
- Bio-energy will contribute at least 14% of the EU energy mix by 2020.
- Carbon capture and storage technologies will become cost-competitive within a carbon-pricing environment by 2020-2025.
- Existing nuclear technologies will continue to provide around 30% of EU electricity in the next decades and first Generation-IV nuclear reactor prototypes will be in operation by 2020, allowing a commercial deployment by 2040.
- 25 to 30 European cities will be at the forefront of the transition to a low carbon economy by 2020.

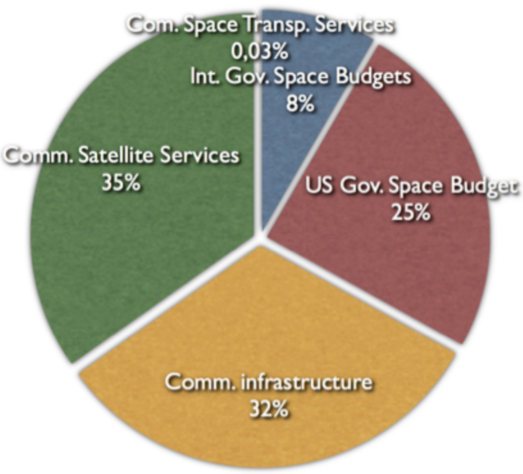

Fig. 3. Repartition of the global space sector (graph based on data provided in [26])

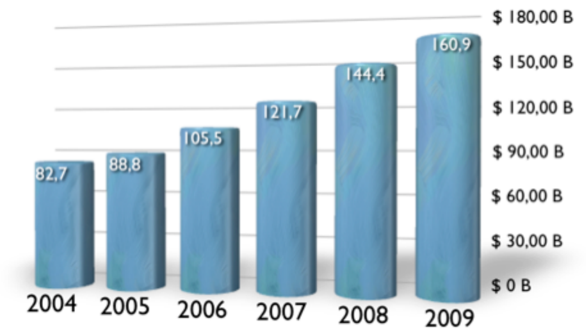

Fig. 0. Evolution of the global revenues of the satellite industry from 2004 to 2009 in billions of US $ (graph based on data provided in [27])

The SET-Plan as proposed by the Commission has six main investment areas:

- Wind Energy (€6 billion)
- Solar Energy (PV & CSP) (€16 billion)
- Bioenergy (€9 billion)
- Carbon Capture and Storage (CCS) (€10.5 - 16.5 billion)
- Electricity grid (€2 billion)
- Sustainable Nuclear Energy (€5 - 10 billion)
- Smart Cities and Energy Efficiency (€10 - 12 billion)

All together these are summing up to the €58-71 billion estimated as needed by the Commission. Fig. 0 shows the relative repartition of the proposed total investment within the SET-Plan.

5. Comparison – Energy and Space Sectors

The space and energy sectors have some noticeable commonalities such as a strong strategic importance, very long lead times for the market introduction of new technologies, an inherent cautious attitude towards radical changes in the short to medium term, the need for substantial investments into early R&D and thus the generally required involvement of governments.

On the other hand, the two sectors also have some substantial fundamental differences. Most importantly the overall market size, the maturity of the energy market with respect to the space market, which is essentially still largely dependent on governmental needs, requirements and investments.[13-25]

Putting these in pure numbers shows the orders of magnitude difference in total investments and market size: In 2009, the total space market has been estimated to be about $261 billion, with $86 billion government spending on space (out of which about 75% or $64 billion are from the US government alone). The relative repartition of the space market into major segments is shown in Fig. 3.[26] These are furthermore concentrated on a few countries and linked usually to high strategic value.

Worldwide, the space sector has continued its growth in the last years, despite the economic downturn. Following the statistics published by the U.S.-based Satellite Industry Association, the global revenues for the satellite industry amounted to $160.9 billion in 2009, with satellite manufacturing and launch services as the two fastest-growing segments worldwide, followed by the satellite services sector, which continues to demonstrate increased 11% growth globally as the main demand driver.[27]

Per industry segment, the satellite television revenues amounted to $71.8 billion, satellite manufacturing revenues worldwide grew by 29 percent, from $10.5 billion in 2008 to $13.5 billion in 2009, launch revenues increased by 18 percent in 2009 despite a slight decrease from 49 commercially-procured launches in 2008 to 46 in 2009 (U.S. launch revenues of $1.9 billion) and satellite ground equipment revenues increased by 8 percent to $49.9 billion (led by consumer-oriented products such as satellite TV and broadband, mobile satellite, and GPS devices).[27]

These numbers are relatively small compared to the revenues generated in the energy sector. They are roughly in the same order of magnitude as the combined global revenue for the three major clean-energy sectors alone: solar photovoltaics, wind, and biofuels, which together generated $139.1 billion in 2009. In this context it is worth recalling that these renewable energy sources together are not even generating 4% of the total electricity. Their very fast total increase in the last decade is expected to continue to arrive at about $325.9 billion by 2019. It is unlikely that the space sector will follow a similar growth pattern within the next decade.

While the space sector is comparable to the wind, solar photovoltaic and biomass energy sector segment combined in terms of revenues, these energy sectors are substantially larger in terms of employment. Only the solar and wind energy sector is employing an estimated 820 000 persons. There are no reliable estimates on the worldwide space industry employees known to the author, mainly due to the lack of reliable information from China, India and Russia. Given that in the largest space power, the United States, roughly 250000 persons are employed in the space industry and about 35000 in Europe, total worldwide employment in the space sector can be estimated being roughly half the one of the solar and wind energy sector.

6. Transition to a sustainable, low-carbon energy system as key to 21st century human development

Within the general frame of an increasingly closer cooperation between the European Union (EU) and the European Space Agency (ESA), the two organizations have recently launched a reflection on how space in general, and space applications and space technology in particular can contribute to the overall objectives of the European Union as defined in the SET-Plan. This reflection is led within ESA by the Director General's Policy Office and includes all potentially concerned directorates. On the EU side, the effort is led by Energy Directorate General.[28]

The joint reflection has led to the identification of thematic fields of cooperation between ESA and EU in the fields of energy and space: [28]

a. Transfer of technologies – Short to medium term
b. Transfer of technologies – Long term
c. Space-born sources of energy – Very long term
d. Use of space data for optimising (e.g. the location of) energy installations – Short term
e. Use of technologies for monitoring – Short to medium term

The selection of key EU technology challenges for the next 10 years to meet the 2020 targets have been provided by the commission as being the following:

- Make second generation biofuels competitive alternatives to fossil fuels, while respecting the sustainability of their production;
- Enable commercial use of technologies for CO_2 capture, transport and storage through demonstration at industrial scale, including whole system efficiency and advanced research;
- Double the power generation capacity of the largest wind turbines, with off-shore wind as the lead application;
- Demonstrate commercial readiness of large-scale Photovoltaic (PV) and Concentrated Solar Power;
- Enable a single, smart European electricity grid able to accommodate the massive integration of renewable and de-centralised energy sources;
- Bring to mass market more efficient energy conversion and end-use devices and systems, in buildings, transport and industry, such as poly-generation and fuel cells;
- Maintain competitiveness in fission technologies, together with long-term waste management solutions;

Similarly, for the long-term the EU has provided the following key technology challenges to meet Europe's ambitions for the 2050 vision:

- Bring the next generation of renewable energy technologies to market competitiveness;
- Achieve a breakthrough in the cost-efficiency of energy storage technologies;
- Develop the technologies and create the conditions to enable industry to commercialise hydrogen fuel cell vehicles;
- Complete the preparations for the demonstration of a new generation (Gen-IV) of fission reactors for increased sustainability;
- Complete the construction of the ITER fusion facility and ensure early industry participation in the preparation of demonstration actions;
- Elaborate alternative visions and transition strategies towards the development of the Trans-European energy networks and other systems necessary to support the low carbon economy of the future;
- Achieve breakthroughs in enabling research for energy efficiency: e.g. materials, nano-science, information and communication technologies, bio-science and computation.

Many of these key technologies are addressed by one or several of the proposals that ESA has proposed as support from space in form of space activities, space assets or space technologies. In particular, the ESA-internal cross-directoral working group has described 15 projects covering the entire time-span. While referring to Duvaux-Bechon and Sabatier for details, the titles of these are recalled here.[28] It is worth noting that these are by no means spanning all those space uses and space applications that are of potential interest to achieve the goals set by the European Commission but represent only a small selection, for which also criteria such as the potential to start immediately have been taken into account.

Under the heading of space applications for energy policy enforcement, the following two activities have been proposed:

- Earth observation services in support of renewable energy sector and carbon capture and storage
- Benchmarking and promoting best practices in energy efficiency and sustainability

Among space applications for energy systems management, the following six specific proposals have been described:

- Intelligent integrated grid monitoring, management and control
- Intelligent planning, monitoring and diagnostic applications
- Pipeline remote monitoring system
- Prediction of disruptive geomagnetically induced currents in networks
- Small-scale power plant management and integration with electricity grid
- Space infrastructure as enabling factor to increase the safety of nuclear end-to-end energy production

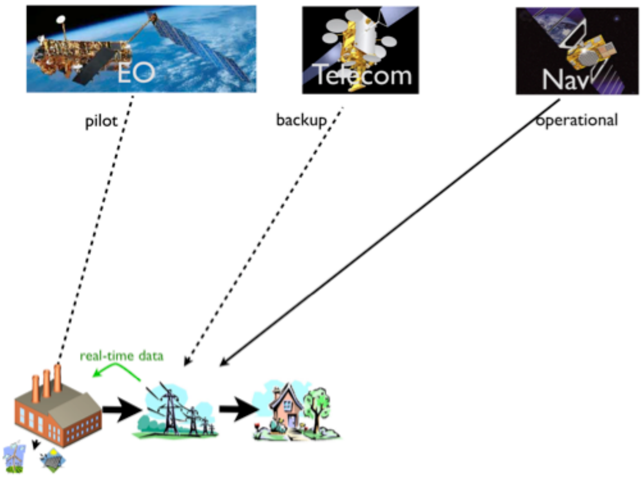

Fig. 5. Schematic representation of current uses of space for terrestrial electricity networks.

Among the technology transfer heading, the two specific activity proposals have been identified as being ready for immediate implementation:

- Adaptation of high-efficiency solar cells and modules handling and testing methods
- Transfer of power conversion innovative solutions

Under the heading of long-term research topics of potential benefit to the other subjects, the following five activities were described as being ready for short-notice start:

- Improved heat exchangers
- Processes for cleaning crystalline silicon (c-Si) for photovoltaic cells
- Analysis of diffusion and Soret coefficients
- Solid nano-structured metal powder fuel
- Lightweight high-efficiency thermoelectric material to convert waste heat into electricity
- Space solar power plant systems

It is expected that some of these activities would be selected by the European Commission for rapid implementation, e.g. in form of pilot projects, during which experience with concrete direct cooperation between the space and energy sectors can be gained eventually leading to a larger, much more substantial interaction for the benefit of both.

7. Example Future Energy Grid - SmartGrid

One of the example topics in this area, which has already progressed quite substantially is related to the role space can play in the already visible evolution of the electric grid. This example is taken for the purpose of this paper in order to illustrate the potential radical changes that part of the energy sector is likely to experience and the role space can play given its unique characteristics. In addition this topic is a good example of potentially radical innovation emerging at the intersections of two well-established domains.

Essentially, the current electricity grid is based on the foundation developed 100 years ago and never seriously questioned since then.[29)] It relies essentially on a limited number of interconnected centralised relatively large power plants, usually complemented by a number of smaller ones, that generate electricity in a fully controlled manner, which is then distributed via main and secondary lines up to the final consumers. The final users are in this system essentially passive consumers with very little actual choice.

Over the years, the usually regional grids have been interconnected into national ones, which are still dominating though regional interconnections of national grids are increasingly important. The management of the grid essentially involves the careful planning of the generation and transmission capacity, and on a day-to-day basis the forecast of the consumption profile in order to anticipate and adapt the generation patterns, involving temporary storage in e.g. hydroelectric plants.

Space components already play a role in the organisation of current electricity grids since global navigation satellite systems offer the time-precision needed that enables measuring the system-wide AC phase as well as timing events and synchronizing controls.[30)]

Furthermore, the use of Earth observation data already in pilot or (pre-)operational stages include data for atmospheric and cloud modelling (e.g. Meteosat), solar irradiation and wind forecast data (e.g. at the European Centre for Medium-Range Weather Forecasts, ECMWF), solar irradiation and wind maps for solar and wind-plant installation and operation planning as well as accuracy improvements in assessing hydroelectric plants.

Telecommunication satellites are currently mainly used for rather isolated cases, such as grid-node connections in isolated remote sites or when the rapidity of deployment is critical, or in general as secure / backup channels.

While dominated by incremental improvements over decades, the electricity grid is expected to change radically over the next few decades. In the words of the European Commission, "*Electricity networks have to respond to three interrelated challenges – creating a real internal market; integrating a massive increase of intermittent energy sources; and managing complex interactions between suppliers and customers.*"[2)] Interestingly, the second and third of these challenges have been identified already in 2004 during a conference on the prospect of solar power provided from orbital platforms organised by ESA as representing a clear need for solutions provided ideally from space.[31)] The subsequent study "space4energy" with in the General Studies Programme of ESA was confirming this assessment and laying the foundations of ongoing activities in this field by ESA ever since.[32)] The main objective of the study has been to evaluate the contribution of space technologies in terms of

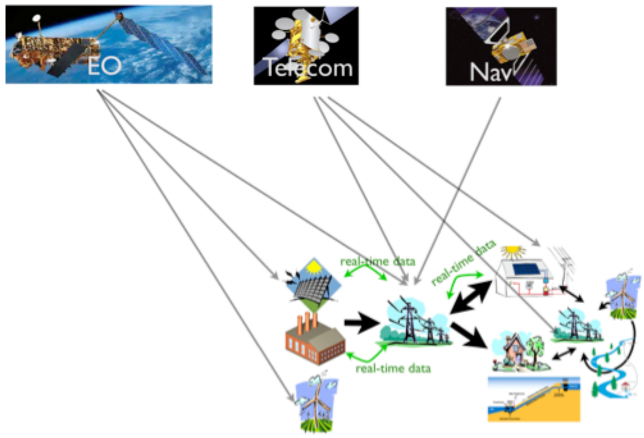

Fig. 6. Expected space contributions to future energy grid organisations.

Earth observation, telecommunications and navigation satellites applied in the electrical power grids management, when distributed renewable energy plans are present in the grids. A quantitative assessment has been carried out in terms of well-identified indicators. Improvement by space technologies have been assessed related to a better exploitation of the renewable resources (power grid generation) and to an improvements on power grid performances (power grid distribution), which were substantiated by realistic simulations.[32), 33)]

The future energy grid is very likely to resemble a much more diverse and complex system. The clear separation between producers on the one hand and passive consumers on the other is expected to gradually blur. Very likely there generation side will be characterised by a mix of some large power stations combined with many small electricity generators. These will range of small microplants, connected to local microgrids to even consumer side fuel cells in buildings or cars connected to renewable energy sources. Most prominently, the share of small, renewable and thus intermittent energy sources is likely to be substantially larger than today, requiring not only a efficient distribution of so generated power but also a reliable forecast of their generation level and location. At least part of the now essentially passive consumers are likely to take advantage of the market power that smart meters and the added control over their own or shared generation and storage are likely to provide.

The electric grid will therefore need to be able to provide full two-way electric flow connected with high-precision and secure data. It will furthermore need to accommodate a high and very diverse number of very small, intermittent producers alongside medium and large generation plants and optimise the distribution of electricity, taking into account geographical, specificities, weather now- and forecast as well as expected consumption patterns dynamically changing similar to stock prices. A schematic layout of such a system, together with potential contributions from space is shown in fig. 6.

7. Conclusions

Energy choices have changed almost every aspect of society, economy and even politics during the last 200 years. The upcoming changes in our energy system are expected to be the most substantial at least since the introduction of nuclear energy about 40 years ago. The massive introduction of renewable power sources and the changes in the electricity distribution system are multiyear, even multi-decadal processes. Energy systems developed for space applications have since 50 years been developed and used with requirements of long-term sustainability and efficiency and space can therefore be considered as a lead market for such technologies. In addition to transferring some of these technologies, services provided from and via space applications have some unique characteristics that can help in this crucial transition into a carbon-neutral, possibly post-fossil fuel energy system.

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