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SPACE AND ENERGY - CURRENT STATUS AND OUTLOOK

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Abstract

The 19th century has brought one of the most dramatic change in the energy system fuelling human activities after the discovery of fire: from a biomass burning society at its beginning to a society obtaining 80% of its primary energy from fossil fuel (coal) burning at its end in western economies. The 20th century has seen two further radical changes: the introduction of two other forms of fossil fuel, oil and gas, enabling the emerging transport industry and the introduction of nuclear power, together reducing the share of coal to less than 20% at the end of the century.

Gradually, a consensus has emerged over the last years that, after decades of relative stagnation, the energy sector is bound to undergo substantial changes over coming decades, driven by a combination of energy security and independence concerns, energy competitiveness and efficiency, and energy-related environmental effects.

The space sector has been a lead market for some terrestrial energy technologies. Space-based sensors already allow optimising the location of renewable power plants and improving the efficiency of electric power grids. Technological advances in energy systems for satellites benefit ground applications. While small with respect to the economically large energy sectors, space can significantly contribute to it. Its potential contributions are multiplied by the expected changes to the energy sector for the next decades.

This paper provides an analysis of the current status of space and energy related activities and presents an outlook of potential future contributions.

Keywords: energy systems, sustainability, space and energy

1. INTRODUCTION

The 19th century has brought one of the most dramatic change in the energy system fuelling human activities after the discovery of fire: from an almost entirely biomass burning society at its beginning to a society obtaining almost 80% of its primary energy from fossil fuel (coal) burning in western economies. The 20th century has seen two further radical changes: 1. the introduction of two other forms of fossil fuel, oil and gas, enabling the emerging transport industry and 2. the introduction of nuclear power, both together reducing the share of coal to less than 20% at the end of the century. The introduction of civilian nuclear power plants in the second half of the 20th century has diversified the electricity generation in some countries, which however still remains dominated by coal powered plants. In its 2010 World Energy Outlook, the International Energy Agency (IEA) predicts that "globally, coal remains the dominant source of electricity generation in 2035, although its share declines from 41% in 2008 to 32% by 2035. In OECD countries, coal-fired generation drops by one-third between now and 2035, becoming the third-largest source of electricity generation." [1]

Gradually, a consensus has emerged over the last years that, after decades of relative stagnation, the energy sector is bound to undergo substantial changes over coming decades, driven by a combination of energy security and power supply dependence, energy competitiveness and efficiency, and energy-related environmental effects. In the words of the IEA, we face an "urgently needed transformation of the global energy system" towards a more sustainable, de-carbonised energy system.[1]

The space sector has been a lead market for some terrestrial energy technologies. Space-based sensors already allow optimising the location of renewable power plants and improving the efficiency of electric power grids. Technological advances for energy systems for satellites benefit ground applications. While small with respect to the economically large energy sectors, space can significantly contribute to it. Its potential contributions are multiplied by the expected changes to the energy sector for the next decades.

This paper provides an analysis of the current status of space and energy related activities and presents an outlook of potential future contributions.

1.1. Why space should consider contributing more to the energy sector?

There is a widespread current consensus that global climate change is one of the most important challenges for humanity for at least the first half of the 21st century. The energy sector is one of the most important emitters of CO_2, the most important greenhouse gas. Stabilising climate change at 2°C implies stabilising carbon emissions. These in turn are dependent on the combination of power sources we use and energy technologies.

Contributing to solving the energy challenge can be considered as:

1. A duty for ESA as a responsible organisation with the means to contribute, as well as
2. An opportunity to develop the space sector for new users and applications.

Barrett [2] argues that emissions of CO_2 and other greenhouse gases can be reduced significantly using existing technologies, but stabilising concentrations will require nothing less than a technological revolution, because it will require fundamental change, achieved within a relatively short period of time.

Along the same lines and based on the insight of the International Energy Agency, Dordain [3] emphasises in "Agenda 2015", the most recent strategy document for ESA, the importance of the energy sector and its potential for space:

> "According to the OECD, achieving global energy security, climate change and energy access goals will require nothing short of an energy revolution, implying major improvements in the full set of low-carbon energy technologies, as well as unprecedented intervention by governments in developing policies that work with and influence energy and consumer markets. In all energy scenarios, the world primary energy demand increases until 2025, mainly driven by developing countries, reflecting their faster rates of growth of economic activity, industrial production, population and urbanisation. Renewable energy sources (solar energy, wind etc.) will have to play a central role in moving the world onto a more secure, reliable and sustainable energy path, especially for electricity demand, which is expected to grow more strongly than any other final form of energy, however with fossil fuels still providing the majority of our energy. Around 2025 the energy question is expected to remain also a source of major tension (economic and geopolitical)". [3]

The energy sector is unlikely to seek potential space solutions of its own initiative. The two sectors, have too few traditional links and connections. It is therefore necessary for the space sector to take the first steps. First promising applications and technologies are most likely small niche applications for the energy sector but at the same time potentially large for the much smaller space sector.

1.2. ESA's space and energy initiative

ESA has therefore started in 2012 a new initiative targeting specifically the energy sector. This initiative builds upon recent and ongoing activities performed across ESA since many years. A first step, initiated in 2008, consisted of an analysis of those activities, leading to the internal coordination of those efforts. This further allowed to increase their visibility outside and, through their coordination, the formulation of new, more ambitious overall goals.

ESA has been contributing since years to the energy sector in various domains, mainly via its General Studies programme [4, 5], the Earth Observation programmes [6] and Integrated Applications programmes [7], but also with activities in the Human Spaceflight [8] and Technology directorates [9]. The ongoing activities have established initial working links with the European Commission on the topic [10]. Even before, already several projects were funded by the European Commission. [8].

These activities are mostly targeting the development of applications based on existing means. The objective of the new cross-cutting initiative is to develop or spin-in the necessary technologies and identify infrastructure and equipment that would be needed to expand further the support of the space sector to the energy sector.

This initiative is made of two components, which are described in section 3:

1. "Space and energy technologies", exploiting the technological synergies between the two sectors;
2. "Infrastructures and equipment for new services", corresponding to a dedicated energy-related space programme, which involves specific and new space infrastructures.

2. SPACE AND ENERGY - TWO VERY DIFFERENT SECTORS?

For the purposes of the present paper, space is considered as a tool. As a consequence, the focus is put on the energy sector needs at large, and how space projects, technologies or applications can contribute to the current challenges and upcoming changes in the energy sector. In order for this *rapprochement* to be successful, a practical and effective mechanisms to foster the today still limited dialogue between these two sectors will need to be developed, and maintained. This requires going beyond generic and high-level exchanges by involving the specialists of the two sectors. Such detailed exchanges are needed to allow space energy technology experts to fully understand the plans, requirements, technical limitations and boundary conditions, R&D efforts and market expectations of the energy sector on the one hand, and on the other hand, to explain space technology and concept solutions to terrestrial energy sector specialists. As a consequence, ESA is currently engaging into such a dialogue, which needs to go beyond agency-level contacts relatively early in the process.

The following section of this paper therefore attempts providing an overview of the energy sector and based on its main characteristics presents a summary comparison of the two sectors. This comparison will allow appreciating their substantial differences, such as in market sizes, as well as some striking similarities. The first section is further subdivided into a short presentation of the current energy situation followed by an analysis of the main trends within the energy sector. A third, dedicated subsection is focussing on an analysis of energy transitions to better apprehend the change processes and their driving mechanisms of past energy transitions in view of benefitting for the preparation of upcoming ones.

2.1. Energy Sector

2.1.1. Current Energy Situation

Any energy discussion is fundamentally along one of the three main strategic pillars schematically depictured in Fig. 1:

Energy Security - i.e. the control over and timely access to supply;

Energy Supply and Competitiveness - i.e. the availability of energy should not be a limiting factor for social, economic, military or social policies; energy should be competitively priced since affordable energy has proven to be one of the key drivers of industrial growth;

Environment and Climate - i.e. Energy systems (power generation, energy conversion and storage) impact the environment; environmental secondary costs are increasingly factored into the overall tradeoff.

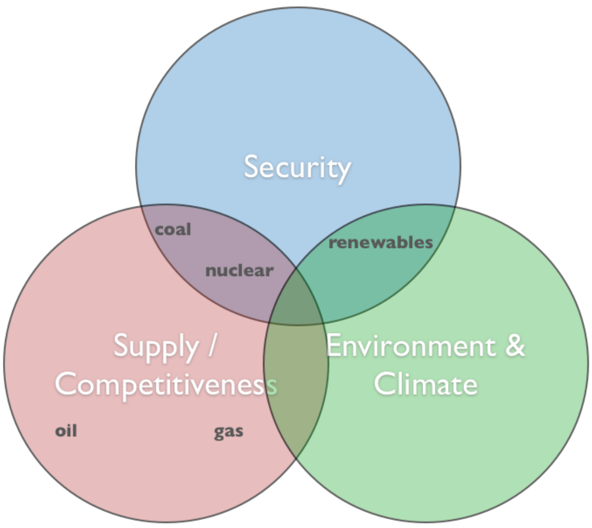

Figure 1: Three main elements of energy strategy discussions.

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. Power 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: "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." [11]

In 2008 the European Commission reports that imports comprise 61% of EU gas gross inland consumption. [12] 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 liquid natural gas. By 2020, as EU indigenous production continues to decline, the percentage of gas imports is expected to increase to 73% from 61% in 2008.

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." [11]

2.1.2. Main Energy Trends

Following the IEA, "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." [13]

The transport sector accounts for 97% of the average 1% annual increase in oil use until 2030. 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$/yr in case of the EU, 400 B$/yr in case of the 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 coordinated international mechanisms." [13]

Even under the most optimistic "green scenarios", the IEA projected that fossil fuels would remain the worlds vital source of energy. In the most likely scenario of the IEA/OECD, the uses of all three main fossil fuels are expected to increase until 2030, mainly due to the needs in developing countries.[1, 13, 14]

In a business-as-usual scenario, world primary energy demand would 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% per 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, excluding hydro) are growing most rapidly, their low current share will only increase, from 2.5% in 2007 to a total of 8.6% in 2030 in a business following current policies. Wind power is expected to see 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.[14]

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. [14]

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 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 is projected to 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 by about 20% in 2009 compared to 2008.

Specific to the photovoltaic sector, given it's paramount importance for space missions, photovoltaic technology has progressed considerably fast in the last years and it still shows high potential for further development, resulting in dramatic cost reduction of the photovoltaic module: thanks to the increasing competitiveness, the photovoltaic industry is expected to assume more and more importance within the Energy sector.

Almost 30 GW of new photovoltaic systems were connected to the grid worldwide in 2011, about 40% more than the new installations in 2010 (reaching the cumulative installed capacity of almost 70 GW). [15]

Analysts concur that the global demand for photovoltaic installations will continue to grow in the coming years, when a slower growth in Europe, due to reduced support schemes and to financial limitations, will be compensated by Asia and USA increasing their share of PV installation demand. [16]

2.1.3. *Energy transitions*

Energy transitions of the amplitude of the one that is argued to be required in order to put the world energy system onto sustainable footing have happened in the past. It is therefore useful to try to understand the mechanisms how these occurred and what factors influenced their speed.

Fouquet has recently published a review of past energy transitions with the explicit goal to "identify features that may be useful for future transitions". [17] While not surprisingly, Fouquet reports that the main economic drivers identified for energy transitions were the opportunities to produce cheaper or better energy services, the study also found that "the existence of a niche market willing to pay more for these characteristics enabled new energy sources and technologies to be refined gradually until they could compete with the incumbent energy source." [17]

Following this logic, it can be argued, that the increasing importance of renewable energy sources in general are an indicator for a possible upcoming energy revolution. Within the mix of renewable energy source, the solar energy utilisation is the fastest growing subsector, even if still at a relatively low overall importance as highlighted in the section above. The space sector has been what Fouquet termed the *"niche market willing to pay more"* for photovoltaic technology, maturing it and gradually increasing its competitiveness.

The durations of past energy transitions range from 50 to more than hundred years, counting the time from the innovation to uptake and to diffusion. While this is not a natural limitation for energy transitions to come, it underlines the relative conservativeness and inertia of the energy sector, and provides a frame for planning for any upcoming transition.

Fouquet [17] concludes that "a successful transition will need governments to provide protection of this niche market, possibly for decades" and that based on past experiences, a complete transition to a low carbon economy is likely to be very slow. Space is one of such niche markets for advanced photovoltaic technologies in particular and for very high energy efficiency technology in general.

2.2. Space and Energy Sectors - Overview Comparison

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 fundamental differences. Most importantly the overall market size and the maturity of the energy market with respect to the space market, which is essentially still largely dependent on governmental needs, requirements and investments. [12, 18–24]

The total investments and market sizes show the orders of magnitude difference between the two sectors: 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 were estimated as coming from the US government alone). The relative repartition of the space market into major segments is shown in Fig. 2. [24] These are furthermore concentrated on a few countries and linked usually to high strategic values.

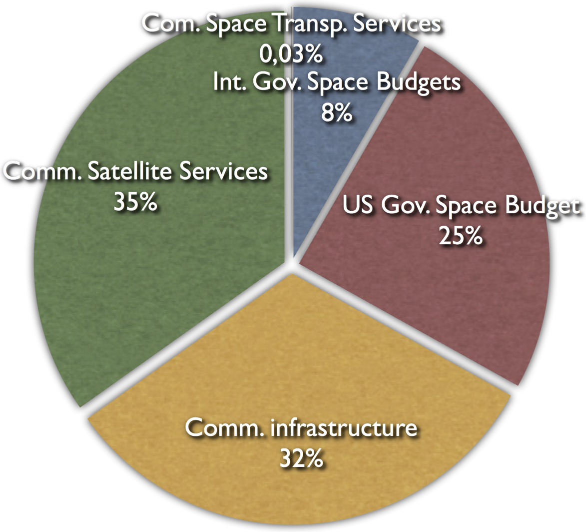

Figure 2: Repartition of the global space sector (graph based on data provided in [24])

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. [21]

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). [21]

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 authors, 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 in 2009.

Specific to the photovoltaic market, space applications occupy a minuscule niche of this market in full expansion (few MW for space compared to tenths of GW per year for terrestrial applications); nevertheless, it has always played a key role from the technology development point of view: as a matter of fact, driven more by performance improvement requirements rather than by cost reduction at photovoltaic component level (because the cost reduction at spacecraft system level induced by the improved performance is much more relevant), the space solar cell development has often been the precursor for terrestrial photovoltaic performance advancements. It is still the case for one of the emerging technologies for large terrestrial solar plants: the concentrator photovoltaic (CPV) installations are based on high efficiency solar cells (multi-junction III-V compounds solar cells) developed for space applications.

3. ONGOING 'SPACE & ENERGY' ACTIVITIES

3.1. Institutional Cooperation

Within the general frame of an increasingly closer cooperation between the European Union (EU) and ESA, the two organisations have started some reflections 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 includes all potentially concerned directorates in ESA. On the EU side, the natural interface is the Energy Directorate General. [10]

The joint reflection has identified in 2010 the following potential thematic fields of cooperation between ESA and EU in the fields of energy and space: [10]

1. Transfer of technologies – Short to medium term
2. Transfer of technologies – Long term
3. Space-born power sources – Very long term
4. Use of space data for optimising (e.g. the location of) energy installations – Short term
5. Use of technologies for monitoring – Short to medium term

The identification of key EU technology challenges to meet the 2020 targets have been defined by the commission [25] 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 decentralised 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 identified the following key technology challenges to meet Europes ambitions for the 2050 vision [25]:

- 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.

Nearly all these key technology challenges were addressed by one or several of the proposals that ESA has proposed at the end of 2009 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 Sabater for details, the themes of these are recalled here. It is worth noting that these are by no mean 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 quickly were taken into account.

Under the heading of space applications for energy policy enforcement, the following two activities were 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 were 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

Under the technology transfer heading, two specific activity proposals were identified as being ready for immediate implementation:

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

A joint EC/ESA presentation of the project was given to the FP7 Energy Programme Committee on 1 October 2009 in order to draw attention on the potential of space activities to support the evolution towards a low-carbon society. The Committee suggested the organisation of a workshop with space and energy experts to validate the interest of the proposed working together and to identify proposed lines of action. This workshop was held on 15 January 2010 with the following conclusions:

a) The added value of space and energy activities is widely recognised together with the important scope of cooperation;
b) There is a need for further and deeper discussions with all the actors and the existing networks
c) There is a need to continue understanding concrete action options and to put in place a process for continuation

d) There are already potential actions that could start immediately
e) ESA and EC to build a work programme that should lead to a programme proposal for the upcoming highest decision body within ESA, it's council at ministerial level.

The recommendations on the areas to exploit were the following:

- On Policy enforcement: Bio-fuels, Energy efficiency, CO_2 storage, Monitoring of infrastructure projects and Applications in transport
- On Applications for energy system management: Mapping of renewable energy resources, Carbon Capture & Storage and Smart Grids
- On Technology Transfer: Robotics, Materials, Energy storage, Monitoring and maintenance. Priorities in technology transfer have been identified for:
    1. Energy storage for renewable energy sources and vehicles
    2. Thermal control technologies
    3. Advanced materials
- For Long-term research, large areas of potential collaboration have been identified. Given the number of topics identified for these two categories of research, it was stated that ESA research should build links with EERA and other research organisations in Europe, and detailed expert discussions should be promoted to define an R&D programme.

Since 2009 some of the initial projects that were proposed have started or made progress in the frame of the "normal" ESA activities, without a specific support from the EC, while some were selected by the EC through their processes. Progress has been slowed down by the reorganisation of EC (responsibility of energy going from the then DG TREN to DG ENER with a change in the staff responsible).

Following a suggestion of the EU Energy Programme Committee, the EC decided to include some elements in its FP7 Call 5 "Work Programme 2012 - Cooperation - Theme 9 - Space" [26, 27], but not in the "Energy" theme. This was meant to trigger some initial reflections on the subject. The activity "SPACEKey technologies for in-space activities" states:

> "To allow cross-fertilisation for these energy supply relevant topics, possible future terrestrial applications of technologies could be identified to meet power generation and storage needs, as well as adaptation of technologies currently used on earth for enhanced performance in space." [26]

Discussion are expected to restart with the EC to understand whether the energy sector can mature towards understanding the potential benefits of closer collaboration with the space sector. A conference is planned for 2013, at the request of the Bavarian Ministry of Economic Affairs, on "Energy and space" to bring the two communities together.

In the mean time, and in view of the preparation of the ESA Council at Ministerial level in November 2012, a specific line of activity is being proposed to ESA Member States on two lines of action: space technologies that could be useful to energy technologies, and the identification of space infrastructures and equipment that could provide new services. These two lines of action are presented in the next chapters.

3.2. Space and energy technologies

Space has shown its potential as a lead market for terrestrial energy technologies (e.g. photovoltaic). In addition to further improvements in this area, space can also play a similar role for the research and development of high-energy density advanced storage technologies, a key requirement for the decarbonisation of the transport sector. ESA-led research on metal-powder based energy storage and ESA's established cooperation with non-space industry showing their strong interest in the topic already provide a solid basis for further up-scaling. Another well-known case concerns the heat pipes, invented for space applications in 1963 and not only largely used as thermal control systems in space but also a spin off technology for terrestrial applications, such as air conditioning, electronic cooling, heat recovery, temperature stabilisation. Identified technological areas for high potential synergetic developments are: power generation, management and distribution, energy storage, hydrogen storage, thermal control, robotics, life support and recycling technology and remote sensing. In the following lines, we provide a non-exhaustive overview of synergetic technology development areas, as identified and discussed in a dedicated workshop with Space Industries and Energy Sector representatives organised by ESA in June 2012. [28]

3.2.1. PV technology and power management design.

The Space application is a minuscule niche of the Photovoltaic market (few MW compared to tenths of GW per year); nevertheless, it has always played a key role from the technology development point of view: as a matter of fact, driven more by performance improvement requirements rather than by cost reduction at photovoltaic component level (because the cost reduction at spacecraft system level induced by the improved performance is much more relevant), the space solar cell development has often been the precursor for terrestrial photovoltaic performance advancements. It is still the case for one of the emerging technologies for large terrestrial solar plants: current highest efficiency cells are "multi-junction" III-V compound-based technology cells using different materials to absorb different wavelengths of light. Developed for space (radiation hardened, but high cost), this solar cell technology is a cost effective option for large scale terrestrial power generation when used under optical concentration. Under ESA funding, European Industry and Research Centres developed and qualified GaAs based triple junction solar cells with an efficiency approaching 30% in 2009.

In other words, a derivative of the space solar cell is now available for terrestrial concentrator systems, using the experience and technology developed for this triple junction space cell: based on similar solar cell design adapted for the different operation conditions, space and terrestrial CPV applications provide the benefit of combining the long experience of manufacturing space solar cells with the much higher production volumes required for terrestrial CPV. [29]

GaAs based concentrator photovoltaic systems, which are particularly suited for areas of high direct illumination represent only a very small fraction of the terrestrial market at the moment (lower than 1%). Nevertheless, thanks to a cell efficiency of 50% to be expected by 2020, these systems have the potential to capture a much bigger share of the market, which is expected to grow in total to over 100GW per year by 2030 according to pessimistic scenarios (IEA) and much faster in accelerated scenarios. In the short term, the space market for GaAs based cells is likely to remain more significant than the terrestrial market. It is clear that synergies and communalities in the space and terrestrial cell technology further developments play a major role in the affordability and competitivity in both markets. Moreover, the terrestrial PV manufacturers and users would benefit from the space know how for GaAs cell reliability and for power management and distribution. As a matter of fact, the reliability issue is now crucial for terrestrial photovoltaics, in absence of previous experience, as the lifetime of the PV modules is an important factor in the energy cost calculation.

3.2.2. Energy Storage (Batteries and Fuel Cells)

Space battery technology is generally a spin-in from terrestrial technology, however in some cases the space niche application has developed faster than the terrestrial mass production (like Li ion battery, largely used for spacecraft and not yet in terrestrial automotive). The testing and modelling activities performed for space are very relevant to terrestrial energy, for example for automotive application. While for advanced next generation developments, the space application can only make efforts to follow the R&D progress and ensure that the space requirements are taken into account, a leading role is played by space in the device modelling, an area where joint space and energy development activities are envisaged.

Although most of ESA fuel cells differ from terrestrial energy technologies due to the mission and performance requirements, the basic hardware development up to a TRL 4 to 5 requires the same development effort. Space and energy synergetic developments performed in the past in the frame of ESA programmes include studies on Regenerative Fuel Cells (electrode / electrolyte membranes have been developed which allow for cheaper mass production of high performance and highly efficient terrestrial electrolysers for production of ultra clean hydrogen avoiding fossil fuels), Liquid / Gas Phase Separation development (investigation in detail of the benefit to employ this system to improve closed hydrogen loop design efficiency, water and thermal management in fuel cell powered zero-emission cars). A synergetic development is envisaged to design, manufacture and test a regenerative fuel cell system (RFCS) in the range of 5 kW and a life test with a power profile relevant for human exploration, e.g lunar rover. Such regenerative fuel cell system can also be used for terrestrial applications like small stationary power plants. Fully autonomous power plant could be set up by associating a RFCS with a renewable energy source (sun, wind).

3.2.3. Hydrogen production and storage

Hydrogen can be produced from a variety of feed stocks; in the past from natural gas and coal, in the future from renewable resources, such as biomass and water. The slush hydrogen production technology, which offers a method to design more compact launchers without compromising the performance, has been identified as one of the technologies which is of interest for applications also outside the space sector. A pilot plant, to demonstrate the technology which is suitable for large-scale production of slush hydrogen (SLH2), is under test.

SLH2 would enhance the benefits of hydrogen storage: local/regional storage of hydrogen, produced from water during periods with excess capacity from wind and solar power, can be used as an energy buffer; the produced hydrogen is also a potential source of energy for fuel-cell powered vehicles, where compact and safe storage of the hydrogen can be offered with the SLH2 method.

While hydrogen is one of the main candidates for automotive and aeronautical applications in the future, the slush technology can be used with liquid natural gas (LNG) as well, with not only the advantage of increasing the cryogen density, but also avoiding boil-off and consequent emissions of methane, a very potent greenhouse gas.

For LNG, with infrastructure modifications for slush production, ship transport and storage could be made more efficient and environmentally friendly. The SLH2 pilot plant could be used also for trials with slush natural gas production. Within ESA Future Launchers Preparatory Programme, storage of cryogens (LH2 and LHe) have been subject of study in different activities: much attention is focussed on ways to reduce mass of major stage components, such as tanks, feed-lines and inter-stage structures, by applying CFRP.

For vessels which have to be designed to hold cryogenic propellants achieving sufficient leak tightness is a major challenge. The state-of-the-art is that technological solutions exist for reducing leakage and boil-off levels sufficiently to offer an attractive alternative to other methods for storing hydrogen for use in hydrogen powered vehicles. The next step will be to compare requirements for launcher and satellite applications to the needs of automotive and aeronautical industries in order to see what adaptations the technology suitable for terrestrial use can make.

3.2.4. Thermal control

In the thermal control domain there are a number of technologies which are very beneficial to improve/optimise energy conversion processes and /or reduce thermal losses; and thereby reducing the energy need for additional heating/cooling. Heat pipes providing high efficient heat transport and the possibility to iso-thermalise areas have been largely used for spacecraft, each platform hosting several hundreds of such devices. More recently, two-phase heat transport systems (heat pipes and especially in the last years loop heat pipes) have been developed for a number of space applications and have become the baseline for advanced thermal control systems.

Based on the experience gained for space, the objective is to adapt and extend the design (different working fluids, different container materials, etc.) of such devices for terrestrial use. Heat pipes could be integrated into batteries and fuel cells, in order to efficiently remove the dissipated heat, to better control the temperature levels and profiles in such devices, thereby increasing the efficiency of the energy conversion process in such devices.

Moreover, for the two-phase heat transport (heat pipes, loop heat pipes) technology area, the following synergetic developments can be envisaged, to make heat recovery more efficient also in terrestrial applications:

1. providing heat recovery with hermetically separated sides (e.g. heat pipe heat exchanger which guarantees that hot but "dirty" exhaust air is not mixed with the clean air to be heated)
2. providing heating at one place using waste heat from another place, transport function making processes more efficient by removing "waste" heat at the source,
3. cooling of electronic equipment (like electrical motors, computing centres, etc.).

The use of solar energy using conversion processes based on higher temperatures (use of solar concentrators) and thermodynamic cycles (e.g. Stirling cycle) can provide high conversion efficiencies. For such process high temperature loop heat pipes can provide efficient means to transport the heat from the solar concentrator to the thermodynamic cycle (e.g. Stirling engine). Such high temperature LHP – using liquid metals as working fluid – will need to be developed.

Another area of synergetic development for space and energy applications is in the temperature-dependent thermal coatings, which change their thermo-optical properties with temperature such as to minimise the need of electric heater power. While for space the interest is in minimising the need of electrical power during eclipse, the terrestrial application interest is in building thermal control, for instance by reducing heating from sun during day time and avoiding losses at night. The mechanism how to change the properties – either passively as a function of temperature or actively by applying an e.g. electric field will need to be addressed, taking into account weather resistance, long-time exposure to atmospheric conditions and long-term stability under such conditions.

Another area of synergy is the thermal Insulation and heat storage for industrial processes and buildings: based on materials investigated for insulation for e.g. Mars environment (e.g. Aerogel), it is worthy to investigate to what extent such materials can be used for insulation of buildings and/or industrial plants. Also technologies for heat storage based on phase-change materials (PCM) will have to be investigated for their use in terrestrial applications.

3.2.5. Robotics and remote control

A study performed in the frame of the ESA Technology Transfer Program (TTP) [30] has identified future opportunities in the synergies between automation and robotics (A&R) technologies from space and the oil and gas (O&G) sector. According to the study, trend to introduce more autonomy in oil and gas operation (e.g. subsea operations) is expected to attract the interest in the advanced technologies offered by the space industry. The advantage of advanced remote operations would not be only economical, i.e. in terms of increased efficiency and reduction of human resources costs, but especially in terms of improved safety (e.g. subsea, in the Arctic and in the desert).

The guidelines conventionally adopted in operation in the Oil and Gas sector are: to keep the manipulation system simple and to program task execution not through SW but, rather, through the engineering of specific and effective tools which are easily operated by robots. For instance, the conventional Remotely Operated Vehicle with manipulators, remotely operated from surface can be upgraded with vision systems developed for space and by space robotic controllers; these technologies could be integrated with subsea-graded hardware. The added value of space technology is expected to become significant in correlation with the introduction of more and more autonomy of undersea operations, which is taking place.

The same technology transfer study highlighted that the robots in the offshore industry are not yet as widely used as they could be and that the relevant technology is often not state-of-the-art. Nevertheless new technological challenges (ultra-deep water, Arctic seas, sour fields, unattended platforms) are expected to foster the utilisation of robotics in the O&G industry. It is expected that more autonomy and task complexity are going to be pursued, in conjunction with the following trends:

- tendency to reduce the dependence of the operations on the surface vessels or even to eliminate such a dependence due to the increasing costs in deep water operations, where the vessel must be equipped with Dynamic Positioning system;
- wider use of AUVs (Autonomous Underwater Vehicles), i.e. free-swimming, unmanned submersible vehicles, initially used for long range surveys in the scientific and military communities and now adopted by the O&G industry for tasks ranging from sea floor mapping to light inspection maintenance and repair tasks;
- tendency to remove human operators from the operation field, both for the harsh environmental conditions (e.g. in the Arctic region or for the risks associated with leakage of H_2S gas) and for cost reasons.

Space technologies of potential interest include:

- vision systems and real-time capable stereo camera for inspection purposes,
- lightweight robotic arms and sophisticated robotic manipulation and robotic controllers,
- haptic rendering applied to virtual reality,
- navigation software,
- teleoperations, and
- control stations.

In summary, the new drive of the Oil and Gas Industry towards A&R comes from: the need to find new sources of energy in regions ever more inaccessible or dangerous (e.g. Arctic), the need to operate equipment with increased safety and profitability (e.g. Integrated Operations), and the need to implement new ways of drilling and production (e.g. sea-bed drilling).

Considering the needs of the energy industry and the needs of space, it is possible to identify some technology activities that have the potential to serve well both sectors:

NOvelty or Anomaly Hunter (NOAH). NOAH endows a robotic explorer with the ability to autonomously perceive and understand their environment, so that it can look for phenomena at any time and any place and record them at their occurrence. This can be useful in the routine surveillance of pipelines, which at present involves thousands of people that drive continuously along the hundreds of kilometres of pipelines in search of leaks. Driving in monotonous desert environment causes several death every year.

Autonomous Quester for Underwater-space Activities (AQUA). AQUA is a global scale navigation software that allows an autonomous robot to succeed in the quest of a distant geographical goal, in absence of global localisation means. Autonomous Underwater Vehicles (AUV) are increasingly used for ocean research. These means are also being proposed for the logistics of arctic sea-bed installations (i.e. supplying material from a surface platform to the possibly far seabed installation). Underwater platforms cannot use GPS to navigate, so they face similar type of problems surface probes face on the Moon, Mars and Europa.

Haptics Telemodeling (HAT). HAT aims at developing a tactile system (made of sensor applied to robotic arms and suitable software) that can reconstruct/(register) a scene (with previous model) by tactile exploration. Remotely Operated Vehicles (ROVs) are often required to operate in very low visibility, due to the murkiness of the water. Sometimes nothing can be seen at all, neither by eye nor by alternative sensor techniques, and the operation has to be aborted.

3.2.6. Life support and recycling technology

Advanced recycling technology is developed to provide the space manned mission with needed consumables (e.g. water, air, food), minimising the mass, the volume and the energy consumption. The experience gained on the development and control of continuous microbial processes for space applications can support further developments of microbial fuel cells. Microbial fuel cells have so far demonstrated the capability of a bio-electrochemical system to produce energy.

Moreover, the experience gained on the development and control of continuous microbial processes for space applications can support further developments of biofuel production, in particular the production of photosynthetic micro-organisms in photo-bioreactor. Photo-bioreactor design for high cell density cultures raises few engineering challenges such as for instance light energy transfer, hydrodynamics, bio-compatible materials and predictive mathematical models, which are being studied. Another synergetic activity may be generated by the system analysis tool developed for life support system evaluation in space: both space and non-space system level resource management tools can be derived and developed. The methodology and simulation platform, including models, have so far focused on mass aspects. Future steps, will include a re-assessment of the energy models and reconsideration of energy fluxes analysis software.

3.2.7. Space weather effects

Time variations of the magnetic field affect magnetic surveying campaigns and directional drilling activities. Related induced voltages in ground systems affect voltage control systems on power grids and pipeline corrosion monitoring systems. Ionospheric scintillations on GNSS signal affect seismic surveying campaigns and precise location of platforms for drilling. Several studies and developments activities have been and still are being performed in the space weather domain with impact on the energy field, providing for instance real-time forecast service for geomagnetically induced current; quickmaps and history of the effects of ionospheric scintillations on GPS/GLONASS Signals; geomagnetic activity forecast, solar wind monitoring and induction modelling, simulation of geomagnetically induced currents in power systems; Influence of solar activity cycles on Earths climate, etc.

3.2.8. Remote sensing instruments (microwave instruments, radars; visible and infrared radiometers)

The energy sectors which take advantage of space missions using remote sensing instruments technology development include: windmills; fossil fuel deposit location; oil, gas and coal extraction; power distribution, hydroelectric energy generation; concentrator photovoltaics. However, rather than a synergy between the space and energy application of the remote sensing technology, this case is better described as service provided by space missions to the energy application. As such, the topic is only mentioned here for sake of completeness but is not further discussed.

3.3. Infrastructures and equipment for new services

This corresponds to a potential future dedicated energy related space programme, which would request specific and new space infrastructures. The objective would be to identify by 2015 if such programme is technically and financially viable for a short/medium term implementation. Three concrete topics, two short and one mid-to-long term ones, are proposed as typical examples for further, more detailed definition:

a) Space means supporting energy-related regulations; e.g. in support of energy efficiency management, independent verification of energy related regulations (international/legal) agreements; space-based tools might include high resolution thermal infrared instruments for energy demand and efficiency observation

b) Space means supporting the currently developed renewable energy infrastructure, including energy grids, increased efficiency and safety of infrastructure, building upon activities already performed within the ESA programmes on the topic
c) Space in support and complement of terrestrial very large-scale solar power infrastructure (type *Desertec*). Ambitious terrestrial solar power plant activities in the EU-MENA region are proposed since a few years with first plants being built. Space contributions are already made on an ad-hoc basis e.g. for plant siting, solar irradiation measurements (involvement of DLR), though much more substantial contributions can be elaborated up to the provision of power from space to reduce expensive storage needs and for power levelling.

The activities would include internal and external studies and research work in order to:

- analyse and perform research on future trends in energy matters and energy from space.
- identify the policies and regulations existing that concern the energy sector and where space programmes can help.
- perform a survey of existing and planned applications and services (involving both space and terrestrial solutions) that help or will help address those policies and regulations e.g. monitoring systems, detectors, infrastructure etc.
- identify user requirements in consultation with stakeholders (Member States, local and regional authorities, space and non-space industries, operators) to better understand the needs, inform on the potentialities of space programmes and define priorities.
- identify the elements that are not yet supported by a space programme or application
- perform internal or industrial feasibility studies for potential programmes or application.
- prepare a coherent programme proposal (or elements within programmes) for the following ESA Council at Ministerial level.

These activities will be performed in coordination and with the support of the Directorates at ESA potentially concerned. This initiative will put an emphasis on the involvement of participants from all Member States, taking benefits of the wide range of energy-related competences available across ESA Member States.

4. OUTLOOK - POTENTIAL SPACE CONTRIBUTION TO A SUSTAINABLE 21ST CENTURY ENERGY SYSTEM

While traditionally operating without strong ties, the previous section has demonstrated that a first analysis conducted mainly by space sector experts was already sufficient to identify a number of promising applications of current space technologies and services in the energy sector. The main focus of these examples were on the use of current or currently planned space developments for terrestrial energy market needs.

Given that this is the result of an effort by space experts to understand how space technologies and services can benefit the terrestrial energy market, it can be expected that a joint analysis will not only derive many more opportunities, but also allow to specify some of the existing ones to much more detail and in addition allow taking into account *future* requirements of the energy sector.

These will then allow updating the current space technology roadmaps to take into account market opportunities in the larger terrestrial energy sector and potential co-development opportunities between space and terrestrial energy technology R&D.

Going beyond the current R&D planning horizon, and thus beyond both ESA's Agenda 2015 and the EU's SET plan, and following the IEA's expectations of a new energy revolution which will radically de-carbonise the world's energy system until the middle of the 21st century, many more potential opportunities arise for space contributions to such a transition. Extrapolating the trend of increasingly integrated energy grids, regional, national and supranational / continental, the borderless and inherently global aspects of space-based services could play a role in monitoring, controlling and regulating increasingly complex energy grids. At the same time, the transition from centrally controlled power production units serving a relatively well known consumer pattern is expected to change radically with the introduction of two-way fluxes, power generating and energy storing consumers behaving individually in order to maximise their economic benefit is expected to challenge current grid management systems. 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. The characteristic of space-based services of being very local and regional/global at the same time could well constitute a unique asset for controlling such systems. A schematic layout of such a system, together with potential contributions from space is shown in Fig. 3.

In a visionary approach to decarbonising Europe's energy system, a new very large scale renewable energy solution has been proposed under the name of *Desertec*. It is essentially based on harnessing sustainable power from the sites in southern Europe, North Africa and the Middle East where renewable, essentially wind and solar energy is most abundant. At the core of the concept are very long high-voltage DC lines connecting the larger Mediterranean region. The concept can almost be compared with such major political efforts as the European Coal and Steel Community, the precursor of the current European Union. It can be argued that a concept such as the one proposed under the name of *Desertec* would have similar large scale effects of cooperation triggered and centred initially around common energy projects. Early studies have demonstrated that such a holistic approach, taking into account land

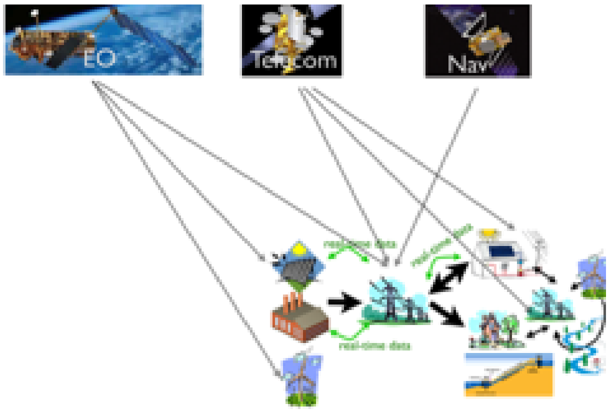

Figure 3: Potential space contributions to future electric grid organisation.

and water use, would offer an integrated solution to food and water shortages in the coming decades for the entire Mediterranean region. First attempts have been made to understand the potential of contributions from space for such a system. Storage requirements due to the intermittency of the main power sources are substantial cost drivers.

5. CONCLUSIONS

Energy choices have changed almost every aspect of society, economy and even international relations 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 multi-annual, 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 has functioned as a lead market for some of these 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.

The present paper has analysed some key aspects of the current energy sector, gave some indications on the activities started in the European Space Agency to analyse how space projects and programmes could support the energy sector, and presented some first steps towards a closer interaction between these two sectors. This would be based on the short term on the development of technologies benefiting both sectors and the identification of the type of infrastructure and equipment that would be needed to support the development of new services. The technologies considered were explicited as well as some steps to define support activities.

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